International Journal of Environmental Science and Technology (2022) 19:9991–10006
https://doi.org/10.1007/s13762-021-03837-7

ORIGINAL PAPER

Environmental assessment of municipal solid waste collection/transport using biomethane in mid-sized metropolitan areas of developing countries

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Received: 8 July 2021 / Revised: 7 October 2021 / Accepted: 30 November 2021 / Published online: 28 January 2022

Abstract

The novelty of this paper is the focus solely on municipal solid waste collection/transport in mid-sized metropolitan regions of developing countries, using biomethane (which can be supplied by the municipal solid waste management system) an alternative fuel and different waste collection methods. The eight proposed scenarios, compared to the baseline scenario, combine diesel and biowaste, door-to-door and bring collection methods, as well as two different levels of source-separated collection. The results have shown if the collection vehicles use biomethane, the impacts will always be significantly lower than using diesel (between 68–98%, depending on the impact category and scenario), even accounting with the uncertainty of the results. In this particular case-study, increasing source-separated collection also reduced the transport impacts in 40–50%, as the transfer stations are closer to the recycling facilities than the landfills. This is because the fuel consumption of transport is a function of distance, so is the impact. Therefore, this study recommends: using biomethane produced from anaerobic digestion of organic waste instead of diesel to expand circular municipal solid waste management; establishing transfer stations for the municipalities located more than 25 km away from waste management facilities; expanding the collection coverage to 100%; increasing source-separated collection and recycling.

Keywords Life cycle assessment · Waste collection · Waste transport · Biomethane · Developing countries

Abbreviations

C&T	Collection and transport of municipal solid waste
CNG	Compressed natural gas
DtD	Door-to-door
EM	Eutrophication marine
ET	Eutrophication terrestrial
GVMR	Great Vitória Metropolitan Region
GWP100	Global warming power—climate change in 100 years
H_2S	Hydrogen sulfide
HD	High diversions scenario
IPCC	International Panel on Climate Change
ISO	International Standard Organization
LCA	Life cycle assessment
LD	Low diversions scenario
MRF	Materials recovery facilities
MSW	Municipal solid waste
PLANARES	National plan for solid waste management (*Plano Nacional de Resíduos Sólidos*)
PM	Particulate matter
POF	Photochemical ozone formation
SM	Supplementary material
SSC	Source-separated collection
TA	Terrestrial acidification
TS	Transfer station
WCV	Waste collection vehicle

Editorial responsibility: Chenxi Li.

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Introduction

In Brazil, municipal solid waste (MSW) management is going through a heterogeneous transition process. Depending on the region, and generally depending of the economic development, final disposal still ranges from dumps to licensed landfills. Espírito Santo State, in Southeast Brazil, already disposes most of its waste properly (SNIS 2020), although irregular dumping points still exist. But MSW management is still focused on a linear model with low source-separated collection (SSC), instead of a circular one that diverts waste from landfills, with high SSC. This contradicts the waste hierarchy (Brazil 2010) and the National Plan for Solid Waste Management (PLANARES, short for *Plano Nacional de Resíduos Sólidos*), drafted by the Brazilian Ministry of the Environment (MMA 2012), which has proposed for 2015 a *minimum* target of 25% and 30% for diversions of biowaste and recyclables for landfills, respectively. Unfortunately, the latest PLANARES draft, yet unapproved to the date of this study, planned unambitious diversion targets of recyclable and organic waste of 25.8% and 18.1%, respectively, were proposed for 2040 (MMA 2020)

So, not only landfill diversions conform to the concept of Circular Economy, specifically to Cycling, one of the four circular business model strategies of the framework proposed by Geissdoerfer et al. (2018a, b), but also waste collection is considered by Takahashi (2020) a pivot to this concept. Which is why this study is aimed at finding strategies to increase SSC, an instrument to divert waste from landfills, in a sustainable way. The author analyses two very different Circular Economy models in Sweden and Japan, economic and administrative rationalism, which have in common curbside collection, being the Swedish model the most successful by far. D'Adamo et al. (2021) found out that a circular model for Rome, that reintroduces biomethane from waste into the transport system, replacing natural gas would be both economically and environmentally sustainable. And lastly, Baena-Moreno et al. (2020) performed a techno-economic analysis of coproducing biomethane and bioethanol from biowaste, revealing that subsidies are necessary to achieve profitable results. To find out more about the environmental results of this practice, a literature review of studies on MSW collection was performed.

So, 34 life cycle assessment (LCA) papers from the past five years, 14 LCAs focus exclusively on waste collection, of which four were carried out in developing countries (Pop et al. 2017; Gilardino et al. 2017; Yıldız-Geyhan et al. 2019; Ferronato et al. 2021) and only consider the use of diesel as fuel for the waste collection vehicles (WCV). As for alternative fuels, five studies from developed countries must be highlighted: Zabeo et al. (2017) analyzed the use of compressed natural gas (CNG) as a replacement for diesel; Pérez et al. (2017) compared replacing CNG, currently used in Madrid, Spain (3.2 million inhabitants), by biomethane; Costa et al. (2019) established a comparison between diesel and biomethane in Sinistra Piave Basin (population circa 300,000), Italy. Lastly, the next two papers also considered electricity as an energy source for the trucks. Winslow et al. (2019) assessed the diesel alternatives in Florida, USA, for landfill gas in MSW transport: upgrade to biomethane, electricity production to grid and to electric trucks. And, Chàfer et al. (2019) add hybrid technology to the scrutiny, by comparing diesel and diesel-electric, gas and gas-electric vehicles with fully electric collection trucks in Barcelona, Spain.

Regarding the collection methods, half of the 14 studies feature more than one collection method, being the most frequent door-to-door (DtD) or Bring, where the residents have to dispose their waste in containers. Two studies (Chàfer et al. 2019; Pérez et al. 2020) show the environmental impact of a high-tech method, pneumatic collection, while only one (Ferronato et al. 2021) has a low-tech method that is a cross between DtD and Bring: Corner Stop. In this method, the residents have to bring their waste to the WCV, that rings a bell when it stops in street intersections at certain schedules. Additionally, most studies consider MSW in general, but there are exceptions. Two studies focused on the organic fraction of MSW only (Laso et al. 2019; Pavlas et al. 2020) and the study by Costa et al. (2019) is even more specific, aimed at food waste and, lastly, Chàfer et al. (2019) excludes glass from MSW collection.

Several studies (Coelho and Lange 2018; Lima et al. 2018; Banias et al. 2020) evaluate an extensive array of treatments or management approaches, but consider a single collection method, which is already consolidated, or do not explore beyond commingled collection or SSC. Regarding the location, there are still more LCA studies performed in developed countries, rather than in emergent ones, although this disparity is attenuating (Zhang et al. 2021). Specifically, the majority of studies on the collection phase (10 out of 14), were carried out in developed countries. Therefore, this review revealed that collection and transport (C&T) is an area with opportunities to deepen the knowledge and obtain more specific answers.

Accordingly, this work is a novelty, as it intends to fill a gap by focusing on environmental assessment of MSW collection in mid-sized metropolitan regions of developing countries, using an alternative fuel and different waste collection methods. The use of biomethane WCV, is a relevant matter, especially in these countries, since their waste has higher percentages of organic waste (Nizami et al. 2017), hence a higher potential for this fuel. The fact that gas engines emit less noise than they diesel counterparts (Milojevic et al. 2016) is not negligible in vehicles that operate in residential areas at night. Therefore, the general goal of this study is to find C&T strategies with lower environmental impacts, by comparing diesel and biomethane scenarios, DtD versus Bring collection methods and different levels of SSC.

