Habitat International 143 (2024) 102990

Contents lists available at ScienceDirect

Habitat International

journal homepage: www.elsevier.com/locate/habitatint

Waste management intervention to boost circular economy and mitigate climate change in cities of developing countries: The case of Brazil

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ARTICLE INFO

Keywords:
Low carbon economy
Circular economy
Sustainable development goals
Environmental education
Innovation
Local capacity

ABSTRACT

Innovations in Municipal Solid Waste Management (MSWM) can better connect circular economy (CE) and climate change (CC) since they have many trade-offs, especially in developing countries. Studies report the main barriers to innovation in MSWM that constrain a more circular economy (CE) and climate responses, but little is known about possible paths for innovation. Thus, this article aims to identify the main enablers of innovations in MSWM. Four municipalities in Brazil were selected because they presented highly innovative actions in the MSWM that reduced trade-offs between CE and CC. Based on an analysis of the economic, environmental, and operational performance of the four MSWM, we found reductions in Greenhouse Gases (GHG - CO_2eq per inhabitant) of up to 90% and lower waste management costs per inhabitant compared to the national average. Four main enablers made the innovations possible to accelerate the transitions to a more circular and low-carbon economy in municipalities: local capacity, intergovernmental collaboration, MSWM with local partners, and environmental education that promotes social participation. This research contributed to developing a method to identify enablers at various system levels and propose technological approaches and practices that enable innovation in MSW management. Such measures can serve as a subsidy for circular disruption and as a basis for intervention in MSWM, especially in developing countries.

1. Introduction

While some studies identify factors that influence the performance of Municipal Solid Waste (MSW) management, measures linked to the circular economy (such as prevention, home composting, reuse, and recycling) may compete with waste treatment technologies. Nevertheless, some technologies (such as waste-to-energy or the use of methane for energy generation from landfills and anaerobic digestion that require large amounts of organic waste) can also mitigate Greenhouse Gas (GHG) emissions (Paes, Medeiros, Mancini, Bortoleto, et al., 2020). Thus, this research aims to identify the enabling factors that can boost innovations in MSW management (MSWM) to improve both the circularity of the economy and GHG mitigation.

Despite the advances of previous research, several research questions remain unexplored in this context: (i) How can environmental education and social mobilization processes leverage good MSW management results? (Chen, Chen, Hou, & Li, 2022; Geng, Sarkis, & Bleischwitz, 2019; Sharma et al., 2020); (ii) how organic waste can be recovered and generate economic and environmental benefits for municipal administrations? (Paes, Medeiros, Mancini, Ribeiro, & Puppim De Oliveira, 2019, 2020a; Sharma et al., 2020; Yuan et al., 2021); (iii) what are the main enablers, governance systems, and partnerships that can break down barriers to innovation? (Durán-Romero et al., 2020; Wang et al., 2021); (iv) what are the possible paths for innovation in MSW Management Systems (MSWMS) in developing countries based on the principles of the circular and low-carbon economy? These paths can

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https://doi.org/10.1016/j.habitatint.2023.102990
Received 14 November 2022; Received in revised form 7 December 2023; Accepted 10 December 2023
Available online 21 December 2023

contribute to a new model of robust local supply chains that help mitigate the effects of possible future pandemics and climate change (Durán-Romero et al., 2020; Hantoko et al., 2021, Okere, Ofodum, Azorji, & Nwosu, 2019; Sharma et al., 2020) and also contribute to the United Nations Sustainable Development Goals (SDG) (Iyamu, Anda, & Ho, 2022).

This study also aims to contribute to the recent debate on circular disruption (Kirchherr, Bauwens, & Ramos, 2023), trying to respond to the following questions still little explored by scholars: i) Who are the main combination of actors driving circular disruption? ii) What are the main barriers, policies and enablers needed to drive circular disruption and pave the way for the future? (Kirchherr et al., 2023).

Thus, the current study fills these research gaps and contributes to advancing knowledge in innovation and capacity building in local governance (municipal level) in the management of MSW, circular economy, and climate change, particularly in developing countries.

Brazil is an interesting country to study those gaps empirically. More than a decade has passed since enacting the National Solid Waste Policy - NSWP (Brasil, 2010). However, limited progress has been made in addressing key issues in waste management. The country still sends approximately 25% of its MSW to inappropriate locations (such as open dumps), and only 2.2% of waste is sorted and recycled (SNIS - Sistema Nacional de Informações em Saneamento Básico, 2019). Therefore, even with such an important legal landmark, there is a deficit in its implementation, as basic issues have not yet been resolved, such as the closure of inadequate disposal sites. Thus, boosting innovations in MSWMS could help the country fully implement the NSWP, and, therefore, more economic circularity together with mitigation of GHG emissions.

This research makes several contributions to the literature and practice. First, it identifies the enablers of good implementation of the MSWM. Some studies highlight the low levels of local technical capacity, lack of environmental awareness in the general population, and lack of participation at various levels of government as barriers to innovation (i.e. Alfaia, de S, Costa, & Campos, 2017; Campos, 2014; Oyake-Ombis, Vliet, & Mol, 2015). However, some cities and regions have managed to overcome barriers, have made advances in good management practices, and show high recovery rates and/or even implement important innovation MSW initiatives, reconciling actions that promote the circular economy and mitigate climate change.

Second, the study points to potential paths to innovation in MSWM, even in places with limited resources, such as developing countries. Cities with less financial resources and different MSWM modalities (public and private systems and mixed systems and in partnership with waste picker associations) can create capacity and innovate to face MSWM challenges. Some necessary paths involve good local governance, development of intersectoral local policies to MSWM (such as education, environment, public services, administration, and agriculture), support from different government levels (such as the States and Federal Government), intense environmental education, and strong participation social.

Finally, this research contributes to the development of a framework to identify enablers at various levels of the system and propose technological interventions and practices that enable innovation in MSW management. Such measures can serve as a subsidy for circular disruption and as a basis for intervention in MSWM, especially in developing countries.

Thus, this work (1) evaluates the economic, environmental, operational, and institutional aspects of MSWMS to assess the results of its implementation; 2) analyzes the main factors (system-level enablers) that contribute to innovation and the transition to sustainability in municipal public policies for linking climate change and circular economy through MSW management and; (3) proposes actions and paths for intervention in the MSW management to pave the way to circular disruption in developing countries, with a review of current models (considered inefficient and linear) of generation of MSW, transport, and disposal, towards a new and more efficient model based on the circular economy and low carbon emissions. The current study also highlights the potential of carbon credits for supporting innovation in MSW Management.

2. MSW management for aligning circular economy and climate change

Section 2.1 present the main concepts and links between MSW management, Circular Economy, and Climate Change and their existing trade-offs. Item 2.2 discusses the main challenges for institutional innovation in a local capacity and presents some of the potential enablers for implementing innovation actions in the management of MSW.

