Climate action and food security: Strategies to reduce GHG emissions from food loss and waste in emerging economies

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Abstract

Peru struggles to upgrade its waste management, with landfilling only just overtaking open dumpsters as the main disposal method. Despite the benefits of this transition, including reduced environmental impacts to water and soil, previous studies demonstrated that greenhouse gas (GHG) emissions may increase if adequate levels of technological sophistication are not implemented. Considering that 58% of municipal solid waste (MSW) is organic, it seems plausible that a relevant portion of emissions can be linked directly to food loss and waste (FLW) management. This study aims to determine the GHG emissions mitigation potential in FLW compared to the current baseline scenario in 24 Peruvian cities, by modelling alternative technologies to treat organic MSW. Life cycle modelling was performed using the waste-LCA software EASETECH. Five treatment scenarios were modelled: i) open dumping; ii) landfilling with no gas treatment; iii) landfilling with landfill gas treatment; iv) landfilling with energy recovery; and, v) anaerobic digestion. GHG emissions of FLW generation proved to be substantially higher than those for FLW treatment. However, if sophisticated technologies are implemented in FLW treatment, an annual reduction of up to 1.56 Mt CO_2eq could be attained. Moreover, despite the health and environmental benefits of a transition to optimized diets, in which, for example, meat consumption is reduced and vegetables are boosted, an important increase in FLW and, therefore, an increase in GHG emissions in the treatment phase is shown. However, if certain technologies, such as energy recovery or anaerobic digestion, were implemented, most carbon losses would be avoided.

Keywords: carbon footprint; dietary patterns; landfilling; Life Cycle Assessment; Peru; waste treatment.

1. Introduction

Food loss and waste (FLW) has become a mainstream social and environmental concern in most developed nations worldwide (Alexander et al., 2017; Usubiaga et al., 2017). On the one hand, in a world that may reach 10 billion people by the second half of the 21st century, it is imperative to improve the efficiency of food supply chains to guarantee human nourishment and food security (Shafiee-Jood and Cai, 2016). On the other hand, the environmental benefits of reducing FLW are plentiful and have recently been widely analyzed in the scientific literature (Kummu et al., 2012; Scherhaufer et al. 2018; Vázquez-Rowe et al., 2019a).

Although the United Nations has included FLW in its sustainable development goals (SDGs) for 2030, proposing to halve FLW by that date (UN, 2019), actions to reduce FLW in developing and emerging nations are still timid (Guo et al., 2019). Accordingly, FLW management strategies proposed in the literature have focused mainly on developed countries. Nevertheless, there are attractive opportunities to support developing economies to address the challenges posed by a transition to a circular economy in the food sector (Stanisavljevic, et al., 2018). In fact, FLW management in developing countries is currently considered to be a major threat to sustainable development and food management systems, as well as for related climate action, circular economy and food security. Fast and chaotic urbanization processes in some countries, and the rapid growth of the middle class, with consequent food consumption pattern changes, in others, have been identified as important barriers towards attaining substantial FLW reductions by 2030 in these countries (Thi et al., 2015). A study published by Bahadur and colleagues (2016) suggests that food loss, i.e., the reduction in edible food available throughout the supply chain until the product reaches the consumer (Hiç et al., 2016), is correlated to investment in developing economies to agricultural technologies, transportation infrastructure and information and communications technologies. In fact, they state that up to 49% of food loss in these nations could be eliminated if improvement factors, together with gross domestic product (GDP), are fostered. In contrast, food waste, which is the fraction discarded by the consumer, appears to have higher ratios in developed nations (Hiç et al., 2016).

Lack of data is also a major limitation to implementing policy actions in developing countries. While robust data regarding FLW estimations and derived environmental and economic impacts have already been computed in European nations (Buzby and Hyman, 2012; Beretta et al., 2017; García-Herrero et al., 2018), the picture in other regions of the world remains diffuse and uncertain (Vilariño et al., 2017; Dal'Magro and Talamini, 2019). In this context, Gustavsson and colleagues (2013) generated a report for the United Nations in which they provided average FLW rates for different regions in the world. To date, together with data from Hiç and colleagues (2016) and a recent study by Chen et al. (2020), this report still remains the most reliable and comprehensive study for many countries.

Peru lacks a comprehensive policy on FLW and, although some isolated strategies related to its valorization have been pushed forward (Quispe et al., 2019), no clear path is foreseen at a national level. In some cases, for instance, agricultural residues informally enter municipal solid waste (MSW) disposition routes. In this context, Peru currently has a rudimentary waste treatment sector, in which landfilling of all types of waste, not only household-generated organics, but also agricultural residues, is only just overtaking open dumpsters as the main final disposition route throughout the country (Ziegler-Rodriguez et al., 2018). Despite the evident benefits of this transition, including substantial reductions in environmental impacts in the water and soil compartments, a study by Ziegler-Rodriguez and colleagues (2019) for three landfills in distinct geoclimatic areas of Peru demonstrated that

GHG emissions and other air emissions could actually show an increase over the use of dumpsters if adequate levels of technological sophistication are not implemented.

The analysis of FLW in Peru has been understudied in the existing literature. For instance, a study by Vázquez-Rowe et al. (2017) presented the greenhouse gas (GHG) emissions of different dietary patterns throughout the country. The study was fed from detailed food consumption data per city, socioeconomic group, and academic level, among others, obtained from the Peruvian National Statistics Institute (i.e., INEI, using the acronym in Spanish). It also used data from Gustavsson et al. (2011) to calculate the total emissions of food production that reach Peruvian households, by including the food produced that is eventually lost or wasted. However, despite the effort to account for the emissions linked to the production of FLW, this study excluded the GHG emissions related to the final disposition of this organic waste.

In a similar line to most countries in Latin America and the Caribbean, the low level of sophistication of the Peruvian waste treatment sector is considered one of the main challenges the nation faces in terms of mitigating its GHG emissions (Margallo et al., 2019; Vázquez-Rowe et al., 2019b). Considering that an average Peruvian household spends between 40% and 55% of its income on food (INEI, 2017), and that approximately 58% of generated municipal solid waste (MSW) is of organic nature (MINAM, 2017), it seems plausible to assume that a relevant chunk of GHG emissions can be attributed directly to the production and disposal management of FLW. In this context, the main objective of this study is to determine the GHG emissions mitigation potential existing in Peruvian FLW as compared to the current baseline scenario, by estimating FLW in Peruvian diets and modelling different technological advancements in the treatment of organic MSW. To this end, a set of scenarios linked to the main Peruvian cities and socioeconomic levels (i.e., quintiles) in the city of Lima were combined with a range of different waste treatment technologies in order to determine the main hotspots and mitigation opportunities to align FLW management in Peru with climate policies and Sustainable Development Goals (SDGs). The results from this study are intended to be of utility in order to steer further research in Latin America and the Caribbean regarding the environmental consequences of FLW, identifying the main methodological and data limitations of conducting a study of these characteristics in the region, as well as providing solid data for policy-makers at a local and regional level to define site-specific policies that could be the basis for global strategies in developing countries.

2. Materials and Methods

2.1 Food consumption data

Food consumption data in Peru is available thanks to the decadal survey conducted by INEI. In fact, the most recent report delivers a detailed study in which over 36,000 Peruvian households participated (ENAPREF, 2012). For modelling purposes, this allowed the construction of 29 diet scenarios based on reported food consumption for different geographical or socioeconomic contexts. Hence, 24 scenarios represent the average diet in the main cities across the nation (see Figure S1 in the Supplementary Excel Material - SEM). The remaining diets (5), in contrast, were modelled, based on the socioeconomic quintile distributions in the city of Lima, which represent different levels of economic expenditure in households (see Table S1 in the SEM). Socioeconomic quintile distributions in other cities were not modelled due to lack of data reported by INEI. Moreover, it should be noted that for each of the 24 cities an alternate scenario was also modelled considering the environmental and nutritional optimization of Peruvian diets computed in Larrea-Gallegos and Vázquez-Rowe (2020).

