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Climate change mitigation potential of transitioning from open dumpsters in Peru: Evaluation of mitigation strategies in critical dumpsites

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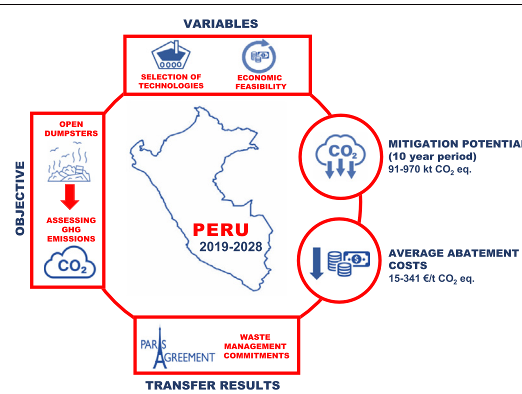
HIGHLIGHTS

- Open dumpsters are an important source of GHGs and marine debris in Latin America.
- The 24 most critical open dumpsites in Peru will add 4.4 Mt CO_2eq from 2019 to 2028.
- Four mitigation strategies are assessed for Peru, economically and environmentally.
- Mitigation potentials ranged from 91 to 970 kt CO_2eq in the ten-year period.
- Average abatement costs for strategies range between 15 and 341 € per t of CO_2 eq.

GRAPHICAL ABSTRACT



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ABSTRACT

Waste management is a critical policy towards the reduction of environmental impacts to air, soil and water. Many Latin American countries, however, lack a correct waste management system in many cities and rural areas, leading to the accumulation of unmanaged waste in illegal or unregulated dumpsites. The case of Peru is of interest, as it hosts 5 of the 50 largest dumpsites in the world. An erratic waste management compromises climate actions for Peru to commit with the Paris Agreement, as no correct closure systems are established for these dumpsites. Therefore, the main objective of this study is to assess the contribution of the past and present biodegradable waste produced and disposed of in the most critical open dumpsters to the overall annual greenhouse gas (GHG) emissions of Peru using the IPCC model. Thereafter, the climate change mitigation potential of possible dumpsite closure strategies based on a selection of technologies, including economic feasibility, were estimated. Results show that cumulative GHG emissions in 2018 for the 24 critical dumpsites evaluated added up to 704 kt CO_2 eq. and a cumulative value of 4.4 Mt CO_2 eq. in the period 2019–2028, representing over 40 % of solid waste emissions expected by 2030. Mitigation potentials for

Abbreviations: AC, Abatement cost; BCR, Benefit-cost ratio; CERs, Certificate Emission Reductions; CDM, Clean Development Mechanism; DOC, Degradable organic carbon; OEFA by its acronym in Spanish, Environmental Evaluation and Inspection Bureau of Peru; FOD, First order decay; GWP, Global warming potential; GHG, Greenhouse gas; MOL, Methane oxidation layer; MINAM by its acronym in Spanish, Ministry of Environment – Peru; MSs, Mitigation strategies; MSW, Municipal Solid Waste; NDCs, Nationally-determined contributions; NPV, Net present value; LFG, Landfill gas; LA&C, Latin America and the Caribbean; LCA, Life Cycle Assessment; O&M, Operation & maintenance; SDGs, Sustainable Development Goals; TERs, Total emission reductions; uSWDS, Unsound solid waste disposal sites.

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these emissions tanged from 91 to 970 kt CO_2 eq. in the ten-year period depending on the mitigation strategies adopted. The costs of these strategies are also discussed and are expected to be of utility to complement Peru's waste management commitments in the frame of the Paris Agreement.

1. Introduction

Waste management is a cross-cutting issue impacting multiple socio-economic aspects, and it is an important leverage point to achieve some critical global environmental, social, and economic challenges translated into the Sustainable Development Goals (SDGs), including climate change (UNEP, 2015; Sharma et al., 2021). Municipal Solid Waste (MSW) management systems are a significant source of greenhouse gas (GHG) emissions, contributing ca. 5 % of global GHG emissions (Jia et al., 2018), and a great part can be attributed to inadequate final disposal sites (e.g., dumpsites and unmanaged landfills), mainly due to fugitive methane (CH_4) emissions, which have a considerably higher global warming potential (GWP) than carbon dioxide (CO_2). In fact, it has been estimated that waste management has the potential to contribute up to a 15 % reduction in GHG emissions (UNEP, 2015), through both the implementation of more sophisticated waste treatment technologies and the establishment of circular economy actions to minimize the generation of waste fractions, especially those linked to organic waste (Sharma et al., 2021). Therefore, adequate waste management strategies and the derived infrastructure are critical to maintain global warming within the acceptable threshold of 1.5 °C recommended by the IPCC (Thacker et al., 2021).

The proliferation of illegal open dumpsters, as well as mismanaged landfills, is a major environmental problem for almost all countries in the world, including several European nations (Quesada-Ruiz et al., 2019). In the region of Latin America and the Caribbean (LA&C), total and per capita waste generation continues to increase, exerting additional stress on the fragile waste management system of all countries in the region. Approximately 45 % of all waste generated in LA&C still ends up in inadequate final disposal sites, including >10,000 dumpsites identified throughout the region (UNEP, 2021). Moreover, income level, consumption patterns and other variables account for a high organic fraction in waste composition in LA&C, ranging from 36 % to 75 % (Margallo et al., 2019). This leads to significant rates of CH_4 emitted to the atmosphere due to waste decomposition (Ziegler-Rodríguez et al., 2019). In addition to climate-related impacts, open dumpsters are an important source of toxic emissions to soil and water, capable of degrading natural water bodies, as well as a disruptor for wildlife, and a possible source for health issues due to both emissions and disease vectors (Ferronato and Torretta, 2019). More recently, they have also been identified as precursors of marine litter, especially plastic (Woods et al., 2021). Consequently, a progressive closure of dumpsites and an effective transition towards sounder waste management options is imperative.

The current study focuses on Peru, an upper-middle income country in Latin America with a GDP of 226.8 billion (current US$) and 32.5 million inhabitants (World Bank, 2021), where the rate of waste disposal through dumping is one of the highest in LA&C, around 47 % (Ziegler-Rodríguez et al., 2019). The remaining fraction (53 %), mostly in the city of Lima, is disposed of in sanitary landfills (UNEP, 2021). In 2018, approximately 11.39 Mt CO_2 eq. representing 6 % of Peru's total GHG emissions (i.e., 186.18 Mt CO_2 eq.), were emitted by the waste sector (Climatewatch, 2019), and around 60 % of that is due to solid waste disposal (6.8 Mt CO_2 eq.) (Gobierno del Perú, 2020a). Peru had only 29 landfills registered in 2017 and 10 out of 25 regions lacked landfilling infrastructure (Ziegler-Rodríguez et al., 2019). However, by May 2022 the number had increased to 72, with some medium-sized cities like Tarapoto, Sullana or Puno inaugurating their sanitary landfills in this period (MINAM, 2021).