2.1. MSW, circular economy and climate change: possible paths

While some policies aim to improve traditional waste management frameworks, others seek to completely reformulate them by implementing decentralized management, prevention, and circular economy (CE) actions (Cleary, 2014; Paes et al., 2019; Wilson & Velis, 2015). Since it was originally proposed, the CE has been presented as restorative and regenerative. Its planning and design aims to ensure products, components, and materials that retain the most significant possible usefulness and value throughout their life cycles, distinguishing between technical and biological cycles (Niero & Kalbar, 2018).

In this context, cities aiming for circular economies integrate all possible flows of matter and energy and consider waste a collection of useful materials for other sectors. Examples of this are the reuse of sludge from sewage treatment plants for energy co-generation (through biodigestion), home-based generation of solar energy, reuse of greywater and rainwater, and the treatment of organic waste to produce compost (for production of food or landscape plants). In addition, the recovery of dry materials through recycling and reuse of products or the reduction in the amount of waste generated or even non-generation (Campbell-Johnston, Cate, Elfering-Petrovic, & Gupta, 2019; Prendeville, Cherim, & Bocken, 2018).

In some regions and cities of the European Union (notably regions of Germany, Austria, Belgium, Denmark, Netherlands, and Sweden), effective implementation of MSW management practices has resulted in close to 90% waste recovery rates. It happened through the combination of actions of reuse, recycling, composting, and waste treatment with energy use (through waste-to-energy systems and/or mechanical biological treatment) (Eurostat, 2019; Kaza et al., 2018).

In such locations, prevention practices have also been implemented through, for example, reuse actions, home composting, and non-generation of packaging (Cleary, 2014; Geng et al., 2019). These initiatives reduce the volume of waste entering a given management system (commonly formed by the stages and activities of collection, transport, sorting, treatment, and final disposal) (Nessi, Rigamonti, & Grosso, 2013; Paes, Medeiros, Mancini, Bortoleto, et al., 2020).

Unlike the vision and speed displayed by some corporations, companies, and governments, other countries, states, and municipalities have made little progress in the effective implementation of public policies that generate social and environmental benefits and/or reduce the impacts of climate change, such as MSW management (Iyamu, Anda, & Ho, 2020).

As an example, in countries like Brazil, Russia, India, China, and South Africa (BRICS), percentages close to 98%, 95%, 93%, 63%, and 100%, respectively, of the waste generated is sent for disposal on the ground (either unsupervised dumps or legal landfills) (Paes, Medeiros, Mancini, Gasol, et al., 2020). According to Schröder, Albaladejo, Ribas, MacEwen, and Tilkanen (2020), in Latin America and the Caribbean, practically all countries depend on landfills or dispose of their waste inadequately, such as open dumps. The authors emphasize that more than 35,000 tons of waste in this region are left uncollected daily, impacting more than 40 million people (about 7% of the population).

Four of the BRICS countries (China, Brazil, India, and Russia) are

among the five largest emitters of greenhouse gases, corresponding to 40% of global emissions (Cai et al., 2020). If a business-*as*-usual scenario was followed, dumpsites would generate 8–10 per cent of anthropogenic greenhouse gas (GHG) emissions by 2025 (United Nations, 2022).

For Brazil, specifically, this value reaches 6.8% (81.75 million t. CO2 eq) when considering direct emissions (from waste treatment and disposal facilities), indirect emissions (electricity and diesel consumption), and avoided emissions (recovery and recycling of waste). Whether improvement actions will be adopted, such as management practices and technologies that integrate composting, recycling, and landfill, MSWMS emissions in Brazil could be reduced by between 6% and 70% (which would correspond to between 4.9 and 57.2 million t. CO2 eq). Furthermore, if technologies were implemented to permit MSW use for energy generation (such as mechanical biological treatment and waste-to-energy systems), emissions could be reduced by up to 90%. In that case, it could generate annual economic benefits (through carbon credits) of US$ 44 to $687 million (Paes, Medeiros, Mancini, Gasol, et al., 2020).

Still considering the potential economic benefits, if specific targets of Brazil's National Solid Waste Plan (*PLNRS,* in its Portuguese acronym) were implemented and some of the MSW were diverted from the conventional public systems of collection, transport, and landfill-based disposal (through preventative actions and circular economy initiatives), Brazilian municipalities could obtain benefits (through savings in municipal public resources), that could vary between 10% and 40% (Paes et al., 2019). Examples of these initiatives would be the residential and/or community composting of organic waste and repairing, reusing, and recycling dry waste.

Therefore, while some regions (developed countries) have already evolved CE-appropriate MSW management procedures and plans, others (i.e. mainly in developing countries) still have to develop an effective and universal MSW collection and proper disposal. Usually, developing countries have low recovery rates, and the informal sector operates the separation and sale of recyclable materials (Do Carmo & Puppim de Oliveira, 2010; Wilson & Velis, 2015). Thus, a mechanism for intervention and financing for improving actions in these locations must be studied and implemented.

However, even with encouraging results in saving public resources and reducing GHG emissions, these mechanisms often represent different and conflicting ideas. For example, energy-use technologies that require large amounts of waste with high calorific value (such as paper and plastics) can compete with key notions of the circular economy (such as reduction, reuse, and recycling). The need to send waste to landfills and anaerobic digestion to maintain methane power plants can compete with decentralized composting initiatives. Reverse logistics actions can also emit considerable GHG from the transport stages (Paes, Medeiros, Mancini, Bortoleto, et al., 2020). Thus, in addition to understanding the possible paths for MSW management, it is important to adopt measures that have synergy within the circular economy and climate change.

2.2. Challenges for innovation in MSW management

Corvellec, Campos, and Zapata (2013) have highlighted the importance of having flexible MSWMSs that allow for changes. In the case of some urban infrastructures (such as incineration in Gothenburg, Sweden), the transition to sustainability may be difficult for the practical application of norms and trends, such as the hierarchy of MSW management (prevention, reuse, and recycling). This rigidity can occur, for example, due to the need to keep a plant's energy generation capacity, making it difficult to implement activities associated with reduction, reuse, repair, and recycling (Corvellec et al., 2013).

In the case of Gothenburg, innovation was facilitated by laws, political changes, and economic incentives (Corvellec et al., 2013). In the United Kingdom, between 2000 and 2011, Manchester went through a process of MSWMS improvement and transition that involved: i) involvement of the entire community in discussions, ii) production of "umbrella" contracts (which cover a large number of services and have long contractual duration, thus enabling greater commitment and investment by companies in MSW recovery), iii) Harmony between public and private interests and; iv) compliance with European legislation (Uyarra & Gee, 2013).

Oluleye, Chan, and Olawumi (2022) carried out an analysis of barriers to the circular economy in the management of building construction and demolition waste (BCDW), based on 38 articles from 23 countries and identified the following aspects as important to be overcome: institutional and regulatory barriers; technology and information; organization and behavior; infrastructural and process; economic and market; and the structure of the circular economy.