The adoption of policies and decision-making should be backed up by specific tools, like LCA, as suggested in this study, produced between mid-2020 and 2021. So, this paper is aimed at the decision-makers of the municipalities of Great Vitória Metropolitan Region (GVMR), the studied location, or any other similar regions, as well as the scientific community. To use this methodology in other regions, the steps are essentially the same, although the scenarios and strategies to propose may differ, according to local laws and regulations. It is noteworthy that the waste collection method is not independent from the treatment method, i.e., whether the waste in separated or commingled determines the downstream flow (Pires et al. 2019).

Materials and methods

The life cycle assessment methodology

To measure the impacts of different strategies to meet the diversion targets, LCA was used. This methodology specifically measures impacts on the environment (air, water and soil) and on human health, which is performed from the perspective of complete life cycles of products, processes or activities (Hauschild and Huijbregts 2015). This methodology has seen its standards evolving since 1993 and is currently standardized by the International Standards Organization norms 14,040 and 14,044 (ISO 2006a, 2006b), the norms used on this study. LCA has four basic phases: (1) goal and scope, (2) life cycle inventory, (3) life cycle impact assessment, (4) interpretation. Because of the uncertainty of the results and data availability, the earlier phases may need to be adjusted as needed.

In this paper, EASETECH, a Danish LCA software (Clavreul et al. 2014) was used, like in Lima et al. (2019, 2018). The choice for this tool is due to the fact that, unlike other LCA tools, it is a specific for waste management (Clavreul et al. 2014). This means thoroughly detailing the elements that comprise the mass and substance flows in each step of a waste management chain, instead of considering a single material flux (Laurent et al. 2014). Additionally, it contains libraries with models for all waste management phases: C&T, waste treatments and recovery, and final disposal (Brogaard and Christensen 2016).

Goal and scope (LCA phase 1)

The goal of this LCA is to compare scenarios with different combinations of collection types (DtD and Bring), different fuels (diesel and biomethane) in order to find out how to expand SSC while minimizing the rise of emissions that this action should hypothetically produce. As for the scope, the chosen functional unit was the collection and transport of one ton (1 t) of MSW to facilities for materials recovery or final disposal (Gilardino et al. 2017). This study limits the LCA to the C&T service only, leaving waste treatments and disposal outside this evaluation. Specifically, the analysis starts when the WCV leave their parking location to the collection routes and ends after the waste is transported directly to a waste disposal facility, or a sorting facility. In addition to the household waste, the incoming MSW flow includes pruning waste and waste from street cleaning services, complying with the National Solid Waste Policy (Brasil 2010).

Studied area

Espírito Santo (Fig. 1) is a small State in Southeast Brazil, with 46,096 km^2. Its rising population of almost 4.0 million in 2019 (IBGE 2020) is estimated to reach 4.7 million in 2040 (ES 2019). The last census from the Brazilian Institute of Geography and Statistics (IBGE 2010) shows that 86% of the State's population is urban. This situation matches other regions of Brazil and other developing countries: population expansion in cities and rising waste generation.

In this paper, the methodology for mid-sized urban areas of developing countries is applied on GVMR, shown in Fig. 1. This area, with almost 2 million inhabitants (ES 2019), is comprised of seven municipalities, ordered by population size: Serra, Vila Velha, Cariacica, Vitória, Guarapari, Viana and Fundão. The choice for this region is justified by the concentration of the majority of the state's population in this location, hence most of the MSW to be managed and the incipient rate of source-separated collection. The other municipalities of this State have a different MSW generation profile and are sparsely populated, when compared to the GVMR, so they were excluded from this study, and must be analyzed separately.

Life cycle inventory (LCA phase 2)

Current MSW management panorama in the studied area

The waste produced by GVMR is mostly brought to transfer stations (TS), by WCV via DtD collection. The ratio of DtD vs Bring collection varies between the municipalities. TS are the first MSW management facilities, where waste is gathered, so larger transport trucks carry it to either waste pickers organizations (recyclable fraction) or landfills (non-recyclables)—Fig. 1. And, the source-separated organic fraction is transported in a composting facility located beside Cariacica landfill that treated 5193.23 t in 2020 (datum from Organobom). This saves costs to transport MSW to final disposal facilities (ES 2019), which are, together with collection, the

