An evaluation of final disposal alternatives for municipal solid waste through life cycle assessment: A case of study in Colombia

Diana M Caicedo-Concha, John J Sandoval-Cobo, Anne Stringfellow and Ramon Fernando Colmenares-Quintero

Cogent Engineering (2021), 8: 1956860
CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

An evaluation of final disposal alternatives for municipal solid waste through life cycle assessment: A case of study in Colombia

Diana M Caicedo-Concha1*, John J Sandoval-Cobo2, Anne Stringfellow3 and Ramon Fernando Colmenares-Quintero4

Abstract: Landfilling is still the most common technology used in developing countries for the final disposal of municipal solid waste (MSW), albeit the negative impacts on the environment such as those caused by the release of greenhouse gases (GHG) that contribute to global warming (GW). The Colombian government set a target of 20% reduction in GHG emissions by year 2030, for which the solid waste management sector has an important role to play. Also, the achievement of the targets of sustainable development goals (SDG) is playing a key role for the government agenda and will do so for the next years. In this context, there is an important room for improvement of the management alternatives in currently operative landfills in the country, especially in terms of measures to reduce fugitive air emissions and leachates. This paper evaluates, using life cycle assessment (LCA) methods, the environmental impacts associated with a landfill in Colombia under four different scenarios: open dumps (zero) and conventional landfill under three landfill gas (LFG) management alternatives: venting (a), flaring (b), and energy recovery (c). The impact categories as well as the life cycle impact assessment

ABOUT THE AUTHOR

Diana M. Caicedo-Concha is a MSc and PhD in Environmental Engineering and currently she is a Professor at the Faculty of Engineering at the Universidad Cooperativa de Colombia. Her research interests are related to sustainable solid waste management and circular economy. Her current research projects include the study of opportunities to add value to domestic and agricultural wastes, the incorporation of circular economy concepts to agricultural and production sectors, education for sustainable development goals, and the application of the research findings to vulnerable zones.

John J. Sandoval-Cobo is a MSc in Civil and Environmental Engineering currently conducting doctoral research on sustainable management alternatives for landfills as a member of the Study and Control of Environmental Pollution Research Group (ECCA) at Universidad del Valle. His research experience include solid and waste-water treatment using sustainable technologies, ground water modelling and remediation of contaminated sites and industrial effluents.

PUBLIC INTEREST STATEMENT

In developing countries, final disposal of municipal solid waste remains mainly on landfilling, although this practice has a negative impact under the environment due to uncontrolled emissions of greenhouse gases (GHG) and leachate, among others. These GHG are highly composed by methane, a gas also used as a fuel for heating and cooking. In context, Colombian government has set: (1) a reduction target of GHG emissions by 2030, (2) multiple targets to contribute to the Sustainable Development Goals (SDG), which includes the objective 7, to ensure access to affordable energy for all. Consequently, there is a need to reduce the fugitive landfill emissions and use that gas as a fuel. In this work, we examined different scenarios for waste disposal and used a life cycle assessment method to assess the environmental impacts and found that the capture and use of biogas has an important effect on the impact reduction.
(LCIA) methods used were determined through the review of LCA studies for MSW management systems in developing countries. Main results show that global warming potential (GWP) was the main environmental impact caused by the landfill operation under the conditions considered; however, GWP was significantly reduced with the shifting from management scenarios with no LFG treatment (a and a: common to most landfills in developing countries) to scenarios where LFG is either flare (b) or utilized for energy production (c). These results suggest that adoption of technologies for LFG capture, burn, and energy recovery must be considered if important reductions of GHGs are expected from the waste management sector, as well as to provide economic incentives to improve the operational sustainability of landfills in developing countries.

Subjects: Environment & Society; Environment & the City; Environmental Change & Pollution

Keywords: landfill; landfill gas; biogas; life cycle analysis; developing countries; sustainable development goals

1. Introduction
Sanitary landfills remain the most common option worldwide to manage waste. Technologies for solid waste management have evolved from open dumps to modern engineered facilities, with special controls for leachates and gas to reduce the environmental impacts of waste disposal. In Colombia, final disposal of municipal solid waste (MSW) in sanitary landfills is the dominant management technology: nearly 81% of the municipalities dispose of their solid waste in landfills, 10% in open dumps and only 9% use recovery plants or another types of treatment(De Planeación, 2016) (Superintendencia de Servicios Públicos Domiciliarios, 2018). Colombian public policies have had a positive impact on the environmental control of waste management, by regulating technical aspects for the construction and operation of landfills. The National Policy for the Integral Management of Solid Waste and the National Strategy for Circular Economy (De Planeación, 2016) (Ministerio de Ambiente y Desarrollo Sostenible, 2019) have included aspects of circular economy which is expected to bring benefits for the protection of human health, the environment and the preservation of natural resources.

Technical standards for the treatment of leachates and biogas in landfills are also being improved, and there are more stringent requirements for design and construction of waste containment, collection systems and treatment processes. Recently, enhanced management strategies such as leachate recirculation (LR) have been included to accelerate degradation and stabilization of wastes, and increase biogas production and space availability in landfills through settlement (Banor et al., 2009) (Gunamantha & Sarto, 2012). At the same time, landfill gas (LFG) is now managed through capture, venting and burning, together with the generation of electric or thermal energy (Gunamantha & Sarto, 2012).

In the current context of climate change and global energy demand, the use of energy from waste has become one strategy for the reduction of greenhouse gas (GHG) emissions and replacement of fossil fuels by other non-conventional energy sources like LFG. The management of the LFG is one of the key aspects in the establishment of strategies for the mitigation of climate change, and both income from the reduction of landfill GHG emissions (CH₄, CO₂) and revenues from LFG utilization constitute an important viability factor for the clean development mechanism of projects (CDM) (USEPA/ISWA, 2012). Furthermore, since uncontrolled methane emissions from landfills are considered as a lost opportunity to capture and use a significant energy resource, the collection and utilization of LFG can contribute
to affordable and clean energy access, as established in Goal 7 of the sustainable development goals (SDG) (United Nations Department of Economic and Social Affairs (UN DESA), 2018).