2.2 Food loss and waste (FLW) data

In this study, we have defined food loss as all related residues linked to the production, processing and distribution stages up to retail (e.g., harvest residues, slaughtering waste), while food waste is labelled as the discarded residues in the remaining stages of the life-cycle (i.e., retail and final consumption) (Bellù, 2017). Although important, the non-organic fraction related to FLW, which has been previously analyzed in the literature (Vitale et al., 2018), is not included in the current study due to lack of data.

No quantitative FLW data for Peru were identified in the bibliography. Therefore, as in many studies for Latin America and the Caribbean and other regions of the world, FLW rates were extracted from Gustavsson and colleagues (2013), as shown in Table 1. This implies that there is no differentiation of FLW rates within food products from the same food category, which probably constitutes the main limitation of the current study.

Table 1. Food loss and waste (FLW) ratios in different stages of the food supply chain in South America per food category (adapted from Gustavsson et al., 2013).

	Agricultural production	**Postharvest handling and storage**	**Process and packaging**	**Distribution**	**Household consumption**
Cereals	6%	4%	2.7%	4%	10%
Roots and tubers	14%	14%	12%	3%	4%
Oilseeds and pulses	6%	3%	8%	2%	2%

Fruits and vegetables	20%	10%	20%	12%	10%
Meat	5.3%	1.1%	5%	5%	6%
Fish and seafood	5.7%	5%	9%	10%	4%
Milk	3.5%	6%	2%	8%	4%

These FLW ratios were then used to calculate the lump sum of FLW generated in each of the 29 case studies modelled, based on the per capita food purchase reported by ENAPREF (2012). Although Gustavsson and colleagues (2013) divide FLW throughout five different stages in the food supply chain, in the current study the first three stages (i.e., agricultural production, postharvest handling and storage, and processing and packaging) were aggregated into one single stage, named production. The rationale behind this modelling choice is that food loss generated in these three stages is disposed of in periurban or rural areas. These areas tend to be outside the area of influence of the main cities. Therefore, it is considered that the waste generated up to the packaging occurs beyond city limits. In contrast, it is assumed that distribution food loss is collected by urban municipal collection services and disposed of in the available disposition or treatment plants in the city (Margallo et al., 2019), in the same way as happens with household food waste (SIGERSOL, 2020). A division was also performed between plant-based and animal-based FLW. The rationale behind this division was to account for differing chemical properties between the two groups of organic waste.

2.3 GHG emissions in food loss and waste (FLW) production and treatment

The embodied GHG emissions for the production and distribution of FLW in Peru were extracted from a previous study by Vázquez-Rowe et al. (2017), which computed the life-cycle GHG emissions of all those food products reported in Peruvian national statistics (ENAPREF, 2012). The specific results are visible in Table 5 of Vázquez-Rowe et al. (2017), as well as in the SEM. As regards lack of data, GHG emissions in the household due to refrigeration, cooking or waste collection services were not included in the scope of the study.

The GHG emissions derived from FLW treatment only include those occurring in the stages that dispose of these organic residues in urban environments. Hence, carbon emissions linked to FLW treatment in the production stage were excluded from the system boundaries given their heterogeneous disposal in rural, peri-urban or industrial contexts in which traceability of these residues is unclear (Margallo et al., 2020).

2.4 Modelling of waste treatment scenarios

Life cycle modelling and the computation of the impact assessment results were carried out using the LCA software, EASETECH (Clavreul et al., 2014). This software permits the modelling of various treatment alternatives, from simple and rudimentary systems such as landfills, to incineration, anaerobic digestion and recycling, or complex and integrated systems in which various alternatives are employed (Clavreul et al., 2014). It enables the user to make a detailed follow-up of all the chemical substances present in the residues throughout the entire treatment system. This feature allows the identification of environmental hotspots and possible sinks (e.g., carbon). Moreover, it should be noted that EASETECH considers that only material fractions containing biogenic carbon, such as food waste, paper or wood, decay into CO_2 and CH_4 (Manfredi et al., 2009), the two main sources of GHG emissions linked to waste decomposition (Gentil et al., 2009).

The software enabled the differentiation of animal- and plant-based fractions as it includes in its modules a section for the definition of the waste input. In this study, due to the heterogeneity of FLW composition and the unavailability of more specific information regarding its chemical composition, the material fractions included in the model were limited to "vegetable food waste", which resembles all the organic fraction linked to plant-based residues, and "animal food waste", which resembles all the organic fraction related to animal-based residues. The information was introduced in the software and modelled for the 29 scenarios (ENAPREF, 2012) considering the specific animal- and vegetable food waste fractions for each scenario. The percentage of plant-based FLW ranged from 58% in Puerto Maldonado to 73% in Cajamarca (see Table S5 in the SEM). From a modelling perspective, these two fractions have slight variations with regard to their composition parameters, as shown in Table 2.

Table 2. Main material properties in the material fractions analyzed according to the EASETECH software (Clavreul et al., 2014). TS= total solids; VS= volatile solids.

Material Property	**Vegetable Food Waste**	**Animal Food Waste**
Water (%)	77.0	57.1
TS (%)	23.0	42.9
VS (% TS)	94.8	91.3
Energy (MJ/kg TS)	18.3	24.6
Biogenic Carbon (% TS)	47.5	55.4

Anaerobically-Degradable Biogenic Carbon (% TS)	42.3	36.0

Five different waste treatment technologies, as shown in Figure 1, were modelled using EASTECH: open dumping (OD), landfilling with no landfill gas treatment (LF), landfilling with landfill gas treatment (LFG), landfilling with energy recovery (LER) and anaerobic digestion (AD). Composting, a recurrent waste treatment technology used in many nations to treat the organic fraction of MSW, was not included in this study due to the fact that previous studies have not identified meaningful GHG emissions mitigation as compared to landfilling-related treatments (Lima et al., 2018). For modelling purposes, a waste input of 1 metric ton of organic residues was considered as the reference flow for all the scenarios assessed. In order to account for waste treatment behavior throughout the nation, data of the 3 major Peruvian geoclimatic regions (i.e., hyper-arid coast, Andean highlands and Amazon rainforest) were identified as having a wide variation from the north of the country to the south. This occurs as these zones cover most of the country in a latitudinal way, according to the Köppen-Geiger climate classification (Köppen, 1936; Rubel and Kottek, 2010) and the National Ecosystems Map of Peru (MINAM, 2019a). Thereafter, 3 specific zones were identified within each of the major geoclimatic regions to account for temperature and rainfall differences (see Table 3), two parameters that are critical when measuring the decomposition rate of organic waste. In other words, a north-south gradient was considered, since the northern zones in each region are those with highest rainfall and temperatures, whereas the southern zones are hyper-arid with lower mean temperatures (SENAMHI, 2019).

