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Environmental assessment of waste handling in rural Brazil: Improvements towards circular economy

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ABSTRACT

Rural areas are often neglected with respect to solid waste management, and if some kind of management is in place it is often inadequate, causing harm to the rural population and environment, especially when open burning and dumping are practiced. These practices are performed in rural areas/isolated communities worldwide. In today's scenario, any actions taken by cities generally do not focus on implementing a circular economy, that is, closing the loops and resource recovery, which are important to increase the quality of life of rural populations. In this sense, this study aimed to assess the environmental impacts of the current waste handling scenario of Quilombola communities located in the rural areas of west-central Brazil to shed light on this issue and provide means to decision-makers to act appropriately. Life cycle assessment was employed for a "current" (combination of waste burning and landfilling) and a "proposed" (source separation and home composting) scenario with 1 ton of municipal solid waste as the functional unit and the ILCD recommended method for impact assessment. The results showed that the current scenario registered environmental burdens for all impact categories assessed, such as 415 kg CO_2 eq. for climate change and 37,174 CTUe for freshwater eutrophication, while in the proposed scenario, the impacts were reduced in all categories. Based on these results, we concluded that the studied population was exposed to several different impacts, especially due to waste burning, which represented 98.8% of emissions to climate change, and that the proposed scenario poses an alternative conducive to a shift towards circular economy and sustainable development concepts. Our study provides important data regarding necessary improvements to current waste handling practices to reduce environmental impacts and enhance the quality of life of the rural population, which will help decision-makers take appropriate actions.

1. Introduction

Solid waste is an issue that affects all societal groups, cultures, regions, and races, and it is not very likely to be solved anytime soon (Cogut, 2016). The amount and complexity of waste generated in the world is expected to increase significantly in the coming decades, with projections estimating up to 2.2 billion tons in 2025 (Kaza et al., 2018). This tendency is due to population growth, economic progress, and new lifestyles of the population. These characteristics vary in different locations; for example, developing countries usually generate less waste than developed countries, but at the same time they usually face more challenges regarding waste handling. Therefore, a thorough decision-making process is essential to assess each specific case and adopt the best system solutions.

One of the most widely used decision-making tools for waste management systems is the life cycle assessment (LCA) approach, which assesses the environmental impacts of a certain product/activity/system in order to track where the most emissions originate, thus enabling the prioritisation of issues to be tackled. LCA is a comprehensive methodology, comprising four stages (goal and scope definition, inventory, impact assessment, and interpretation), that requires a significant amount of data because it assesses the environmental impacts across the full life cycle of a product/system (i.e., from cradle to gate, from extraction to disposal) (European Commission, 2010). The methodology

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can present results in terms of emissions or person equivalent (PE) per stage of the product system, giving a broad perspective of the environmental impacts of the activity in different impact categories.

When no adequate management is in place, solid waste can cause several threats to the environment and to public health, including water contamination, soil degradation, air pollution, and the spread of diseases, which are the types of impacts assessed by LCA (Ferronato and Torretta, 2019). Accordingly, proper waste management is necessary in order to reduce, reuse, recycle, and properly dispose of solid waste and extend the availability of natural resources to facilitate the sustainability of life on our planet (Abdel-Shafy and Mansour, 2018).

Sustainability can favour the implementation of a circular economy (CE) in organisations (Kravchenko et al., 2019; Sehnem et al., 2019). According to Sehnem et al. (2019), sustainability is a major motivator of the CE concept and is mediated by innovation. CE is based on the observation of natural systems and follows five basic principles: design without waste, build resilience through diversity, depend on renewable energies, think systemically, and convert waste into nutrients (Veiga, 2019). Therefore, it is an economic model that aims to efficiently use resources by reducing waste, retaining long-term value, and minimising primary resources and closed loops of products, product parts, and materials within the limits of environmental protection and socioeconomic benefits (Morseletto, 2020). Accordingly, CEs can improve the quality of life in cities by improving air quality, increasing the efficiency of water and sewage treatment systems, reducing the generation and management of solid waste, etc. (Veiga, 2019).

For the implementation of a CE, the territorial dimension is an important factor in the transition phase. Location and physical characteristics influence a territory's potential; for example, urban and rural areas play different roles within the framework. Urban areas feature dominantly in the transition process because they are the production centres and, therefore, can promote the efficient use of resources. On the other hand, rural areas supply the majority of these resources (Gebre and Gebremedhin, 2019).

Waste management in rural areas has become a major challenge for the governments of developing countries (Han et al., 2018). Rural areas have different socioeconomic situations, climates, geographies, cultures, population densities, and other variables compared to urban areas. Therefore, managing the solid waste generated in these regions and implementing reduction strategies has become increasingly essential (Brouwer et al., 2018; Mihai and Grozavu, 2019; Oribe-Garcia et al., 2015). Through studies carried out in rural areas, similarities were found among inadequate final solid waste destinations worldwide, as described by Patwa et al. (2020) who reported that 78% of the worldwide rural population uses open dumps for solid waste disposal, which is a major problem in these areas. In Brazil, it has been reported that 62% of the waste in rural areas is burnt or buried with no safety measures taken (Caiado Couto et al., 2020). In China's rural areas, most of the waste is burned or deposited on roads, rivers, or open dump sites (Cao et al., 2018; Zeng et al., 2016).