Given the multiple management strategies for MSW, there is a need to evaluate the technical, environmental, and economic performance of each option to select the most viable technology for specific sites before implementation. Life cycle Assessment (LCA) is one most frequently used methodology for evaluation of the environmental performance of MSW management scenarios (Christensen, 2020). LCA can be used to study environmental aspects and potential impacts during the life cycle of waste management (i.e. from raw materials extraction to their final disposal) (Boldrin et al., 2011). An inventory of inputs and products associated with different management scenarios is developed and potential impacts can be analysed (Icontec, 2006). Therefore, performing an accurate LCA requires contextualized information.

In this paper, we describe the process followed for the environmental evaluation of different solid waste technologies in Colombia and present some results for a case of study where a LCA methodology was followed.

2. LCA impact categories
LCA was used for the assessment of diverse scenarios for the management of MSW in Cali, Colombia. An analysis to define the impact categories and the Life Cycle Inventory Evaluation method was performed. The approach followed was first to conduct a literature review to identify studies where different LCA methodologies were used to evaluate MSW management systems that included final disposal in landfills, and then with the categories and method identified to run the simulations. The literature analysis was performed using the SCOPUS data base and covered LCA studies in emerging and low- and middle-income countries published between 2000 and 2018 (Table 1).

Within the impact categories identified, some of them are well established and are used to estimate the environmental impacts associated with a good degree of certainty. These are the global warming potential (GWP), formation of photochemical oxidants (POF), ozone depletion potential (OD), terrestrial acidification potential (AP), aquatic eutrophication potential (EPT) and ionizing radiation (IR). On the other hand, categories such as human toxicity (HT) and ecotoxicity (EH) have a higher degree of uncertainty due to a more limited availability of information for quantification and interpretation (Urp Andrs, 2014), difficulties in finding both regionalised data to feed into the inventory data and characterisation factors for potentially toxic substances found in landfills (e.g., metals and salts)(Edwards et al., 2017), and when modelling fate and exposure in the environment given the spatial and temporal variability of emission characteristics (Laner, 2009).

Table 1 describes the technological alternatives, impact categories and methods used for LCA, found in the studies reviewed. A discussion of the main findings for each of the impact categories follows.

| LF: Conventional landfill; CO: Methane Oxidation through landfill covers; Cp+v: Biogas capture + venting; Cp+q: Biogas capture+ burning; Cp+Ae: Biogas capture+ energy use; CP: Composting; AD: Anaerobic digestion; IC: Incineration; LR: Leachate recirculation; LT: Leachate treatment; RE: Recycling; MBT: Mechanical and Biological Treatment; AnMBT: Anaerobic Mechanical and Biological Treatment; AeMBT: Aerobic Mechanical and Biological Treatment; MRF: Materials Recovery Facility. |
Table 1. Impact categories and methods identified in LCA studies

| Technological Alternatives | Country | Impact categories | LCA Method | Reference |
|----------------------------|---------|-------------------|------------|-----------|
| LF+(Cp+Ae)                 | Iran    | GWP, HT, EPT, AP  | Eco-indicator 99 | (Abduli & Mansoor Yonesi, 2011) |
| LF                         | NA      | GWP, AP, EPT, OD, HT, POF | CML 2001 & Eco-indicator 99 | (Arafat et al., 2015) |
| LF+(Cp+Ae)                 | Canada  | GWP, AP, EPT      | ___        | (Assamoii & Lawryshyn, 2012) |
| CP+LF                     | China   | GWP, HT, OD, EPT, AP | IMPACT 2002 | (Hong et al., 2010) |
| LF+(Cp+Ae)                 | Indonesia | GWP, POF, AP, EPT | ___        | (Aye & Widjaya, 2006) |
| RE+LF (Cp+Ae) vs RE+CP+LF (Cp+Ae) | Turkey | GWP, POF, HT, AP, EPT | ___        | (Banar et al., 2009) |
| LF+(Cp+Ae)                 | Indonesia | GWP, POF, AP, EPT | CML 2000   | (Gunamantha & Sarto, 2012) |
| LF vs MBT+LF               | China   | GWP, AP, EPT      | ___        | (Hong, 2006) |
| LF vs LF+(Cp+Ae)           | Brazil  | GWP, AP, EPT      | ___        | (Mendes et al., 2004) |
| LF vs LF+(Cp+Ae)           | Sri Lanka | GWP, AP, EPT    | ___        | (Menikpura et al., 2012) |
| LF+LT+(Cp+Ae)              | Malaysia | GWP, POF, HT, AP, EPT | CML 2000   | (Saheri, 2012) |
| LF+LT+(Cp+q) vs LF+(Cp+Ae) | Brazil  | GWP, AP, EPT      | NMS / SAEFL | (Mendes et al., 2003) |
| LF vs RE+LF vs MRF+LF      | Turkey  | GWP, HT, AP, EPT  | IWM        | (Özeler et al., 2006) |
| LF+CO vs LF+LT+(Cp+v) vs LF+LT+(Cp+q) vs LF+LT+(Cp+Ae) vs | Denmark | GWP, POF, OD, AP, EPT, EH | EDIP 97      | (Damgaard et al., 2011) |
| LF+LT+CO+(Cp+q) vs LF+LT+CO+(Cp+Ae) | Brazil | GWP, POF, OD, AP, EPT | ILCD      | (Lima et al., 2018) |
| LF+LF+(Cp+qe/q/v)          | China   | GWP, POF, OD, AP  | EDIP 97 & IPCC 2007 | (Zhao et al., 2011) |
| LF                         | Greece  | GWP, AP, ET, HT, POF | Eco-indicator 97 | (Abeliotis et al., 2012) |
| LF+(Cp+q) vs LF+(Cp+Ae)    | Italy   | GWP, AP, EPT      | ___        | (Cherubini et al., 2009) |
| LF vs LF+(Cp+Ae) vs MRF+LF+(Cp+Ae) vs CP+LF+(Cp+Ae) vs MRF+AD+LF+(Cp+Ae) | China | GWP | CML 2004 | (W. Zhao et al., 2009) |
| RE+CP+LF vs RE+CP+IC+LF vs RE+CP+AnMBT+LF vs RE+CP+AeMBT+LF vs RE+CP+LF vs RE+AD+LF vs RE+AD+CP+IC+LF | Brazil | GWP, POF, AP, EPT | IWM | (Max et al., 2018) |
| LF+LT vs AD+LF+LT vs AD+LF+LT vs MRF+AD+LF+LT | Brazil | GWP, POF, OD, AP, EPT, EH | ILCD | (Carolina, 2017) |

