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Evaluating carbon footprint of municipal solid waste treatment: Methodological proposal and application to a case study

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ABSTRACT

This paper applies the Life Cycle Assessment methodology to develop a simple method to calculate the carbon footprint of the municipal solid waste treatment stage. This simple and structured methodological procedure takes into account: i) direct greenhouse gas emissions produced in waste treatment, taking place within the city boundary (scope 1 of international carbon footprint standards); ii) indirect greenhouse gas emissions related to the use of grid-supplied electricity, as well as fuel production and distribution (scopes 2 and 3 emissions as per international carbon footprint standards); and iii) avoided greenhouse gas emissions as a result of the products obtained (if any) that can replace other products or the raw materials used to produce them. Madrid City (a representative European city), the capital of Spain, was used as a case study to prove the validity and usefulness of the proposed methodology. In this city, 344 kg of municipal solid wastes were produced per inhabitant in 2013. These wastes were collected separately in different fractions (packaging, glass, paper/cardboard and mixed waste, including organic material). Mixed waste and packaging fractions were processed at the Valdemingómez Technology Park. The current treatment stage was compared with several alternative scenarios which describe hypothetical management routes for the different waste fractions. The carbon footprint for the current situation is equal to 224 kg CO_2 eq/t_{waste}. In comparison to the worst situation, corresponding to the scenario in which municipal wastes were landfilled without energy recovery, the current scenario reduces its carbon footprint by 1597 kg CO_2 eq/t_{waste} (a reduction of 88%). Improvements in the material separation and recovery processes, along with the implementation of biological treatments for the organic fraction, clearly contribute to reducing the carbon footprint of the municipal solid wastes handled in the city of Madrid.

According to the obtained results, the scenarios based on a total recovery of valuable materials and waste-to-energy or anaerobic digestion treatments present the lowest carbon footprint because burden avoided is more important than direct and indirect emissions from treatments. In addition, the consumption of electricity and the emissions derived from its generation (mix of generation), can increase the carbon footprint of power-intensive treatments.

1. Introduction

The European Commission (EC) has set out different priority actions to optimize Municipal Solid Waste (MSW) Management (MSWM) in Europe, which are expected to bring environmental benefits as well as financial savings and social advantages.

The Waste Framework Directive –WFD– (EC, 2008) establishes a legally binding, five-step hierarchy, setting out an order of priorities, starting with 'waste prevention' as the preferred option, followed by 'preparing waste for reuse', 'recycling' and 'other recovery' (e.g. energy recovery), with 'disposal' being the last choice. According to EC (2008), the member states and their municipalities have to "*take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by Life Cycle Thinking (LCT) on the overall impacts of the generation and management of such waste*".

The LCT concept and quantitative tools such as Life Cycle Assessment (LCA) can provide an informed and science-based support to more environmentally sustainable decision-making in

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MSWM (Manfredi et al., 2011), as demonstrated in Laurent et al. (2014).

The LCA methodology can be applied to calculate the emissions of greenhouse gases (GHG) associated with MSW treatments (Lee et al., 2017), thus evaluating the environmental impact (EI) in terms of climate change (CC) for each of the existing technological solutions, that is, the calculation of Carbon Footprint (CF).

The aim of the article is to propose a simple methodology to calculate the CF of MSW treatment stage, built from the reviewed literature and using a consequential LCA approach (Bernstad Saraiva et al., 2017). This methodology can contribute to assess CF of cities under conditions of limited information (Fry et al., 2018). In addition to direct emissions (AM, 2015a), the methodology considers indirect (BSI, 2013, 2011; WRI, 2014) and avoided emissions (Fei et al., 2018; Ferreira et al., 2017). It takes into account emissions from the conventional MSW fractions (mixed waste - including organic material/fraction (OF) -, packaging, paper and cardboard, and glass) and their composition, as a key factor to define MSWM solutions (Bisinella et al., 2017).

Abbreviations a-GHGe, avoided greenhouse gas emissions; aR, all recycling; B, biomethanization; C, composting; CC, climate change; CF, carbon footprint; d-GHGe, direct greenhouse gas emissions; DOC, degradable organic carbon; EC, European Commission; EEA, European Environmental Agency; EF, emission factor; EI, environmental impact; EU, European Union; F1, mixed waste; F2, packaging; F3, paper and cardboard; F4, glass; FC, fossil carbon; Fi, methane/biogas volume fraction; GHG, greenhouse gases; GWP, global warming potential; I, incineration; i-GHGe, indirect greenhouse gas emissions; IPCC, International Panel on Climate Change; L, Landfill/Landfilling; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; LCT, life cycle thinking; LwBr, landfilling without biogas recovery; MBT, mechanical-biological treatment; MCF, methane correction factor; MSW, municipal solid waste; MSWM, municipal solid waste management; OF, organic fraction; OX, oxidation factor; R, recycling; RDF, refuse-derived fuel; SA, sensitivity analysis; SP/MRF, sorting plant and material recovery facility; VTP, Valdemingómez Technology Park; WFD, Waste Framework Directive; WtE, waste-to-energy.