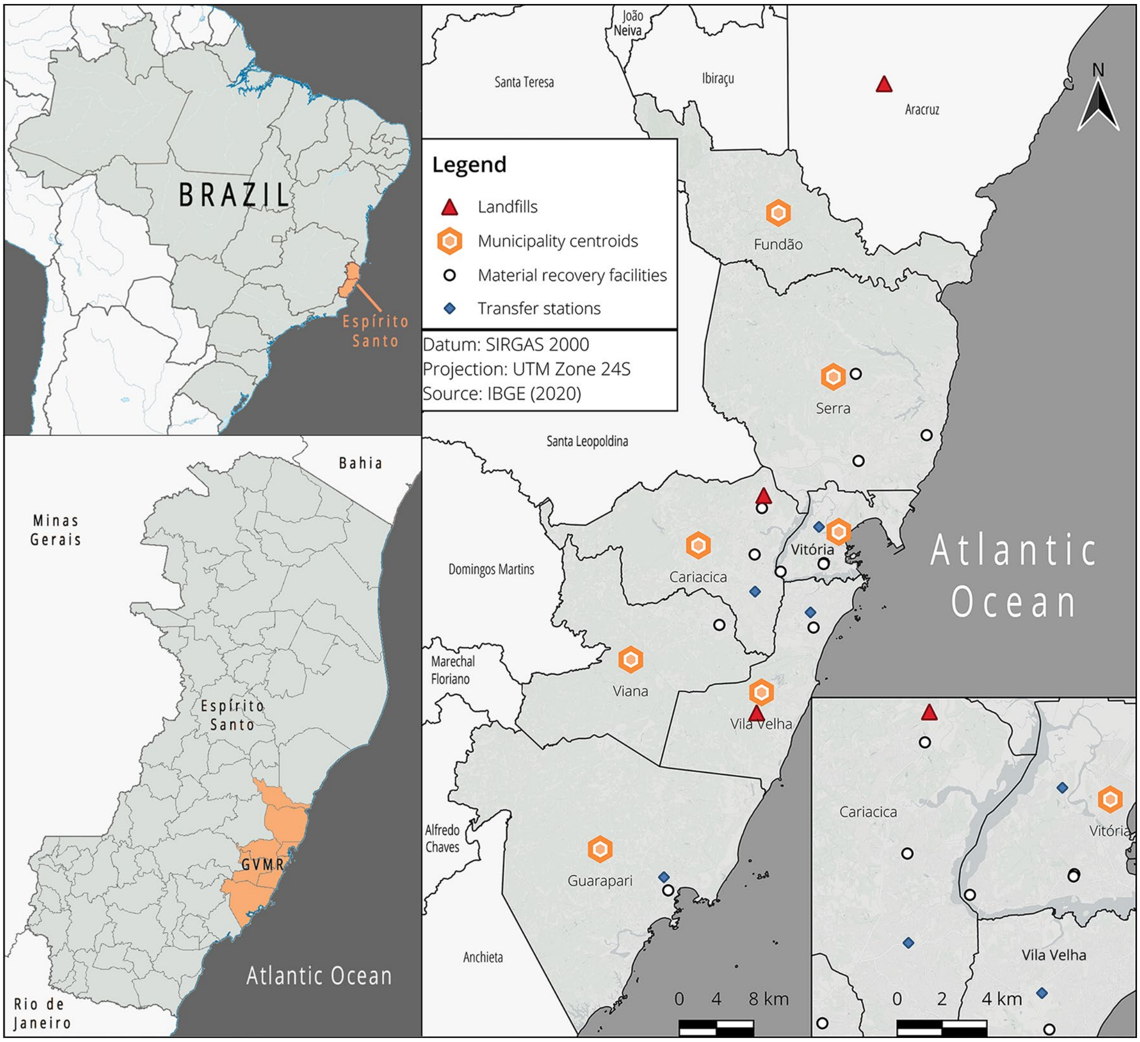

Fig. 1 Great Vitória Metropolitan Region

main operating expense in MSW management (Colvero et al. 2020b). Two small municipalities (Fundão and Viana) are the exception, by sending their waste directly to the landfill of Cariacica, located more than 25 km away. This is the limit beyond it is considered to be more economically viable to move the MSW to a higher capacity truck (Chen and Lo 2016). The TS of Guarapari also receives waste from five other neighbor municipalities, although this MSW was not accounted for in this study, because they were not produced in GVMR.

Commingled waste (97.2%) is disposed of in the licensed landfills of Vila Velha, Cariacica and Aracruz (Table 1). Remains 1.132%, which still represents 7.8 thousand tons yearly, a considerable amount of uncollected waste that can be either absorbed by the land through composting, directly burned, or worse, discarded in gutters, waterways and beaches, causing serious troubles (Fig. 2). The obtention of these data is explained in Sect. 1 of the Supplementary Material (SM) and the intermediate results are in SM Table 1. About the mentioned landfills, they both count on technologies like landfill gas recovery, environmental monitoring, rainwater and leachate drainage, internal leachate treatment and cover their waste daily (SNIS 2019).

Regarding the SSC rate, only 1.57% (0.75% organic + 0.82 recyclable) of the generated MSW in GVMR is collected separately at the source, which is incipient (Table 1). It can be collected at the households (DtD collection), drop-off points on the streets (Bring collection) and directly from companies (Commercial collection). Furthermore, Magalhães (2020) adds that in the same collection route, waste can picked from households, as well as drop-off points and/or companies, blending different collection types (Blend collection). Additionally, Fundão does not practice SSC, despite of being a small peripheric rural municipality that absorbs considerable amounts of biowaste. Another consideration is that glass is currently landfilled. As there are still no recycling

Table 1 MSW panorama in Great Vitória Metropolitan Region

Municipality	Total population	Popul. Density in 2020†	Transfer station	MSW final disposal	Population covered by MSW collection service	Collection per capita	Source-separated collection of recyclables per capita	Population covered by DtD collection
	Inhabitants	inh km^{-2}		Disposal location	Inhabitants	kg inh^{-1} day^{-1}	kg inh^{-1} year^{-1}	Inhabitants
Cariacica	381,285	1406	Private	Landfill Cariacica	378,705	0.68	1.69	258,627
Fundão*	*20,757*	78	No	Sent to Aracruz	*17,530*	0.56	*0.00*	17,530
Guarapari*	*123,166*	220	Private	Sent to Vila Velha	*115,777*	1.38	*4.25*	111,320
Serra	517,510	988	Public	Sent to Cariacica	517,510	0.71	0.88	513,948
Viana	78,239	260	No	Sent to Cariacica	71,777	0.55	2.51	71,777
Vila Velha	493,838	2447	Private	Landfill Vila Velha	491,443	1.20	1.60	491,443
Vitória	362,097	3818	Private	Sent to Cariacica	362,097	1.20	8.59	362,097
TOTAL	1,976,892				1,954,839			1,826,742

Source: SNIS (2020), except where noted. *Values indicated for Fundão and Guarapari are in *italic* (SNIS 2018)

†ES (2019)

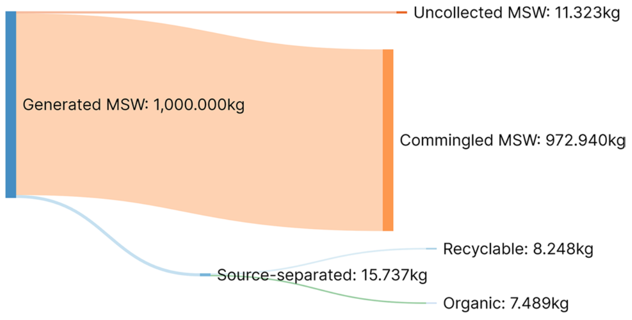

Fig. 2 Sankey diagram of the MSW flow of the current management panorama in Great Vitória Metropolitan Region Source: Adapted from (SNIS 2020, 2018)

industries in ES, sending glass to a recycling industry in another state turns out to be unfeasible economically.

Waste characterization for the studied area

The basic MSW composition in the GVMR was initially estimated from the amounts of recyclable waste for each type of collection (Bring, DtD, Commercial and Blend). These data were kindly provided by the Environmental Sanitation Management Laboratory of UFES (LAGESA-UFES, short for *Laboratório de Gestão do Saneamento Ambiental)* and were obtained from waste pickers organizations for all municipalities of the GVMR, except Fundão (0% SSC). Therefore, the *basic* recyclable waste characterization was: 45% paper/ multilayered packaging, 2.2% metals, 18% glass, 14% plastic, 5.8% Styrofoam, 6.2% others, 8.5% refuse.

Then, the biowaste, that includes pruning and gardening waste from public green spaces (Brasil 2010), was added for the seven municipalities of GVMR—49.02% for the year 2017 (ES 2019). Therefore, the *complete basic* estimated characterization of the waste generated in the GVMR was: 49.02% of organic waste, 23.1% paper/multilayered packaging, 1.1% metals, 9.1% glass, 7.2% plastic, 3% Styrofoam, 3.2% others, 4.3% refuse. These values were used to proportionally estimate the *detailed* characterization for GVMR within each category to be inputted in the LCA software, using the proportions of each subdivisions of waste for Goiás, by Lima et al. (2018), which is presented in Table 2. In order to keep the values consistent with the authors, it was assumed that the fraction of "others" (3.2%) from the surveyed data was *Other non-combustibles* in the detailed characterization, while "refuse" (4.3%) was the sum of *Reject* with *Hazardous waste*.

