

ASSESSMENT OF DETERMINATION OF BIOGENIC GREENHOUSE GAS IN STACK USING THE BALANCE METHOD

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Keywords: INCINERATION PLANTS, GREENHOUSE GAS, BALANCE METHOD, BIOGENIC CARBON CONTENT

Abstract

Taiwan's public incineration plants face challenges in GHG inventories and carbon footprints due to inconsistent emission identification, factors, and data transparency, making comparisons difficult. While Scope 1 (Direct Emissions) and Scope 2 (Indirect Energy Emissions) are primary, Scope 3 (Other Indirect Emissions) exhibits uncertainty due to facility design and waste composition. Consequently, resulting estimates lack consistency and comparability. This study developed a consistent estimation framework for Scope 1 and 2 emissions from waste-to-energy incineration. Based on ISO 18466:2016 mass balance, a MATLAB computational model was created to estimate biogenic carbon content. The model integrates operational data and was validated against Bioma software and refined through plausibility tests and data reconciliation involving oxygen consumption and flue gas composition. Results showed the model's biogenic carbon fractions are consistent with Bioma, confirming validity. Application to multiple plants revealed that data quality, sampling locations, and plant-specific characteristics influence accuracy. Taking Lutsao Incineration Plant as an example, sampling points played a critical role, whereas inadequate data quality led to implausible results. Findings suggest certain ISO 18466:2016 criteria require refinement to reflect non-combustible materials and site-specific operating conditions. Overall, this study provides a practical foundation for improving accuracy and standardizing carbon accounting in the waste-to-energy sector.

1 Introduction

The public incineration plants in Taiwan primarily treat municipal and industrial wastes. However, substantial discrepancies frequently arise among facilities when conducting voluntary greenhouse gas (GHG) inventories or calculating service carbon footprints. These discrepancies are mainly attributable to variations in emission source identification approaches and emission factors, as well as the limited transparency and public accessibility of relevant data. Consequently, GHG inventory results differ markedly across waste incineration plants, hindering meaningful and mutual comparisons.

In organizational GHG inventories conducted in accordance with standards such as ISO 14064-1, assessments generally focus on Scope 1 and Scope 2 emissions that are directly controllable within facility boundaries. In contrast, Scope 3 emissions in product and service carbon footprint assessments, although typically smaller in magnitude, are characterized by high potential variability. Differences in plant design, operational conditions, and emission identification methodologies among waste incineration plants often result in inconsistent carbon footprint outcomes and the absence of a common basis for comparison.

- Scope 1 (Direct Emissions): Greenhouse gas emissions directly generated from sources owned or controlled by the organization.

- Scope 2 (Indirect Energy Emissions): Indirect greenhouse gas emissions from purchased electricity, steam, heating, or cooling consumed by the organization.
- Scope 3 (Other Indirect Emissions): All other indirect greenhouse gas emissions occurring throughout the value chain, excluding Scope 2.

The estimation of GHG emissions from direct waste incineration involves multiple sources of uncertainty and methodological challenges, including the selection of emission factors for municipal solid waste, the proportion of fossil-derived carbon, sampling frequency, and sample representativeness. These uncertainties are further exacerbated by variations in waste sampling and classification practices, such as differences in physical composition and combustible material categories (e.g., paper, textiles, wood and bamboo residues, kitchen waste, plastics, leather and rubber, and others), as well as sample selection procedures. As a result, substantial uncertainty commonly exists in emission calculations, particularly for emissions associated with fossil carbon combustion. In practice, the carbon content of waste — especially the biogenic carbon content — is often unknown, and carbon dioxide emissions are therefore typically estimated using default total carbon content values rather than direct measurements or calculations based on Intergovernmental Panel on Climate Change (IPCC) methodologies.

GHG emissions from waste incinerators could currently be estimated using emission factor-based methods, mass balance approaches, or direct monitoring techniques. Owing to the heterogeneous nature of waste streams, emission factor-based and mass balance approaches are most commonly applied in Taiwan. Under the EU Emissions Trading System (EU ETS), the European Commission has established the Monitoring and Reporting Regulation (MRR), which recognizes ISO 18466:2016 as an approved standard methodology for estimating GHG emissions by integrating monitored operational data with mass balance principles. The United Kingdom similarly recognizes ISO 18466:2016 as an accepted methodology. Although some waste incineration plants in Taiwan have adopted comparable approaches, the plausibility and uncertainty of the underlying operational data have not been systematically evaluated, resulting in potentially large errors in estimated GHG emissions.