The methodology was applied to Madrid as an example of a typical European city. No similar methodologies have been previously applied to this geographical area. The current situation was compared against nine alternative scenarios, based on recent studies, their results and conclusions. Thus, Ardolino et al. (2018) carried out an LCA study that quantifies and compares the potential EI of an anaerobic digestion plant, where the produced biogas is upgraded to biomethane for the transport sector instead of being directly burned in a combined heat and power unit. This study shows the overall environmental sustainability of biomethane production by anaerobic digestion of the separately collected OF from MSW. Bernstad Saraiva et al. (2017) compared three management alternatives for OF from MSW using LCA methodology: a) landfill, b) selective collection of for anaerobic digestion, and c) biomethanization after post-separation of. Erses Yay (2015) conducted a study in Sakarya (Turkey) using LCA methodology. They showed that landfilling and incineration were the worst waste final disposal alternatives in terms of CF, while composting and material recovery showed better performance. Fei et al. (2018) analyzed and compared three MSWM options, showing that raw MSW landfill was the worst management option. Incineration had higher energy efficiency, and mechanical-biological treatment (MBT) had the highest energy efficiency when connected with biogas purification systems, and could avoid pollution more significantly than the other two technologies. Fernández-Nava et al. (2014) analyzed six strategies for managing the MSW generated in Asturias (Spain). The study concluded that biomethanization contributes to reducing the impact in CC. Ferreira et al. (2017) analyzed the packaging waste management system in Belgium. A comparison between two scenarios was developed: the first one comprised the MSWM operations envisaging the recycling of packaging materials, and the second one was developed based on the hypothesis that there was no recycling system and all packaging waste was collected in the refuse collection system. The results were consistent with the hypothesis that the recycling scenario is more environmentally sound. Lee et al. (2017) evaluated landfill GHG emissions and the influence of key parameters depending on MSW stream. Montejo et al. (2013) assessed the environmental performance of MBT plants and results indicated the strong dependency with both energy and materials recovery efficiency. They also included a recommendation for upgrading and/or commissioning of future plants: to optimize materials recovery increasing automation during selection, and to prioritize biogas-electricity production from the OF through direct composting.

The alternative scenarios used as examples to validate the proposed methodology are based on these recent studies and their results, and combine the following treatments: waste-to-energy (WtE) plants, composting, biomethanization (obtaining biomethane to be used as fuel) and landfilling. Some of these scenarios have been established in line with the concept of the circular economy (EEA, 2016).

This paper is one of a three-part investigation aimed to propose methodologies and evaluate the CF of the different stages of MSWM, taking Madrid city as a case study. In the first one, Pérez et al. (2017a) analyzed the CF of the pre-collection stage. In the second one, Pérez et al. (2017b) focused on MSW collection and transport stages. Our methodology was applied to the truck fleet of Madrid under different scenarios. Finally, this paper shows an in-depth assessment of the CF of the treatment stage.

2. Material and methods

2.1. Case study

The city of Madrid is used as a case study to apply and contrast the methodology. Table A1 (Appendix) shows its main macroeconomic data and an overview of its relevance compared to the rest of Spain.

MSW generated in the city are managed by the Madrid City Council, which is responsible for its collection, transport and treatment. They are collected separately into four main fractions (Fig. A1, Appendix): mixed waste (F1, including OF), packaging (F2), paper and cardboard (F3) and glass (F4). In addition, there are specific collection routes for other kinds of waste: batteries, clothes, etc. (AM, 2014a, b).

F1 and F2 are specifically treated at the Valdemingómez Technology Park (VTP), the city's integrated waste management center. Plants and treatments implemented are as follows:

- Las Lomas: sorting plant and material recovery facility (SP/MRF) for F1 and incineration (I) plant with energy production: WtE plant
- La Paloma: SP/MRF for F1 and F2 and biomethanization (B)
- Las Dehesas: SP/MRF for F1 and F2, composting (C), B and operational landfill (L) with biogas recovery
- La Galiana: sealed landfill with biogas recovery and energy valorization of biogas to produce electricity

F3 is transported directly to recyclers, while F4 is taken to