(Continued)
2.1. Global warming (GWP)

GWP is a very important problem that has to be addressed by the waste management sector as discussed by several authors such as (Sandoval-Cobo, 2020)(Caicedo-Concha et al., 2019). Banar M., Cokaygil, Z. and Ozkan, A. (2009) analysed the impacts resulting from MSW management schemes under different recycling levels in Turkey and found that the greatest GWP impact was produced in landfill disposal, where 31% of the biogas was produced and used as a fuel (Banar et al., 2009). GWP impacts can be reduced by ensuring biogas capture efficiencies of between 50 and 75% as investigated by Yang, N. et al. (2013) (Yang et al., 2013). This is one of the reasons why capture and energy use of biogas is a key factor in reducing the main impacts associated with landfill emissions (Damgaard et al., 2011). This has been evidenced in the results of several LCA studies in emerging economies and middle-income countries (Abduli & Mansoor Yonesi, 2011), (Hong et al., 2010), (Liamsanguan & Gheewala, 2008), (Saheri, 2012). In an evaluation made in Sri Lanka, it was concluded that replacing open-air dumps with landfills, where biogas is collected and electricity generated, has the potential to reduce the GWP, acidification (AP) and eutrophication by 71, 10 and 95% (Menikpura et al., 2012). A study in Peru showed that by adopting landfill gas flaring (LFG) in landfills, as opposed to open dumping, can reduce GWP impacts by 50–76% (Ziegler-Rodriguez et al., 2019).

Mendes M.R., Aramaki, T. and Hanaki, K. (2004) compared landfilling and incineration as alternatives for the management of MSW in Sao Paulo and reported only slight reduction in GWP for landfills with energy use over conventional landfills. They attribute this finding to the characteristics of the essentially hydroelectric-based Brazilian energy matrix (Mendes et al., 2004). In
comparison, important impact reductions caused by GHG were obtained for incineration when compared with landfilling with biogas energy recovery for the management of MSW in a province of Thailand, a country with a high energy dependence on fossil fuels (Traivivatana et al., 2017). Xing. W. et al. (2013) found that biogas management is a key decision factor to reduce impacts from landfills operated under stabilization strategies. The burning of biogas in a landfill located in an arid zone in China with leachate recirculation, reduced the impacts of GWP, POF, AP, EPT, HT and EH by 90% compared to conventional landfilling (Xing et al., 2013).

2.2. Formation of photochemical oxidants (POF)

The study of volatile organic compounds (VOC) emissions from MSW in landfills and waste dumps in India demonstrated their relevance to tropospheric ozone formation and health impacts arising from the presence of benzene, toluene and chlorinated species, chemical substances with toxic and carcinogenic effects (Majumdar, 2014). The effect that landfill emissions, and in particular CH₄ and non-methanogenic organic compounds, have on landfill POF has been evidenced in several LCAs in middle-income countries (Banar et al., 2009) [Saheiri, 2012] (Xing et al., 2013). For example, in the study made by Yang et al. (2014), it was found that the capture and effective use of CH₄ reduces not only the impacts of POF but also has effects on the GWP, AP, EPT and HT (Yang et al., 2014).

2.3. Acidification (AP)

Energy recovery from LFG has shown a positive effect in reducing the impacts from landfills located in areas where energy generation is highly dependent on fossil fuels (Aye & Widjaya, 2006). Nitrogen species generated during MSW degradation, such as NH₃ and NO₃⁻, can acidify the soil and bodies of water, either by deposition from air emissions or from the discharge of soluble ammonia in leachate. Therefore, adequate collection and treatment systems for landfill leachates and gas have a significant effect on reducing the impacts of AP (Milutinovi et al., 2017). In particular, uncontrolled ammonia emissions adversely affect AP impacts where the biogas produced is inadequately managed; however, this can be drastically improved when LFG is collected, treated or utilized for energy production (Ferronato et al., 2021). In landfills with energy recovery, through the reduction on biogas uncontrolled emissions, decrease of AP impacts are even greater when SO₂ emissions are also properly treated (Mendes et al., 2004). Other LCA studies indicate that when stabilization management strategies for landfills, such as leachate recirculation, are coupled with LFG energy recovery, AP impacts can be drastically reduced as a result of the elimination of NH₃, H₂S and organic compounds (Xing et al., 2013).

2.4. Eutrophication (EPT)

Selective collection increases the recycling level and has an impact on the influence on the EPT category. It was observed that collection frequency plays an important role as a consequence of both emissions and frequency cut (Özeler et al., 2006). Also, degradation of large quantities of organic matter resulting in greater emissions of micronutrients, especially phosphorus and nitrogen, is evidenced by an increase in the EPT impact (Max et al., 2018).

2.5. Ozone depletion (OD)

According to Damgaard et al. (2011), after GWP, OD is the second largest impact per tonne of landfilled waste, as a result of CFC11 and CFC12 emissions, gases that are only partially oxidised in landfills. It is expected that international prohibition regulations will see a future reduction of fluorocarbon emissions (Damgaard et al., 2011). OD impacts from landfills are also highly related to methane and other non-methane organic compounds (NMOC) and thus, when LFG is combusted, the OD potential due to NMOC (e.g., dichloromethane, carbon tetrachloride and dichloroethane) is significantly attenuated (Ziegler-Rodriguez et al., 2019).
2.6. Abiotic depletion, renewable and non-renewable resources (DAMR)

Banar M., Cokaygil, Z. and Ozkan, A. (2009) relate this category to the extraction of minerals and fossil fuels required for all life cycle stages, that is, extraction, production, transportation, use and disposal (Banar et al., 2009). Max L., Coelho, G. and Celina, L. (2018) analysed the impacts by examining how the inclusion of recycled materials in an integrated management system decreases the impacts from productive chains (Max et al., 2018).