Despite these efforts, fueled by the need to comply with Peru's nationally-determined contributions (NDCs) in the frame of the Paris Agreement (Gobierno del Perú, 2020b), and according to the last available data from the Environmental Evaluation and Inspection Bureau of Peru (OEFA by its acronym in Spanish), 1585 dumpsites spread throughout the nation had been reported by 2019 (see Fig. 1). These data exclude the metropolitan area of Lima and Callao and are probably underrepresented for other regions of the nation. In fact, experts consulted raise these numbers to over 3500 dumpsites (technical staff at OEFA, personal communication, May 2019).

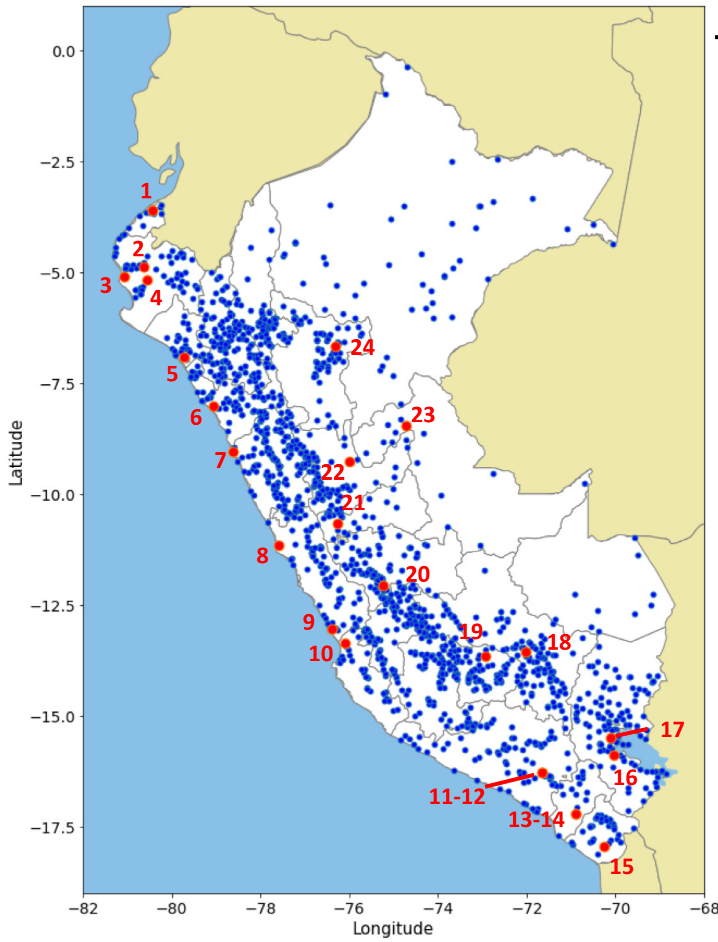
Out of the open dumpsters that are registered by OEFA, a selection of the 24 most critical dumpsites (see the red dots in Fig. 1) have been selected for this study based on the initial list published by OEFA in 2014 (OEFA, 2014). In fact, according to D-Waste (2014), Peru is home to 5 of the 50 biggest dumpsites in the World,[1] being the second country worldwide with the highest number of these sites right after Nigeria. While some of these open dumpsters have recently stopped their activities (e.g., Cancharani in Puno) or have added new cells that operate as sanitary landfills (e.g., Jáquira in Cusco), no formal closure strategy has been implemented for them. In contrast, the dumps at El Milagro (Trujillo) or Quebrada Honda (Arequipa) are still in operation as of May 2022 and constitute the main disposition sites for the second and third largest cities in the nation.

Acknowledging the political will of phasing-out dumpsites by 2030 in LA&C, as stated by the 'voluntary coalition of governments and relevant organizations for the gradual closure of dumpsites in LA&C[2] (UNEP, 2021), there is a clear and urgent need for studies that analyze and evaluate possible strategies to close dumpsites considering the sustainability and affordability in the local context. Thus, the possible strategies must consider, on the one hand, the climate change mitigation potential and its possible contribution to the commitment of Peru within the updated first NDC. On the other hand, the economic feasibility that must be integrated in the analysis either considering the abatement cost for the NDC or including the revenues from selling the Certificate Emission Reductions (CERs) achieved through the Clean Development Mechanism (CDM). Finally, it is also important to focus the analysis on simple strategies ("low technology") able to largely mitigate site-specific CH_4 emissions (e.g., landfill gas flaring or biocovers to increase CH_4 oxidation) and readily deployed at any site.

The evaluation of waste management systems and possible strategies to transition towards more sustainable options in LA&C and other developing countries has been analyzed recently in the literature using different perspectives. A first group of studies apply a life cycle perspective using Life Cycle Assessment (LCA). Margallo et al. (2019), for instance, performed a critical review of the situation of the waste management sector in LA&C from an environmental perspective and assessed potential alternative waste management strategies by means of LCA. The authors concluded that all kinds of landfilling should be avoided but they highlighted that local factors will influence the environmental performance of other specific technologies. Ziegler-Rodríguez et al. (2019) studied the specific case of Peru, also using a life-cycle perspective, and concluded that biogas treatment is a critical aspect to be taken into consideration in order to mitigate GHG emissions. They also highlighted that the different geoclimatic and technological conditions are key variables in the assessment, an issue further developed by Vázquez-Rowe et al. (2021) by analyzing the most appropriate technologies to treat food loss and waste in different Peruvian cities. Espinoza Pérez et al. (2021) assessed the environmental performance of different types of final disposal of MSW in Valdivia (Chile) using LCA and concluded that prioritization of regional sophisticated landfills in medium-sized cities would have a great incidence in terms of GHG mitigation. Goulart Coelho and Lange (2018) applied LCA

[1] Those are Cancharani (Puno), El Milagro (Trujillo), Jáquira (Cusco), Quebrada Honda (Arequipa), and Reque (Reque).

[2] Established within the framework of the XXI Meeting of the Forum of Ministers of the Environment of LA&C (Buenos Aires, Argentina, October 9–12, 2018).