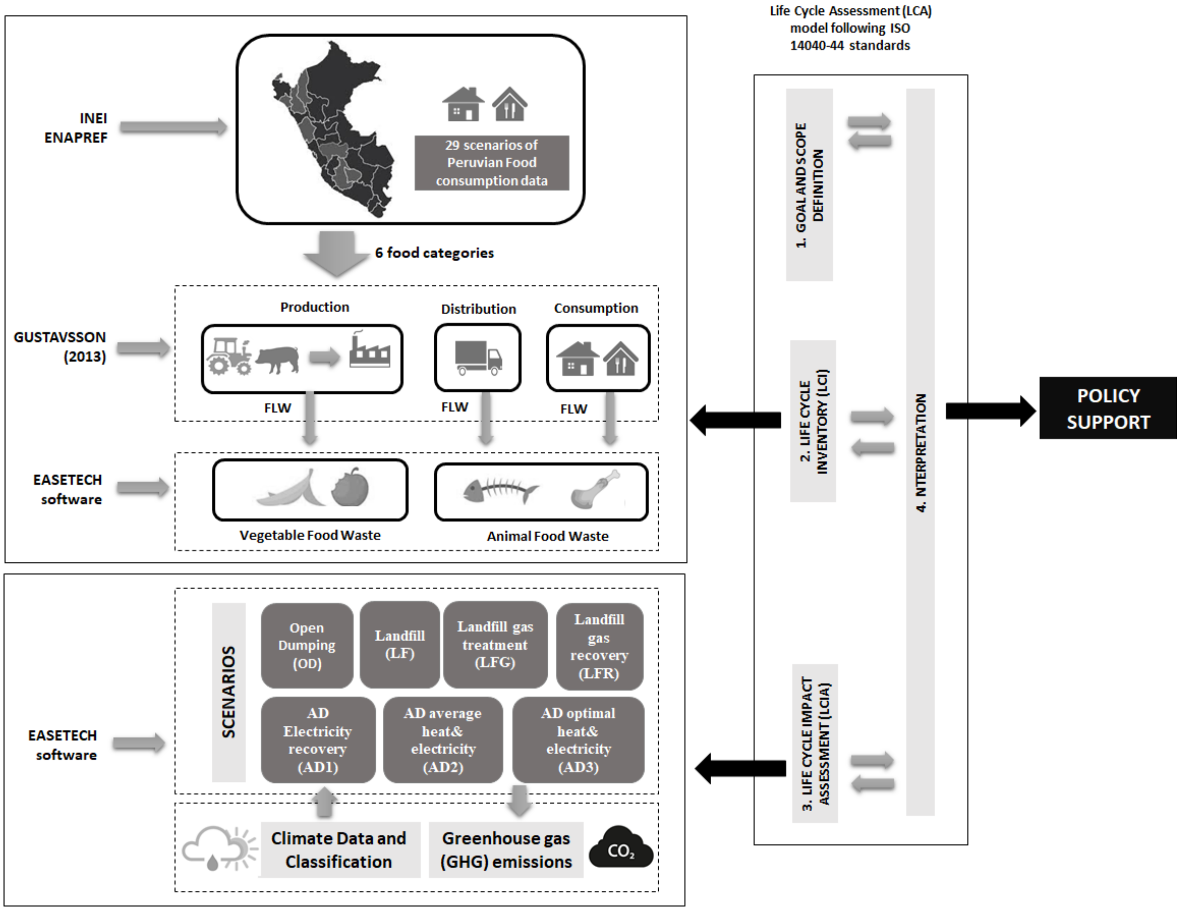

Figure 1. Methodological approach for food loss and waste (FLW) management in selected Peruvian cities.

Table 3. Climate data and classification for selected Peruvian cities. Rainfall and temperature are critical parameters to monitor the decomposition of organic matter in final disposition sites. The final column shows the current waste treatment technology in each city.

City	Rainfall	Average mean temperature	Climate	Current predominant waste treatment technology
Lima - Callao Metropolitan Area	18.7	16	Temperate Dry	LFG
Abancay	685	16.7	Temperate Dry	Dumpster

Arequipa	75	14.5	Temperate Dry	Dumpster
Ayacucho	575	15.4	Temperate Dry	LFG
Cajamarca	795	13	Temperate Wet	Landfill
Cerro de Pasco	999	5.5	Temperate Wet	Dumpster
Chachapoyas	811	15.6	Temperate Wet	Dumpster
Chiclayo	21	22.1	Tropical Dry	Dumpster
Chimbote	14	19	Temperate Dry	Dumpster
Cusco	985	14	Temperate Wet	Landfill[1]
Huancavelica	784	9	Temperate Wet	Dumpster
Huancayo	517	12	Temperate Dry	Dumpster
Huánuco	388	18.7	Temperate Dry	Dumpster
Huaraz	632	13.5	Temperate Dry	Landfill
Ica	8	19.3	Temperate Dry	Open dumpster[2]
Moquegua	15	17.1	Temperate Dry	Dumpster
Piura	49	24.2	Tropical Dry	Dumpster
Pucallpa	1667	26.4	Tropical Wet	Dumpster
Puerto Maldonado	2221	25.4	Tropical Wet	Dumpster
Puno	696	8.4	Temperate Wet	LFG[3]
Tacna	18	17.8	Temperate Dry	Dumpster
Tarapoto	1188	25	Tropical Wet	LFG[3]
Trujillo	3	19.1	Temperate Dry	Dumpster
Tumbes	175	25.3	Tropical Dry	Dumpster

LFG: landfilling with landfill gas treatment.

[1]The landfill in Cusco is built in the district of Haquira, where the old open dumpster was located. Although it currently operates as a landfill, it is yet to be recognized by the Ministry of the Environment.

[2] Although inaugurated as a landfill, this final disposition site in the city of Ica currently operates as an open dumpster.

[3] The landfills in the cities of Puno and Tarapoto were inaugurated in late 2019 with landfill gas treatment technology. Although the amount of biogas in the first few months of operation is intermittent and, therefore, no flaring is being applied, for the sake of this study flaring was considered throughout.

In the case of OD, it must be noted that it is currently the business-as-usual disposal of waste in most Peruvian cities, including some of the largest, such as Arequipa and Trujillo. Deep dumping conditions were assumed for this study, following the decomposition rates provided by the IPCC 2006 method (IPCC, 2006). In contrast, OD and LF scenarios were not modelled for the city of Lima and a small group of other cities (see Table 3), considering that their sanitary landfills already include landfill gas treatment technology.

OD and the three landfilling scenarios (i.e., LF, LFG, LER) were modelled based on the inventories generated in a previous study by Ziegler-Rodriguez and colleagues (2019), which are available for download at the Peruvian LCA database, *Perú LCA* (Vázquez-Rowe et al., 2019c). In these inventories, modelling of landfill gas generation was based on a first order decay rate (Christensen et al., 2009) for a 100-year time horizon. However, while LF, LFG and LER scenarios have their biogas production directly processed in the software's modules, in the OD scenario a methane correction factor had to be applied to account for a higher concentration of oxygen (i.e., aerobic conditions) in an open dumpster. This rationale was adopted according to the IPCC's guidelines (IPCC, 2006). Regarding the landfill gas management modelling in the landfilling facilities, the same considerations were taken into account as those provided by Ziegler-Rodriguez et al. (2019).

In terms of AD, there is currently no existing large-scale AD system destined to the treatment of MSW or food waste in Peru. Consequently, the system modelled was based on guidelines and research studies conducted for similar scenarios. Hence, the intended AD is defined as a dry mesophilic process based on a waste-to-energy guideline for MSW management in developing countries (GIZ, 2017). According to this guideline, a mesophilic system, with temperatures ranging from 35 to 48 degrees Celsius, is more stable and suitable for large scale systems with solid-waste feedstock. Moreover, batch digesters are recommended because they are the most economically and technically viable technologies for the intended purposes. In contrast, although thermophilic digesters can boost the reduction of pathogens and the reactor volume, their operation can be more complicated as these reactors are less stable and need more complex heating and insulation systems, which translates into a higher construction and operation cost (Meegoda et al., 2018).