Also, on BCDW, another study that analyzed 55 documents from 21 countries, identified the following barriers: social and cultural; political and legislative; financial and economical; technological; and system-level reorientation of CE implementation. Moreover, to overcome these barriers, the following enablers are suggested: holistic CE framework; technology and innovation; policy, education, and awareness; financing and market creation; an integrative framework for practical implementation (Ababio & Lu, 2023).

Therefore, methods and studies have been developed to contribute to innovation and a transition toward a circular and low-carbon economy. Considering the challenges imposed by this transition, the various levels of influence to which public policies are exposed can be especially confronting. In addition, there are difficulties in recognizing the enablers and paths to innovation (Geels, 2002, 2012; Geels & Schot, 2007; Guerrero, Maas, & Hogland, 2013; Puppim de Oliveira, 2009, 2017).

Notably, local governments are ahead of national governments in terms of environmental policies (Bedsworth & Hanak, 2013). Many directly implement policies on housing, energy, local transport, land use, sanitation, and waste management (Sullivan, Gouldson, & Webber, 2012). This fact highlights the fundamental role of cities and local governments in establishing and enacting policies that reflect social and environmental benefits (such as actions to combat climate change) (Puppim de Oliveira, 2019). In addition, national governments are significantly influenced by decisions taken at the local level via social participation in cities (Roppongi, Suwa, & Puppim de Oliveira, 2016).

In this context, it is important to realize that the institutional aspect of policy implementation and how this translates to action has been generally simplified, so it should be studied in greater depth, especially since most municipalities are responsible for managing waste. Their biggest challenges lie in financing, political and social articulation, and local technical capacity (Puppim de Oliveira, 2013, 2017, 2019). In addition, most countries already have laws regulating waste management (although these are often not complied with). There are often opportunities for cooperation and financial support between different levels of government, civil society, companies, and international organizations that can lead to implementing projects, such as the Clean Development Mechanism (CDM) (Puppim de Oliveira, 2013, 2017, 2019).

In places where advances in environmental public policies and MSW management have occurred, such events can be mainly attributed to innovations in institutional practices directly related to implementing actions. These have included: the identification and strengthening of leaders; awareness campaigns; training of those involved, management and monitoring information; strengthening relations between municipal; state, and national governments; stakeholders' participation in planning processes, and monitoring the implementation of policies and results by society (i.e. Roppongi et al., 2016; Puppim de Oliveira, 2017).

Therefore, the main drivers and enablers must be identified, evaluated, and potentialized for institutional innovation measures to be practically and effectively implemented based on the concepts and pillars of sustainability (i.e. United Nations, 2020).

3. Methods

Even with immense challenges in Brazil, several examples of good practices for MSW management have been identified, most notably those developed by 4 selected cities and shown in Table 1 (see also Supplementary Material, Appendix 1, and Appendix 2 for more details on the data and practices of MSWM in the 4 municipalities). Such good practices can be replicated, with necessary adaptations, in other countries and regions with similar characteristics aiming to transition from their current MSWMSs to new systems based on CE principles and GHG emissions reduction.

Region: Region of Brazil (S, South; SE, Southeast; N, North); Inhabitants: number of inhabitants according to Brazilian census for the year 2019; Density Pop.: population density; Temp.: mean annual temperature; Area: area of the municipality; Biome: Brazilian Biomes (AM, Amazon; AF: Atlantic Forest): Average Salary: Average wage of formal workers (2017 values); per capita GDP: gross domestic product per capita (2017 values); Total Revenue: Total money raised by the municipality through taxes and transfers from State and Federal governments (2017 values); Expenditure on MSW: proportion spent on MSW management out of the total collected by the municipality; Profile: profile of the municipality's activities (I: industrial, C: Commerce, S: Services, A: Agriculture, E: Extractivism); HDI-M: municipal human development index (2017 values) (Numerically, the HDI ranges from 0 to 1, and the higher the number, the greater the human development measured in a given location); Sewage: Houses connected to the city's sewer system (2010 values); Urban roads: public roads with adequate urbanization (drainage, paving) (2010 values. (1) IBGE – Instituto Brasileiro de Geografia e Estatísticas (2019); (2) INMET – Instituto Nacional de Meteorologia (2018); (3) SNIS - Sistema Nacional de Informações em Saneamento Básico (2019).

The current study involved fieldwork, literature review, analysis of available national databases, and economic, environmental, and institutional-policy assessments of the MSWMS (as shown in Fig. 1).

3.1. Selection of fieldwork locations

After defining the concepts and research gaps, the study searched two national databases to find MSW management good practices that could generate climate-change-positive results at the country level. For this, public data from the Federal government was used, though: 1) the National Information System on Basic Sanitation (SNIS: *Sistema Nacional de Informações em Saneamento Básico),* which contains data on MSW management systems of Brazilian municipalities, and 2) National Association of Municipal Environmental Organizations (Anamma: *Associação Nacional de Órgãos Municipais de Meio Ambiente*), which contains information on the main political and institutional aspects (such as environmental structures and laws) of the municipalities throughout the country.

The initial selection criterion within the studied municipalities was for locations with MSW recovery rates above 20% - the national waste plan targets for 2028 (Brasil, 2022).

Additional criteria were defined for location selection to increase the case study representativeness, viz contributing to sample variation in.

1) Geographical distribution, land use type, and inhabitant number;
2) MSW management modalities (direct public administration, autarchies, private companies, cooperatives, associations, mixed systems, or other types of partnerships) - for more information about the MSWMS in the 4 cities (see Appendices 1 and 2 - Supplementary Material);
3) Dominant economic activity of cities (agricultural, industrial, services, commerce, forestry, and agro-extractivism).

Based on these filters, we selected.

- two municipalities that showed high rates of MSW recovery Harmonia (in the state of Rio Grande do Sul) and Ibertioga (in the state of Minas Gerais), Fig. 2.
- a metropolis with more than 12 million inhabitants (São Paulo) due to the size and diversity of existing initiatives, and;
- Carauari, located in the state of Amazonas and in the center of the biome (the Amazonian forest occupies 60% of the national territory). It was also possible to study the management of forest and agro-extractivist community waste, where a circularity of residues is required due to the physical isolation of the city.

As an indication of Brazil's demographic distribution, it is worth noting that 15% of its population lives in cities with fewer than 20,000 inhabitants. However, these municipalities represent 68.4% (3808) of the 5570 existing in the country. Thus, about 70% of Brazil's population lives in cities with more than 50,000 inhabitants, representing 12% (649) of the municipalities. On the other hand, 22% of the population lives in 17 cities (0.3%) with more than 1 million inhabitants (IBGE – Instituto Brasileiro de Geografia e Estatísticas, 2019).

Accordingly, the current study's design allowed it to be representative in sampling and broad in application, given the current national geographic, population, socioeconomic, and environmental status and the varying MSW management systems considered (see Table 1).