Nº	District	Province	Department
1	Tumbes	Tumbes	Tumbes
2	Sullana	Sullana	Piura
3	Paita	Paita	Piura
4	Castilla	Piura	Piura
5	Saña	Chiclayo	Lambayeque
6	Huanchaco	Trujillo	La Libertad
7	Chimbote	Santa	Ancash
8	Huacho	Huaura	Lima
9	Imperial	Cañete	Lima
10	Pueblo Nuevo	Chincha	Ica
11-12	Yura	Arequipa	Arequipa
13-14	Moquegua	Mariscal Nieto	Moquegua
15	Ciudad Nueva	Tacna	Tacna
16	Puno	Puno	Puno
17	Juliaca	San Román	Puno
18	Santiago	Cusco	Cusco
19	Abancay	Apurímac	Apurímac
20	Huancayo	Huancayo	Junín
21	Yanacancha	Pasco	Pasco
22	Rupa Rupa	Leoncio Prado	Huánuco
23	Campoverde	Coronel Portillo	Ucayali
24	Juan Guerra	San Martín	San Martín

Note: Both in Arequipa and Mariscal Nieto there are two uSWDSs

Fig. 1. Distribution of the reported dumpsites in Peru in 2019. In red the 24 most critical dumpsites are highlighted, which are described in the adjunct table (Data source: OEFA). uSWDS = unsound solid waste disposal site. Note: the administrative division of Peru is organized in Departments (called nowadays Regions) that are divided in Provinces and these are divided in Districts (districts are equivalent to municipalities or boroughs in other countries).

to investigate eight sustainable waste management strategies in Brazil, demonstrating that incineration plants and direct landfilling must be avoided, focusing on strategies linked to separate collection and material recovery.

A second group of studies analyzed waste management systems and strategies by means of the GHG emissions estimation using the IPCC model (IPCC, 2006). For instance, Maghmoumi et al. (2020) examined possible waste-to-energy strategies in Iran including the economic dimension in an effort to transition from dumpsites to a sounder waste management technology. Similarly, Stanisavljevic et al. (2012) evaluated methane emissions from landfills in Serbia and three potential mitigation strategies: final soil cover, final cover made out of compost, and the installation of an active gas collection system. Sarmento dos Muchangos and Tokai (2020) studied the challenges and opportunities of replacing a dumpsite located in Maputo (Mozambique) with a semi-aerobic landfill (also known as the Fukuoka method). In line with this estimation framework, some studies included the economic feasibility of implementing mitigation strategies in landfills and dumpsites within the CDM framework. As an example, Cristóbal et al. (2021) performed an environmental and techno-economic assessment of a landfill biocover CDM activity in the Seychelles.

The current study belongs to the second group of studies and aims to quantify the GHG emissions linked to the 24 most critical dumpsites in Peru in terms of waste disposal, which represented in 2018 approximately 76 % of total waste ending in dumpsters in the country. The main objective of the study is twofold. On the one hand, to assess the contribution of the past and present biodegradable waste produced and disposed of in the most critical open dumpsters to the overall annual GHG emissions of Peru using the IPCC model. Secondly, to evaluate the climate change mitigation potential of possible dumpsite closure strategies based on a selection of technologies compiled within the CDM methodology booklet (e.g., semi-aerobic aeration) (UNFCCC, 2020), including economic feasibility.

2. Materials and methods

In 2018, roughly 14,300 t of MSW were generated per day in Peru according to INEI (2020). Based on the data reported by OEFA, the 24 critical dumpsites selected in this study receive around 5100 t of waste per day, representing 76 % of the dumped waste considering that 47 % of the total waste generated in Peru are disposed of in dumpsites (i.e., 6724 t/day) (Ziegler-Rodríguez et al., 2018). The data reported by OEFA estimates that the total area affected and potentially degraded by MSW in Peru is 1970 ha, and these critical dumpsites represent around 42 % (i.e., almost 830 ha) of the total area. Thus, the closure of these dumpsites located in 18 different regions would be an important step forward to address the transitioning from open dumpsters in order to reduce pollution problems associated to them.

2.1. Estimation of annual baseline GHG emissions

An estimation of the annual baseline GHG emissions from dumpsites in Peru, referred to here as *unsound solid waste disposal sites (uSWDS)*, was calculated using the most recent IPCC model (IPCC, 2019). This estimation depends on several parameters, e.g., quantity of waste disposed, composition of waste, height and area of the uSWDS, activity time, etc. In many cases it is challenging to obtain accurate data for these parameters, since uSWDS are normally not official disposal sites, and data recording tends to be scarce.

In the current study, data for the identification and characterization of the uSWDS were gathered from OEFA through the official national inventory of degraded areas by MSW (OEFA, 2019) (see Table 1). Further detailed data for each uSWDS analyzed is in Table A1 of the SM.

Data linked to average waste composition in each uSWDS were gathered from the SIGERSOL platform of the Ministry of Environment (MINAM) (MINAM, 2018), which provides an estimation of the different fractions (e.g., organic matter, wood, paper, cardboard, etc.), as well as the density of uncompressed waste (in kg/m^3). These data were available per location (i.e., district, province, and department) in which the uSWDS assessed is located. It is important to notice that waste density data are based on a limited number of samples computed per district. Whenever density data were not available, or an excessively elevated/reduced value was reported, an average value of 300 kg/m^3 was used, as the average values in LA&C region are between 200 and 300 kg/m3 for loose waste (CEPIS, 2003).

Geoclimatic conditions have a great influence on the decomposition rate of organic matter in uSWDS. According to (Ziegler-Rodríguez et al., 2019), Peru can be divided into three major geoclimatic regions (i.e., hyper-arid coast, Andean highlands, Amazon rainforest) following the Köppen-Geiger climate classification. For this study, data for the annual average temperature (°C), total annual precipitation (mm) and reference evapotranspiration (mm/dec) per region were gathered from the Peruvian Meteorological Institute (SENAMHI, 2021). Thereafter, a climate region (either boreal/temperate or tropical) and humidity conditions (either dry or wet) were assigned to each region based on the criteria described in the IPCC model (see Table A1 of the SM).