In view of the substantial variability in existing emission factors and the limited transparency of available data, which collectively hinder comparability among facilities, this study aims to establish a representative and consistent estimation methodology and analytical framework for Scope 1 emissions from waste incineration. To this end, relevant domestic and international literature and regulatory frameworks were reviewed, and the ISO 18466:2016 standard methodology was adopted to develop a predictive model for GHG emission estimation and biogenic carbon content. The predicted results of the Model were compared with those generated by commercial software (Bioma) to evaluate consistency and reliability. Furthermore, the model was applied to calculate the biogenic carbon content of incinerated waste, thereby clarifying the rationality of biogenic GHG emission estimates and assessing the feasibility of applying ISO 18466:2016 to GHG emission estimation in public waste incineration plants.

2. Methodology

2.1 Development of software for estimating biogenic carbon content in incinerated waste

In this study, a computational prediction model was developed based on the mass balance approach specified in ISO 18466:2016 to estimate the biogenic carbon content of waste combusted in waste-to-energy (WtE) incineration plants. The theoretical framework of the model is derived from the mass balance methodology proposed [1].

To assess the applicability of this methodology under domestic conditions and to account for variations in waste characteristics and operational practices among waste incineration plants in Taiwan, a software tool comparable to Bioma was developed and tailored to local conditions in this study [2]. The model was implemented using MATLAB, and its outcomes were systematically compared with those generated by the Bioma software to verify consistency, reliability, and numerical agreement.

2.2 Plausibility test of operational data

Because the proposed method relies heavily on operational data from waste incineration plants, to estimate the biogenic

carbon content of the combusted waste, the plausibility of input data is critical to the reliability of the results. Accordingly, all operational data were subjected to plausibility tests prior to data reconciliation and model execution. This section describes the theoretical basis of the plausibility assessment.

Biogenic and fossil fuels differ substantially in carbon content and calorific value, which in turn result in different amount of oxygen consumption and carbon dioxide generation in combustion. Compared to fossil materials, biogenic materials consume less oxygen and generate less thermal energy. Therefore, by assuming that the waste is totally fossil or biogenic, a pair of upper and lower limit could be constructed. Because municipal solid waste cannot consist exclusively of either biogenic or fossil materials, in a plot of carbon content, or the plot of oxygen consumption vs lower heat energy value, the carbon content or the oxygen consumption from input data should fall between the limits. Input of operational data, such as the composition of the flue gas, offers the evaluation of the carbon content and oxygen consumption and also the steam conversion data offers the lower heating values.

2.3 Data Reconciliation Method

Data reconciliation was performed using a least-squares optimization approach within a linear programming framework. The waste feed was first partitioned into four components: non-combustible materials, biogenic combustible materials, fossil combustible materials, and moisture. With a set of mass and energy balance constraints, the optimal composition was determined by minimizing an objective function which was defined as the weighted sum of squared differences between measured and reconciled values of waste input data, flue gas data, and elemental compositions of biogenic and fossil-derived materials. Elemental concentrations of the combustible fractions of the biogenic matter and fossil matters, which are input parameters, are kept fixed throughout the reconciliation process. Boie formula is used to calculated lower calorific values of the biogenic and fossil fractions in both plausibility test and the energy balance equation in the reconciliation. An additional water balance is listed in the ISO 18466:2016, though it is allowed to be neglected as mentioned in the standard. Another balance equation called “Difference between O₂ consumption and CO₂ production” can be excluded from the reconciliation process, because this equation is in fact a linear combination of carbon balance and oxygen consumption balance and the three are linearly dependent [3-6].

The inverse of the covariance matrix was applied as the weighting factor to account for measurement uncertainty. Because the formulation is inherently nonlinear, ISO 18466:2016 approximates the nonlinear constraints using linearized expressions combined with an iterative solution procedure. Although this transformation guarantees the existence of a solution, the resulting reconciled values are not necessarily assured to fully represent actual operating conditions.