Proposed scenarios

In order to find the best C&T strategies, establishing scenarios to compare with the current panorama (Baseline scenario) is necessary. To do so, the eight hypothetical scenarios (Table 3) based on the provisional PLANARES (MMA

Table 2 Estimated MSW characterization for Great Vitória Metropolitan Region

Paper†	**23.06%**	*Plastic (continued)*	
Office paper	9.95%	Soft plastic (2D Plastic)	4.01%
Dirty paper	0.80%	Plastic products (Other plastic)	0.75%
Magazines	0.20%	Non-recyclable plastic (Styrofoam)	*2.97%*
Newsprints	0.80%	**Organic**†	**49.02%**
Other clean cardboard	10.21%	Vegetable food waste	43.14%
Juice cartons (Multilayered packaging)	1.10%	Animal food waste	5.88%
Metal†	**1.14%**	**Reject**†	**7.41%**
Food cans (Ferrous metal)	1.02%	Diapers, sanitary towels, tampons (Sanitary waste)	1.28%
Beverage cans (Aluminum)	0.11%	Rubber	0.23%
Glass†	**9.10%**	Shoes, leather	0.19%
Clear glass	7.58%	Other combustibles (Foam)	0.09%
Brown glass (Colored glass)	1.52%	Textiles	2.11%
Plastic†	**10.17%**	Wood	0.33%
Hard plastic	2.06%	Other non-combustibles†	3.18%
Plastic bottles (PET)	0.37%	**Hazardous waste**	**0.11%**
Continues in next column…	Total	100.00%	

The remaining were proportionally estimated from the of Lima et al. (2018)

†Initial GVMR values, obtained from the waste pickers organizations and ES (2019)

Table 3 Scenarios proposed for this study

			Diesel	Biomethane
0. Baseline scenario	Low diversions (LD)	Door-to-door bring	1. Diesel LD DtD	2. Biomethane LD DtD
			3. Diesel LD Bring	4. Biomethane LD
	High diversions (HD)	Door-to-door bring	5. Diesel HD DtD	6. Biomethane HD DtD
			7. Diesel HD Bring	8. Biomethane HD Bring

2012) waste diversion targets from 2031 (SM Table 2) will be presented in this item.

The Baseline scenario (0) was built according to the flows shown on Fig. 2. As for the proposed scenarios, in addition to the targets, the sorting efficiency of the materials recovery facilities (MRFs) was taken into account. To attain the diversion targets, the actual amount of waste to be collected has to be higher than the target itself, as some source-separated waste cannot be recycled or composted and will be landfilled anyway. So, using data from Portuguese waste biowaste and recycling plants (APA 2019), it was possible to estimate efficiency values to calculate the real collection amount to guarantee the diversion targets.

So, for the low diversions (*LD)* scenarios (1 to 4), the average value of the Portuguese sorting facilities efficiencies (76%) was used, while for the high diversions (*HD)* scenarios (5 to 8), a figure of 95% represents the high-tech MRFs. Likewise, for organic pretreatments, the values assumed were 64.7% and 82.4%, respectively. With the waste characterization and the Baseline and proposed scenarios defined, the mass of each type of waste was calculated and presented in SM Table 3 for Baseline scenario, SM Table 4 for the LD scenarios and SM Table 5 for the HD scenarios. Odd scenarios use diesel, whereas even scenarios use biomethane. Scenarios 1, 2, 5, 6 use DtD collection, whereas 3, 4, 7, 8 use Bring collection (Table 3). The overall preliminary waste distribution for both scenarios is shown in Fig. 3.

Collection types, transport and fuel consumption inputted in the model

DtD collection, also called curbside, full-service, alley pickup and house containers (Rodrigues et al. 2016), consists in a vehicle, with a scheduled route timetable, picking up the waste bags that are left by the citizens next to their door, at the sidewalk (Martinho et al. 2017). Alternatively, waste can be also deposited in 15 to 30-L containers at each household doorstep or 360 L in case of restaurants or shops (Tsalis et al. 2018). According to Martinho et al. (2017), the

Table 4 Consumption values used in the simulation

	Commingled collection	Door-to-door separated collection	Drop-off separated collection
Diesel collection (F_{eff} = **1.1375** km L^{-1})	($C_{w\,w}$ = L t^{-1})	($C_{w\,w}$ = L t^{-1})	($C_{w\,w}$ = L t^{-1})
Teixeira et al. (2014)—Portugal	3.96	15.37	–
Lima et al. (2019)—Brazil	4.3	11.3	–
Larsen et al. (2009)—Denmark	3	–	–
Nguyen and Wilson (2010)—Canada	3.2	12.9	–
Møller and Christensen (2007)—Denmark	–	7.2	–
Paes et al. (2020)—Brazil	2.43	7.06	–
Gredmaier et al. (2013)—Germany/UK	–	10.9	4.1; 4.3
Min.; **Average**; Max	2.43; **3.38**; 4.3	7.06; **10.8;** 15.37	4.1; **4.25;** 4.4
Std. dev	σ = 0.67	σ = 2.96	σ = 0.10
Biomethane Collection (F_{eff} = 1.1375 + 10% = **1.25125** km L^{-1})			
Diesel Transport ($C_{w\,w}$ = L t^{-1})	0.06 [distance in km]	(Lima et al. 2018)	
Biomethane Transport ($C_{w\,w}$ = L t^{-1})	(0.06 + 10%) [distance in km]		

$C_{w\,w}$—Consumption per wet weight unit of collected MSW; F_{eff}—fuel efficiency, in distance traveled per unit of fuel

Table 5 Mean value of emission factors found in the literature

	CO_2	CO	NO_X	HC	PM
	E_{dst} (kg km^{-1}) $E_{w\,w}$ (kg kg$_w^{-1}$)	E_{dst} (kg km^{-1}) $E_{w\,w}$(kg kg$_w^{-1}$)	E_{dst} (kg km^{-1}) $E_{w\,w}$ (kg kg$_w^{-1}$)	E_{dst} (kg km^{-1}) $E_{w\,w}$ (kg kg$_w^{-1}$)	E_{dst} (kg km^{-1}) $E_{w\,w}$ (kg kg$_w^{-1}$)
Diesel—average ($\overline{E_{dst}}$)	*2.57*	*$1.03\cdot10^{-2}$*	*$2.15\cdot10^{-2}$*	*$1.32\cdot10^{-3}$*	*$9.60\cdot10^{-5}$*
Std. dev. (σ)	*0.17*	*$4.80\cdot10^{-3}$*	*$7.72\cdot10^{-3}$*	*$1.30\cdot10^{-3}$*	*$6.11\cdot10^{-5}$*
Source: Farzaneh et al. (2009); Fontaras et al. 2012); Sandhu et al. (2014)					
Commingled collection	$9.86\cdot10^{-3}$	$3.97\cdot10^{-5}$	$8.24\cdot10^{-5}$	$5.07\cdot10^{-6}$	$3.69\cdot10^{-7}$
Door-to-door (DtD) collection	$3.15\cdot10^{-2}$	$1.27\cdot10^{-4}$	$2.63\cdot10^{-4}$	$1.62\cdot10^{-5}$	$1.18\cdot10^{-6}$
Bring collection	$1.24\cdot10^{-2}$	$4.99\cdot10^{-5}$	$1.04\cdot10^{-4}$	$6.38\cdot10^{-6}$	$4.64\cdot10^{-7}$
Blend (70% DtD/30% bring)	$2.58\cdot10^{-2}$	$1.04\cdot10^{-4}$	$2.15\cdot10^{-4}$	$1.33\cdot10^{-5}$	$9.64\cdot10^{-7}$
Biomethane—average ($\overline{E_{dst}}$)	*2.69*	*$1.36\cdot10^{-2}$*	*$2.86\cdot10^{-3}$*	*$2.27\cdot10^{-3}$*	*$1.49\cdot10^{-5}$*
Std. dev. (σ)	*0.80*	*$5.29\cdot10^{-3}$*	*$1.93\cdot10^{-3}$*	*$9.48\cdot10^{-3}$*	*$7.72\cdot10^{-6}$*
Source: Alberici et al. (2003); Fontaras et al. (2012); Hesterberg et al. (2008); López et al. (2009); Sandhu et al. (2020); EEA (2009)					
Commingled biomethane collection	$1.14\cdot10^{-2}$	$5.76\cdot10^{-5}$	$1.21\cdot10^{-5}$	$9.58\cdot10^{-6}$	$6.28\cdot10^{-8}$
DtD biomethane collection	$3.63\cdot10^{-2}$	$1.84\cdot10^{-4}$	$3.86\cdot10^{-5}$	$3.06\cdot10^{-5}$	$2.01\cdot10^{-7}$
Bring biomethane collection	$1.43\cdot10^{-2}$	$7.24\cdot10^{-5}$	$1.59\cdot10^{-5}$	$1.21\cdot10^{-5}$	$7.90\cdot10^{-8}$
Comparison biomethane/diesel	*+ 11%*	*+ 32%*	*− 87%*	*+ 72%*	*− 83%*
Distance basis (Commingled MSW basis)	(+ 15%)	(+ 45%)	(− 85%)	(+ 89%)	(− 83%)