Despite the availability of most parameters needed to model emissions, important information concerning the height (*h*) of uSWDSs, that influence the existing aeration conditions (i.e., aerobic or anaerobic) and, thus, the conversion of organic matter to CH_4, were not available and were estimated based on existing data following Eq. (1).

$$h = \Sigma_{t=0}^{(T\_ACT)} \frac{CANT\_RRSS * 312 * (1-0.01)^t}{Area * \alpha * \frac{Density}{1000}} \quad (1)$$
$$s.t. \quad \alpha = 0, t = 0; \quad \alpha = 1.5, t > 1 \; and \; t < 4; \quad \alpha = 2, t \geq 4$$

where CANT_RRSS is the daily quantity of waste received by a given uSWDS (in t/day) multiplied by the number of days per year receiving wastes (i.e., 312 days per year, considering 52 weeks in a year and 6 days per week). Eq. (1) considers a decrease in waste generation for previous years (i.e., 1 %) due to the lower consumption in the past, and it considers the total number of years that the uSWDS has been active (T_ACT). Thereafter, the depth of the dumpsite in each year was calculated using the total amount of waste, the density of waste per district, and the area of each dumpsite. Finally, the total height was considered to be the sum of the yearly depths. Eq. (1) also considered that the waste was covered and compressed by the weight of the material that was deposited above every year. Thus, a compression factor (α) of 0.0 was used for the most recent year in the calculation; α = 1.5 for waste deposited between one and three years earlier; and α = 2 for the waste deposited four years earlier (CEPIS, 2003).

Table 1
Main parameters obtained for the analysis.

Parameter	Definition	Units
Location	Geographical administrative location	District, Province and Department
	UTM coordinates	East, North and Zone
Extension (Area)	Area covered by the uSWDS	m^2
Time of activity (T_ACT)	For how long have been used the uSWDS	years
Quantity of residues (Q_RES)	Daily quantity of residues received by the uSWDS	t/day

Baseline emissions ($BE_{CH4,uSWDS,y}$), reported in t CO_2 eq. per year, were estimated using the IPCC model as in the "Methodological tool – Emissions from solid waste disposal sites" (UNFCCC, 2017). For this, Eq. (2), which is based on a first order decay (FOD) assuming an exponential decrease of CH_4 generation over time, was applied.

$$BE_{CH4,uSWDS,y} = \varphi * (1-f) * GWP_{CH4} * (1-OX) * \frac{16}{12} * F * DOC_f * MCF \times \Sigma_{x=1}^{y} \Sigma_j W_{j,x} * DOC_j * e^{-k_j*(x-y)} * \left(1-e^{-k_j}\right) \quad (2)$$

where j is the waste type category; x is the year during the uSWDS disposal period; y is the year for which methane emissions were calculated; φ is the model correction factor to account for model uncertainties (a factor of 0.8 is used in the present study); f is the fraction of methane captured and flared, combusted or used in another manner (a value of 0 is considered for uSWDS); GWP_{CH4} is the GWP of methane, valid for the relevant commitment period, set as 28 (in t CO_2/t CH_4) (Myhre et al., 2013); OX is the oxidation factor which reflects the amount of methane from uSWDS that was oxidized in the soil or other material covering the waste (a default value of 0 was applied); F is the volume fraction of methane in the biogas of uSWDS (a default value of 0.5 was considered); DOCf is the fraction of degradable organic carbon (DOC) that can decompose (the default value for MSW is 0.5); MCF is the methane correction factor that depends on the type of SWDS, either managed or unmanaged; for the latter (i.e., uSWDS) it also depends on the height (either deep (h ≥ 5 m) or shallow (h < 5 m)); $W_{j,x}$ is the amount of organic waste type j disposed on the uSWDS in the year x (in metric tons); DOC_j is the fraction of degradable organic carbon (by weight) in the waste type j; k_j is the decay rate for the waste type j that depends on the climatic conditions where the uSWDS was located. The detailed values used for this study are shown in Supporting Material (Tables A2-A4). Note that default values are used when no further info is available.

2.2. Evaluation of mitigation strategies

Peru has a program at the national level where the progressive closure of dumpsites is included among its goals, considering as alternatives the final closure and the conversion to a sanitary landfill (CEPIS, 2003). A preventive approach when planning the closure of dumpsites is crucial in order to avoid, mitigate and control environmental, social and economic impacts. Thus, the evaluation proposed in this study considers the mitigation potential of GHG emissions along with financial indicators that reveal the economic feasibility.

Different strategies appear as feasible to mitigate GHG emissions in the waste management sector (UNFCCC, 2020). A first group is based on diverting waste from landfilling towards the production of energy using an alternative waste treatment such as incineration, gasification or anaerobic digestion. A second group is based on circular economy principles and energy efficiency recovering and recycling materials from wastes. A third group is focused on GHG destruction eliminating, or using, CH_4 emissions once they have been produced. The latter includes landfill gas (LFG) recovery, flare or use, as well as the application of the methane oxidation layer (MOL). Finally, a fourth group promotes GHG emissions avoidance either by diverting waste from landfilling towards other uses, in line with the circular economy principles (e.g., biomass wastes used as feedstock in pulp and paper, cardboard, fiberboard or bio-oil production), or by modifying the disposal site to reduce the production of CH_4 (e.g., aeration of landfills, such as the Fukuoka method).

The mitigation strategies (MSs) selected in this study are in line with Peru's program categories (i.e., final closure and conversion to sanitary landfill) and consider the fact that many of the technologies theoretically projected and sold by companies for solid waste management in developing countries are not appropriate neither from the local experience and knowledge nor from a technological viability point of view. Inadequate planning has resulted in many systems being built, only to close shortly after costly start-up, operation and maintenance activities (EPA, 2012). The four MS evaluated are:

MS1 – Closure and covering the dumpsite with a soil layer.

MS2 – Closure and avoidance of the release of CH_4 through biological oxidation by covering the dumpsite with a MOL.

MS3 – Closure and avoidance of LFG emissions by passive aeration of the dumpsite.

MS4 – Closure and installation of an active LFG collection system with flaring.

It is important to highlight that these MS have certain application constraints depending on certain characteristics of the uSWDS such as size (m^2), quantity of residues in place (t), amount of LFG in terms of gas flow rate (m^3/h) or the specific CH_4 emissions (m^3/m^2h). Thus, MS1 can be applied to all types of uSWDS since it is the formal closure and consists on the disposition of the final layer, previous leveling and compacting existing garbage heaps, among other actions. MS2 can be implemented as a small-scale measure only in uSWDS that present low residual surface CH_4 emissions (<0.004 m^3/m^2 h) and an area lower than 100,000 m^2 due to possible constraints concerning availability of compost in the local market. MS3 can be implemented only in deep uSWDS (h > 5 m), since waste in shallow uSWDS generally decomposes aerobically. Finally, for feasibility reasons, MS4 can be implemented in deep uSWDs that present at least one million metric tons of waste in place (UN, 2007) and present a gas flow rate higher than 500 m^3LFG/h for open flares (IDB, 2009).