3 Results

3.1 Comparison of calculation results between the developed program and existing software

This section presents a comparison between the calculation results obtained using the MATLAB-based program developed in this study and those generated by the commercial software Bioma. Figures 1 and 2 show the plausibility checks of carbon content for Furnace No. 1 at the Houli Incineration Plant during September–October 2022. The two figures are nearly identical. The plausibility checks from our program and commercial software exhibit a high degree of consistency.

This strong agreement confirms that the plausibility screening procedures implemented in the developed program yield performs equally well comparing to the commercial software. The data qualification rate for the carbon-content validation is 93.44%, indicating that the majority of the operational data satisfy the plausibility criteria. Furthermore, a direct comparison of the biogenic carbon fractions calculated using the two software packages shows that the estimated values are nearly identical, thereby confirming the numerical correctness and computational reliability of the developed program.

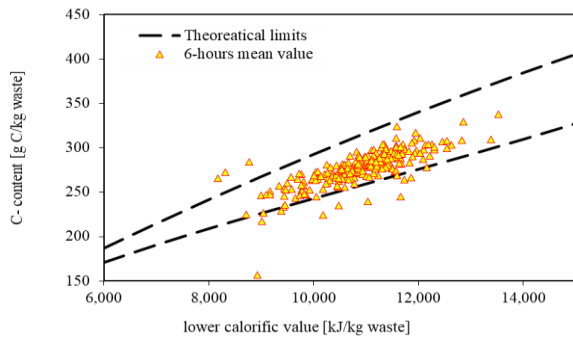


Fig. 1 Carbon content plausibility check for Furnace No. 1 at the Houli Incineration Plant (September–October 2022) using Bioma software.

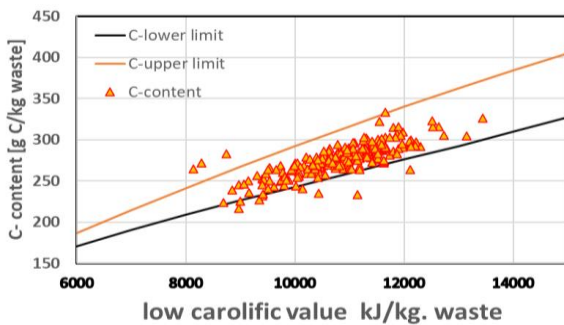


Fig. 2 Carbon content plausibility check for Furnace No. 1 at the Houli Incineration Plant (September–October 2022) using the MATLAB-based program developed in this study.

3.2 Calculation results for other incineration plants

After verifying the consistency between the Bioma software and the developed MATLAB-based program, the latter was

further applied to datasets from other incineration plants to evaluate its broader applicability. Figures 3 and 4 present the results for Furnace No. 2 at the Houli Incineration Plant during September–October 2022.

The plausibility checks reveal several anomalies:

- (1) the overall data qualification rate is relatively low;
- (2) approximately one-quarter of the data points exhibit abnormally low oxygen consumption; and
- (3) a large proportion of data points in the carbon-content validation plot exceed the theoretical upper limit.

These results indicate that the adopted dataset does not satisfy the plausibility criteria, leading to unreliable estimates of the biogenic combustible fraction. As expected, the biogenic carbon fractions obtained after data reconciliation are highly unrealistic. As shown in Figure 5, most values exceed 80%, and many are greater than 100%. These outcomes are consistent with the failed plausibility checks.

Operational experiences at the Houli Incineration Plant suggests that the flue gas passes through a scrubber for particulate removal, during which high-pressure air is frequently used to clean ash deposits in the ductwork. In addition, aged ducts allow ambient air infiltration through structural leaks by furnace effects. These factors substantially alter the composition of flue gas measured. Consequently, we turned to the stack flue gas data from the Chiayi Lucao Incineration Plant where the repairs of flue gas channel was just finished.