In 2019, once study locations had been defined, the fieldwork was carried out in the 4 chosen municipalities, using semi-structured interviews, surveys of information in official documents and publications,

Table 1
Geographical, socioeconomic, and environmental indicators of the selected municipalities.

Aspects	Indicator	Unit	Harmonia	São Paulo	Ibertioga	Carauari	Brazil
Geographics	Latitude	–	29°32′52″S	23°33′01″S	21°25′48″S	4°52′58″S	–
	Longitude	–	51°25′33″W	46°38′02″W	43°57′46″W	66°53′45″O	–
	Altitude	m	126	760	1045	87	–
	Region	–	S	SE	SE	N	–
Population	Population (1)	Inhabitants	4866	12,252,023	5021	28,294	190,732,194
	Pop. Dens. (1)	Inhab/km^2	101.0	8055.2	14.5	1.1	22.4
Environment	Temperature (2)	°C	19.4	20.1	19.1	26.2	–
	Precipitation (2)	Mm/yr.	1454	1616	1512	2587	–
	Area (km^2) (1)	km^2	48.2	1521.00	346.24	25,778.66	8,515,759
	Biome (1)		AF	AF	AF	AM	–
	Sewage ((1)	%	42.1	92.6	70.7	23.9	80.6
	Urban roads (1)	%	20.0	50.3	7.4	11.0	–
Economy	Mean Salary (1)	Min. Salary	2.4	4.2	1.5	1.9	–
	per capita GDP (1)	R$	34,308.46	57,759.39	12,659.93	10,074.99	31,833.50
	Total Income (1)	Millions R$	72,295	54,010.996	15,681	61,010	–
	Expenditure on MSWM (3)	%	2.65	4.91	3.15	1.36	–
	Profile (1)	–	A	I, C, S	A	A, E	–
Social	IDH-M (1)	–	0.833	0.805	0.657	0.549	–

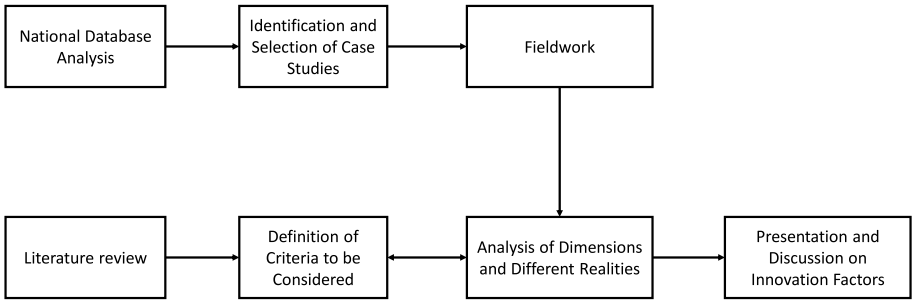

Fig. 1. Flow chart of procedures and methodological steps involved in the research and results generation for the current study.

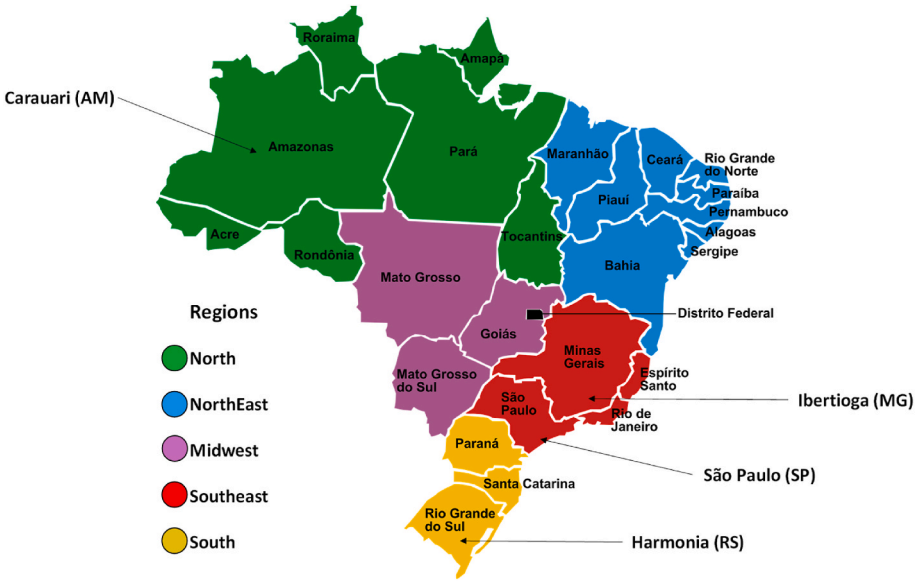

Fig. 2. Location of selected and studied municipalities.

and knowledge of the MSWMS for each location, always searching for enablers at the levels of the system. For information about the content of the semi-structured interviews and the position/functions of the interviewees (see Appendices 3 and 4 - Supplementary Material).

3.;2. Tools for environmental, economic, and institutional analysis

The CO2ZW(R) tool (Sevigne Itoiz, Gasol, Farreny, Rieradevall, & Gabarrell, 2013) was used for the environmental dimension and analysis of MSW impacts on climate change, using the modification made by Paes, Medeiros, Mancini, Gasol, et al. (2020) to adapt the method to Brazilian realities. This tool was conceived using Life Cycle Assessment (LCA) concepts and therefore considers both direct (from waste treatment and disposal facilities) and indirect emissions (from electricity and fuel consumption), in addition to those avoided by waste recovery and recycling (Paes, Medeiros, Mancini, Gasol, et al., 2020; Sevigne Itoiz et al., 2013).

The economic dimension was based on complex and extensive thematic studies (Massarutto, Carli, & Graffi, 2011; Petit-Boix et al., 2017; Paes et al., 2019, 2020b). Therefore, operational and investment MSWMS costs were considered for each evaluated location. Without these data, updated values from Brazilian government official publications (i.e. SNIS - Sistema Nacional de Informações em Saneamento Básico, 2019) were used.

For the analysis of institutional aspects and factors that enable innovation in SGRSU, literature review work was carried out, in addition to fieldwork that sought to verify whether the factors were implemented (I), in progress (P), or not implemented (NI). Both for defining innovation factors and for verifying the implementation of measures, the study by Guerrero et al. (2013) was used as the main reference, which defined the main factors that influence the elements (generation, collection, transport, treatment, recycling, and final disposal) and the aspects (environmental, social, economic, technical, political and institutional) of MSWMS. The results identified in the literature and ratified in the fieldwork, and the new enablers found in the case studies, are shown in Table 3 (Chapter on Results).

Thus, appropriate literature and direct experience from the study locations allowed the definition and analysis of the main influencing factors (system-level enablers) for innovation in local MSW management based on the principles of circular and low-carbon economies. Finally, based on political-institutional, economic, and environmental information (Table 2), it was also possible to propose a system of governance and financing that could encourage good local management practices by creating a National Carbon Credit Fund linked to MSW Management, as seen in Fig. 3.