2.2.1. Evaluation of GHG mitigation

In order to evaluate the GHG mitigation potential of each MS, the total emission reductions (TER_{uSWDS}) were calculated for each uSWDS (Eq. (3)) for an established period of 10 years (i.e., 2019–2028). The timeframe selection is based on the typical length for the crediting period of CDM projects and the starting year is designated due to data reliability (see Section 2.3).

$$TER_{uSWDS} = \Sigma_y ER_{uSWDS,y} \ \forall \ uSWDS \tag{3}$$

where $ER_{uSWDS,y}$ is the yearly emission reduction in each uSWDS calculated generally according to the CDM methodologies as shown in Eq. (4).

$$ER_{uSWDS,y} = BE_{CH4,uSWDS,y} - \left(PE_{uSWDS,y} + LE_{uSWDS,y}\right) \tag{4}$$

where BE refers to the baseline emissions as calculated in Eq. (2). It is important to highlight that for MS1 and MS2, BE is multiplied by a factor (Af) representing the area fraction of the uSWDS that will be covered with MOL or soil up to year "y". In this case study, Af equals one in all cases to represent that the coverage is fully implemented from the first year onwards. PE refers to the project emissions after the MS selected has been implemented (including secondary emissions from, for example, transport, energy production and fossil fuel consumption). Finally, LE refers to the leakage of emissions, if occurring (considered as zero for this study). PE and LE are specific for each MS and are calculated according to their respective approved CDM methodologies. Thus, for MS2, MS3, and MS4, CDM methodologies AMS-III.AX (UNFCCC, 2011), AM0093 (UNFCCC, 2012), and AMC0001 (UNFCCC, 2019) were applied, respectively (see Eqs. (5)–(7)). MS1 was estimated following the same CDM methodology as MS2 but changing the oxidation factor of the soil cover accordingly. Detailed calculations are shown in Supporting Material.

$$PE_{uSWDS,y} = PE_{EC,y} + PE_{FC,y} + PE_{transp,y} + PE_{MOL/soilcover,y} \ \forall \ MS1 \ and \ MS2 \tag{5}$$

$$PE_{uSWDS,y} = PE_{EC,y} + PE_{FC,y} + PE_{CH_4,a,y} + PE_{N_2O,a,y} \ \forall \ MS3 \tag{6}$$

$$PE_{uSWDS,y} = PE_{EC,y} + PE_{FC,y} + PE_{DT,y} + PE_{SP,y} + PE_{CH_4,f,y} \ \forall \ MS4 \tag{7}$$

where: i) $PE_{EC,y}$ are the emissions from electricity consumption due to project activity in year "y" (t CO_2/y); ii) $PE_{FC,y}$ are the emissions from fossil fuel consumption due to project activity in year "y" (t CO_2/y); iii) $PE_{transp,y}$ are the emissions from incremental transportation in year "y" (t CO_2/y); iv) $PE_{MOL/soilcover,y}$ represents the residual emissions of the uSWDS from either MOL or soil covered areas (after oxidation) in year "y" (t CO_2/y); v) $PE_{CH4,a,y}$ are the CH_4 emissions from aeration of the landfill in year "y" (t CO_2/y); vi) $PE_{N2O,a,y}$ are the N_2O emissions from aeration of the landfill in year "y" (t CO_2/y); vii) $PE_{DT,y}$ are the emissions from the distribution of compressed/liquified LFG using trucks in year "y" (t CO_2/y); viii) $PE_{SP,y}$ are the emissions from the supply of LFG to consumers through a dedicated pipeline in year "y" (t CO_2/y); and, ix) $PE_{CH4,f,y}$ are the CH_4 emissions from flares in year "y" (t CO_2/y).

The evaluation was performed for the waste already placed in the uSWDS when the MS was implemented. A dumpsite should not be closed if there is no alternative for the final disposal of MSW because the problem will persist. Therefore, in this study, the current evaluation has not considered the fate and contribution of new generated waste after the MS is implemented in the dumpsite, relying on its correct management by means of environmentally sound options.

2.2.2. Evaluation of economic indicators

The economic feasibility of the different MS is a key parameter for their implementation, but the calculation process is complex as local market conditions and site-specific technological details cannot be fully captured at a high granularity level. It is important to highlight that within its NDCs, Peru considers the possibility of selling emission reductions in international markets (e.g., through the CDM) produced by mitigation activities, whenever it does not hinder the fulfilment of the national commitment. Thus, in order to avoid double counting, the economic feasibility can be analyzed either considering the abatement cost of the NDCs or including the revenues from selling the CERs achieved through CDM.

The first approach calculates the abatement cost (AC) as shown in Eq. (8). This may allow prioritizing the possible MS within the different dumpsites based on the lowest value.

$$AC_{uSWDS} = \frac{\Sigma_{t=0}^{T} \dfrac{CF_t[Costs]}{(1+i)^t}}{TER_{uSWDS}} \tag{8}$$

where CF_t is the cash flow in period t for a total period of $T = 10$ years, considering only capital and operation & maintenance (O&M) costs shown in Table 2. The discount rate i of period t was set in this study at 7 %.

The second approach considers that the different mitigation actions are registered in the CDM in order to obtain CERs that can be sold in the emissions market. It is important to highlight that MS1 is not a methodology from the CDM and, consequently, it will not generate CERs. In the current study, the benefit-cost ratio (BCR) that shows the relationship between the relative costs and benefits expressed in monetary terms (Eq. (9)) was applied. If BCR is >1, the MS is expected to deliver a positive net present value (NPV). However, if the value is lower than 1, the costs outweigh the benefits.

$$BCR_{uSWDS} = \frac{|\,PV[Benefits]\,|}{|\,PV[Costs]\,|} = \frac{\Sigma_{t=0}^{T} \dfrac{CF_t[Benefits]}{(1+i)^t}}{\Sigma_{t=0}^{T} \dfrac{CF_t[Costs]}{(1+i)^t}} \tag{9}$$

where CF_t is the cash flow in period t for a total period of $T = 10$ years, considering all costs shown in Table 2 including capital costs, O&M costs, as well as preparation costs (including CDM project development), and CDM annual costs. The discount rate i of period t was set in this study at 7 %. Benefits comprise the revenues calculated as the quantity of CERs obtained, that equal the $ER_{uSWDS,y}$, multiplied by their value on the market.

Table 2
Cost factors (including capital, O&M, preparation and CDM annual) per mitigation strategy.