Accordingly, in rural areas, waste burning is commonly practiced by the residents because municipal solid waste (MSW) is not collected or no suitable place for final waste disposal exists in most of these areas. In a study conducted by Lima and Paulo (2018) in rural areas of Brazil, it was observed that only 30% of the communities had access to solid waste collection that deposited waste in dumps or landfills, showing that even when the municipalities take action, those actions are not sustainable or in line with a circular economy. Furthermore, when there is no waste collection, residents handle the waste as they see fit, sometimes by burning and other times by dumping it in their backyards or on vacant land in the surrounding area, which leads to the formation of waste dumps. Although these can be small deposits, these places create additional demand for replacement and transportation services (Veiga, 2019). In general, solid waste management studies do not consider social aspects, even though they are relevant, as verified by Vieira and Matheus (2018) who showed that isolated inequality is important for planning. Waste management problems include not only a lack of money and equipment, but also cultural and social aspects, such as education and beliefs (Vieira and Matheus, 2018). Environmental aspects such as climate change and combatting social inequalities are not considered in waste policies; however, these issues should be assessed and addressed because they influence sustainable development (SD) and marginalised communities that usually have residents that work in waste recycling and play a significant role in the waste chain.

Lima and Paulo (2018) carried out their study in Quilombola communities, which are remnant communities founded by runaway black slaves, mainly in Latin America, now inhabited by their descendants. As the founders were runaway slaves, these communities are usually isolated and located in rural areas, with only a few having reached urban zones, and they thus often lack provisioning services such as drinking water and waste management. The authors verified the social indicator of waste management through risk analysis, and their results showed that the greatest risk the Quilombola population is subjected to is the emergence of vectors in waste that can cause different types of diseases, followed by open air burning of the waste. Isolated communities, such as the Quilombolas, indigenous communities, or even settlements, usually have non-hegemonic practices related to waste management, which is often overlooked in both waste planning and social studies (Siragusa and Arzyutov, 2020).

According to the Brazilian National Solid Waste Policy (PNRS in Portuguese), the entire municipality should be considered when planning solid waste management (urban and rural areas) and the indicators for assessing the sustainability of waste management systems include political, economic, environmental, cultural, and social indicators (de et al., 2019). It is important to assess all indicators when taking action regarding solid waste handling in cities and adjacent areas in order to maintain the sustainability of systems and introduce the concept of CE.

The CE concept is an inspirational strategy to create value while minimising resource consumption and environmental impacts; however, it is necessary to ensure that CE practices will indeed reduce negative environmental and social impacts. In this sense, to measure environmental performance, compare circular strategies, and ensure a positive environmental balance, LCA is one of the tools that can strengthen proposed projects. According to Morseletto (2020), LCA is an effective environmental management tool because it can be applied broadly in CEs and thus support decision-making. In recent years, several LCA studies of urban waste management have been performed, including the work of Trentin et al. (2019), Ziegler-Rodriguez et al. (2019), and Ferronato et al. (2020), but none have been carried out in rural areas. Previous studies on waste management in rural areas instead focused on the impacts generated by landfills close to rural areas (Makarenko and Budak, 2017), the factors that influence the presence of domestic waste in rural areas in developing countries (Han et al., 2018), and the development of an anaerobic/semi-aerobic bioreactor for the treatment of domestic solid waste in rural areas (Han et al., 2019). These studies did not adopt a consolidated approach, such as LCA, that enables the comprehensive assessment and interpretation needed to improve waste management decision-making.

In today's scenario, a change in current waste management practices is urgently needed, not only to improve the quality of life of the rural population, but also environmental and economic conditions. Changes in waste handling behaviour and policies are necessary to create a better and more circular economy, but it also requires environmental education and changes in the economic paradigm. Therefore, in order to fill the existing research gap and to provide data to support decision-making, the aim of this study is to apply LCA to solid waste handling in rural areas, and to compare the baseline scenario, reflecting existing waste handling, with a proposed scenario exploring alternatives aimed at closing the loop in a circular economy. Further, we attempt to expose the threats involved in open waste burning, and quantitatively predict potential environmental impact mitigation for rural communities to raise awareness and concern to effect a change in behaviour and policies.

2. Material and methods

Mato Grosso do Sul is located in west-central Brazil and comprises an area of 357,660 km^2 with 2.4 million inhabitants, 85.6% of which live in urban areas and 14.4% in rural areas (INPUT, 2020). There are 22 Quilombola communities in the state, 12 of which are located in rural areas. In this study, these rural communities were assessed regarding their waste management systems using LCA. The state, the communities, and their locations are presented in Fig. 1.

The communities are, on average, 25 km away from their respective municipalities, and together comprise 620 households, including 2171 inhabitants (MPF, 2020), as shown in Table 1. Waste generation was considered as per capita generation of 0.63 kg $inhab^{-1}$ day^{-1} (total of 3247.6 kg day^{-1}) and the gravimetric composition was set to 67% organics, 5% paper and cardboard, 11% plastics, 10% glass, 5% metal, and 2% other (Andrino et al., 2018).

LCA was performed using the EASETECH modelling software developed in Denmark for complete mass and substance flows of waste management systems (Clavreul et al., 2014). The impact assessment was performed using the International Reference Life Cycle Data System (ILCD) recommended method 2014, with the long-term compartment included and global geographic representation of the normalisation factors. We considered 12 impact categories that are presented in Table 2 along with their abbreviations, units, and normalisation factors (DTU, 2016).

The functional unit (FU) was set to 1 ton (1000 kg) of MSW generated in the rural Quilombola communities of Mato Grosso do Sul, as it is the most commonly used FU for waste systems and thus enables comparison across different studies. The scenarios were based on Lima and Paulo (2018) who determined different waste scenarios based on a questionnaire answered by members of the communities in the state. The waste management in the municipalities consists mainly of landfilling and, in a few cases, open dumps; therefore, the scenarios modelled were (1) “current”; the baseline scenario with 24.7% of the waste collected and landfilled, 72.9% burned on the ground, and 2.4% buried (Fig. 2); and (2) “proposed” with source separation, where recyclables are sold in the city, home composting of the organic fraction, and rejects sent to the city for landfilling (Fig. 3).

Figs. 2 and 3 present the mass flows for the two modelled scenarios in

Table 1
Information regarding the 12 rural communities in the state of Mato Grosso do Sul analysed in this study.