A set of studies identified in the literature to review anaerobic digestion of food waste for biogas production (Zhang et al., 2014), design considerations and operational performances of anaerobic digesters (Mir et al., 2016), and process stability in mesophilic anaerobic digesters for food waste (Meegoda et al., 2018) were considered in order to produce a more precise and robust model. The main parameters extracted from these studies included: i) a methane yield of approximately 60%, which matches the theoretical methane yield related to the specific feedstock of the modeled food-waste flows; ii) an organic loading rate of around 12 and 15 kg/volatile solids/day (Zhang et al., 2014); iii) a hydraulic retention time fluctuating between 15 and 30 days (Mir et al., 2016; Meegoda et al., 2018); and, iv) a volatile solid destruction rate ranging from 40% (Zhang et al., 2014) to up to 80% (Mir et al., 2016). All these parameters were introduced in the model constructed in the EASETECH software, which also includes a module for anaerobic digestion. This module was adapted to the desired conditions with the abovementioned parameters to represent the required scenarios. In order to compare this system with the previously modelled open dumping and landfilling scenarios, a system expansion was conducted in which energy produced by the recovered biogas substituted marginal electricity generated by natural gas in thermal power stations which feed the Peruvian electricity mix and which represent an important energy source in the country (Vázquez-Rowe et al., 2015).[1]

For energy generation with AD biogas, 3 scenarios were modelled with 2 different technologies taking into consideration current and future Peruvian energy infrastructure and needs. Considering that Peru is a producer of natural gas, many regions have heat and power supply facilities installed, not only for electric generation, but also for industries, such as cement production (Vázquez-Rowe et al., 2015; Vázquez-Rowe et al., 2019d). In contrast, despite the fact that use of biogas for vehicles could have been considered, the precarious situation of the transport system in most of the country makes this scenario unlikely (Verán-Leigh et al., 2019). Firstly, an ideal combined heat and power (CHP) plant was modelled, with an average efficiency of 75%. To this end, an electric generation efficiency of 25% and a heat generation of 50% were assumed, considering that these are the best-case-scenario efficiency values for this type of plants (Clarke Energy, 2013; Hakawati et al., 2017). The second scenario had an electric generation efficiency of 30%, and a heat generation of 40%, assuming that this plant is not as efficient as the first scenario, and to assess the energy production variations (Hakawati et al., 2017). The last modelled scenario implemented an alternate technology: a combined-cycle gas Turbine, common in the Peruvian energy sector, considering electricity generation exclusively with an optimum efficiency of 40% (Hakawati et al., 2017). Digestate obtained from the AD scenario was assumed to comply with heavy metals thresholds to replace the direct spreading of inorganic fertilizers on local croplands (Koszel and Lorencowicz, 2015; Panuccio et al., 2019).

[1] An emission factor of 768 g CO_2eq per kWh was assumed for the natural gas substituted by energy recovery from landfills and AD generated biogas was natural gas.

2.5 Calculating total GHG emissions from FLW

The final step of the computation model consists in aggregating the total GHG emissions that occur on an annual basis in each city due to generated FLW. More specifically, this lump sum is constituted by two different metrics. On the one hand, the embodied GHG emissions from the production of FLW are computed at a city-wide level, as described in Section 2.3. On the other hand, the GHG emissions linked to the different existing or modelled waste disposition or treatment scenarios are computed using the IPCC 2013 assessment model (IPCC, 2013). Considering that the function of the system under study is to estimate the FLW-derived GHG emissions of the food intake of an average citizen in a Peruvian city, the functional unit that was used was one citizen per year in each of the scenarios modelled.

2.6 Limitations of the methodological framework

An important limitation to the study, as mentioned above, is that comprehensive FLW ratios for the Peruvian food sector were not available. Moreover, it should be noted that household food purchase data constitutes the best available data in terms of temporal scale. However, these data, published by INEI in 2012, were collected between 2008 and 2009 (ENAPREF, 2012). Therefore, considering the fact that Peru has been one of the countries worldwide that has grown the most in the 21st century (World Bank, 2020), it is possible that notable changes have occurred in dietary patterns in certain social groups, namely the expanding middle class. Having said this, important malnourishment patterns persist in certain social groups, as well as in the Amazon basin and rural areas throughout most of the nation (Acosta and Haddad, 2014). In addition, it should be noted that these data only consider food that is ultimately purchased by households, excluding food consumed away from home.

FLW is usually a heterogeneous mix of residues, most of which are of organic origin, but can be mixed with certain impurities, such as plastics, metals, glass and other materials

(Carlsson et al., 2015). In the case of AD, however, it is necessary to have a digestible slurry of organic waste. In this respect, pre-treatment methods are necessary to guarantee this level of quality (Bernstad et al., 2013). However, these processes were not considered within the system boundaries of the system analyzed due to lack of data availability and absence of currently existing FLW AD facilities. Moreover, it should be noted that the exclusion of inorganic waste related to the production and disposal of FLW also constitutes a limitation to the study. The rationale for this exclusion was linked to the lack of data on packaging materials available for food diets in Peru.

Packaging size and material, although not discussed in this study, can also influence FLW generation (Wikstrom et al., 2019). Some strategies are targeting an extension of the shelf life of products (Schanes et al., 2018), the use of packaging materials that enhance ventilation and protection (Verghese et al., 2015), or temperature control (Pennanen et al., 2015), and the adaptation of packaging sizes to social demands (Nordin and Selke, 2010). However, it should be noted that the adaptation of the packaging industry to the COVID-19 outbreak could lead to midterm health-driven changes in the sector that may not necessarily have an environmental benefit (Klemes et al., 2020).

3. Results and discussion

3.1 FLW in Peruvian cities

On average, Peru generated 269 kg FLW per capita, 89% of which is generated as food loss, whereas only 11% corresponds to food waste. Annual per capita FLW ranges from approximately 220 kg to 320 kg across Peruvian cities, as shown in Figure 2. Moreover, food loss linked to production, excluding distribution, represented at least 75% of total FLW, with the highest value for this group observed in the city of Huancavelica (ca. 80%). The remaining food loss fraction (i.e., distribution) represented a similar percentage of total FLW as that of food waste (i.e., consumption).

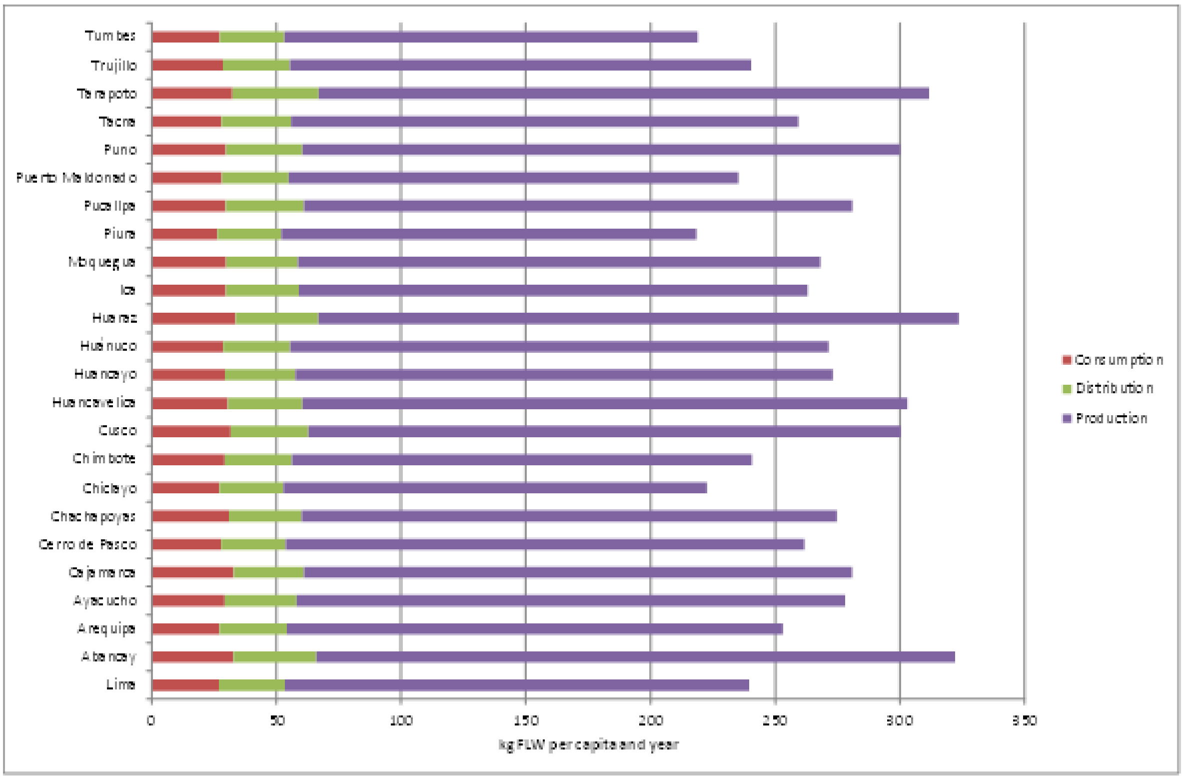

Figure 2. Annual per capita food loss and waste (FLW) in selected Peruvian cities divided per stage of the food supply chain.