Mitigation strategy (MS)	Capital costs[a]	O&M costs (annual)[a]	Preparation costs[b]	CDM costs (annual)[b]	Sources
Soil cover (MS1)	8–10 $/m^2$ surface	NA	NA	NA	Berge et al., 2009; Stanisavljevic et al., 2012
MOL (MS2)	12–16 $/m^2$ surface	NA	18,500–117,000 $	5000 $ + 2 % of CERs	EPA, 2011; Stanisavljevic et al., 2012
Semi-aerobic (MS3)	13–14 $/m^2$ surface	4 $/m^2$ surface	38,500–610,000 $		Chong et al., 2005; Berge et al., 2009 Rahim and Jamaluddin, 2015
LFG flare (MS4)	15–21 $/m^2$ surface	1.2–1.5 $/m^2$ surface			EPA, 2020; Duffy, 2019; Berge et al., 2009

O&M – Operation and maintenance; MOL – Methane Oxidation Layer; LFG – Landfill Gas; CDM – Clean Development Mechanism; CER – Certificate Emission Reduction.
[a] Conversion rate of 4046 m^2 per acre.
[b] Source: UNEP (2007).

2.3. Limitations

Although general data on dumpsites characterization were available, and are currently considered the best source, certain data limitations were identified. Firstly, the data reported for certain dumpsites was inconsistent and for that reason the study has been constrained to the main dumpsites with verifiable data. Secondly, important data for the calculation of the baseline emissions such as the height of the dumpsite was missing and was inferred in an indicative way (see Eq. (1)) in order to differentiate deep ($h > 5$ m) from shallow ($h < 5$ m) dumpsites and thus assign the MCF. For correct values of height, more data concerning the topography of the site would be needed, as well as a visual on-site inspection. Similarly, data on waste density arriving to the dumpsite was scarce and inconsistent; hence, average waste densities have been used when needed.

The calculation of emissions from the open burning of waste at the dumpsite following the IPCC model was not performed because it would add more uncertainty to the study due to lack of quantitative data. However, it is a natural or human-induced phenomenon occurring in many dumpsites that could potentially alter the results presented in the current study.

Concerning the temporal starting point for the analysis (i.e., 2018), it has been fixed based on data reliability. Changing the temporal starting point of the analysis may lead to unrealistic situations due to possible changes in the dumpsite status within the country. Besides, for the main objective of this study, the authors consider that the results and conclusions obtained are valid and relevant for the political discussion and to support waste management-related policies.

3. Results and discussion

The cumulative GHG baseline emissions in 2018 estimated for the 24 critical uSWDSs included in this study add up to 704 kt CO_2 eq. As shown in Fig. 2, the one in Trujillo was the uSWDS with the highest GHG emissions (193 kt CO_2 eq.), followed by the uSWDS in Piura (79 kt CO_2 eq.) and Cusco (61 kt CO_2 eq.). Interestingly, these three sites represent almost 50 % of the total emissions for the 24 sites assessed. Note that in Arequipa there are two differentiated uSWDS (even if one close to the other), and if their emissions were accounted together the contribution would be 78 kt CO_2 eq. (at the same level of the uSWDS in Piura and higher that the one in Cusco), and the contribution of those five sites would be almost 60 % of the total emissions for the 24 sites assessed. The individual contribution of all the sites inventoried can be observed in Table A5 in the SM.

The three uSWDSs mentioned above, despite being the main contributors to GHG emissions, present a medium-high GHG emission rate per area (0.45 t CO_2 eq. per m^2 in Trujillo, 0.12 t CO_2 eq. per m^2 in Piura, and 0.96 t CO_2 eq. per m^2 in Cusco), considering that the range is between 0.005 (i.e., Chincha) and 1.47 t CO_2 eq. per m^2 (i.e., Tingo María – Leoncio Prado). After Leoncio Prado, the highest ratios are in Chimbote and Tarapoto with 1.37 t CO_2 eq. per m^2, and 1.1 t CO_2 eq. per m^2, respectively. Concerning the emissions per t of waste received, the top three contributors also present medium-high rations. The ratio in Trujillo is 182 t CO_2 eq. per t of waste, in Piura 188 t CO_2 eq. per t of waste, and in Cusco 157 t CO_2 eq. per t of waste, being the range between 233 t CO_2 eq. per t of waste in Pucallpa (Coronel Portillo) and 21 t CO_2 eq. per t of waste in Moquegua.

According to the provisions presented for the NDCs (Gobierno del Perú, 2020a), the contribution of the solid waste subsector in the Business as Usual scenario in 2030 would represent 3.4 % (i.e., 10 $MtCO_2$ eq.) of total emissions (298 $MtCO_2$ eq.). The commitment of Peru within the updated first NDC (UNFCCC, 2021) limited GHG emissions to a maximum level of 209 $MtCO_2$ eq. (unconditional) and 179 $MtCO_2$ eq. (conditional, i.e. if international means of support are provided) by 2030. The quantification of the GHG emissions for the time period of 10 years (2019–2028) in this study reveals that the cumulative quantity emitted by those 24 critical dumpsites would reach 4.4 Mt CO_2 eq. Thus, this quantity represents 44 % of the solid waste emissions expected by 2030, and almost 2.1 % and 2.5 % of the conditional and unconditional commitment, respectively.

Consequently, it is important to evaluate the relative importance of the GHG mitigation potential from closing critical dumpsites in the NDCs commitment. In this sense, Table 3 shows the analysis for the different MSs proposed. Thus, the different mitigation potentials for the estimated period of 10 years range between 91 kt CO_2 eq. for MS4 and 733 kt CO_2 eq. for MS3. An optimized mitigation strategy (i.e., maximizing the TER) for the 24 critical dumpsites, selecting the MS with the highest total mitigation potential for each one, would lead to a mitigation potential of 970 kt CO_2 eq. including six dumpsites with MS1, eight dumpsites with MS2, and 10 dumpsites with MS3. From these results, it is clear that MS4 is not the best option for any of the three eligible dumpsites, since there is always an alternate MS that presents a higher mitigation potential. Moreover, MS2 presents in all cases increased mitigation potential as compared to MS1 and MS3. When comparing