2.7. Human toxicity (HT)

Chromium (Cr), as a heavy metal, is primarily responsible for impacts in the HT category (Abduli & Mansoor Yonesi, 2011). However as explained by Abeliotis, K., Kalogeropoulos, A. and Lasaridi, K. (2012), recovery of heavy metals can improve the environmental performance of MSW management systems (Abeliotis et al., 2012).

Figure 1 summarizes the impact categories more frequently used in LCA in the selected studies. Based on that the impact categories for LCA in landfills were defined for the case of this study. Table 2 summarizes the normalization factors for the impact categories considered. The method more frequently reported corresponds to ILCD, recommended by the European Commission (European Commission, 2010); therefore, it was selected for the life cycle inventory in the research here explained.
Table 2. Impact categories and normalization factors used in this study

| Environmental Impact Category | Normalization | Units (per person) |
|-------------------------------|---------------|--------------------|
| Global Warming (GWP)         | 7.07E+03      | Kg CO₂ eq          |
| Formation of photochemical oxidants (POF) | 4.53E+01 | Kg NMVOC eq         |
| Ozone depletion (OD)         | 1.22E-02      | Kg CFC-11 eq       |
| Acidification potential (AP) | 5.61E+01      | mol H+ eq          |
| Eutrophication (EPT)         | 6.54E+00      | Kg P eq            |
| Human Toxicity, carcinogens (HTP) | 7.07E+03 | CTUh               |
| Human Toxicity, non carcinogens (HTPₜₐ) | 1.55E-04 | CTUh               |
| Abiotic depletion, resources renewable and non-renewable (DAMR) | 1.24E-05 | Kg Sb eq           |

3. Methodology

EASETECH V.2.8.9 program was used for modelling different scenarios using life cycle assessment (LCA) methodology. That software is a computer model used for the evaluation of the overall consumption of resources and environmental impacts generated by waste management systems. The program allows the modelling of highly heterogeneous material flows, such as MSW deposited in intrinsically heterogeneous systems like landfills, the impacts of treatment technologies, characterization of impacts, normalized impact profile, and weighted impact profile, among other features (Clavreul et al., 2014). EASETECH and former versions of the model (e.g., EASEWASTE), as well as other modelling software’s, have been used in LCA studies for various MSW management systems, including the environmental assessment of landfills ((Mendes et al., 2004), (Abeliotis et al., 2012), (Cherubini et al., 2009),(Ziegler-Rodriguez et al., 2019)), however few comprehensive modelling studies of this type have been conducted for low- and middle-income developing countries.

The LCA study was conducted following the international standard ISO 14040:2006 (ISO—ICONTEC, 2007) and the different phases covered are schematically shown in Figure 2.

The study area is a regional landfill located in the department of Valle del Cauca-Colombia, which serves more than 18 municipalities. The landfill receives an average of 570 tons/day of waste, has an active surface area of 19.8 ha and a capacity of expansion of 57.55 ha, where near 1.3 million of m3 of waste can be placed. The region has an average temperature of 21.3 °C and average annual rainfall of 1,597 mm but due to the presence of a bimodal period of precipitation in Colombia, the monthly rainfall can increase 150–300 mm during the rainy seasons. A further description of the landfill site could be found in investigations described by Sandoval-Cobo et al., (2020) (Sandoval-Cobo, 2020) and Caicedo-Concha et al., (2019) (Caicedo-Concha et al., 2019).

3.1. Characteristics of the waste used

Table 3 shows the physical composition of the MSW, which corresponds to the characteristics of fresh waste disposed of at the regional landfill described above; it has a moisture content of 51.9% and total solids content of 48.1%. An elemental composition analysis (32.8 %C, 5.5 %H, 5.8 %N, 0.1 %S) of a representative sample from the regional landfill was determined using a FlashEA 1112 Elemental Analyser (Thermo Finnigan, Italy) according to procedures described by (Caicedo-Concha et al., 2019). An oxygen content of 22.7 % was estimated from a review of ultimate analyses reported in selected studies for MSW with similar composition ((Mendes et al., 2004) (Cherubini et al., 2009) (Zhao et al., 2009) (Manaf et al., 2009)). A methane production
potential of 470.8 m$^3$ CH$_4$/ton VS for the waste was calculated based in the waste elemental composition according to Cárdenas Cleves, L.M. et al., (2016) (Cárdenas Cleves et al., 2016) and a 56% CH$_4$ content of biogas was calculated according to Olesen & Damgaard (2014) (Urup Anders, 2014).

### 3.2. Definition of scenarios

Four management scenarios were analysed, each consisting of a combination of different treatment processes or technologies. All the scenarios considered the application of daily, intermediate, and final cover materials which contribute to the oxidation of methane, CH$_4$, generated at the disposal site. The scenarios were:

**Scenario zero (0):** waste is disposed considering technical criteria for the collection and treatment of leachate. The collected fraction of leachate is assumed to be treated in a leachate treatment plant where pollutants remain after the treatment, while the uncollected fraction is assumed to reach the groundwater. Release of biogas to the atmosphere is done partially by venting pipes and partially uncontrolled, also some oxidation takes place through the cover layers and their effectiveness varies for different periods during the landfill lifetime.

**Scenario a:** describes the current management of MSW for most controlled landfills in Colombia where waste is disposed considering technical criteria for the collection and treatment of leachate, as described in scenario zero. There is capture and venting of biogas, with improved gas collection efficiencies in comparison with scenario zero, but there is no gas mitigation processes besides oxidation through cover layers.

**Scenario b:** considers the management of MSW through a landfill with infrastructure for the collection and leachate treatment. Biogas is captured and sent for combustion in flares.

**Scenario c:** considers the management of MSW through a landfill with infrastructure for the collection and leachate treatment, as for scenarios 0, a and b. Biogas is captured and sent to a combustion engine for electricity production with 37% energy recovery efficiency as reported by (Urup Anders, 2014).