Community	Municipality	N° of Households	N° of Residents	Waste Generation
Furnas do Dionísio	Jaraguari/MS	100	350	220.5 $kg.day^{-1}$
Furnas de Boa Sorte	Corguinho/MS	60	210	132.3 $kg.day^{-1}$
Família Os Pretos	Terenos/MS	33	116	73.1 $kg.day^{-1}$
Furnas dos Baianos	Aquidauana	22	77	48.5 $kg.day^{-1}$
Ourolândia	Rio Negro/MS	10	35	22.1 $kg.day^{-1}$
Chácara Buriti	Campo Grande/MS	32	112	70.6 $kg.day^{-1}$
Família Malaquias	Figueirão/MS	46	161	101.4 $kg.day^{-1}$
Família Quintino	Pedro Gomes/MS	34	119	75.0 $kg.day^{-1}$
Família Bispo	Sonora/MS	12	42	26.5 $kg.day^{-1}$
São Miguel	Maracaju/MS	53	186	117.2 $kg.day^{-1}$
Águas do Miranda	Bonito/MS	22	77	48.5 $kg.day^{-1}$
Picadinha	Dourados/MS	196	686	432.2 $kg.day^{-1}$
		TOTAL	2171	1367.8 $kg.day^{-1}$

Source: Adapted from Andrino et al. (2018) and Lima et al. (2018).

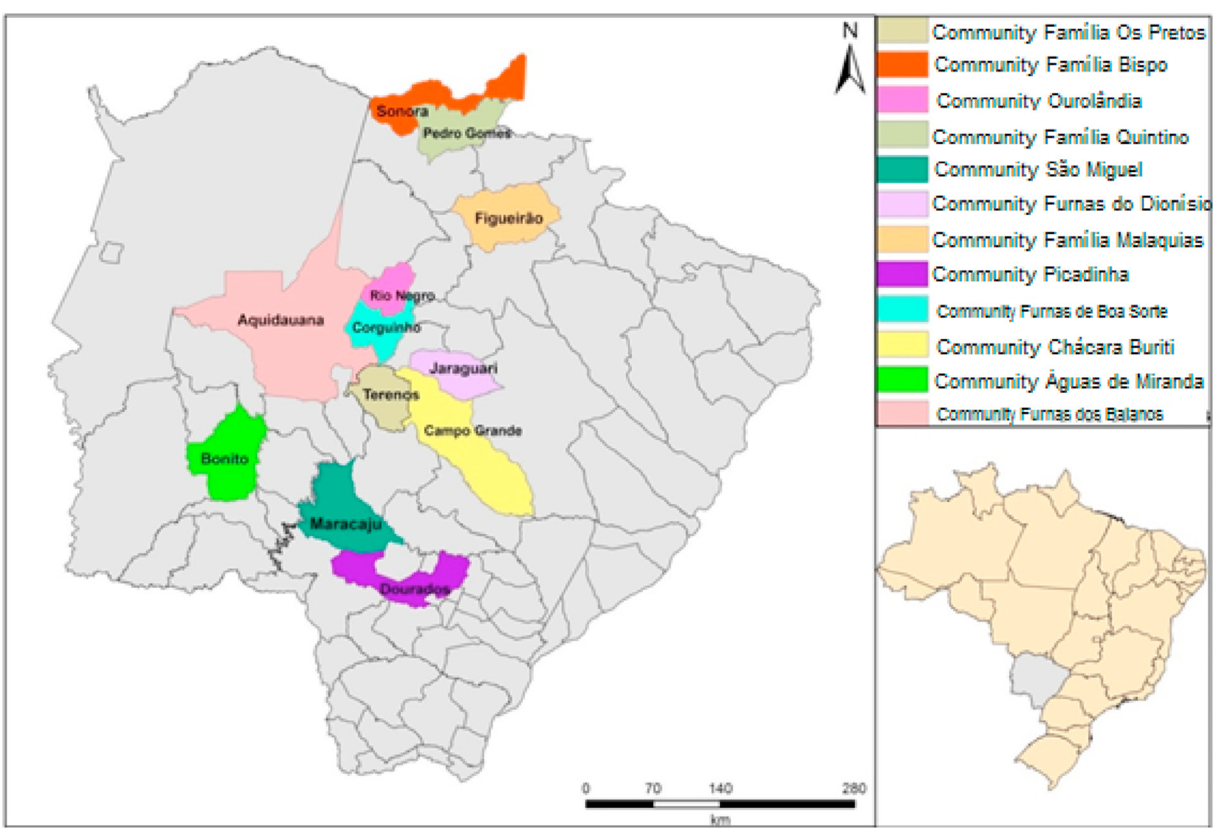

Fig. 1. State of Mato do Grosso do Sul and the distribution of Quilombola communities in the territory.
Source: Lima and Paulo (2018).

Table 2
ILCD impact categories, abbreviations, units, and normalisation factors.

ILCD Impact Category	Abbreviation	Unit	Normalisation factor
Climate change (expressed in terms of Global Warming Potential - GWP)	GWP100	kg CO_2 eq. PE^{-1} $year^{-1}$	7070
Ozone depletion	ODP	kg CFC-11 eq. PE^{-1} $year^{-1}$	0.0122
Human toxicity, cancer effects	HT, CE	CTUh PE^{-1} $year^{-1}$	1.24E-05
Human toxicity, non-cancer effects	HT, non CE	CTUh PE^{-1} $year^{-1}$	0.000155
Particulate matter	PM	kg PM2.5 eq. PE^{-1} $year^{-1}$	5.07
Photochemical ozone formation	POF	kg NMVOC eq. PE^{-1} $year^{-1}$	45.3
Terrestrial Acidification	TAD	mol H+ eq. PE^{-1} $year^{-1}$	56.1
Eutrophication terrestrial	EPT	mol N eq. PE^{-1} $year^{-1}$	164
Eutrophication freshwater	EPF	kg P eq. PE^{-1} $year^{-1}$	6.54
Eutrophication marine	EPM	kg N eq.	30.4
Ecotoxicity freshwater	ECF	CTUe	3740
Depletion of abiotic resources, mineral, fossils and renewables	DAMR	kg Sb eq.	0.193

Source: DTU (2016).