Figure 3 shows that Peruvian values are in line with the average values reported for seven world regions by the FAO (Gustavsson et al., 2011). In fact, the values for Peru appear to be slightly higher than those for Latin America (i.e., 225 kg FLW per capita). Nevertheless, in line with other developing or emerging regions in the world, in both cases FLW is produced in upstream phases (i.e., production and distribution) as food loss rather than in the retail and consumption stages as food waste. In contrast, developed nations show much higher generation of food waste, while food loss is somewhat lower. However, although the total amount of FLW in North America (300 kg per capita and year) is approximately 15% higher than for Peru, not all developed regions presented higher FLW rates (e.g. Industrialized Asia).

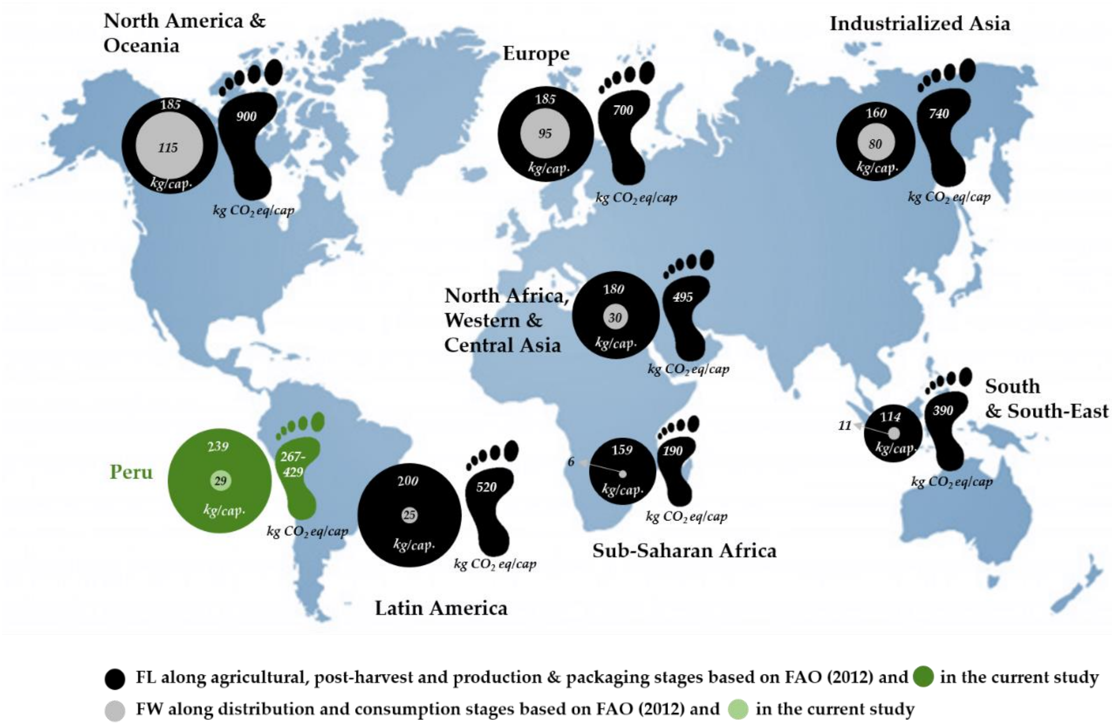

Figure 3. Food loss (FL) and waste (FW) and carbon footprint in seven world regions (North America and Oceania, Latin America, Europe, Sub-Saharan Africa, North Africa and Western and Central Asia; South and SouthEast Asia, industrialized Asia) as compared to Peru in the current study (data for world regions adapted from Laso et al., 2020)

When the city of Lima is analyzed per socioeconomic quintiles, FLW varies considerably. For instance, the segment with lowest expenditure (Q1) wastes 158 kg per capita annually, whereas the highest segment (i.e., Q5) generates ca. 340 kg per capita. No relevant variations across quintiles are observed, however, in terms of the proportion of FLW generated in each stage. Interestingly, the results shown for the city of Lima are in line with those presented in Figure 3: areas or socioeconomic groups with higher income generate a larger amount of FLW.

3.2 Greenhouse gas (GHG) emissions embedded in the production of FLW

GHG emissions linked to the production of food that is finally not destined to direct human consumption in households due to the inefficiencies in the food supply chains ranged from 178 kg CO_2eq in the case of Piura to 293 kg CO_2eq in the city of Cusco (see Table 4), with an average value of 233 kg CO_2eq across Peru. The average value for the city of Lima was estimated at 211 kg CO_2eq, although when the different socioeconomic quintiles are assessed in detail, the results range from 132 kg CO_2eq for the lowest expenditure quintile (i.e., Q1) to 309 kg CO_2eq in the case of the highest (Q5).

Table 4. Greenhouse gas (GHG) emissions embedded in the production of food loss and waste (FLW). Results are represented per capita and year for selected Peruvian cities. It should be noted that the results only consider food that is ultimately purchased by households, excluding food consumed away from home.

GHG emissions per capita (kg CO_2eq/year)	**Lima**	**Arequipa**	**Cusco**	**Piura**	**Pucallpa**	**Puno**
FLW linked to household consumption	221	250	293	178	195	281
Current diet (ENAPREF, 2012)	948	1166	1350	792	813	1253
% FLW over total	*23.3*	*21.5*	*21.7*	*22.5*	*24.0*	*22.4*
FLW linked to an optimized household consumption	273	291	293	285	323	292

Optimized diet (Larrea-Gallegos and Vázquez-Rowe, 2020)	995	1162	1200	1005	1119	1165
% FLW over total	*27.4*	*25.1*	*24.4*	*28.3*	*28.9*	*25.1*

FLW: food loss and waste; GHG: greenhouse gas.

Interestingly, when Larrea-Gallegos and Vázquez-Rowe (2020) applied a linear programming model to optimize the Peruvian diet in different Peruvian cities, results showed significant mitigation opportunities in 20 out of 24 cities assessed, thanks to lower red meat consumption and a higher consumption of low-carbon food products (i.e., fruits and vegetables). However, those reductions were based on the optimization of purchased food in the household, excluding the disruptions in FLW occurring upstream in the supply chain. When these values are corrected with the addition of FLW-related GHG emissions, cities like Lima flip to an increase in environmental impact. This is of particular interest from two opposing perspectives. On the one hand, the optimization of Peruvian diets to attain improved nutrition and environmental benefits is accompanied by a relevant increase in FLW and, in most cases, embodied carbon, as depicted in Table 4. Therefore, public policies should advocate strategies to lower FLW throughout the supply chain and adequately manage it. On the other hand, the higher FLW amounts for these optimized diets imply a higher availability of energy, nutrients and other added-value products in FLW if circularity policies are sought, as will be discussed below.

The increase of available FLW is particularly high in those cities, such as Piura or Pucallpa, in which a current rampant deficit in the intake of certain food products (e.g., fruits and vegetables) has been identified. For instance, in the case of Pucallpa, the increase of GHG emissions linked to the production of FLW is of 128 kg CO_2eq per functional unit. In contrast, in cities like Cusco (+0.40 kg CO_2eq) or Puno (+11.1 kg CO_2eq), the increase in embodied GHG emissions linked to FLW is close to zero due to the higher red meat consumption in the southern Andes. In other words, although there is a net increase in the generation of FLW, the lower GHG emissions per mass of fruits and vegetables as compared to red meat neutralizes the increment.