4. Results and discussions

The results are presented as an analysis of economic, environmental, and operational aspects (indicators in Table 2) and the main factors (system-level enablers) of innovation identified during case studies (Fig. 3). Finally (item 4.3), a proposal for intervention in the MSWMS is presented by implementing i) actions focused on prevention, circular economy, and technologies for local realities and ii) the creation of a National Carbon Credit Fund for the MSW management to finance these actions through the identified enablers and paths.

Table 2
Environmental, economic, operational, and institutional results of the MSWMs studied.

Indicator	Unit	Harmonia	São Paulo	Ibertioga	Carauari	Brazil
	Year	**2019**	**2019**	**2019**	**2017**	**2018**
Environmental	kg CO2eq/inhab.	37.02	144.46	43.98	107.26	365.07
Economic	R$/inhab.	89.17	169.48	94.95	32.74	130.47[5]
	%[1]	2.65	4.91	3.15	1.36	–
Operational	%[2]	100.00	70.00	100.00	NI	–
	%[3]	55.57	2.10	67.41	2.50	1,87[5]
Institutional	Planning and Regulation	MG	MG	MG	MG	–
	Ordinary Collection	PC	PC	MG	MG	(9)[5]
	Selective collection	PC	PC and IC	MG	CI	(10)[5]
	Segregation	PC	RMCC and IC	MG	CI	(11)[5]
	Compost	RC	MG/PC[4]	MG	ACI	–
	Landfill	PC	PC	MG	MG	(12)[5]
	Help at the Government Level	No	FG	SG	No	–

1 MSW Expenditure as Total Proportion of the Municipality's Annual Budget; [2]Coverage rate of the door-to-door selective collection concerning the urban population; [3]Waste Recovery Index as a percentage of total managed by the municipality; NI: No information.

Table 3
Factors and aspects for innovation in MSW management in each of the studied municipalities.

Four main enablers	Factors/aspects	Harmonia	São Paulo	Ibertioga	Carauari
Local Capacity	• Intersectoral action of municipal departments[1]	I	P	I	P
	• *Institutionalization of the team, actions, and projects 2*	I	P	I	P
	• *Collaborative initiatives with other government levels and institutions 1*	I	I	I	I
	• *Support from local leaders for MSW actions 1*	I	P	I	P
	• *Availability and clarity of data and information 1*	I	P	I	P
	• *Knowledge of good MSW Management practices1*	I	I	I	I
	• *Efficient Use of Public Resources 2*	I	P	I	P
Government Level Collaboration	• *Direct participation of the States 2*	NI	NI	I	NI
	• *Direct participation of the Federal Government1*	NI	I	NI	NI
	• *Indirect participation of the States and the Federal Government1*	I	I	I	NI
Environmental Education and Social Participation	• *Environmental theme in a transcurricular and multidisciplinary way in schools 1*	I	P	P	P
	• *Integrate the themes of waste, composting, and vegetable gardens in schools 2*	I	P	P	NI
	• *Promote events on important commemorative dates 1*	I	I	I	I
	• *Promote social participation 1*	I	I	I	P
	• *Carry out waste management plans with the participation of all stakeholders 1*	I	I	I	P
MSWMS through Local Partnerships	• *Involvement of all drivers and enablers in decision-making processes 1*	I	I	I	P
	• *Provision of MSW management services based on local possibilities 1*	I	P	I	P
	• *Good contracts for the provision of public services 2*	I	P	I	NI
	• *Involvement of the productive sectors in the reverse logistics stages 1*	I	P	I	NI

I: Action implemented; P: Action in progress; NI: Action not implemented. [1]Based on literature and confirmed by fieldwork; [2]Aspects found/discovered in the fieldwork.

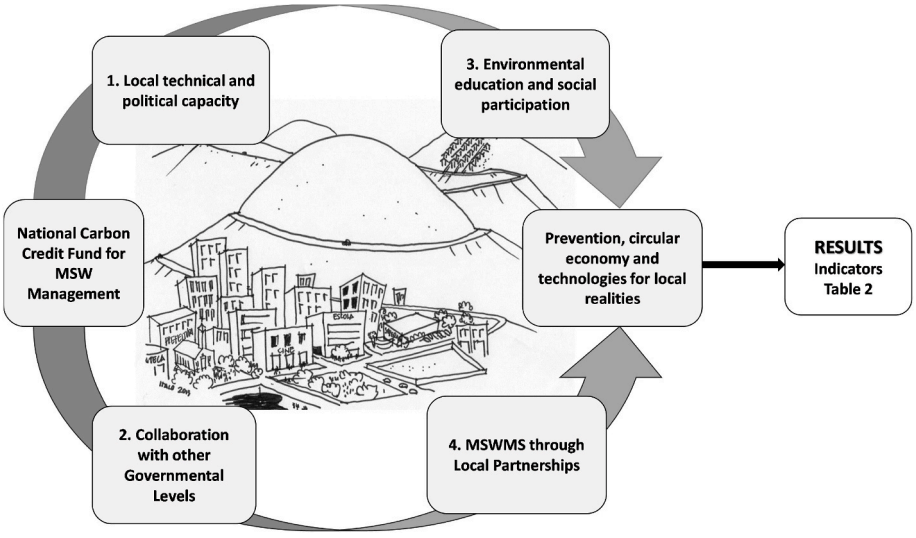

Fig. 3. Enablers and innovation paths for MSW management in developing countries promoting synergistic actions between Circular Economy and Climate Change.

PC: Private Company; MG: Municipal Government; RMCC: Recyclable Material Collectors Cooperative; IC: Informal Collectors; RC: Residential Composting in Schools and Small Commercial Establishments; ACI: Autonomous and Community Initiatives without Government Support or Control; Federal Government (FG); State Governments (SG); [4]Investment and operation carried out by outsourced companies; however, the areas are public granted by the City of São Paulo.

(9) Private companies hired by City Halls (39.1%) and; Municipal Government (60.9%); (10) Private companies hired by Municipalities (50.6%); Cooperatives and/or Collector Associations with support from Municipalities (33.4%) and; City Halls (16.0%); (11) Waste pickers Cooperatives and/or Associations (54.0%); City Halls (27.6%); Private companies (11.7%); Others (6.7%); (12) City Halls (83.6%); Private companies (13.0%); Consortia (1,3); Waste pickers Cooperatives and/or Associations (0.7%) and Others (1.3%) [5](SNIS - Sistema Nacional de Informações em Saneamento Básico, 2019).

Note: See Appendices 1 and 2 (Supplementary Material) for more information about the MSWMS in the 4 cities.