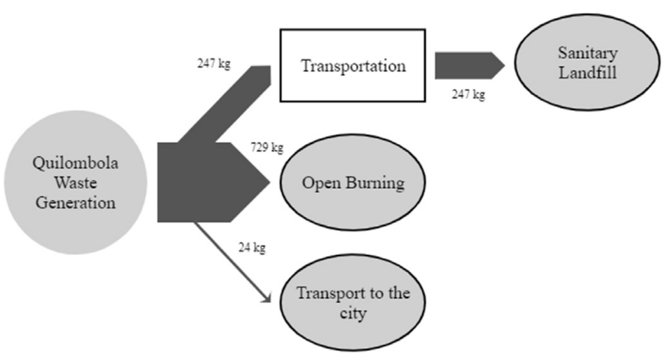

Fig. 2. Flow diagram of the "current scenario" of waste management in the Quilombola communities.

order to facilitate comprehension. The system boundaries were drawn as shown in the figures and, because both systems end with the recyclables being transported to the city, recycling and co-production of materials were not addressed.

Currently, some residents perform a kind of source separation, giving

Table 3
Mass transfers for the proposed scenario.

Material fraction	Gravimetric Composition (%)	Mass Transfers (%)		
		Dry	Organics	Rejects
Animal food waste	8.12	–	100	–
Beverage cans (aluminum)	1.76	100	–	–
Brown glass	7.89	100	–	–
Clear glass	2.2	100	–	–
Diapers, sanitary towels, tampons	2.02	–	–	100
Food cans (tinplate/steel)	3.13	100	–	–
Hard plastic	0.89	50	–	50
Non-recyclable plastic	0.22	–	–	100
Office paper	0.62	50	–	50
Other clean cardboard	3.67	50	–	50
Plastic bottles	0.66	100	–	–
Plastic products (toys, hangers, pens)	0.49	50	–	50
Soft plastic	8.84	50	–	50
Vegetable food waste	59.49	–	100	–

organic waste to animals, selecting what will be burned, etc. Thus, for the proposed scenario, the transfer coefficients were stipulated as shown in Table 3, which lists the mass transfers used for the proposed scenario and the waste fractions employed in EASETECH.

For the inventory, we applied the processes already part of EASETECH and others that were taken from ecoinvent. Ecoinvent is a broad database of environmental impacts of global products and systems. It provides inventory data for a variety of products from which those that best fit our scenario were chosen, as shown above (Wernet et al., 2016). We further considered transportation on highways via trucks <7.5t, with the average distance to the municipalities (i.e., 25 km). The sanitary landfill was modelled using the process used by Lima et al. (2018; 2019) with flare treatment for the biogas, adapted to Brazilian conditions. Open dumping and home composting of Lima et al. (2018; 2019) were also used, while open dumping, a variation of landfilling with no measures taken (no cover and no soil protection), and home composting were considered as windrow composting and adapted from the already existing EASETECH process. For MSW open burning, the global process of ecoinvent "municipal solid waste, treatment of municipal solid waste, open burning, GLO" was imported into the software.

Biogenic carbon was modelled according to the definitions in EASETECH. For landfills, biogenic carbon that is not anaerobically degradable will remain after 100 years. Therefore, while the degradable carbon is emitted as gas, the residues are "stored" and considered sequestrated (non-emitted).

EASETECH generated the results in form of characterised and normalised potential impacts, which were then transferred to Microsoft Excel where the data was plotted and analysed.

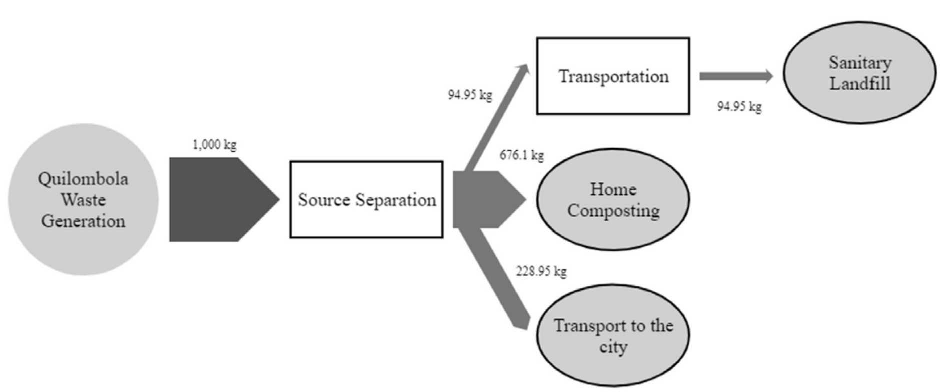

Fig. 3. Flow diagram of the "proposed scenario" for waste management in the Quilombola communities.

2.1. Sensitivity analysis

A sensitivity analysis was performed through the variation of a few key parameters that are important and relevant for the assessment (Table 4). As in EASETECH, the waste not degrading in a landfill was considered stored and, hence, based on the biological carbon being sequestered, the carbon storage was counted as a negative fossil carbon emission. Therefore, for both scenarios, we set the landfill from 100 to 0 carbon storage in order to determine to what extent this parameter influenced the results. We also changed the transportation to landfill to 150 km, as Brazil is a large country, and in some communities the waste has to be taken to another municipality, suggesting transportation as a possible crucial parameter. Further, in the current scenario, a different open dump process, taken from the ecoinvent database, and a different open burning scenario, taken from the literature, were tested, as described in Table 4.