---

| Waste category          | %  | Average Colombia $^a$ |
|-------------------------|----|-----------------------|
| Food                    | 45.9 | 61.5$^b$ |
| Yard waste              | 5.9  |           |
| Paper and Cardboard     | 5.6  | 6.6        |
| Plastics                | 22.3 | 10.8       |
| Sanitary                | 8.8  | -          |
| Textiles                | 5.0  | 2.7        |
| Metals                  | 0.3  | 1.0        |
| Wood                    | 1.2  | 0.5        |
| Glass                   | 2.4  | 2.4        |
| Ceramic                 | 0.3  | -          |
| Rubber and Leather      | 1.3  | -          |
| Others                  | 0.9  | 14.4       |

$a$: Fresh MSW produced in major cities; $b$: Organics, mainly consisting of food and yard waste (BID, 2015).
3.3. Scope definition
The functional unit defined was 1 tonne of fresh MSW disposed in the study area and the impact categories evaluated correspond to those shown in Table 2.

The stages related with collection, transportation, and previous treatment of MSW were not considered within the analysis. Energy consumption and preparation of materials for the disposal areas were considered, whilst fuel consumption for the transportation of residues to the landfill site was excluded. Inventories related to impacts generated to produce 1 kWh of electricity considered the Colombian energy matrix, also replacement of energy sources, produced from capture and use of biogas were analysed. Likewise, diesel inventory included the crude produced in oil refinery process.

3.4. LCA analysis
EASETECH v.2.3.6 software and the database Ecoinvent were used. Information of the consumption data, energy, materials and water, for construction and operation of the landfill disposal infrastructure were obtained from data provided by the site operator. Parameters such as elemental analysis, energy and CH₄ potentials were described in section 3.1. The life cycle impact analysis was carried out using the ILCD methodology as described in session 2, a method that has been used in previous LCA studies in Latin America (Bernstad Saraiva Schott et al., 2016) (Laurent, 2014).

4. Results and discussion
Figure 3 shows the environmental impacts associated with the different landfilling scenarios in terms of the contribution of each impact category. The greater GWP impacts were found in scenarios 0 and a, these are scenarios with no treatment of landfill gas. Scenarios 0 and a showed impacts that were at least one order of magnitude greater than those where gas was either flared or used for energy production (scenarios b and c). Impacts associated to the other

| Scenario   | GWP kg CO₂ | ODP kg CFC-11 | HTP kg CTUh | POF kg NNMVOC | AP mol H+ | EPT kg P | DAMR kg Sb |
|------------|------------|---------------|-------------|----------------|-----------|----------|------------|
| Scenario 0 | 2.24E+03   | 1.01E-05      | 1.98E-06    | 1.04E+00       | 1.66E-03  | 3.46E-04 | 6.18E-07  |
| Scenario a | 2.28E+03   | 1.00E-05      | 2.01E-06    | 1.05E+00       | 1.66E-03  | 3.46E-04 | 6.18E-07  |
| Scenario b | 8.80E+02   | 3.54E-06      | 1.90E-06    | 4.75E-01       | 9.61E-02  | 3.46E-04 | 6.18E-07  |
| Scenario c | 5.08E+02   | 2.24E-06      | 1.91E-06    | 1.18E+00       | 7.23E-01  | 3.46E-04 | 6.18E-07  |
categories such OD, HTP, POF AP, EPT and DAMR were much smaller and marginal in comparison with those obtained for GWP.

Although smaller than GWP, AP impacts in landfills can increase or decrease with LFG management options adopted. For instance, ammonia in uncollected gas is a major contributor to acidification in scenarios 0 and a; however, AP impacts can also increase when LFG is flared, due to substances resulting from its combustion (e.g., SOx and NOx), even when LFG is used for energy generation and proper treatment of acidification-related substances is not properly implemented.

Like GWP, HT impacts (aggregated as HTP) are slightly high in scenarios 0 and a in comparison with those where gas is flared or utilised for energy production, due to the oxidation of organic compounds found in landfill gas (COV’s, hydrocarbons, benzene, etc). However, it is important to consider that energy recovery processes for LFG generates substances of relevance to toxicity-related impact categories, for instance, dioxin formation during LFG combustion (Mendes et al., 2004). These results confirm the environmental benefits that a proper management of landfill gas can bring to landfills, which are even more relevant for the case of low- and middle-income countries where MSW is mainly disposed of in open dumps or landfills without the necessary measurements for an efficient collection and treatment of biogas.

Discounting the impacts associated with landfill gas, leachate treatment is the process that contributes the most to the HTP and EPT categories for all the scenarios, whilst the construction and operation of the landfill contribute to impacts related to AP and DAMR categories. Since for all scenarios, the same level of leachate management was considered, impact categories influenced by the fate of substances were not affected by the scenarios modelled, as it was the case for EPT and DAMR impacts. However, impacts produced by the uncontrolled management of leachate in landfills were significant for categories such as EPT, AP and DAMR, therefore appropriate leachate collection and treatment measures are required for a better environmental landfilling performance.

Figure 4 displays a close-up analysis for the GWP category. Landfill site processes such as construction and operation of disposal sites (C&O), leachate and gas collection systems, gas treatment technologies (venting, flaring and utilization for energy production) and leachate treatment in a wastewater treatment plant (Tt Leachate) were analysed. The contribution of the different processes is represented by a weighted value, in which the final impact potential of each scenario is 100%.

For scenarios 0 and a, gas venting and the uncontrolled release of biogas are the process that most contribute to the impact categories. The impact measured (left side) shows an impact reduction from over than 2000 kg CO₂ -Eq to 1000 and 500 kg CO₂ -Eq for scenarios b and c, respectively, this represents an important impact reduction for the scenarios where biogas is either combusted or used for energy generation and results in reduction of methane and NMOC emissions.
The contribution to GWP (right side) for scenarios 0 and a is due to gas venting (≈60%) and uncontrolled gas emission (≈40%). For scenarios b and c, contribution to GWP is mainly due to uncollected gas, which is a consequence of the 37% energy recovery efficiency used for the calculations and reported by (Urup Anders, 2014); whereas for scenario c, the utilization of gas, this is its combustion and transformation to CO₂, makes a contribution of nearly 5%.

Normalized results in Figure 5 indicate that improvements in the use of technology for final disposal of MSW represent a better performance in the environmental management. Scenario c shows the best environmental performance due to the reduction of GWP impacts, because of the energy substitution achieved with the implementation of collecting, burning and electricity generating system from biogas. In addition, improvements in biogas capture efficiency represent a lower emission of fugitive biogas to the environment. The net GWP load for scenario 0 and scenario a is significant, since biogas is emitted in an uncontrolled manner, a situation that represents the operation conditions in open-air dumps and most of the conventional landfills in developing countries.