CO_2 carbon dioxide, *CO* carbon monoxide, *NO_X* nitrogen oxides, *HC* hydrocarbons, *PM* particulate matter;

$E_{w\,w}$ emissions per wet weight unit of MSW, E_{dst} emissions per unit of distance traveled

advantage of this method is the improved quality of recyclable materials, or a lower fraction of contaminants. Another plus is the comfort for the citizens, as they do not need to walk to a container to dispose of the waste, which reportedly results in twice the SSC than in drop-off collection (27 vs 13 kg inhabitant^{-1} year^{-1}), according to Dahlén and Lagerkvist (2010), but they have to commit to the specific waste truck schedule. A study conducted in Bari, Southern Italy, has revealed that the satisfaction level of the population with this mode is generally good (Laurieri et al. 2020) and

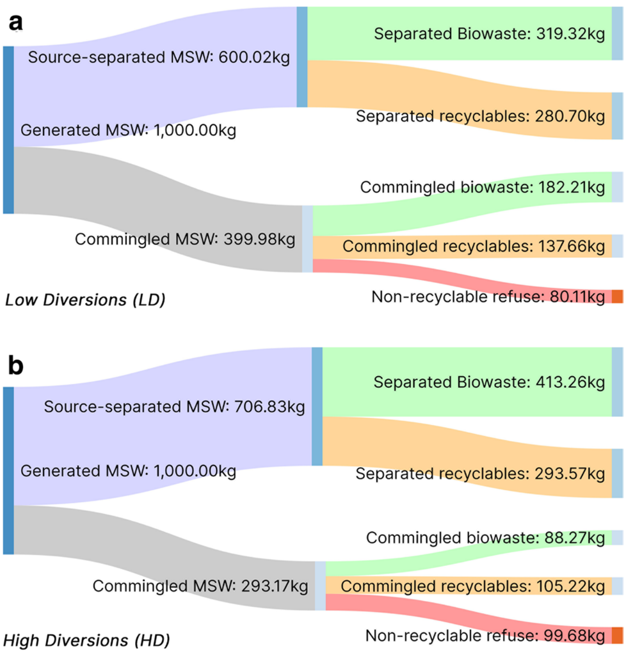

Fig. 3 Sankey diagrams of the proposed low (*LD*) and high diversions (*HD*) scenarios

from a sample of 150 citizens from Xanthi, Greece, 72.7% were keen on replacing the current collection system with DtD collection. (Tsalis et al. 2018). However, Calabrò and Satira (2020) affirm that this method requires educational programs in order to foster extensive public engagement.

In turn, drop-off or *Bring* systems (Rodrigues et al. 2016) require the citizens to collaborate and bring their waste to the street containers. According to Martinho et al. (2017), the collection truck takes less time to collect the waste (less stops and lower stopping time) and less workers are required, because they do not need to fetch the waste bags in every door. As for the downsides of this method: lower potential for source-separation (Laurieri et al. 2020); higher contamination of organic waste than in the DtD method, which invalidates the use of digestate from anaerobic digestion as a natural fertilizer (Gredmaier et al. 2013). The authors suggest this method when organic waste contamination is not a problem and householders are disciplined, as the fuel consumption is lower than DtD.

Lastly, *commingled*, mixed or undifferentiated waste collection, uses rear-loading 10t-trucks to carry waste to the TS (Lima et al. 2019). This waste can be either be collected from households or waste bins scattered in the streets. This method is the least fuel-consuming, but contamination can be a problem for waste treatments. Teixeira et al. (2014) report that commingled collection when compared to DtD collection. decreases the collection distance per ton of waste to 13%, approximately one fourth of the fuel consumption, one fifth of the cost and fourfold more crew productivity, which is measured in t h^{-1} $worker^{-1}$.

The main element that distinguishes the environmental impact of the different types of collection is the amount of fuel burned by the collection trucks (assuming that trucks are used to collect the waste). Various factors influence consumption figures, such as vehicle automation level, the skill of the crew (Jaunich et al. 2016) and waste density. Since the fuel consumption of the WCV of GVMR was not available, the consumption figures used on this study, in liters per ton of collected waste (L t^{-1}), were obtained from the average of values found in the literature, which are presented in Table 4. Note should be made that the extreme values for commingled collection, using diesel, are from two Brazilian studies. For DtD collection, the variance is higher, but the value from Paes et al. (2020) is, again a low extreme, while Lima et al. (2019) indicated an intermediate value, but higher than average. Although the values used are from different countries, even in different cities from the same country, the result may vary substantially, so when local data are unavailable, a sensitivity analysis is strongly advised.

Additionally, the mean consumption in km per liter of fuel (km L^{-1}) of diesel was estimated from the literature (Table 4), in order to calculate the emissions for both fuels, described in item 2.3.5. This value ranged between 0.85–1.3 km L^{-1} (Clark et al. 1998; Agar et al. 2007; Hesterberg et al. 2008; Thiruvengadam et al. 2010; Fontaras et al. 2012) and 1–1.4 km L^{-1} (Sandhu et al., 2014).

Biogas can be produced by anaerobic digestion of biowaste in biodigesters, landfill gas recovery systems, as well as wastewater treatment plants (IEA 2020). To be useable as a fuel in vehicles, biogas must be “upgraded,” since this gas is mainly constituted by methane (50–60%), hydrogen sulfide (H_2S), CO_2 and trace elements in variable proportions. This treatment nearly purifies biogas into biomethane, by removing H_2S, which is corrosive, liquid water and vapor and CO_2, using technologies like water scrubbing, adsorption and membrane separation (Awe et al. 2017; IEA 2020), making it equivalent to natural gas. Then, biomethane can be compressed or liquefied. Since its lower heating value is inferior than diesel’s, a 10% increase in consumption per km, was assumed, as Cong et al. (2017) and Jensen et al. (2017).

For the Baseline scenario, that also contemplates two more methods, *Commercial collection* was attributed the same value as the DtD collection value (10.8 L t^{-1}). This is because WCV pick the waste from the companies like in households. As for *Blend collection*, there is no information on how much DtD vs Bring collection. But, since the established method in GVMR is DtD, a weight proportion of 70/30 (DtD/Bring) was considered to calculate the unit consumption of blend collection—8.83 L t^{-1}. In any case, the uncertainty of this number only affects a fraction of the almost insignificant SSC rate (0.74%).