3. Results

The LCA results are presented, either characterised or normalised, in milli Person Equivalent (mPE) for easy comprehension. Positive results represent environmental burdens, and negative results represent savings. In Table 5, the net characterised results from both scenarios in each of the assessed impact categories are presented. Net denotes the sum of the burdens and savings from each process for each of the categories.

As can be seen in Table 5, the proposed scenario performed better across all assessed impact categories. The current scenario not only had the worst overall performance, but it registered environmental burdens for all impact categories. We must point out that global warming potential (GWP) and ecotoxicity freshwater (ECF) have very high values, mainly originating from MSW open burning, which was expected given that it is a forbidden practice in most places. As for the proposed scenario, the impact values in all categories are lower than those in the current scenario, resulting in savings for most categories (e.g., GWP, ECF, and DAMR) due to the compost application on land, which avoids the use of fertilisers.

Fig. 3 shows the net normalisation results in mPE (milli Person Equivalents) per impact category. Without in-depth analysis, it is apparent that the environmental impacts in all impact categories decreased from the current to the proposed scenario. However, in HT, non-CE, POF, and EPM, the proposed scenario also registered environmental burdens from landfill and home composting.

Comparing Table 5 and Fig. 4 it highlights how important the normalisation factors are. For depletion of abiotic resources, mineral fossil and renewable (DAMR), for example, the result presented in Table 5 suggests a small savings component; however, Fig. 4 clearly shows that it brings high savings to the category in mPE. Moreover, in the normalised results, the category with the highest environmental burden is human toxicity, cancer effects (HT, CE - 51,112.54 mPE), followed by ECF (9939.58 mPE), and humand toxicity, non-cancer effects (HT, non-CE - 8061.85 mPE).

Table 4
Parameters varied in the sensitivity analysis in the current and proposed scenarios.

SCENARIO VARIATION	CURRENT	PROPOSED
Open Dump	Process from ecoinvent database: “municipal solid waste, treatment of municipal solid waste, open dump, GLO”	–
No storage	From 100 to 0	From 100 to 0
Transportation	Set to 150 km	Set to 150 km
Open Burning	Based on EASETECH model and emissions from Das et al. (2018).	–

Table 5
Characterised results per impact category from the ILCD recommended method.

IMPACT CATEGORY	UNIT	CURRENT	PROPOSED
Climate Change (GWP)	kg CO_2 eq.	414.86	−27.08
Ozone Depletion (ODP)	kg CFC-11 eq.	2.10E-05	1.20E-08
Human Toxicity, Cancer Effects (HT, CE)	CTUh	6.34E-4	−6.47E-08
Human Toxicity, non Cancer Effects (HT, non CE)	CTUh	0.0013	3.40E-06
Particulate Matter (PM)	kg PM2.5 eq.	8.42	−6.56E-05
Photochemical Ozone Formation (POF)	kg NMVOC eq.	6.07	2.52
Terrestrial Acidification (TAD)	mol H+ eq.	2.51	−0.0014
Eutrophication Terrestrial (EPT)	mol N eq.	13.77	0.045
Eutrophication Freshwater (EPF)	kg P eq.	0.64	−0.016
Eutrophication Marine (EPM)	kg N eq.	1.31	2.01E-3
Ecotoxicity Freshwater (ECF)	CTUe	37,174.04	−1.45
Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR)	kg Sb eq.	2.19E-05	−0.12

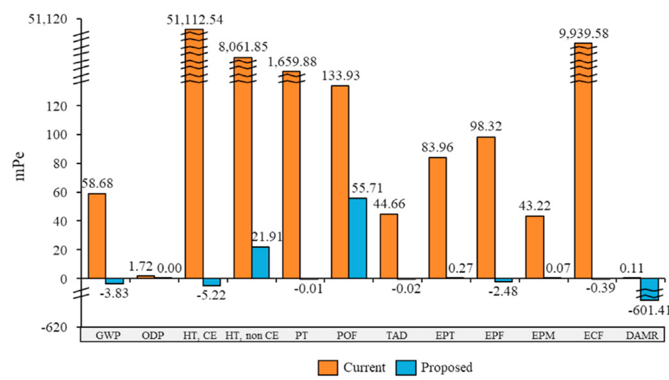

Fig. 4. Normalised results in mPE (mili person equivalent) for Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non-Cancer Effects (HT, non-CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, and Mineral fossil and Renewable (DAMR).

Furthermore, for climate change (in terms of GWP), the environmental burden was reduced to small savings from the current to the proposed scenario (from 58.7 mPE to −3.8 mPE), and for Particulate Matter (PM), which registered extremely high burdens in the current scenario (1659.88 mPE), the burden also dropped to a slight saving in the proposed scenario (−0.01 mPE). Fig. 5, which presents the specific contributions from all considered processes in kg CO_2eq., shows that the burdens were greatly reduced, from 414.9 kg CO_2eq. in the current scenario to −27.1 kg CO_2eq. in the proposed scenario. The highest contributions originate from waste burning without any kind of control or measure and account for 98.8% of the emissions. In contrast, for the proposed scenario, most emissions originate from home composting (2.26 kg CO_2eq.), which are not completely nulled by the avoidance of fertiliser usage due to the application of compost to soil (−1.52 kg CO_2eq.). This may seem surprising if one is unfamiliar with the fact that composting causes emissions, which are in fact quite high when compared to transportation, for example; however, these emissions are usually compensated for by fertiliser usage and are smaller than landfill emissions.