The analysis suggests the need for generating regionalized and normalized set of parameters to reflect the local situation. For this study, a set of parameters as presented in Table 2 were used. As it is discussed in European Commission (2010), the decision whether to use global data or data for specific country shall be justified on the consideration of where are the supported decisions be made and sufficiently completed availability of inventory data for the chosen country among others.

5. Conclusions
The implementation of solid waste management strategies should be a joint work, supported by economic, environmental, technical, and social studies. This paper has focused on the environmental impacts of different landfill technology options from traditional ways of disposing of residential waste towards more modern practices such as biogas capture and use.

From a bibliographic review, it was possible to determine that the categories of impact applicable to the Colombian context are related to those commonly reported in LCA studies for MSW
management scenarios, thus enabling the identification and evaluation of environmental impacts attributable to waste management. Impact categories such as global warming (GWP), acidification (AP) and eutrophication (EPT) were reported more frequently in waste management LCA studies.

The LCA analysis demonstrated that infrastructure built for the capture and use of biogas represents the option with the best environmental performance. This is concluded as a result of the impact reduction from more than 2000 kg CO2-Eq in scenarios with absence of gas management (0 and a) to less than 1000 kg CO2-Eq (scenario b) and 500 kg CO2-Eq (scenario c), these are scenarios where: biogas is capture and sent for combustion in flares (scenario b) and biogas is captured and sent to a combustion engine for electricity production with 37% energy recovery efficiency (scenario c).

The impact categories and analysis methods could vary between regions around the world. As an example, the energetic matrix in Colombia relies, more than 70%, on hydroelectric whereas in Europe this type of energy is not abundant, also, biodiversity is an asset of special value for Colombia. These country particularities arose questions about the relevance of the normalization factors used in the ILCD method, which uses a 7.07E+03 for GWP (global warming potential), in comparison with 1.24E+5 to DAMR (abiotic depletion, resources renewable and non-renewable).

The environmental evaluation must be supplied with the best available information, in this way the results can represent the reality of the scenarios and allow certainty for each context. It is essential to have a method of normalization, for the development. Cooperation between companies and the state in the sense of environmental assessment could represent an advance in issues of emissions inventories, which will allow to obtain robust and proprietary databases for the Colombian context.

Acknowledgements
This project is funded through Engineering X, an international collaboration founded by the Royal Academy of Engineering and Lloyd’s Register Foundation in the United Kingdom. This award is part of the Engineering X “Engineering Skills Where They Are Most Needed Mission”, which seeks to support the delivery of skills and education programmes that will lead to the development of much needed engineering skills capacity, enhanced safety standards, and infrastructure that remains safe and fit for purpose. Project reference # ESMN1921111777 “SDGs-challenges based learning in engineering curricula at the Universidad Cooperativa de Colombia: Enhancing the engineering skills in a developing country” and the UCC ID is INV2850. Also, the authors would like to thank the Universidad del Valle and the Universidad Cooperativa de Colombia for financing the projects entitled “Stabilization strategies for MSW landfills in developing countries CI-2908” and “Valorisation of solid waste INV1688” as well as Minciencias for granting John J Sandoval-Coba a doctoral scholarship (call 647-2014). The authors also acknowledge the support of the engineer Paola Ramirez in gathering the data used for this paper.

Funding
This work was supported by the Lloyd’s Register Foundation [# ESMN1921111777], Newton Fund [# ESMN1921111777], Universidad Cooperativa de Colombia [INV1688]; Royal Academy of Engineering [# ESMN1921111777]; Universidad del Valle [CI-2908].

Author details
Diana M Caicedo-Concha1
E-mail: diana.caicedoc@campusucc.edu.co
ORCID ID: http://orcid.org/0000-0003-4031-4568
John J Sandoval-Coba2
ORCID ID: http://orcid.org/0000-0002-2608-7699
Anne Stringfellow2
Ramon Fernando Colmenares-Quintero4
ORCID ID: http://orcid.org/0000-0003-1166-1982

1 Faculty of Engineering, Universidad Cooperativa De Colombia, Cali, Colombia.
2 Faculty of Engineering, Universidad Del Valle, Cali, Colombia.
3 Faculty of Engineering, University of Southampton, Southampton, UK.
4 Faculty of Engineering, Universidad Cooperativa De Colombia, Medellin, Colombia.

Citation information
Cite this article as: An evaluation of final disposal alternatives for municipal solid waste through life cycle assessment: A case of study in Colombia, Diana M Caicedo-Concha, John J Sandoval-Coba, Anne Stringfellow & Ramon Fernando Colmenares-Quintero, Cogent Engineering (2021), 8: 1956860.

References
Abdulí, A. N., & Mansoor Yonesi, A. (2011). Life cycle assessment (LCA) of solid waste management strategies in Tehran: Landfill and composting plus landfill. Environmental Monitoring and Assessment, 178(1), 487–498. https://doi.org/10.1007/s10661-010-1707-x
Abeliotis, K., Kalogeropoulos, A., & Lascaridis, K. (2012). Life cycle assessment of the MBT plant in Ana Liossi, Athens, Greece. Waste Manag, 32(1), 213–219. https://doi.org/10.1016/j.wasman.2011.09.002
Arafat, H. A., Jijakli, K., & Ahson, A. (Oct 2015). Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. Journal of Cleaner Production, 105, 233–240. https://doi.org/10.1016/j.jclepro.2013.11.071
Assamoi, B., & Lowryshyn, Y. (2012). The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. Waste Manag, 32(5), 1019–1030. https://doi.org/10.1016/j.wasman.2011.10.023
Aye, L., & Widjoyo, E. R. (2006). Environmental and economic analyses of waste disposal options for
traditional markets in Indonesia. Waste Manag, 26 (10), 1180–1191. https://doi.org/10.1016/j.wasman.2005.09.010

Bonar, M., Cokaygil, Z., & Ozkan, A. (2009). Life cycle assessment of solid waste management options for Eskisehir, Turkey. Waste Manag, 29(1), 54–62. https://doi.org/10.1016/j.wasman.2007.12.006