3.3 Greenhouse gas (GHG) emissions due to FLW final disposal

GHG emissions linked to the disposal of FLW generated in the distribution and consumption stages, as shown in Table 5, ranged from 32.2 kg CO_2eq per capita and year in the case of Ayacucho (LFG) to 136.1 kg CO_2eq/year in the city of Cusco (LF). The reason for this large range is the fact that Ayacucho, alongside Lima, Puno and Tarapoto, are the only cities assessed that currently have an LFG, whereas the remaining urban areas analyzed either dump their waste or dispose of it in LF sites. Hence, when cities with LFG are excluded, the lower range starts at 98.4 kg CO_2eq (Piura). It should be noted, as highlighted by Ziegler-Rodriguez et al. (2019), that limiting the transition from dumpsters to landfills with no landfill gas treatment (i.e., LF scenario) would increase the GHG emissions from a range of 110 kg CO_2eq (Puerto Maldonado) to 141 kg CO_2eq (Abancay).

Table 5. Greenhouse gas (GHG) emissions of food loss and waste (FLW) treated for selected Peruvian cities. It should be noted that treatment emissions include FLW occurring in urban environments: food waste, and food loss due to distribution activities, excluding food loss from production.

GHG emissions per capita (kg CO_2eq/year)	Lima	Arequipa	Cusco	Piura	Pucallpa	Puno
OD	NA	102	NA	98.4	113	NA

LF	NA	119	136	114	125	NA
LFG	56.1	30.5	35.1	56.2	63.7	33.6
LER	33.0	23.0	26.5	35.3	58.2	25.4
AD1	-12.0	-12.1	-13.9	-12.2	-13.4	-12.8
AD2	-12.8	-12.8	-14.7	-12.6	-12.6	-13.7
AD3	-13.7	-13.7	-15.8	-13.8	-15.2	-14.6

NA= not applicable; OD= open dumpster; LF= landfill; LFG= landfill with flaring; LER= landfill with energy recovery; AD1= anaerobic digestion with electricity production only; AD2= anaerobic digestion with average heat and electricity production; AD3= anaerobic digestion with optimal heat and electricity production.

If LFG technology is implemented in all cities assuming *ceteris paribus* conditions, the city with the lowest environmental impact per capita and year is Arequipa (31 kg CO_2eq), whereas the highest is Tarapoto (71 kg CO_2eq). Upgrading the entire system analyzed to LFG technology in landfills would imply a reduction of 0.37 Mt CO_2eq per year to 0.94 Mt CO_2eq. While this reduction is substantial (-29%), it still presents two important limitations from an environmental perspective: i) the management system would not be upgraded for the city of Lima and 2 other cities (i.e., Puno and Tarapoto); and, ii) LFG technology, while an important step towards reducing the carbon profile of waste treatment, does not foster the circularity of resources embedded in organic waste (e.g., energy or nutrients).

The implementation of waste-to-energy technologies which aim to improve the circularity of the Peruvian urban waste treatment system reveal important net reductions in GHG emissions, as shown in Figure 4c. The technical feasibility of the application of some of these technologies has been previously analyzed with success for Lima and other main cities in Latin America (Kahhat et al., 2018). On the one hand, the implementation of LER technology throughout the cities assessed would imply a reduction of 0.72 Mt CO_2eq (-55%) as compared to the existing current scenarios. Assuming that this scenario were achievable by 2030, it would translate into a higher reduction in GHG emissions in the solid waste sector than the average reduction proposed for Peru (i.e., -30%). In this case, the highest emissions per capita would be achieved in Huaraz (43 kg CO_2eq/year). On the other hand, the implementation of AD technology would increase the net GHG emission mitigation to up to 1.56 Mt CO_2eq in the case of AD3 (-119%). For AD treatment, negative GHG emission impacts would be attained in all the cities evaluated. No major differences in GHG emission reduction were identified between the three AD technologies modelled, which would suggest that other environmental indicators (e.g., ozone depletion or eutrophication), as well as economic and social criteria, would have to be applied to understand the convenience of a specific technology.

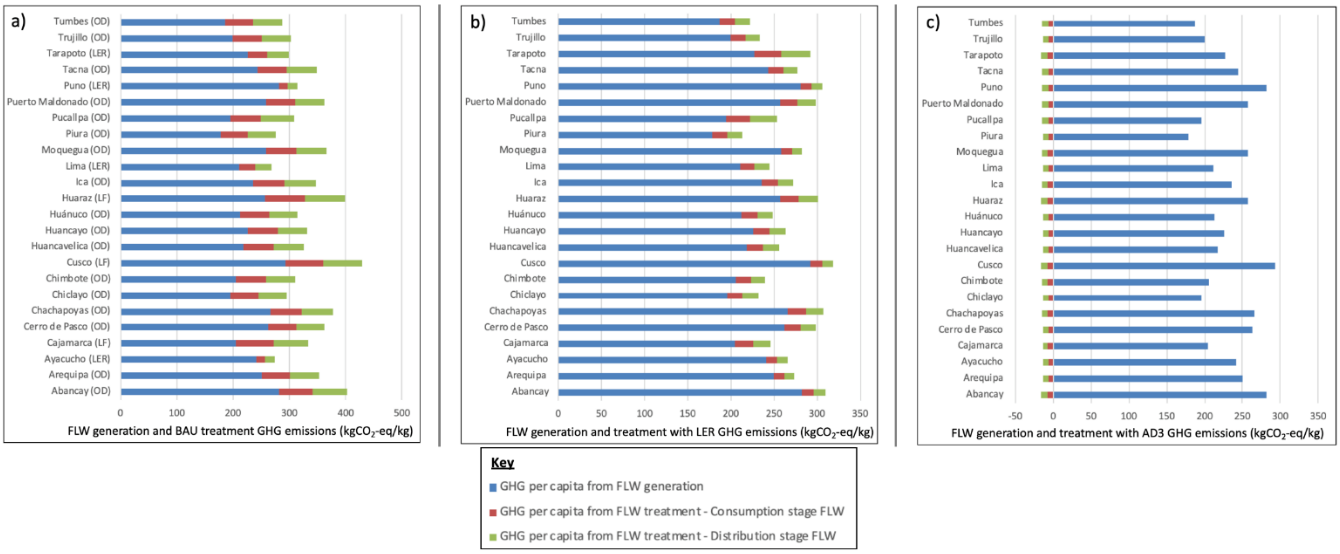

Figure 4. GHG values of FLW generation and FLW treatment. The graph in a) shows the values for the current treatment scenario for each city (in brackets). The graph in b) presents the values for FLW treated with LER in every city, and c) shows values for FLW treated in the best-case scenario, with AD3 in every city.

Results from this study suggest that household FLW in Peru represents 4.34 Mt of organic waste per year under business-as-usual (BAU) conditions. Of this total number, approximately 963 kton are reaching urban disposal facilities, mainly open dumpsters. This leads to a total of 1.31 Mt CO_2eq emitted in final disposition sites across the nation due to household FLW. In this BAU scenario, ca. 45% of total emissions (i.e., 0.594 Mt CO_2eq) occur in LFG premises in the city of Lima, 1.8% in other LFG sites in other cities, 7.2% in LF sites (i.e., Cajamarca and Cusco), whereas the remaining 46% is emitted in open dumpsters in the other major cities included in the study.

If waste treatment results for the different socioeconomic quintiles in the city of Lima are analyzed, the highest (i.e., Q5) generates GHG emissions 43% above average for LFG and LER technology. However, for AD technologies the mitigation of GHG emissions in this quintile is up to 60% higher than the average value for the city. These results suggest that a differentiated policy on urban-generated FLW depending on socioeconomic quintiles could be feasible. For instance, AD technologies may be fostered to trigger GHG mitigation in high expenditure quintiles, whereas policies to avoid an increase in FLW in lower expenditure quintiles could be put forward while improving diets in these social groups.