Regarding the transport of MSW accumulated in TS (in larger trucks, as described by the end of item 2.3.1), the calculations differ from collection, as the distance now is taken into account, as in Colvero et al. (2020a, b). Since this study focuses on the entire GVMR, the distances used to compute the consumptions/emissions were the average value of all transport distances to landfills (29.46 km—SM Table 6) and to waste pickers organizations (7.49 km—SM Table 7). For the transport with biomethane, a 10% increase in consumption was assumed, just as in the collection phase (Cong et al., 2017; Jensen et al., 2017).

Emission factors used in the model

Regarding the emission factors for each pollutant, the Ecoinvent database has a complete dataset for diesel WCV, but not for gas WCV. For this reason, these data were not used. Instead, the emission factors of carbon dioxide and monoxide (CO_2 and CO), nitrogen oxides (NO_X), hydrocarbons (HC) and particulate matter (PM) were obtained from Farzaneh et al. (2009), Fontaras et al. (2012) and Sandhu et al. (2014) for diesel, and from Alberici et al. (2003), Hesterberg et al. (2008), López et al. (2009), ASM et al. (2002), Fontaras et al. (2012), Sandhu et al. (2020) for natural gas/biomethane (SM Table 8), so the comparison would encompass the same categories of pollutants. Therefore, the average of the values collected from the literature per km traveled both for diesel and biomethane is presented in Table 5, in *italic*.

Regarding the unit emissions, it is worth mentioning that, although biomethane is believed to be a "clean fuel" and the PM/NO_X emissions are 9–10 times lower, heavy-duty diesel vehicles can still produce less CO_2, due to a better fuel consumption and substantially less CO and HC. About the type of HC, diesel engines emit non-methane volatile organic compounds, whereas of natural gas/biomethane engines, > 95% of exhaust HC is methane, according to Yoon et al. (2013).

For Collection, in order to convert the obtained values in km to wet weight basis, to be inputted in EASETECH, Eq. 1 was applied:

$$E_{ww} = F_{\text{eff}} \bullet C_{ww} \bullet E_{\text{dst}} \tag{1}$$

in which $E_{w\,w}$ is the emission of a pollutant per weight unit of collected MSW ($\text{kg}_{\text{emitted}}\ \text{kg}_{\text{waste}}{}^{-1}$), F_{eff} is the fuel efficiency, in distance traveled per unit of fuel (km L^{-1}), $C_{w\,w}$ is the consumption per weight unit of collected MSW (L $\text{kg}_{\text{waste}}{}^{-1}$) and E_{dst} is the emission of a pollutant per unit of distance traveled ($\text{kg}_{\text{emitted}}$ km^{-1}).

Since the consumption value per unit weight of collected waste ($C_{w\,w}$) is different for each collection type, so are the emissions ($E_{w\,w}$). So, these had to be calculated for all collection types, which are also presented in Table 5. With these values, the amount of emitted pollutants can be estimated, just by multiplying them by the amounts of collected waste.

For Transport, the process is similar, with the detail of $C_{w\,w}$ being a function of distance, in km (Table 4). SM Table 6 and SM Table 7 show the coordinates and distance values between TS-landfill and TS-WPO respectively, for each city. These steps, together with the MSW weight values from Items 2.3.2 and 2.3.3, have allowed to obtain the inventory of the emissions for each scenario, presented in SM Table 9.

Impact assessment (LCA phase 3)

The life cycle impact assessment method used was the International Reference Life Cycle Data System (ILCD) (EC-JRC 2010), with six impact categories: Climate change (*GWP100*), Particulate Matter smaller than 2.5 µm (*PM2.5*), Photochemical Ozone Formation (*POF*), Terrestrial Acidification (*TA*), Eutrophication Terrestrial (*ET*) and Eutrophication Marine (*EM*). These impact categories measure the impacts associated with the emission values obtained from the literature. The unit impacts per kg of emissions for this method are indicated in SM Tables 10 and 11 for diesel and biomethane, respectively. The ILCD-recommended normalization factors from SM Table 12 were used to convert the values in miliPerson Equivalents (mPE), therefore allowing for the comparison between impact categories.

Sensitivity analysis

There are various parameters with uncertainties due to the shortage of available primary data, which is a common problem in developing countries that hinders the possibility of carrying out reliable studies for these regions (Laurent et al. 2014). Therefore, according to (ISO 2006a, 2006b), a sensitivity analysis was performed (Pires et al. 2017; Pérez et al. 2017, 2020; Lima et al. 2018, 2019). These uncertainties refer, mostly, to estimated waste characterization and generation, unit emissions and fuel consumption and traveled distances. In order to account for the variation of secondary data, the LCA was repeated four times, using sets of the minimum and maximum values found on literature for each emitted substance (SM Table 8) and fuel consumption for each collection type (Table 4). As for transport, a ± 20% variation was set for the consumption figures in the second sensitivity analysis. For C&T with biomethane, the 10% decrease in fuel economy was left unchanged.

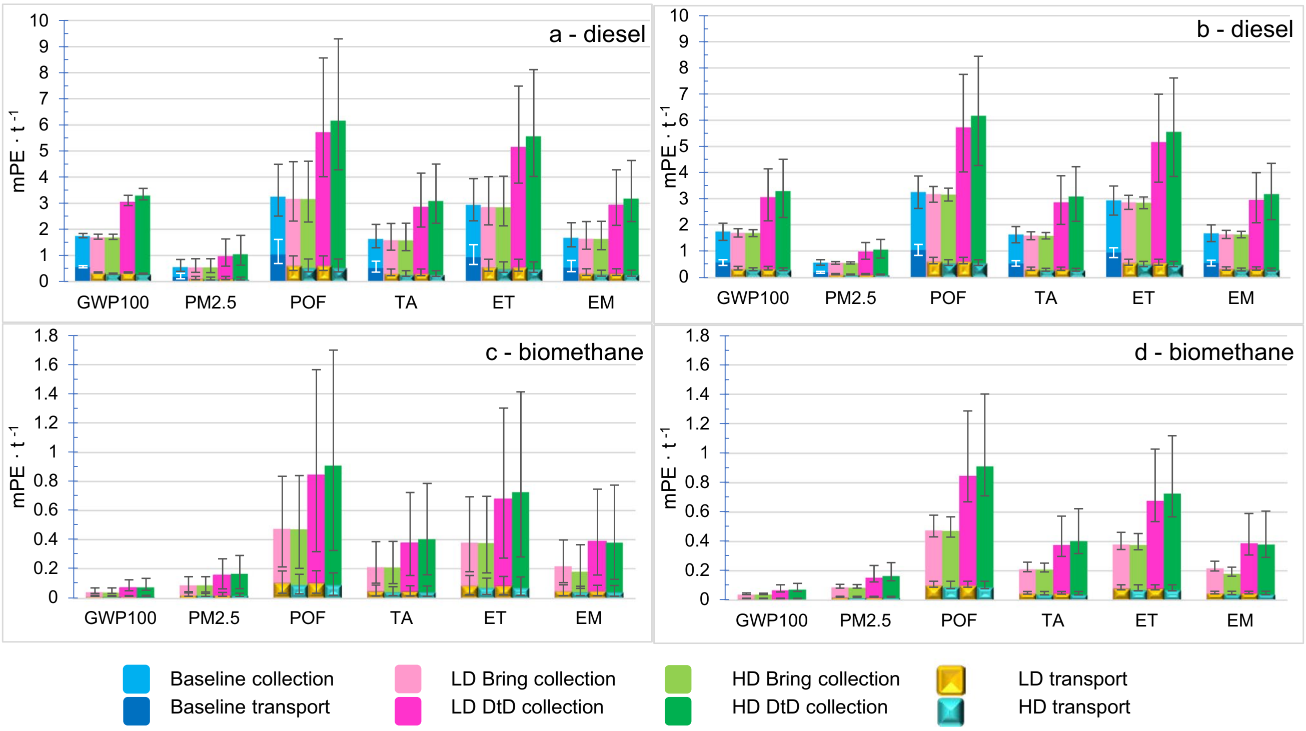

Fig. 4 Normalized results with the respective errors for collection/transport using diesel and biomethane. **a**, **c**: values and errors calculated using extreme *emission* values; **b**, **d**: values and errors calculated using extreme *fuel consumption* values. *GWP100* climate change, *PM2.5* particulate matter < 2.5 μm, *POF* photochemical ozone formation, *TA* terrestrial acidification, *ET* eutrophication terrestrial, *EM* eutrophication marine, *LD* low diversions, *HD* high diversions