Bernstad Saraivo Schott, A., Wenzel, H., & la Cour Jansen, J. (Feb 2016). Identification of decisive factors for greenhouse gas emissions in comparative lifecycle assessments of food waste management – an analytical review. J. Clean. Prod, 13-24. https://doi.org/10.1016/j.jclepro.2016.01.079

BID. (2015). Estudio tecnologías alternativas de disposición final a aprovechamiento de residuos sólidos. Propuesta de ajuste al Decreto 838 de 2005. https://colaboracion.dnp.gov.co/CDT/Conpes/Econ%2383micos3874.pdf

Boldrin, A., Neidel, T. L., Dampgaard, A., Bhandar, G. S., Møller, J., & Christensen, T. H. (2011). Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE. Waste Manag, 31(4), 619–630. https://doi.org/10.1016/j.wasman.2010.10.025

Caicedo-Concha, D. M., Sandoval-Cobo, J. J., Fernandez, C.-Q. R., Marmolejo-Rebollén, L. F., Torres-Lozada, P., & Sonia, H. (2019). The potential of methane production using aged landfill waste in developing countries: A case of study in Colombia. Cogent Eng, 6(1), 1-15. https://doi.org/10.1080/23311916.2019.1664682

Cárdenas Cleves, L. M., Parra Orobit, B. A., Torres Lozada, P., & Vásquez Franco, C. H. (2016). Perspectivas del enoyo de potencial bioquímico de metano – FBM para el control del proceso de digestión anaerobia de residuos. Rev. Investig. Optim. y Nuevos procesos en Ing, 29(1), 95–108. http://www.scielo.org.co/scielo.php?script=psole-1002x2016000100009&s=sci_abstract&sl=es

Carolina, A. (2017). “Life Cycle Assessment and Multi-criteria Decision Analysis: Selection of a strategy for domestic food waste management in Rio de Janeiro.” Journal of Cleaner Production, 143, 744 - 756.

Cherubini, F., Bargigli, S., & Ugliotti, S. (2009). Life cycle assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration. Energy, 34 (12), 2116–2123. https://doi.org/10.1016/j.energy.2008.08.023

Chi, Y., Dong, J., Tang, Y., Huang, Q., & Ni, M. (2015). Life cycle assessment of municipal solid waste source-separated collection and integrated waste management systems in Hangzhou, China. J. Mater. Cycles Waste Manag, 17(4), 695–706. https://doi.org/10.1007/s10163-014-0300-8

Christensen, T. H. (2009). Application of LCA modelling in integrated waste management. Waste Manag, 118, 313-322. https://doi.org/10.1016/j.wasman.2020.08.034

Clavreul, J., Baumeister, H., Christensen, T. H., & Dampgaard, A. (Oct 2014). An environmental assessment system for environmental technologies. Environmental Modelling and Software, 60, 18–30. https://doi.org/10.1016/j.envsoft.2014.06.007

Dampgaard, A., Manfredi, S., Merrild, H. Stensææ, S., & Christensen, T. H. (2011). LCA and economic evaluation of landfill leachate and gas technologies. Waste Manag, 31(7), 1532–1541. https://doi.org/10.1016/j.wasman.2011.02.027

de Planeacion, D. N. (2016). Política nacional para la gestión de residuos sólidos. CONPES 3874, I, 73. https://colaboracion.dnp.gov.co/CDT/Conpes/Econ%383micos3874.pdf

Edwards, J., Othman, M., Cossin, E., & Burn, S. (2017). Anaerobic co-digestion of municipal food waste and sewage sludge: A comparative life cycle assessment in the context of a waste service provision. Bioresource Technology, 223, 237–249. https://doi.org/10.1016/j.biortech.2016.10.044

European Commission. (2010). International Reference Life Cycle Data System (ILCD) Handbook and General Guide for Life Cycle Assessment. DOI: 10.2788/94987

Ferronato, N. Moresco, L., Guisbert Lizarruza, G. E., Gorrity Portillo, M. A., Conti, F., & Torretta, V. (2021). Sensitivity analysis and improvements of the recycling rate in municipal solid waste life cycle assessment: focus on a Latin American developing context. Waste Manag, 128, 1–15. https://doi.org/10.1016/j.wasman.2021.04.043

Gunamanthana, M., & Sarto, S. (2012). Life cycle assessment of municipal solid waste treatment to energy options: case study of KARTAMANTUL region, Yogyakarta. Renew. Energy, 41, 277–284. https://doi.org/10.1016/j.renene.2011.11.008

Hong, J., Li, X., & Zhaojie, C. (Nov 2010). Life cycle assessment of four municipal solid waste management scenarios in China. Waste Manag, 30(11), 2362–2369. https://doi.org/10.1016/j.wasman.2010.03.038

Hong, R. J. (2006). Life cycle assessment of BMF-based integrated municipal solid waste management: case study in Pudong, China. Resour. Conserv. Recycl, 49 (2), 129–146. https://doi.org/10.1016/j.resconrec.2006.03.007

Iconotec. (2006). “Gestión ambiental. Análisis de Ciclo de Vida. Principios y marco de referencia. UNE-EN ISO 14040:2006”.

ISO. (2006). ISO 14040:2006(ES). Gestión ambiental — Análisis del ciclo de vida — Principios y marco de referencia.