When the results considering an optimization in the Peruvian diet following the results obtained in Larrea-Gallegos and Vázquez-Rowe (2020) are analyzed, different tendencies can be observed depending on the level of sophistication of the waste treatment technologies (see Figure 5). As discussed in section 3.2, optimized diets showed a substantial increase in FLW as compared to the existing diets in each city. Interestingly, this implied an increase in total GHG emissions for OD, LF, LFG and LER technologies that ranges between 9% and 44% depending on the city and the inherent variations in food purchase. In contrast, the more FLW available for the AD scenarios translated into a higher level of energy substitution and, therefore, more succulent mitigations were obtained in those cities in which the optimized diets showed a higher level of variation as compared to existing diets. For instance, in Pucallpa, located in the Amazon basin, GHG emissions would increase up to 40% for OD, LF, LFG and

LER scenarios if we considered an optimized diet. In contrast, the additional mitigation of GHG emissions would be 24% lower for the AD scenarios.

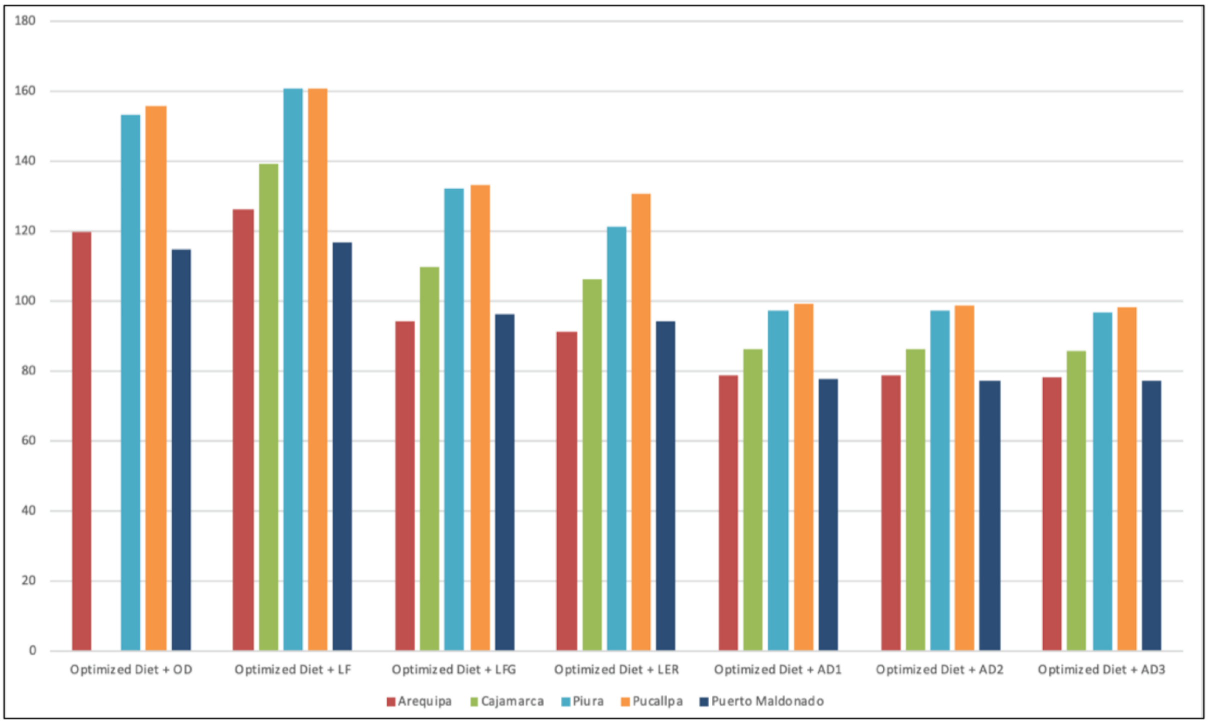

Figure 5. Relative potential climate change impact (%) of optimized diets in selected Peruvian cities for different food loss and waste (FLW) treatment technologies relative to current diet scenarios.

The comparative results between current and optimized diets demonstrate that the migration from landfills to municipal scale digesters to treat the organic matter fraction derived from FLW should be accompanied by food policy initiatives to improve the daily food intake of Peruvian families. While achieving the ideal optimal values used in this study may be utopic, aligning food security public policy with those values would trigger additional carbon mitigation and foster the circularity of MSW in Peru.

3.4 Total GHG emissions related to FLW production and disposal

Per capita carbon footprint of the production, distribution, consumption and treatment of FLW in Peru ranges from 267 to 429 kg CO_2eq. As shown in Figure 3, these data are below the Latin American average (520 kg CO_2eq per capita), substantially lower than the results in the Global North (e.g., North America, Europe or Oceania) and considerably higher than in Sub-Saharan Africa (190 kg CO_2eq per capita), as estimated by Laso et al. (2020). However, it should be noted that methodological differences remain between the two studies. Hence, the exclusion of non-urban food loss treatment and consumption-related impacts in terms of embedded GHG emissions in the current study are probably underrepresenting the emissions for Peru as compared to the continent-wide results reported above. Moreover, a recent study by Chen and colleagues (2020) estimated mean worldwide annual per capita GHG emissions linked to FLW at 453 kg CO_2eq, slightly higher than the values reported for Peru. In this sense, besides the amount of FLW, the type of food wasted or lost in each country, the climate and the final treatment of organic waste has a high influence on GHG emissions generation.

When production and disposal of FLW are combined, the results show that production represents the higher proportion of GHG emissions, ranging from 60% to 90% depending on the city assessed, and in line with similar studies in the literature (Scherhaufer et al., 2018). In the current scenario for each city, the percentage of waste treatment ranges from 11% in Puno (LFG technology) to 37% in Pucallpa (OD disposal). As the level of sophistication of waste treatment systems is improved, the prevalence of GHG emissions in this stage becomes substantially lower; to the extent that AD technologies actually reduce the total emissions by up to 42% when compared to OD realities across the nation (see Table 6).

Table 6. Relative variation in FLW-related GHG emissions (FLW production and treatment) in selected Peruvian cities when comparing the business-as-usual waste treatment disposal to more sophisticated treatment technologies.

	OD	LF	LFG	LER	AD1	AD2	AD3
Lima	NA	NA	BAU	-9	-26	-26	-26
Arequipa	BAU	+5	-20	-22	-32	-33	-33
Cajamarca	NA	BAU	-24	-26	-42	-43	-43
Cusco	NA	BAU	-24	-26	-35	-35	-35
Piura	BAU	+5	-15	-23	-40	-40	-41
Pucallpa	BAU	+4	-16	-18	-41	-41	-42
Puerto Maldonado	BAU	+2	-16	-18	-32	-32	-33
Puno	NA	NA	BAU	-3	-15	-15	-15
Trujillo	BAU	+5	-15	-23	-38	-38	-39

OD= open dumping; LF= landfilling with no landfill gas treatment; LFG= landfilling with landfill gas treatment; LER= landfilling with energy recovery; AD1= anaerobic digestion with electricity production only; AD2 = anaerobic digestion with average heat and electricity production; AD3 = anaerobic digestion with optimal heat and electricity production.

BAU: business-as-usual; NA: not applicable.