Results and discussion

Interpretation (LCA phase 4)

Figure 4 shows the normalized LCA outputs, also available numerically in SM Table 13, for the Baseline scenario, and SM Table 14, for the proposed scenarios. Comparing the Baseline scenario with the proposed diesel scenarios, which expand SSC (from 1.57% to 60.0–70.6% of the total weight generated—Fig. 3) and collect 1.13% of uncollected waste, there are mainly two very different results. In the Bring scenarios a 3% decrease in total environmental impacts can be observed. This is because of the important savings in the Transport part, that compensated the increase of 15–18% in the Collection fraction. Contrarywise, in the DtD scenarios, the impacts increased by 76–90%, yet the absolute value is small, considering the values of studies that included the remaining management steps of 1 t of MSW, like treatment and disposal (Lima et al. 2018; Colvero et al. 2020a). Conversely, if only the DtD and Bring scenarios are compared, the impact of the latter is about half of DtD. This value is large, when compared to the results by Pérez et al. (2020), which have a differential around 10%, between these collection methods, which can be explained by the fact that the scenario with DtD collection for mixed waste and packaging, still uses containers for paper and glass, the different assumptions, study area, and broader scope, therefore it is hard to establish comparisons between both studies. On the other hand, Gilardino et al. (2017) have observed a 41% reduction of the impacts motivated by air pollution in Peru, for the same collection methods, corroborating our results.

Still on the Transport component, surprisingly, in this particular case, not only the proposed diesel scenarios performed better than the baseline scenario (0) by 39–47%, but scenarios 5 and 7, with high diversions have performed better than the other two (1 and 3) with lower diversions. This detail can be explained by the smaller transport distance from the TS to the sorting facilities (7.5 km—SM Table 6) versus the average distance to the landfills (29.5 km—SM Table 7) in this metropolitan area, which directly influences fuel consumption (Table 4). So, minimizing the distance between waste management facilities is crucial on fuel consumption, that influences environmental, economic and operational performance (Teixeira et al. 2014). But choosing these locations requires observing the Brazilian laws and regulations that permit or restrict construction areas for these facilities, based on multiple criteria (Colvero et al. 2018). Furthermore, the Transport is lower than Collection in all scenarios, as the Transport consumption is much smaller than Collection, in GVMR. This fact shows the importance of using TS to transport waste in larger vehicles, which is not currently done by Fundão and Viana.

As for the alternative biomethane scenarios, they performed much better in all impact categories, especially in the *Climate change (GWP100)*, which is 96% less than the Baseline scenario. For the remaining biomethane scenarios, the impacts decreased in 75–77% in the *TA, ET* and *EM* categories, 72–74% for *POF*, and 70–72% for *PM2.5,* compared to the Baseline scenario. Like in the diesel scenarios, for the Bring scenarios, the *HD* scenario also had a total impact slightly inferior to the *LD* scenario in all impact categories. Again, the decrease of transport impacts, explained above, was higher than the increase in the collection impacts, due to the increase in SSC, in which the facilities are closer than landfills.

As for which impacts are higher in relative terms, compared to the total impact of each scenario, for both fuels, the major difference is in *GWP100 (*15%—diesel vs 3%—biomethane*)*, which is a concern for diesel. Oppositely, *POF* is proportionally higher for biomethane (27% vs 34%). For the remaining categories, the percentages are similar (differences of 1–2%). In respect to the emissions that motivate those impacts, analyzing Table 5, allows to infer that for the same collection type, diesel WCV emit less CO_2 (-13%) and CO (-31%), which is partly motivated by a 10% better fuel economy, but also the incomplete combustion of gas (Paolini et al. 2018).

Additionally, biomethane vehicles produce about 85% less NO_X and PM. As for HC, it can be a concern for CNG WCV, due to the fugitive methane leaks through the crankcase, tank venting and boil-off emissions, that can be mitigated (Clark et al. 2017). According to Cong et al. (2017), between 57–62% of the methane emissions by biomethane vehicles are due to engine losses and fuel station losses. Cooper et al. (2019) confirms that the supply chain and fuel station methane emissions, which were not accounted in this study, are less impactful than tailpipe emissions. Nevertheless, methane has a GWP over 100 years that is 28 times higher than CO_2, according to the Intergovernmental Panel on Climate Change (IPCC 2014); therefore emissions must be kept under 7.8–9 g km^{-1} to guarantee a lower *GWP100* than diesel (Cooper et al. 2019). Nevertheless, *GWP100* is 15 times higher in diesel scenarios. This is because the CO_2 emitted by diesel WCV is from a fossil source, whereas the CO_2 from biomethane is considered non-fossil, so the impact is null, even though the amount of CO_2 each produce is roughly the same. This is noteworthy, as the CO_2 emissions are in the order of magnitude of kg, whereas the emissions of hydrocarbons are 10 to 100 times lower.

Two indicators especially concern to air quality: for *PM2.5*, the main contributors are PM, CO and NO_X, while *POF* is affected by HC instead of PM. Firstly, biomethane performs much better than diesel in respect to PM, which affects *PM2.5* the most. Secondly, although diesel engines produce 21% less CO than biomethane, which is in line with the study by Cooper et al. (2019) on natural gas trucks, this pollutant contributes little to the results: its impact is 10 times lower than NO_X, where biomethane also greatly surpasses diesel (− 87%). Regarding *POF*, even though hydrocarbons are much higher on biomethane WCV, again, the type of HC makes the difference. In this case, on the opposite side: methane has 100 times less impact on O_3 formation (which causes problems to the human health, at urban level) than the non-methane volatile organic compounds that diesels produce, according to the unit impacts from the European Commission's Joint Research Centre (EC-JRC 2010).

Expanding SSC in order to divert waste from landfills, via recycling and proper biowaste treatment, is not only a way to properly manage MSW to decrease environmental damage, but also a target to be attained. However, to achieve these diversions, collecting and transporting MSW also has an environmental cost, even if it is undoubtably less than not collecting or landfilling (Coelho and Lange 2018; Lima et al. 2018, 2019). That said, when using diesel, the best theoretical scenario (*5. Diesel HD DtD*), i.e., that potentializes diversions the most, was also the worst, indicator-wise. However, the alternative of using biomethane can annulate this disadvantage for the environment, since its use can reduce to approximately 1/4 the impact in the worst case (when the mean diesel result is compared with the maximum result in the *6. Biomethane HD DtD* scenario). Even though the impact of extraction, transport and distribution of these fuels was not taken into account, the results undoubtably point to the recommendation of using biomethane produced from biowaste and other organic matter by anaerobic digestion and, of course, to keep up with the once exigent PLANARES diversion targets.