ISO – ICONTEC. (2007). Norma técnica Colombiana TTC-ISO 14040. Iconotec, (571), 1–24. https://hendidaciontec.org/tp-gestion-ambiental-analisis-del-ciclo-de-vida-principios-y-marco-de-referencia-ntc-iso14040-2007.html

Loner, D. (2009). The consideration of long-term emissions from landfills within life-cycle assessment. Waste Manag, Res, 27(5), 463–470. https://doi.org/10.1177/0734242X09023335

Laurent, A. (Mar 2014). Review of LCA studies of solid waste management systems–part II: Methodological guidance for a better practice. Waste Manag, 34(3), 589–606. https://doi.org/10.1016/j.wasman.2013.12.004

Li, Zhang, C. & Gheewala, S. H. (2009). LCA: A decision support tool for environmental assessment of MSW management systems. Journal of Environmental Management, 87(1), 132–138. https://doi.org/10.1016/j.jenvman.2007.01.003

Lima, P. D. M., Colvera, D. A., Gomes, A. P., Wenzel, H., Schalch, V., & Cimpan, C. (2018). Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. Waste Manag, 78, 857–870. https://doi.org/10.1016/j.wasman.2018.07.007

Mujumdar, D. (2016). Emission, speciation, and evaluation of impacts of non-methane volatile organic compounds from open dump site. Journal of the Air & Waste Management Association, 67(7), 834–845. https://www.tandfonline.com/doi/full/10.1080/10962247.2013.873747
Manaf, L. A., Samah, M. A. A., & Zulkki, N. I. M. (2009). Municipal solid waste management in Malaysia: practices and challenges. Waste Manag, 29(11), 2902–2906. https://doi.org/10.1016/j.wasman.2008.07.015

Max, L., Coelho, G., & Celina, L. (2018). Resources, conservation and recycling applying life cycle assessment to support environmentally sustainable waste management strategies in Brazil. “Resources, Conserv. Recycl, 128, 438–450. https://doi.org/10.1016/j.resource.2016.09.026

Mendes, M. R., Aramaki, T., & Hanaki, K. (2003). Assessment of the environmental impact of management measures for the biodegradable fraction of municipal solid waste in Sao Paulo City. Waste Manag, 23(5), 403-409. https://doi.org/10.1016/S0956-053X(03)00058-8

Mendes, M. R., Aramaki, T., & Hanaki, K. (2004). Comparison of the environmental impact of incineration and landfilling in Sao Paulo City as determined by LCA. Resour. Conserv. Recycl, 41(1), 47–63. https://doi.org/10.1016/j.resconrec.2003.08.003

Menikpura, S. N., Gheewala, S. H., & Bonnet, S. (2012). Sustainability assessment of municipal solid waste management in Sri Lanka: problems and prospects. J. Mater. Cycles Waste Manag, 14(3), 181-192. https://doi.org/10.1007/s10163-012-0055-z

Milutinović, B., Stefanović, G., Đeki, P. S., Mijailović, I., & Tomić, M. (2017). Environmental assessment of waste management scenarios with energy recovery using life cycle assessment and multi-criteria analysis. Energy, 137, 917–926. https://doi.org/10.1016/j.energy.2017.02.167

Ministerio de Ambiente y Desarrollo Sostenible. (2019). Estrategia Nacional de Economía Circular.

Özeler, D., Yetiş, U., & Demirer, G. N. (2008). Life cycle assessment of municipal solid waste management methods: ankara case study. Environ. Int, 32(3), 405–411. https://doi.org/10.1016/j.envint.2005.10.002

Sahehi, S. (2012). Life cycle assessment for solid waste disposal options in Malaysia. Polish J. Environ. Stud, 21(5), 1377–1382.

Sandoval-Caba, J. J. (2020). Methane potential and degradation kinetics of fresh and excavated municipal solid waste from a tropical landfill in Colombia. Sustain. Environ. Res, 30(1). https://doi.org/10.1186/s42834-020-00048-6

Superintendencia de Servicios Públicos Domiciliarios. (2018). Informe de Disposición Final de Residuos Sólidos – 2017.

Traivivatana, S., Wangjirnanon, W., Junlakarn, S., & Wansophark, N. (Oct 2017). Thailand energy outlook for the Thailand integrated energy blueprint (TIEB). Energy Procedia, 138, 399–404. https://doi.org/10.1016/j.egypro.2017.10.179

United Nations Department of Economic and Social Affairs (UN DESA). (2018). “Sustainable Development Goals Report 2018,” p. 64.

Urup Anders, A. D. O. (2014). “Landfilling in EASETECH.” p. 46.

USEPA/ISWA. (2012). International Best Practices Guide for Landfill Gas Energy Project. U.S. Environmental Protection Agency and ISWA (International Waste Management Association).

Xing, W., Lu, W., Zhao, Y., Zhung, X., Deng, W., & Christensen, T. H. (2013). Environmental impact assessment of leachate recirculation in landfill of municipal solid waste by comparing with evaporation and discharge (EASEWASTE). Waste Manag, 33(2), 382–389. https://www.sciencedirect.com/science/article/abs/pii/S0956053X12004795

Yang, N., Danggaard, A., Lü, F., Shao, L. M., Brogaard, L. K. S., & He, P. J. (2014). Environmental impact assessment on the construction and operation of municipal solid waste sanitary landfills in developing countries: China case study. Waste Manag, 34(5), 929–937. https://doi.org/10.1016/j.wasman.2014.02.017

Yang, N., Zhong, H., Shao, L.-M., Lü, F., & He, P.-J. (Nov 2013). Greenhouse gas emissions during MSW landfilling in China: influence of waste characteristics and LFG treatment measures. Journal of Environmental Management, 129(5), 510–521. https://doi.org/10.1016/j.jenvman.2013.08.039

Zhao, W., van der Voet, E., Zhang, Y., & Huppes, G. (2009). Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: case study of Tianjin, China. The Science of the Total Environment, 407(5), 1517–1526. https://doi.org/10.1016/j.scitotenv.2008.11.007

Zhao, Y., Christensen, T. H., Lu, W., Wu, H., & Wang, H. (2011). Environmental impact assessment of solid waste management in Beijing City, China. Waste Manag, 31(4), 793–799. https://doi.org/10.1016/j.wasman.2010.11.007

Zhao, Y., Wang, H.-T., Lu, W.-Y., Danggaard, A., & Christensen, T. H. (2009). Life-cycle assessment of the municipal solid waste management system in Hangzhou, China (EASEWASTE). Waste Manag Res, 27(4), 399–406. https://doi.org/10.1177/0734242X09103823

Ziegler-Rodriguez, K., Margallo, M., Aldaco, R., Vázquez-Rowe, I., & Kohhat, R. (2019). Transitioning from open dumps to landfilling in Peru: environmental benefits and challenges from a life-cycle perspective. Journal of Cleaner Production, 229, 989–1003. https://doi.org/10.1016/j.jclepro.2019.05.015