Fig. 5 also shows that landfills register savings for both scenarios, −26.27 kg CO_2eq. and −28.98 kg CO_2eq. in the current and proposed scenarios, respectively. This is due to the biogenic carbon considered stored (sequestered) and because the organic material was composted and not degraded in the landfill. The carbon considered stored in the

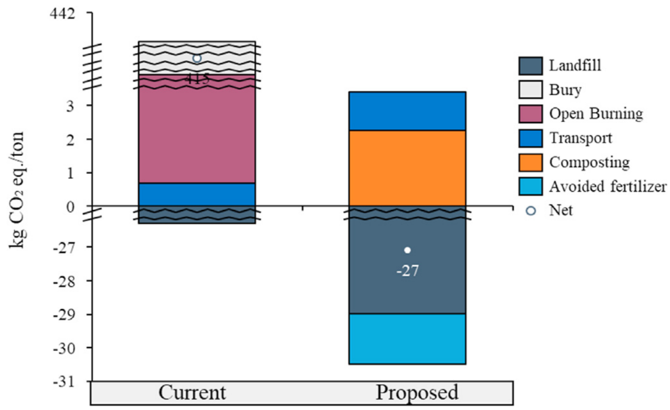

Fig. 5. Characterised contributions to climate change in kg CO_2eq.

ground and not emitted was further analysed in the sensitivity analysis, which is discussed in sequence.

Considering the daily waste generation presented in Table 1, we also calculated the GWP for each community per day and per year, as shown in Table 6. As can be seen, within one year the communities generate around 207,112.46 kg CO_2eq. in total and the community with the highest emissions is the one with the largest population, that is, Picadinha (65,446.18 kg CO_2eq./year), followed by Furnas do Dionísio (33,389.36 kg CO_2eq.). Furthermore, the Quilombola population emits 0.26 kg CO_2eq./cap.day and 95.4 kg CO_2eq./cap.year.

3.1. Sensitivity analysis results

Fig. 6 and Table 5 show the results of the performed sensitivity analysis. As can be seen in Fig. 6, for the normalised climate change (GWP) results, the no storage for landfill scenarios are the most sensitive when compared with the baseline scenarios (current and proposed) which is consistent with the results of Lima et al. (2018). For the other parameters analysed the deviations from the baseline are smaller and for open dump from ecoinvent and open burning from the literature the burdens were reduced.

Table 7 shows the characterised results for the sensitivity scenarios. It is noteworthy that in the current scenario the parameter that deviated the most from the baseline was the open burning taken from the literature. For the proposed scenario, all variations stayed within a reasonable range. Furthermore, an increase in distance travelled to a landfill in the current scenario results deviated the most from the baseline in 10 out of 12 categories, while the no storage in the proposed scenario deviated the least from the baseline in 9 out of the 12 categories.

4. Discussion

4.1. Data and method's gaps

Quilombola communities in Brazil are mostly located in rural areas; therefore, they are often neglected with respect to provisioning services, including solid waste management. Lima and Paulo (2018) verified that the residents of these communities are, among other hazards, exposed to risks associated with open air burning of solid waste, when the municipality does not provide some type of waste collection service. It was confirmed in this study that besides social risks, the residents are exposed to major environmental risks when more than 70% of the residents still practice open air burning. Even with big changes in the scenario, that is, a very optimistic approach, the population is still exposed to high environmental burdens. The results presented here can be extrapolated to rural areas of Brazil in general, as the conditions are similar across the country as verified by Andrino et al. (2018).

We verified that the current scenario results in high normalised

Table 6
Daily and yearly impacts on climate change for each community.

Community	Residents	Waste Generation (tons)		Impacts (kg CO_2eq.)	
		Per day	Per year	Per day	Per year
Furnas do Dionísio	350	0.22	80.48	91.48	33,389.36
Furnas de Boa Sorte	210	0.13	48.29	54.89	20,033.62
Família Os Pretos	116	0.07	26.68	30.33	11,069.22
Furnas dos Baianos	77	0.05	17.70	20.12	7344.15
Ourolândia	35	0.02	8.05	9.15	3338.94
Chácara Buriti	112	0.07	25.75	29.27	10,684.60
Família Malaquias	161	0.10	37.02	42.08	15,359.11
Família Quintino	119	0.07	27.36	31.10	11,352.38
Família Bispo	42	0.03	9.66	10.98	4006.72
São Miguel	186	0.12	42.77	48.61	17,744.06
Águas do Miranda	77	0.05	17.70	20.12	7344.15
Picadinha	686	0.43	157.75	179.30	65,446.18
	2171	1.37	499.23	567.43	207,112.46

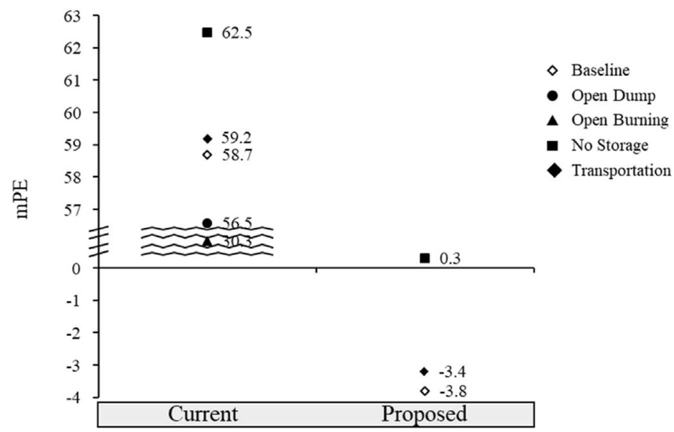

Fig. 6. Sensitivity results compared to the baseline scenarios normalised for Climate Change (GWP) in mPE.

environmental burdens in all impact categories, which can be inferred to be the current situation in most rural communities globally. The human toxicity category, with 51,112 mPE per ton of waste, represents a large amount of toxic substances that may affect human health in the form of different types of diseases. As for freshwater ecotoxicity, 9940 mPE has a significant impact on freshwater ecosystems, caused by toxic elements in air, soil, and water. These examples show how important a change in waste management scenario is for these communities, because not only can human health be affected, but also our water ecosystems, etc.