In respect to the use of DtD vs Bring collection, the high level of diversions requires the collaboration of the citizens to separate their waste at the source. In the study by Di Maria and Micale (2013), the highest SSC rate scenario, with 52%, requires DtD collection. Nevertheless, for the area they analyzed, an intermediate solution is suggested for economical and operational reasons: using both DtD collection for heavier waste, like glass, and Bring collection for light packaging and metals. On the contrary, for small towns with less than 5000 inhabitants Gallardo et al. (2012) concluded that the preferable collection scheme is to use Bring collection for glass and DtD for the remaining fractions. And for populations of more than 50,000, the same authors obtained the best results with collecting commingled and biowaste DtD, and lightweight packaging and glass in drop-off containers. So, this choice should be made according to the municipality, since the population, density and waste characterization vary drastically. And, the municipalities that sent their waste to a landfill, situated more than 25 km away from the waste generating center, should establish TS, as the lack of them and the use of smaller sized trucks causes higher global warming factors (Yaman et al. 2019).

Finally, regarding waste administration, there are very important considerations to make in light of circular economy. Even though this study limits to an environmental analysis of theoretical scenarios, in reality, the achievement of these targets, i.e., getting the population to separate their waste at the source, is highly dependent on policies to foster easy sustainable consumption, easy waste sorting and economic incentives for those who recycle (Takahashi 2020). In Sweden, with economic rationalism, the responsibility for collection and recycling is attributed to producers, while municipalities are in charge of planning and granting information (Takahashi 2020). For the consumers, this means that the waste management costs, like collection and recycling is embedded in price of the products when purchase and, in case of beverage containers, they are reimbursed for their return, at a reported return rate of 80%, according to the Swedish Environmental Protection Agency (2005). Conversely, Japan uses administrative rationalism, the traditional approach that uses general taxes to manage waste, with the responsibility attributed to the consumers instead of the producers and economic arrangements distinct from the Swedish. (Takahashi 2020) Therefore, for the success of waste collection in GVMR and other areas similar with a waste management paradigms, it is strongly recommended that they switch from a low cost, primitive collection model focused on administrative rationalism, a systematized model aimed at economic rationalism, easiness for the customer, perceiving recycling as profit, without disregarding the local reality.

Sensitivity analysis

The result of the sensitivity analysis is shown, together with the results, in Fig. 4. The numerical values are presented in SM Tables 15 and 16, reflecting the changes in unit emissions and consumptions. The deviations can be significantly high, more than 100% in some situations, when the maximum and minimum values for consumptions (Table 4) and emissions (SM Table 8) are applied, in particular for the scenarios with DtD collection and certain impact categories. A direct proportionality relation is verified between the magnitude of the absolute values of deviation and the actual impact values. As the consumptions in the DtD scenarios vary between 7.06 and 15.37 L t^{-1}, more than doubling the smallest value found on literature, not only their impacts are the greatest, but the same is also true for the deviation values.

Moreover, the impact category *POF* has the highest deviations, for both diesel and biomethane, as it is mostly affected by hydrocarbons, which have a high relative variation (-84%, + 139% for diesel and -44%, + 69% for biomethane—SM Table 8). *ET* is second on deviations, which in this case is affected by NO_X. Although NOx does not vary as much as hydrocarbons in diesel, it is one order of magnitude larger and has its unit impact multiplied by 4.26, the highest unit impact. As for EM and TA, the deviations are similar (differential between both < 0.03 mPE t^{-1}—SM Table 15), as both are affected by NO_X. In *GWP100*, the lower result in the Baseline scenario (4.5 mPE t^{-1}) in the emissions sensibility analysis (Fig. 4 b) is roughly 1/3 of the highest in DtD HD scenario (1.5 mPE t^{-1}), which is comparable to Teixeira et al. (2014), from Portugal.

So, the sensitivity analysis reveals that there are uncertainties from varying both the *emissions* and *consumption* values. This is a telltale that both these parameters require more attention in order to collect regional data and produce more reasonable studies. Specific factors like the type of WCV, geography and traffic of the city and building density (Gentil et al. 2010), vehicle's capacity use, MSW density, and driver's behavior can impact the fuel consumption significantly (Yaman et al. 2019). As for emissions, there are regional and technical particularities that affect these figures, such as fuel characteristics, used engine technology and maintenance. Due to the aging source of some data, it is possible that the evolution of technology may not be reflected accurately. Another uncertainty source in this study is waste generation and characterization, which is an estimate that crosses data from more than one source. Therefore, values found in the bibliography and databases may or may not reflect accurately the conditions of the studied region. Despite of those significant uncertainties and the exclusion of well-to-tank impacts, this did not change the recommendations and conclusions.

Conclusions

This study focused exclusively on MSW C&T strategies for a mid-sized metropolitan area in a developing country, using a metropolitan area in Southwest Brazil as a subject. So, an LCA that compared a combination of two fuels, diesel vs biomethane, two levels of SSC, high vs low and two types of collection, Bring vs DtD, to the current scenario was performed.

The results, with diesel, have shown that collecting all the waste and increasing the SSC rate from 1.57% to 60–71%, in order to reach the waste diversion targets from landfills will increase the environmental impacts by 76–90%, if the collection is performed DtD, but with Bring collection, the impacts decreased by 3%. However, if biomethane vehicles are used, the impact is always inferior in relation to the diesel scenarios, decreasing by 70–96%, even when taking the uncertainty of the results into account. Specifically, in this case-study, the average transport distance to the sorting facilities (7.5 km) is lower than to the landfills (29.5 km), thus the scenarios with more SSC also diminished the transport impacts by 39–47%, partially compensating the increase in collection with diesel. This highlights the importance of selecting well the location of the waste management facilities to improve the performance of the system as a whole.

In light of the results, the use of biomethane is recommended to decrease the environmental impact of the C&T phase. Additionally, the increased impacts of SSC should not get in the way of expanding it to divert waste from landfills, so the governments and public managers should not be uncertain to aim for *HD* scenarios, environmentally speaking. As for the collection type DtD, it has the most potential to obtain uncontaminated sorted materials, but Bring can be used in conjunction with DtD for lower density materials, like light packaging or metals.

The development of this paper demonstrated the necessity of carrying out more studies to collect more regional data, especially in developing countries, on waste characterization, fuel consumption for C&T and emissions for biomethane vehicles, in order to enhance LCA databases and improve the precision of further researches. Also, in this paper, only the fuel use was considered (tank-to-wheel LCA). Even though biomethane can and should be produced by anaerobic digestion of organic waste, these impacts (well-to-tank LCA) were not compared with the diesel production. Also, the vehicle and waste bin life cycle could also be accounted in future researches. Additionally, changing from a waste collection system based on precepts of administrative rationalism to a paradigm of economic rationalism that agrees with the local reality, culture, society, climate and economy to encourage the collaboration of citizens to participate on waste management is crucial. This reveals a research gap, that is also an opportunity for future studies in developing countries.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13762-021-03837-7.

Acknowledgements This study was partly financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (College and Graduate Education Improvement Coordination), Brazil (CAPES), Finance Code 001. The authors also acknowledge the financial support given by Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (Espírito Santo Research and Innovation Support Foundation—FAPES) project 107/2019.

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