4.1. Integrated analysis of the cases and indicators

With the economic aspects, it was noted that two of the three municipalities that least committed resources from the total budget (Harmonia and Ibertioga) were with the best economic, environmental, and waste recovery indicators. On the other hand, São Paulo had the highest budget dedicated to MSW, the highest costs and emissions per inhabitant, and low waste recovery indicators. Such results show that developing countries may have more sustainable MSWMS than previously thought since, as discussed by other authors, developing countries' cities often lack the technical capacity and appropriate economic and technological resources, and small cities also lack the scale for investments and good MSW management (e.g. Alfaia et al., 2017; Campos, 2014; Guerrero et al., 2013; Gupta, Yadav, & Kumar, 2015; Raia, Bhattarai, & Neupane, 2019). Regarding the economic aspects (costs per inhabitant), only São Paulo had a higher cost than the national average (+30%). Harmonia, Ibertioga, and Carauari also present cost reductions, respectively, of 32%, 27%, and 75%, compared to the Brazilian average.

For environmental analyses, it is notable that the best results (emissions per inhabitant) are related to low per capita MSW generation (as at Carauari), treatment via (home) composting and recycling (as at Harmonia and Ibertioga), in addition to the reuse of methane from landfill for energy generation (São Paulo). Harmonia, São Paulo, Ibertioga, and Carauari had reductions of 90%, 60%, 88%, and 71%, respectively, compared to national emissions (CO2eq.).

When analyzing operational aspects and indicators in São Paulo, even with a 70% selective collection coverage rate (of the urban population), the recyclables recovery rate was only 2.1%. Therefore, even with greater investments related to MSW management-related expenses, or the high coverage of selective collection, the effectiveness of good economic (R$/inhabitant), environmental (kg CO2eq/inhabitant), and operational indicators (MSW recovery as % of the total generated), also depend on other factors, such as political, social and institutional aspects – as shown in item 4.2 (enablers and paths to innovation).

Regarding institutional aspects, the 4 cases showed great variability in the management models, ranging from systems operated entirely by local government (Ibertioga) to systems operated by the private sector (Harmonia). In addition, there were hybrid systems, which relied on the actions of the public authorities, private companies, waste pickers associations, and initiatives from the community itself (i.e. São Paulo and Carauari).

Based on these diagnoses and literature, the main aspects and enablers of innovation in MSW management in each of the municipalities are presented in Table 3. Fig. 3, in addition to the enablers and factors, also presents how the National Carbon Credit Fund can finance these possible paths to implement preventive actions, circular economy, and technologies to achieve the results presented in Table 2.

4.2. Aspects and enablers for MSW management innovation

The four main axes for management and innovation in MSW management derived from analysis of the main enablers found by the literature review and field case studies are: Local Capacity, Intergovernmental Collaboration, Education and Social Participation, and MSWMS built and conducted with local partners. The enablers are presented in detail in Table 3 and Fig. 3 and throughout the following chapter 4.2.

4.2.1. Local capacity

Technical and local political capacity is considered a key element for unlocking and facilitating innovation processes. It is noted that Harmonia and Ibertioga, which presented the best environmental and waste recovery indicators, are municipalities with all the innovation factors already implemented. Meanwhile São Paulo and Carauari still have the less local technical capacity, with several actions in progress (being implemented), and had the lowest waste recovery rates. Based on these experiences and initiatives, the following aspects/factors at the local level were identified as important.

i) *Intersectoral action of municipal departments.* As an example of synchronized and collaborative actions, sectors such as finance, administration, and government can be highlighted, which must have up-to-date and reliable data and political support for MSW management actions. Other examples are the active involvement of the environmental sector in the planning, management, and control of waste activities; of the agricultural sector in composting and vegetable gardens (residential and/or community); the education sector in environmental education projects; the health sector contributing with guidance on the correct separation and handling of waste and inspection of homes and businesses to ensure compliance; the works and/or public services sector in the provision of waste management services. These initiatives could be observed in the cities of Harmonia and Ibertioga.

ii) *Institutionalization of the team, actions, and projects.* Employee turnover in MSW management was high in the cities evaluated, except Harmonia. This f*act resulted in difficulty in carrying out actions, which affected the progress and continuity of such actions and projects. To avoid this, it is important that teams (from the local public administration) work directly with MSW management and that their composition is not directly affected by government changes when municipal elections take place.*

iii) *Fundraising and collaborative initiatives with other government levels and institutions. All municipalities studied had the development of actions, projects, and/or programs in the environmental area in collaboration with different levels of government (at the States and National levels) and/or institutions (such as universities, NGOs, institutes, unions, companies, and international organizations). For example, the city of Ibertioga has partnerships with the state government, the city of Harmonia with private companies and agricultural associations, São Paulo has resources from the federal government, and Carauari has partnerships with research institutes, universities, companies, and community organizations.*

iv) *Support from local leaders for MSW actions. Without prioritization and political support for waste management, the difficulty in mobilizing resources (financial, human, and technological) and integrating sectors/departments/secretariats of municipal administration will be increased. Therefore, success and progress on good indicators depend on a strong commitment to MSW as a political priority. This was found and reported by all cities.*

v) *Availability and clarity of data and information. Performance was poorer where there was difficulty in finding, understanding, and organizing data (as in Sao Paulo and Carauari). Therefore, knowledge and transparency concerning MSW management information,*

such as generation of waste (total and/or per capita*), types of collection and transport, treatment and/or final disposal, as well as information on contracts, economic aspects, and waste-based actions and projects, are key elements of a good MSWMS performance. vi) Knowledge of good MSW Management practices. Finding good results did not require great work, high investments, or complex technologies. Instead, a thorough knowledge of the local situation allows particular study sites to overcome obstacles and implement good practices. For this, technical and political involvement and continuous training processes became essential to acquiring the knowledge, skills, and attitudes required for effective and successful waste management, thus including technical and social competencies.*

vii) *Efficient Use of Public Resources. As shown in item 4.1 (Table 2), the municipality that spent the largest portion of the municipal budget and had the l*argest per-inhabitant allocation on waste management was not the most efficient regarding the environment and MSW recovery. Therefore, investment in employee training, population mobilization, and environmental education can generate important results for local governments.

4.2.2. Government-level collaboration

Another fundamental (facilitating) aspect of innovation processes in MSW Management is the presence of collaboration and participation initiatives by the state and federal governments. This paper's results corroborate the study by Guerrero et al. (2013) that analyzed the main challenges of MSW management in 36 cities in developing countries. Important federative entities can participate directly and indirectly in MSW management.

The direct participation of the States can occur through financial and technical support to municipalities, as occurred in Ibertioga. This can occur through 1) Transfer of resources via state taxation to municipalities with good rates of MSW management and recovery; 2) Remuneration of waste pickers cooperatives and associations that perform well; and 3) Technical support and training for municipalities in the construction and operation of sorting, composting and sanitary landfill centers; creation and management of cooperatives and associations, and formation of public consortia.

The indirect participation of the States and the Federal Government can occur through good transport capacity and regional infrastructures, such as good transport routes and the existence of recycling industries, which can contribute to reverse remanufacturing and logistics processes, in addition to investments in science and technology. The difficulty in transporting waste from small cities in the Amazon region to locations with recycling industries is reported by studies in the region (i.e. Paes, Campos-Silva, & Puppim de Oliveira, 2021) and also found by fieldwork in this study.