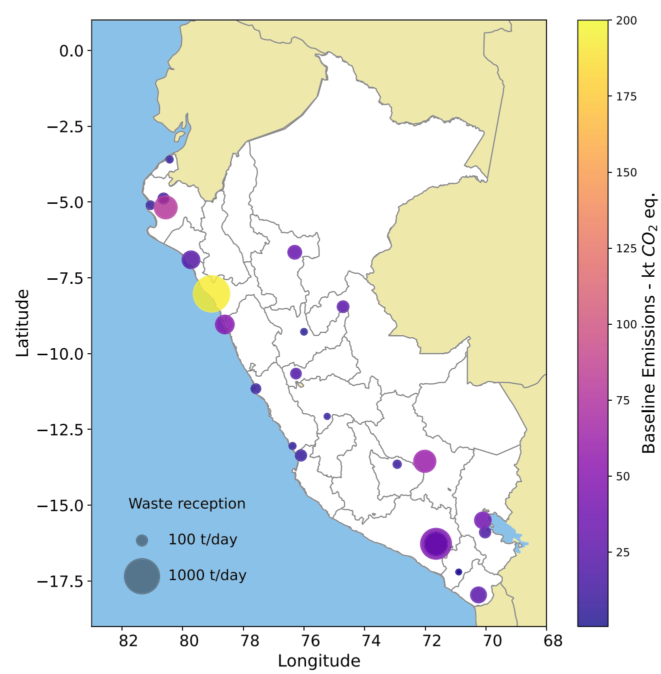


Fig. 2. Baseline GHG emissions in 2018 for the 24 critical dumpsites in Peru in kt CO_2 eq. The size of the circles denotes the quantity of waste received daily in the dumpsite.

Table 3
Results for the environmental and economic assessment of the different mitigation strategies.

Mitigation Strategy (MS)	Number of uSWDS included	GHG mitigation potential for 10 years (kt CO_2 eq.)		Abatement costs (AC) framework			
		Total	Range per uSWDS	Costs (M€)	Range costs per uSWDS (M€)	Average AC (€/t CO_2 eq.)	Range AC per uSWDS (€/t CO_2 eq.)
MS1	24	436	0.36–133	75	0.015–28	172	9–2865
MS2	8	340	1.8–164	5	0.19–1.2	15	7–249
MS3	18	733	4.3–196	100	0.07–27	136	17–1231
MS4	3	91	14.4–54.6	31	1.8–18	341	122–817
Combined MS (max TER)	24	970	1.8–196	138	0.07–28	142	7–2865
Combined MS (min AC)	24	709	1.7–164	76	0.015–28	107	7–2865

MS1 and MS3, MS3 shows more mitigation potential than MS1 except for one specific site (i.e., the open dump in Pucallpa – Coronel Portillo).

When putting the quantities obtained into context, it is important to acknowledge that the reduction potential of the four measures proposed in the NDCs for 2030 in the solid waste subsector (i.e., construction of 20 semi-aerobic sanitary landfills, organic solid waste segregation programs and construction of 30 composting plants, construction of 5 sanitary landfills with LFG capture and flares, and the use of LFG generated in 3 sanitary landfills for energy production) adds up to 600 kt CO_2 eq. of avoided emissions (Gobierno de Perú, 2020b). However, this quantity only considers the reduction potential of measures dealing with waste quantities generated and managed in future years until 2030, ignoring the reduction potential of possible measures related to the waste already inadequately disposed of in uSWDSs. Bearing this in mind, and considering that Peru is within the group of nations that have recently pledged to cut by one third methane emissions by 2030 (Masood and Tollefson, 2021), methane emissions from pre-existing MSW should gain relevance in Peru's commitments.

In terms of economic feasibility, first of all, the analysis considers the cost of abating GHG emissions that might be important for the NCDs consecution analysis. Table 3 shows the analysis for the different MSs proposed. Thus, the total costs for the estimated period of 10 years range from 5 M€ (MS2) to 100 M€ (MS3). The most interesting indicator is the average AC that indicates the price for preventing one metric ton of CO_2 eq. for each MS, being the highest for MS4 and the lowest for MS2. An optimized mitigation strategy (i.e., minimizing the AC) for the 24 critical dumpsites, selecting the MS with the lowest AC for each one, would lead to a total cost of 76 M€ and an average AC of 107 €/t CO_2 eq., including 16 dumpsites with MS1 technology and eight dumpsites with MS2. Based on the results, it is clear that MS3 and MS4 are not cost-efficient technologies. Comparing the two optimized strategies, there is a clear trade-off between the environmental and the economic objective. A reduction of 16 % in GHG mitigation potential from the maximum potential leads to a reduction in the total costs of 45 % and a reduction in the average AC of 25 %.

When the mitigation actions are registered in the CDM, the BCR is calculated for different prices of the CER in the market, since at the price of 0.6 €/t CO_2 eq. in April 2021 (SendeCO2, 2021) profitability is not possible in any case. Fig. 3 shows the number of actions that would be profitable within each MS at different prices of the CER up to 50 €/t CO_2 eq. that may be possible in the future depending on the restrictions imposed on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) developed by the International Civil Aviation Organization (ICAO) (Cristóbal et al., 2021). For 20 €/t CO_2 eq., only two MS1 actions may be profitable (in Chimbote and Tingo María) and three MS2 actions (in Abancay, Arequipa and Pasco). This number increases to seven in the case of MS1 and five for MS2 at 50 €/t CO_2 eq. At this price, there is one MS3 action that is profitable (i.e., the uSWDS in Chimbote). MS4 actions require much higher CER prices than 50 €/t CO_2 eq. to become profitable, something that seems unlikely in the short and medium term, even with CORSIA.

3.1. Scenario analysis - case study of Trujillo

In order to fathom the importance of an adequate closure and a prompt action in uSWDSs, the analysis of three plausible scenarios in the most critical dumpsite in Peru, that is, *Botadero "El Milagro"*, in Trujillo, was considered. "*El Milagro*" has been active since 1989, receiving ca. 1000 t of waste daily and covering an area of roughly 45 ha. A sanitary landfill has been planned nearby and will receive the waste once it is opened. According to Peruvian law (Law 1278 on the Comprehensive Management of Solid Waste), new sanitary landfills with high waste volume must incorporate a centralized landfill gas capture and burn technology (CDKN, 2018).

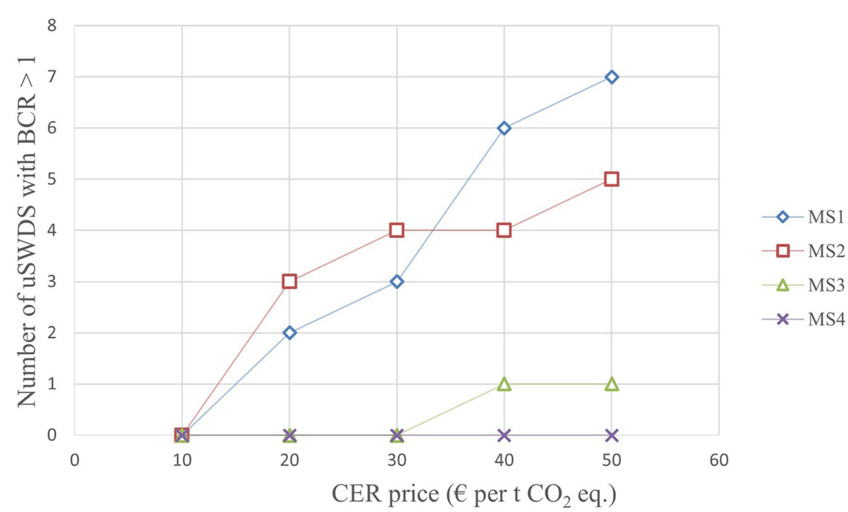


Fig. 3. Number of actions in uSWDSs with BCR > 1 for the different MSs depending on the CER price in the market.