Figures 6 and 7 present the plausibility check results for carbon content and oxygen consumption, respectively. While the carbon-content qualification rate is high, the oxygen-consumption qualification rate remains low. Nevertheless, the calculated biogenic carbon fraction (Figure 8) appears highly reasonable, with most values clustered around 50%. The Lucao Plant case further suggests that reasonable biogenic carbon fractions may still be obtained even when the prescribed validation criteria are not fully met, implying that the current plausibility checks defined in ISO 18466:2016 may require refinement. In ISO 18466:2016, the upper limit and lower limit are the theoretical values when only biogenic matter or only fossil matter is attributed to the waste mixture, respectively and the lower heating value of the waste is subsequently derived from the recovered thermal energy. In standard, the limits are evaluated from the consideration that 1 g of carbon corresponds to a total amount of energy between 33.25 kJ and 44 kJ, and similarly to 1 mole of consumed oxygen corresponds to an amount of energy between 360 kJ and 400 kJ. The energy mentioned above are rather inaccurate and illogical. It is well known that combustible materials either fossil or biogenic, frequently contain considerable amount of hydrogen, which contribute considerable amount of energy and oxygen consumption while combusting. The assumption above wrongly singles out the contribution from carbon content neglects the contribution from other elemental ingredients.

Followed discussion points out some possible aspects that the refinements to the check could be fine-tuned and accessed.

1. The upper and lower bounds of LHV are calculated under the assumption of 100% combustible fuel, which is unrealistic for municipal solid waste due to the presence of non-combustible materials. In consistency, normalization to the fraction of the combustible in the waste are suggested, when evaluating the LHV of the waste.

2. The data conciliation in ISO 18466:2016 requires the fixed input data of the composition of the moisture and ash free biogenic and fossil matter. Nevertheless, once the composition is at hand, one can easily construct the limits for only biogenic matter or only fossil matter by Boie formula, and deploy them in the plausibility check instead of following those checks in ISO 18466:2016. And these limits could be more realistic than those suggested in ISO 18466:2016. In ISO 18466:2016 the limits are derived from the assumption that combustion of 1 g carbon corresponds to a total amount of energy between 33.25 kJ and 44 kJ, to 1 mole of consumed oxygen corresponds to an amount of energy between 360 kJ and 400 kJ, since the former is self-consistent from the point of view that using the same set of information, while the latter is rather inaccurate and illogical.

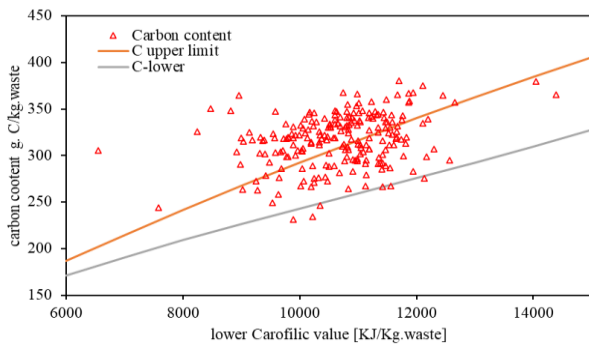


Fig. 3 Carbon content plausibility check for Furnace No. 2 at the Houli Incineration Plant (September–October 2022). using the MATLAB-based program developed in this study.

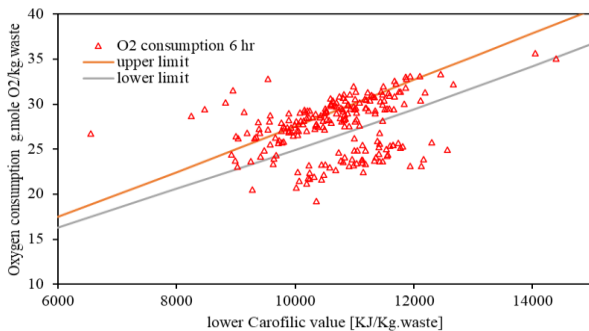


Fig. 4 Oxygen consumption plausibility check for Furnace No. 2 at the Houli Incineration Plant (September–October 2022). using the MATLAB-based program developed in this study.

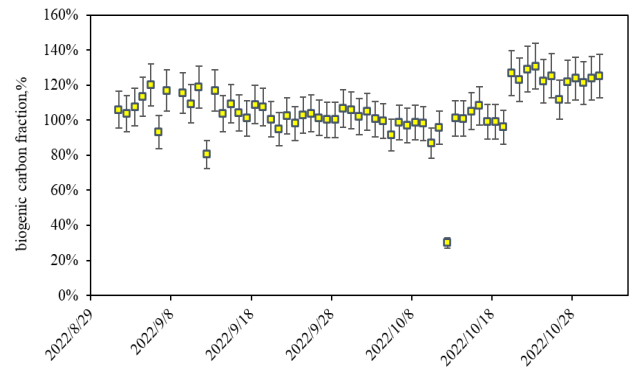


Fig. 5 Estimated daily biogenic carbon fraction of input waste for Furnace No. 2 at the Houli Incineration Plant (September–October 2022) calculated using the developed MATLAB program.