However, in Brazil, the effectiveness of certain local policies, such as MSW management, is strongly linked to direct participation via the availability of financial resources from the Federal Government (Paes, Bellezoni, & Puppim De Oliveira, 2021). This fact was shown in the current study with the resources used for infrastructure and training actions for cooperatives and waste pickers in São Paulo.

4.2.3. Environmental education and social participation

Implementing environmental education actions, projects, and programs in municipal schools form an urgent and fundamental measure to underpin changes in a population's habits. National curriculum parameters (the guidelines developed by the Federal Government to guide education in Brazil) already have such mandatory themes as ethics, environment, and health. While schools are supposed to teach these *trans*-curricular and multidisciplinary, such actions have yet to be carried out in many places.

This current study highlights actions that integrate such themes of waste, composting, and vegetable gardens in schools (as well as in neighborhoods and communities) that can generate positive results and economic and environmental benefits for cities. One example involves the vegetable garden and composting projects in schools in Harmonia. Together with environmental education activities, these projects have raised the awareness in the population of the benefits of the recovery of organic waste for compost production and fertilizing home gardens, so avoiding the purchase of fruits and vegetables whose provenance is unknown. As a result, almost half of the organic waste in this city is diverted from MSWMS, generating important economic and environmental benefits (Table 2) and contributing to the food security of the entire city.

Together with pedagogical projects, which work in an integrated and multidisciplinary way, commemorative dates (such as world environment, water, land, and forest days, among others) provide important opportunities for mobilization and awareness-raising of students and the population in general. More information about these initiatives can be found in Appendix 1 (Supplementary Material).

Along with Environmental Education, Social Participation processes can form excellent tools for mobilizing the population and exercising democratic participation. Some of the paths identified in the study locations used participation of the population in municipal councils (and other governmental levels, if applicable) dedicated to waste issues, in the legislative sections, and at public hearings and consultations. This may occur, for example, during the preparation of plans and local by-laws relating to waste management - as demonstrated by Corvellec et al. (2013) in the changes and implementation of laws in Gothenburg and by Uyarra and Gee (2013) in the case of Manchester, where the mobilization and debate with the population made it possible to innovate in the management of MSW to comply with European Union guidelines.

Therefore, waste management plans provide great opportunities for mobilization and debates with society, based on the involvement of as many social actors as possible, a situation seen to be occurring in the municipality of Harmonia and São Paulo (where innovative initiatives, such as mechanized sorting centers and composting yards, emerged through debates to build the MSW management plan).

4.2.4. MSWMS through local partnerships

It is barely possible to create value chains and obtain good results without knowing and involving the main stakeholders in creating and conducting waste management actions and policies. By incorporating such an analysis and ensuring the diverse interests of stakeholders are recognized and balanced, it is possible to attain the synergy and integration of forces required to achieve common goals.

Conflicts of interest can occur when, for example, service providers are paid per ton of waste collected, transported, or treated. In such cases, divergent interests may occur, and, as a result, conscious consumption practices may be disincentivized, as may those for waste prevention and non-generation (Nessi et al., 2013). In some cases, there may still be divergences in recycling or composting initiatives, which can divert waste from the ordinary collection, transport, and final disposal (Paes, Medeiros, Mancini, Bortoleto, et al., 2020).

Examples of good practice and model paths to be followed in this subject can be seen in Harmonia, where the payment is made for a complete waste management service (including collection, transport, sorting, treatment, and final disposal in landfill), combined with targets for MSW recovery, a situation like the one reported by Uyarra and Gee (2013) in Manchester. This approach can encourage MSW recovery (through sorting, recycling, and/or composting) in locations close to waste generation since long-distance transportation and the payment to dispose of large quantities in landfills can become less advantageous options.

In addition to the provision of services by the private sector (as in Harmonia) and by the city hall itself (Ibertioga) - see Table 2/Institutional Indicator and Supplementary Material (Appendices 1 and 2) -, the field study also found composting initiatives carried out by the population itself, and the work of waste-pickers who gather dry waste send (in an independent and unconnected to the municipal administration) for the scrap and recyclable materials trade (as in Carauari). There are

also locations where companies partner with waste pickers cooperatives or associations and, via a contractual obligation, send dry waste to these cooperatives (which also reduces costs with final disposal). This fact occurs in São Paulo.

Therefore, these local potentialities must be understood and encouraged (bottom-up actions), as localities that sought to transfer municipal solid waste management to the states (equal and top-down actions for all cities) were not successful in their policies (i.e. Iyamu et al., 2022).

4.3. Pathways for intervention in MSW management

4.3.1. Focus on prevention, circular economy, and technologies to local realities

As presented in items 4.1 and 4.2, the lower the volume of waste sent to the MSWMS, the greater the financial savings in public spending on transport and final disposal activities, and the reduction in environmental impacts arising from these management steps, as illustrated for the municipalities of Harmonia and Ibertioga in Table 2. Additionally, some waste with the potential to be reused in production chains can generate jobs and economic development, thus contributing to a more circular and less linear economy. This can be seen in the city of São Paulo, which has 24 cooperatives with approximately 900 waste pickers and over 1400 registered autonomous collectors. There were also 30 more cooperatives not authorized by the municipal government and an estimated 10 to 12 thousand informal waste pickers (Paes, Bellezoni, & Puppim De Oliveira, 2021).

Therefore, initiatives where MSW management policies are structured and implemented via a management hierarchy using decentralized and local actions (such as voluntary delivery points and composting in neighborhoods, schools, and homes), are more viable than large-scale projects and technologies (which are normally used for centralized processing of large quantities of wastes).

At Carauari (AM), studies found several initiatives (such as composting and waste recovery) that had been implemented for agricultural and extractive production by the community itself (Paes, Campos-Silva, & Puppim de Oliveira, 2021). In addition, the informal sector of recyclable material collectors has also been working to divert the flow of these materials from the city's MSWMS, sending them by boat to Manaus, the Amazonas State capital (there is no road between the city). Carauari is located approximately 787 km (in a straight line) from Manaus, and the boat travel lasts 5 days.

As shown in item 4.1, significant investments in works and technologies are unnecessary to obtain the high waste recovery rates that characterize good environmental, economic, and operational results. The technological innovations studied in Brazil are concentrated in composting, sorting, recycling, and energy use of landfill-generated methane.

However, even with these technologies in use, there may also be a need to deploy other waste treatment and energy generation technologies, such as waste-to-energy systems and/or biodigesters, as some of these alternatives may be necessary and viable (since they need more investments and waste volumes) (Paes, Medeiros, Mancini, Gasol, et al., 2020; Paes, Bellezoni, & Puppim De Oliveira, 2021). This would be the case for cities like São Paulo, which have zoning restrictions (since composting units and landfills need larger areas), or, for example, with a large number of inhabitants and greater availability of resources. However, such initiatives must not jeopardize the recycling and recovery of materials and their entire production chain or even encourage the population's consumption, to maintain or increase the generation of MSW simply to keep the power plants in operation.