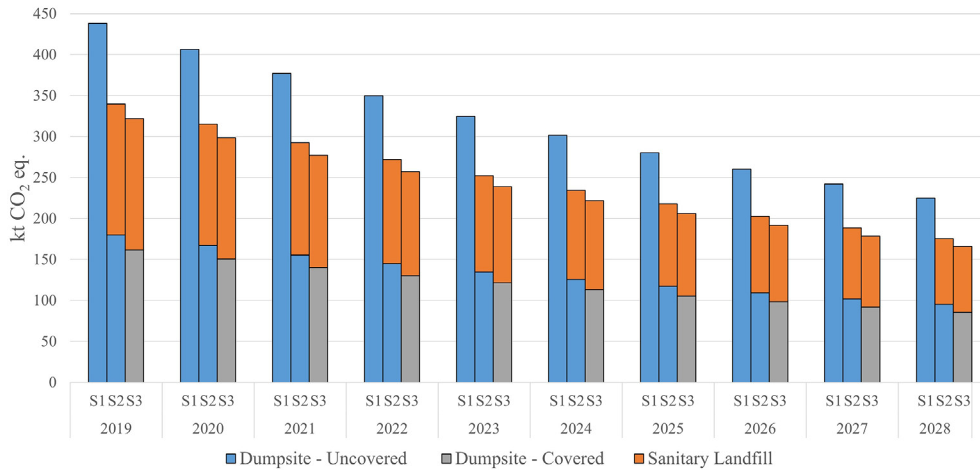


Fig. 4. GHG emissions for the ten years period analyzed for the three scenarios proposed (S1-pessimistic, S2-more optimistic, S3-the most optimistic) in Trujillo.

The first scenario (S1) is the most pessimistic and foresees that the construction of the sanitary landfill is not happening, and the dumpsite continues receiving wastes until 2028 without adequate management. The second scenario (S2) is more optimistic and foresees that the sanitary landfill is built in 2019 as planned. Note that it was finally postponed to 2021 but, for the sake of the calculations, we assume that it was open in 2019 to assess the importance of the prompt action. Therefore, the dumpsite will no longer receive waste, but will remain without an appropriate closure. Finally, the third scenario (S3) is the most optimistic and foresees that the sanitary landfill is built in 2019 as planned, and the dumpsite is correctly closed using the simplest technology (cover with soil). For all scenarios, an annual growth rate of waste generation equal to 1 % was considered based on data from 2018, assuming that waste composition in that year would be constant for subsequent periods. For the sanitary landfill, methane capture efficiency was set at 50 %, and the flare efficiency at 90 %.

Results in Fig. 4 show that the proper disposal of wastes in the sanitary landfill instead of the open dumpsite (comparing S2 with S1) can mitigate between 99 kt CO_2 eq. in 2019 and 50 kt CO_2 eq. in 2028, accounting for a total of 715 kt CO_2 eq. within the ten-year period. Besides, delaying the proper closure of the dumpsite (comparing S2 where the dumpsite is not properly covered with S3 that implements the action just after the sanitary landfill is open and active) implies an additional emission of 133 kt CO_2 eq. within the ten-year period. Total emissions attributable to waste management inaction are roughly 848 kt CO_2 eq. for the ten-year period, representing 0.3 % of the solid waste emissions expected by 2030.

4. Conclusions

Peru is slowly advancing with its commitments to reduce GHG emissions in the waste management sector. For this, it has initiated a plan to transition from open dumps to sanitary landfills in all major cities. However, the adequate closure of the open dumpsters in these cities has not been considered, despite the succulent GHG emission mitigation that this action could entail. In this sense, the results from this study demonstrate that if a site-specific approach is established in order to use adapted closure systems (e.g., MOL, semi-aerobic) to different dumpsters across the nation, close to 1 Mt CO_2 eq. could be mitigated by 2030. This would leave Peru in a much better position to continue with decarbonization policies in the 2030–2050. In other words, with most cities having sanitary landfills, in most cases with LFG technology, and with these dumpsters managed with adequate closure systems, policies by 2030 could shift in two directions: i) extending effective controlled waste disposition sites to rural communities, which is discussed in depth in the current study; and, ii) establishing circular economy waste policy perspectives in cities, aiming at minimizing the amount of waste that eventually reaches final disposition sites through resource recovery and recycling actions, issues that must be resolved in future studies in the particular context of Peru and other developing nations.

It is important to note that land use represents approximately two thirds of Peruvian mitigation efforts in the Paris Agreement, and it seems plausible to assume that Peru will face important challenges to meet its mitigation targets, mainly because zero deforestation schemes in the Amazon Forest are struggling to be implemented effectively due to a variety of reasons, including an increasing number of forest fires due to climate change, or the informal expansion of illegal, informal or unregulated gold mining activities, among others. Therefore, it is imperative for authorities to seek alternative mitigation efforts in other sectors, such as the one described for waste in this study, as well as the appropriate economic funds to implement them, to compensate for the barriers that are being experienced in the management of carbon stocks in the Amazon.

CRediT authorship contribution statement

- Jorge Cristobal: Investigation, formal analysis, writing-original draft preparation, Writing-editing, conceptualization.
- Ian Vázquez: Investigation, writing, formal analysis, methodology, writing-original draft preparation, conceptualization.
- María Margallo: Writing, Investigation, formal analysis.
- Kurt Ziegler-Rodriguez: Investigation, formal analysis.
- Eduardo Rodríguez: Investigation, formal analysis.
- Jara Laso: Investigation, formal analysis.
- Israel Ruiz-Salmón: Investigation, formal analysis, supervision.
- Ranzy-Kahatt: Investigation, Writing, formal analysis, methodology, writing-original draft preparation, conceptualization.
- Rubén Aldaco: Investigation, formal analysis, Writing-editing.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157295.

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