Published research on waste LCA in rural areas is scarce globally and generally very specific, making it difficult to compare results across different studies. Yadav and Samadder (2018) assessed the impacts of open burning of waste in an urban context in India. They obtained 9420 kg CO_2eq. for a scenario that also includes open dumping and landfilling, which is higher than our result due to the additional contributions, but it nevertheless illustrates how impactful this practice is. Open burning can trigger a variety of health impacts, such as acute and chronic respiratory diseases, cardiovascular diseases, and cancer, in addition to impacts on local climate. The smoke that is emitted contains PM, carcinogenic dioxins, and numerous other harmful pollutants such as nitrogen oxides (NOx), sulfur dioxide (SO_2), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) (Das et al., 2018). Therefore, it is important that the communities that still perform this practice are not neglected with regard to providing adequate waste disposal means; on the contrary, they require special attention to minimise the social and environmental impacts they are exposed to.

Even though landfilling has its own restrictions and is associated with high environmental burdens (Lima et al., 2018; Yadav and Samadder,

Table 7
Characterised sensitivity results for Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non-Cancer Effects (HT, non CE), Particulate Matter (PM), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, and Mineral fossil and Renewable (DAMR).

Scenario	Open Dump	Current NS	Current Transp.	Open Burning	Proposed NS	Proposed Transp.
GWP	399.80	441.61	418.27	213.89	2.08	−25.99
ODP	−1.47E-06	2.10E-05	2.10E-05	2.25E-05	1.20E-08	1.24E-08
HT, CE	6.34E-04	6.34E-04	6.34E-04	1.36E-07	−6.47E-08	−6.32E-08
HT, non CE	1.25E-03	1.25E-03	1.25E-03	7.11E-06	3.40E-06	3.67E-06
PM	8.42	8.42	8.42	5.45E-03	−6.56E-05	3.28E-05
POF	6.06	6.07	6.08	0.64	2.52	2.53
TAD	2.51	2.51	2.52	0.47	−1.38E-03	2.11E-03
EPT	13.77	13.77	13.82	2.66	0.04	0.06
EPF	0.64	0.64	0.64	1.04E-04	−0.02	−0.02
EPM	1.28	1.31	1.32	0.29	2.01E-03	3.33E-03
ECF	37,170.01	37,174.04	37,174.82	10.96	−1.45	−1.20
DAMR	2.19E-05	2.19E-05	2.49E-05	2.06E-05	−0.12	−0.12

Note: The red script marks the highest impact values and the green script the lowest values in each impact category.

2018), in the case of the Quilombolas, considering the precariousness of their services, the practice would improve their living conditions significantly because it would reduce their exposure to waste. In Campo Grande, the capital of Mato Grosso do Sul, Lima et al. (2019) found 137 kg CO_2eq. for the current scenario (landfilling with flare), compared to 85 kg CO_2eq. in a prospective scenario with lower amounts of waste going to the landfill. Their results illustrate the importance of recycling and the avoidance of certain materials in the assessment.

Urban areas are responsible for 70% of greenhouse gas (GHG) emissions, and waste management is responsible for about 4% of GHG emissions worldwide (Observatório do Clima, 2018). According to Crippa et al. (2019), global emissions were 49 Gt CO_2eq. in 2018, and Brazil was responsible for 1.3% of the total, that is, 642 t CO_2eq. In this study, we determined a per capita generation of 95 kg CO_2 eq.year^{-1} in the Quilombola communities assessed, which represents 4% of the average per capita emissions in Brazil (2372 kg CO_2 eq.year^{-1}). Considering that most emissions are usually from urban areas, the fact that the rural population accounts for 4% of waste-related emissions is quite concerning, and reinforces the need for primary data and additional studies to verify the representativeness of the practice and the threats associated with it, which is why we performed this LCA, with an innovative approach towards rural communities.

LCA is usually associated with several sources of uncertainty, which should be minimised as much as possible. In this particular assessment, due to a lack of primary data in rural areas in general, they are a source of uncertainty, regardless of the region in the world or the subject of concern. From the waste composition to the processes employed for each scenario, we identified several issues that could alter the results, including the estimation of the organic fraction because it was not performed by gravimetric analysis (Andrino et al., 2018), the lack of a Brazilian database, and the process for Brazil in ecoinvent. Open burning is another aspect that is very commonly neglected and, therefore, the available data is not sufficient to support complete, reliable research. Furthermore, as pointed out by Das et al. (2018), the few inventories made also hold large uncertainties due to the difficulties related to the field. We believe that it is important to not only present our study's results, but also the uncertainties and difficulties associated with performing the study, in order to provide encouragement for further research and database construction in rural territories.

In this sense, the sensitivity analysis is a very important step of the assessment, because it can identify sources of uncertainty as shown here with the comparison of the open burning category from ecoinvent and from the literature, which revealed discrepancies that can only be solved with field research. Parameters such as burning/oxidation efficiencies, emission factors for different pollutants (e.g., dioxin, furans, particulate matter, carbon monoxide, sulfur oxides, nitrogen oxides, benzene, and toluene), and waste-to-energy potential should be evaluated to avoid these discrepancies. Kumari et al. (2019) verified emission factors for open burning in India, but the data of Das et al. (2018) was used in this study because it was more complete and could easily be implemented in EASETECH. Another parameter that needs to be considered further due to the great importance showed is carbon storage because in our proposed scenario, as it became an environmental burden instead of a saving in the sensitivity analysis, showing considerable variation.

Further, in regards to the LCA methodology, it has limitations of its own, which can lead to certain scepticism. Even though LCA is a comprehensive assessment that highlights potential environmental tradeoffs and provides structure to an investigation, it is also based on assumptions and specific scenarios that can be changed from one study to another, leading to different results (Curran, 2014). Most of the times, LCA needs to be complemented with other decision-making tools as it does not clearly state what the best option is. Therefore, social assessments such as risk assessment, and economic assessments should be carried out to complement not only this research but most LCAs performed in a variety of fields.