The climate action benefits of improving waste treatment systems across the country by mitigating GHG emissions is an important message that can be extracted from the current study. However, most GHG emissions are still attributable to the complex and dispersed FLW occurring along the supply chain, which inevitably leads to identifying what actions can be taken to reduce the actual volumes of FLW that are being generated across the country. The average Peruvian diet, which is considered far from healthy with its deficit in the consumption of fruit and vegetables, the most food loss-prone food categories, adds an additional challenge when seeking solutions. In other words, policies and awareness will not only have to be directed towards promoting healthy and sustainable diets. In fact, these will have to seek measures to avoid losses throughout the food supply chain, such as i) investing in infrastructure in the food processing industry by applying best available techniques; ii) improving the transport system and nodes within the nation, reducing travelling hours and guaranteeing better quality cooling and/or freezing supply chains; iii) fostering capacity building in the processing industry to develop better food handling practices; iv) reverting current trends that downgrade what is commonly termed as "ugly food"; or, v) fostering the revalorization of FLW in agricultural environments or its donation in the subsequent stages of the supply chain (e.g., wholesale, retail or waste at canteens or restaurants).

Furthermore, the geographical dispersal of food loss in the early stages of the supply chain (i.e., production and processing), although only assessed in terms of mass in the present study, provides interesting challenges that must be explored. On the one hand, these could be an important source of energy through decentralized AD or other energy-recovery technologies to reduce the dependency on the external energy grid. On the other hand, the higher homogeneity of the residues at these stages may also allow for a higher added-value recuperation of food loss properties for medicinal and pharmaceutical purposes, for instance.

3.5 Policy support and future outlook

Based on the results computed, leapfrogging will be necessary in the implementation of waste treatment systems in Peru in order to attain noticeable reductions in GHG emissions from FLW. Regardless of the benefits in other environmental impacts, such as eutrophication or eco-toxicity (Ziegler-Rodriguez et al., 2019), a gradual transition from open dumping to conventional landfilling with no LFG treatment, and with only timid advancements in more sophisticated technologies, would set back mitigation hopes by at least a decade (Vázquez-

Rowe et al., 2019b). In this sense, a direct leap from open dumpsters to landfills with LFG treatment is needed in a vast majority of cities throughout the country to start to visualize certain mitigation targets. It is obvious, considering the results of the study, that landfills with energy recovery and especially AD technologies would provide noticeable improvements in GHG emission reductions. However, it should be noted that although energy recovery in landfills had been planned by the Peruvian government as part of its nationally-determined contributions (NDCs), it was later discarded in the final report (MINAM, 2019b), leaving landfill gas treatment and semi-aerobic landfills as the most sophisticated technologies Peruvian authorities are willing to finance (GIZ, 2017). Moreover, sluggish policy-making and legislation procedures, with projects taking several years to be approved, as well as difficulty in obtaining funding for these in international markets, are an important setback for short-term implementation of LER and AD in the country. In fact, it is highly unlikely that these types of plants will be functioning in Peru prior to the Paris Agreement deadline in 2030, especially due to the post-COVID-19 economic recession the country is experiencing.

The challenges of implementing AD solutions in Peru are multiple and not limited to governance alone. For instance, capacity building is much needed in a country that still lacks skilled labor in this sector. In fact, from a technical perspective, issues such as a shortage of constant substrate, the need for constant control and monitoring to avoid, for instance, harmful intermediate compounds (Banks et al., 2012), instability in the reactor (Zhang et al., 2013) or foaming (Grimberg et al., 2015), are important aspects that require skilled personnel. Waste collection services must also guarantee that the separation of the organic waste fraction is consistently performed correctly. In this sense, although collection coverage in Peru is very high in urban environments (Margallo et al., 2019), its separation is not always optimal. Moreover, AD technologies are capital intensive and require robust financing mechanisms to attain economic sustainability (Xu et al., 2017). Sorting should also be seen as an opportunity to enhance the treatment of other waste fractions (e.g., packaging material residues generated in different stages of the logistic activities and in the household), which, although beyond the scope of the current study, would benefit from this perspective (Bottani et al., 2019; Vitale et al., 2018).

Another issue that must be addressed is the environmental optimization results of the Peruvian diet using nutritional and economic restrictions, which imply a higher consumption of fruits, vegetables and other plant-based products, while reducing the consumption of red meat and added-sugar products (Larrea-Gallegos and Vázquez-Rowe, 2020). Although relevant GHG reductions in the upstream processes of food consumption were identified by Larrea-Gallegos and Vázquez-Rowe (2020) when Peruvian diets are optimized, a progressive implementation of healthy and sustainable diets translates into higher GHG emissions in the disposal of FLW, due mainly to the higher FLW ratios linked to fruits and vegetables in South America and in other areas of the world (García-Herrero et al., 2018). However, as demonstrated in the current study, these higher emissions can be neutralized by implementing AD technologies for organic waste throughout the nation.

Peru’s economic expansion in the period 2001-2019 suggested a promising context in which multiple SDGs would be met by 2030. Moreover, timid efforts by the Ministry of the Environment (MINAM), as well as foreign cooperation in waste treatment disposition sites, namely from the Japanese and Swiss aid agencies, suggested that the Peruvian waste-related GHG mitigation targets for 2030 in the Paris Agreement would be largely met, even though we argue that these lack ambition, as discussed in this paper and in Vázquez-Rowe et al. (2019b). However, the COVID-19 pandemic has brought the country to a standstill, with a predicted reduction in GDP of 12% for 2020 (World Bank, 2020). Hence, it is plausible to assume that Peru will face important disruptions in consumer demand (i.e., limited household expenditure).

Future research should delve into how the “ripple” and “bullwhip” effects (Dolgui et al., 2020) related to this important shock to Peru’s economy will affect dietary patterns in Peru, as well as derived FLW generation and associated environmental impacts (Aldaco et al., 2020).

5. Conclusions

Feeding a nation is still a challenging milestone for public policy across the world. In developing nations, such as Peru, the historic nutritional drawbacks of the average diet are slowly being mitigated thanks to economic growth and a range of public policies that include awareness campaigns or subsidies to school canteens, among others. However, it must be highlighted that the economic crisis that is looming as a consequence of the COVID-19 pandemic is likely to detain or revert years of improvement, compromising the accomplishment of several SDGs.

From an FLW perspective, results suggest that population growth, middle class expansion and an improvement in the average diet, with a higher consumption of fruits and vegetables, will hamper Peru’s efforts to comply with SDG 12.3 to halve FLW by 2030. As an alternative, the implementation of improved waste management systems is a valuable strategy to foster the circularity of FLW. In fact, the results obtained suggest that up to ca. 1.6 Mt CO_2eq could be mitigated annually by implementing sophisticated waste management technology in urban environments designed to treat FLW from diets.

The results presented demonstrate that organic waste from dietary patterns in Peru are an important resource that must be recovered beyond its disposal in landfilling cells and, therefore, not only aiming at basic GHG emission mitigation strategies. The economic resources for this are limited and it will take time for Peru to converge with current standards in terms of coverage and technology as compared to Europe or North America. Further research must delve into the GHG emissions mitigation opportunities at a rural level linked to the small-scale residues that are being generated in the production and processing stages, especially considering that agro-exports are an important portion of agricultural and seafood production in Peru, increasing the numbers for domestic consumption included in this study. Moreover, the circular economy opportunities that FLW recovery strategies generate in terms of energy, nutrients, water or other added-value resources (e.g., pharmaceutical properties), must be explored considering a wider range of environmental impact categories (e.g., resource depletion or water degradation indicators). These two efforts combined will enable the definition of a holistic, site- and product-specific organic waste treatment map for Peru for the next few decades.

We consider that this study contributes significantly to simplifying the decision-making process related to FLW environmental management. Moreover, the prevention and minimization of FLW can contribute from a social and economic point of view. In this context, overcoming the technical limitations of collection, production and distribution, reinforcing consumer behavior, and/or learning from the mistakes of developed countries are some of the ways that can lead to success for a transition to the circular economy of foods in upper/middle income countries.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

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Supplementary Excel Material

The Supplementary Excel Material provides raw data and GHG emission calculations for the 29 scenarios modelled in the current study. This file builds on the data initially published in https://doi.org/10.1371/journal.pone.0188182.s001, in which a lower amount of processed data were available.

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