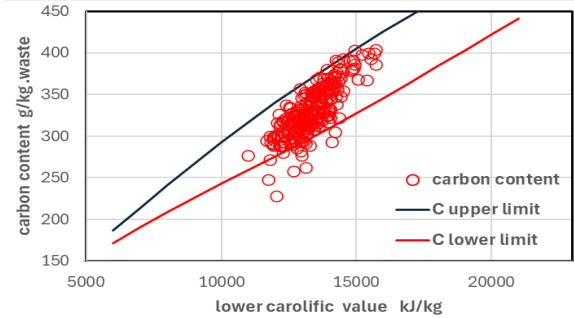


Fig. 6 Carbon content plausibility check for Furnace No. 1 at the Chiayi Lucao Incineration Plant (January–February 2025).

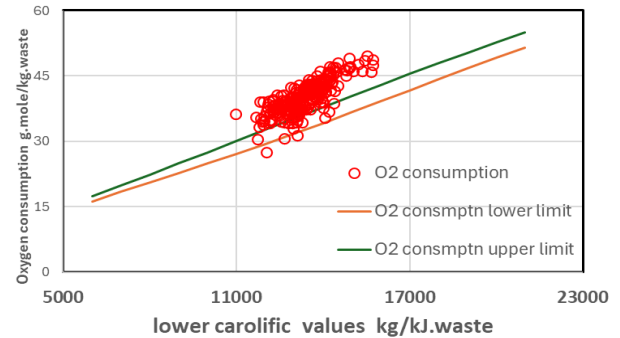


Fig. 7 Oxygen consumption plausibility check for Furnace No. 1 at the Chiayi Lucao Incineration Plant (January–February 2025).

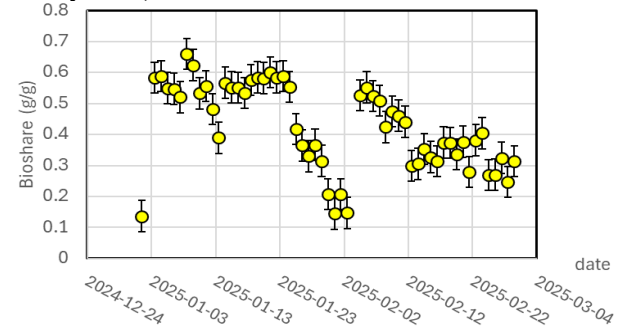


Fig. 8 Estimated daily biogenic carbon fraction of combusted waste for Furnace No. 1 at the Chiayi Lucao Incineration Plant (January–February 2025).

4 Conclusion

In this study, a computational tool based on ISO 18466:2016 was developed to estimate the biogenic carbon fraction of the mixture of municipal and industrial waste using operational data from waste incineration plants. The results from the developed software are consistent with those obtained from the commercial software Bioma, confirming its numerical accuracy and methodological validity.

Application of the method to the Chiayi Lucao Incineration Plant, though failed in the plausibility tests, still yielded reasonable and stable biogenic share, whereas its bioshare outcome at the Houli Incineration Plant was unsatisfactory due to the failure in data plausibility tests. These findings implied that the plausibility tests in the standard might need some fine tune to better reflect the characteristics of municipal solid waste and plant-specific operating conditions. Perspectives that the finetune could possibly follow are raised.

The developed software demonstrates promising potential for estimating biogenic carbon fractions in domestic waste incineration plants. With further methodological improvements, it may also be applicable to other combustion systems beyond municipal solid waste incineration.

5 Acknowledgements

This research was supported by a grant from the Climate Change Administration, Ministry of Environment. The views expressed in this report do not represent the opinions of the Ministry of Environment. Furthermore, we thank Professor

Fellner for providing the operational simulation software, which made this project possible.

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