4.2. *Sustainability of waste systems*

In the past, waste generation resulting from production and consumption was accepted by common sense as a necessary side effect. Nowadays, this idea is increasingly rejected in favour of the ideal of eliminating waste and assuming a responsible attitude towards resources and the environment (towards CE). However, moving from the ideal to the concrete will require comprehensive interventions to facilitate the application of waste handling approaches such as reduction, reuse, and recycling (Veiga, 2019). According to Salvia et al. (2018), CE has great potential to provide appropriate waste management in rural areas, especially with respect to agri-food systems. In a broader perspective, considering all rural areas of the territory, it also has a lot of potential due to the reduction in quality and quantity of economic, social, and environmental capital in these areas. The "proposed" scenario of this study is in line with the SD concept in that it was designed considering the environmental, social, and economic needs of the population, aiming to increase resource recovery from waste and raise awareness towards waste minimisation. However, in order for it to work, actions and incentives from the municipalities, such as waste and education policies and changes in behaviour, together with a strong environmental and sanitation education of the population are required. The scenario has also been confirmed as socially and environmentally beneficial for residents as well as the surrounding population.

Turning waste into products and recovering resources is crucial to close loops in a CE. Hence, we find it important to stress that the sale of recyclables and the revenues that would come from it were not modelled in this work, but play a big part in CE and SD concepts. Although these aspects have not been modelled, they are strongly recommended and are the main goal of the proposed scenario, which provides support for further studies in the area and for the proposal of environmental/climate policies that could also provide incentives to new advantageous business models. Another alternative worthy of consideration is biochar, which is a product of the incomplete combustion of organics that can serve as a soil amendment to increase fertility. In rural areas, the use of organic waste for biochar production can produce positive effects due to carbon sequestration in the soil, which can overcome the negative impacts on the environment of this practice. Besides, it adds economic value to agricultural production, either locally or in surrounding areas, as the product can be sold (Sparrevik et al., 2014). In this sense, an economic assessment should be performed in addition to this LCA, as it could not only take these factors into consideration, but also close the sustainability loop around waste management in the communities and provide data for decision-makers to help decide on appropriate actions to improve quality of life of these populations.

Pereira and Fernandino (2019) performed a sustainability assessment of waste management in a small town in northeast Brazil, using political, economic, environmental, cultural, and social indicators as stated in the PNRS. According to their classification, the communities assessed in this work present low municipal solid waste sustainability or are even unsustainable. Beside the more evident factors (such as burning and dumping), this is due to the lack of a waste management plan, absence of selective waste collection, and lack of environmental education.

Further, Ddiba et al. (2020) verified that when shifting towards a CE, strategic investments are needed, combined with public policies and collaboration between stakeholders across sectors and governance levels. The public sector is currently not significantly involved in resource recovery initiatives; instead, private investments are called on to solve many of the problems found in the communities studied here. Therefore, the government needs to improve collaboration to boost the participation of stakeholders in the transition to CE, thus improving its overall governance capacity. Environmental education is also needed, as part of the collaboration and public policies, in order for residents to be able to take action (stakeholders' participation) and change their current conditions regarding waste management, or lack thereof.

The path towards a CE is quite long, especially where waste management is far behind the norm. Nonetheless, it can be achieved by starting from what already exists and taking care not to dismantle the waste management structure that the population is already used to. The recommendations provided here consider their habits and customs and propose alternatives that would result in only minor changes in their routine, but considerable changes in social and environmental impacts. We propose flexible adaptations in the system to enable a gradual evolvement that could be conveniently applied to similar conditions worldwide. It is not possible to go from one extreme to another without a transition period, as stated by Veiga (2019). The distance between the starting point and the ideal is large, and the processes involved are complex. This is why our study contributes to the transition period, providing data and information in an effort to draw attention to these marginalised areas and raise awareness of the issues they face. The future is in the direction of having more sustainability assessments that can guide the way for decision-makers, for rural and marginalised areas worldwide that should be considered in the urban contexts. Further, there is a need to search for financial resources, to implement technologies, for technological innovation, and, most importantly, to change the mentality of the population and decision-makers, without which there will be no transition. Therefore, the results obtained in the present study, combined with the social assessment previously performed, may help decision-makers pave the way for the implementation of more sustainable systems within the concept of CE.

5. Conclusions

An environmental assessment was performed for waste handling in rural Quilombola communities in west-central Brazil by comparing the current scenario of burning most of the waste with a proposed source separation (for home composting and landfilling) scenario. We found that based on their current waste-handling practices the Quilombola residents emit around 95.4 kg CO_2eq./cap.year, which is representative of this population compared to the urban population.

Based on drastic changes to the current situation of waste management, which reflects the current legislation, the proposed scenario presented positive impacts in a few impact categories; however, most categories registered environmental savings and a significant decrease in environmental burdens, especially for climate change. We conclude that a combination of home composting and transportation of recyclables to the municipalities is the optimal first step to greatly reduce the environmental impacts to which the Quilombola population is exposed to, which include health hazards, and to improve air quality.

In addition to contributing to knowledge on waste management in rural areas and proposing a scenario in line with CE, the performed LCA provided data that is consistent with previous studies that showed waste burning to be the environmentally most concerning practice performed in rural areas/isolated communities. The practice emits approximately 410 kg CO_2eq./ton of waste, accounting for 98.8% of the total emissions to climate change, which raises concerns about this neglected issue.

Finally, we conclude that public policies combined with greater collaboration of stakeholders and environmental education are needed to increase the understanding of the population and decision-makers of the importance of the issues assessed here. This will facilitate an economic assessment and thus the closing of the sustainability loop of the proposed scenario.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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