An important tool that could contribute to implementing these actions, used in several countries, but still little implemented in Brazil, is the well-known economic instruments to encourage environmental improvement (Paes, Medeiros, Mancini, Bortoleto, et al., 2020). Examples are the fees on more polluting treatment units (such as landfills) and those related to population (such as pay as you throw) (Iyamu et al., 2020). These initiatives were not found in these case studies, but they could compose actions to encourage improvements in MSWMS.

4.3.2. Creation of the national carbon credits fund for MSW management

Through the environmental and economic analyses (Table 2) of the 4 case studies, it was possible to propose the creation of a National Carbon Credit Fund for MSW Management. This fund could be coordinated by the central (federal) government and count on the participation of States and Municipalities in the deliberation of projects and resources. This initiative could help to break down some barriers pointed out by authors (i.e. Roppongi et al., 2016; Puppim de Oliveira, 2017), such as financing, local capacity, and articulation between different levels of government. This is a path already pointed out as promising for developing countries (e.g. Iyamu et al., 2020).

This fund could use the example of the city of São Paulo (see Supplementary Material – Appendices 1 and 2), which finances environmental actions in the municipality through a CDM project and carbon credit access. However, the national fund could use the resources exclusively for the Management of MSW of the accredited municipalities. Municipalities may be responsible for providing information on initiatives implemented in the localities, while States (which already have bodies responsible for environmental licensing and inspection) would assess these measures.

A part of the fund's financial resources ($\sim = 10\%$) could be set aside for administrative management and maintenance of a permanent team that would train local governments to implement the innovation measures presented here, as is also done in São Paulo. According to Paes, Medeiros, Mancini, Gasol, et al. (2020), with MSWMS improvements, Brazil could obtain annual benefits from CDM projects and CO2 credits ranging from US$ 44 to US$ 687 million.

4.4. Implications of the research findings and future studies

This study sheds light on important paths for intervention in MSW management, especially in developing countries, which still have systems in the early stages of development, relying on open dumps, low amounts of MSW recovery, and the strong role of the informal sector throughout the recycling production chain (Costa et al., 2022).

These paths demonstrated that investments in a technical and local political capacity, environmental education and social participation could overcome the economic barriers many cities in developing countries face. The National Carbon Credits Fund for MSW Management could therefore finance the actions of municipalities that structure their system based on these pillars.

The initiatives identified and studied here and their respective results can contribute to several UN Sustainable Development Goals, as already highlighted by other studies (e.g. Iyamu et al., 2022; Lemaire & Limbourg, 2019), such as Eradication of poverty and hunger (1 and 2); Quality education (4); Affordable and clean energy (7); Innovation and infrastructure (9); Sustainable Cities and Communities (11); Responsible consumption and production (12); Action against Global Climate Change (13) and; Partnerships and Means of Implementation (17).

Although currently relevant, studies have reported a lack of progress in achieving the circular economy and sustainability due to the focus of the literature on CE (Kirchherr et al., 2023). Indeed, many scholars tend to analyze barriers to the circular economy with a vast literature developed around this (i.e. Govindan & Hasanagic, 2018; Hartley, Roosendaal, & Kirchherr, 2022; Kirchherr et al., 2018; Van Keulen & Kirchherr, 2021), but few studies demonstrate the paths and enablers to enable circular disruption, especially in developing countries (i.e. Dewick, Bengtsson, Cohen, Sarkis, & Schröder, 2020; 2022; Kirchherr et al., 2023).

Thus, this research also intends to contribute to the recent debate about tearing apart everyday life's economic and societal nodes. It is meant to provoke thinking about how radical change may

fundamentally upend the existing sociotechnical system and replace it with a more sustainable model (Kirchherr et al., 2023). It was noticed (for the area of waste management) that important initiatives at a niche level (such as environmental education in schools and neighborhoods) can have a positive impact on the circular disruption of the socio-technical regime and the landscape. Just as good management and public policies can positively impact individual initiatives (niches), and also the landscape. However, it should be noted that this is a study focused on waste management and that other drivers of the economy and circular disruption would still have to be considered and studied.

Therefore, this study has not yet diagnosed an important area of the circular economy (Henry, Bauwens, Hekkert, & Kirchherr, 2020): how rapid innovation in circular business and Brazilian startups can directly impact MSWMS. It should be the focus of future studies in Brazil and other developing countries. It is also important to better understand how large companies plan their products for circular business (i.e. Mancini et al., 2021) and plan flexible MSWMS that allow for adaptations, as in cases of receiving a smaller amount of organic or recyclable waste.

Other important topics for future studies are: i) what is the real amount of waste and workers in the informal MSW management sector (including waste pickers and recyclable material businesses) and repair activities (such as seamstresses, shoemakers, and electronics repair activities)? ii) how self-sufficient are and can be Brazilian cities and cities in other developing countries? For this, studies about urban metabolism and life cycle thinking in cities would be interesting; iii) how are governance structures organized in cities, states, and the federal government, and how do these structures contribute to the transition to the Circular Economy? iv) how can international agreements, such as climate change, affect the micro, meso, and macro levels of the Circular Economy in developing countries? And; v) how can new business models affect the (circular) economy of cities?

5. Conclusions

This research allowed the identification of the main drivers and enablers of MSW management that can generate synergistic actions between circular economy and climate change.

It has been widely thought that scale could be a barrier to innovation processes in municipal public management. However, small cities (such as Harmonia and Ibertioga, with around 5000 inhabitants) demonstrated that there could be efficiency in MSW management without large amounts of financial resources via actions such as effective prioritization and political will, mobilization and participation of the population, environmental education, and local technical capacity. These cities divert from landfilling 56% and 67% of the municipal solid waste, respectively. This index for the whole country is 2.2%.

São Paulo provided an example of CDM projects to obtain carbon credits and finance environmental actions in the city. Based on this experience, the current research also proposes creating a national carbon credit fund for the implementation of innovation in MSW management.

Carauari and São Paulo also demonstrated that the informal sector could also participate effectively in collecting, separating, and selling waste and recyclable materials. However, the material flows of many activities, including the repair and reuse activities of products (such as furniture, electronics, clothing, and toys), remain little known. So, studies of these aspects could be developed to allow the planned integration of such sectors into public waste management policies.

Finally, it was possible to conclude, through these cases (which can contribute mainly to developing countries which have their MSWMS in the initial stages of evolution), that: i) there is no need for great expenditure or sophisticated technologies to obtain good results; ii) prevention, composting, sorting/recycling and energy use of landfill-generated methane are great technological routes to obtain good results and be in synergy with Circular Economy and Climate Change mitigation actions; iii) Environmental Education and Social Participation, as well as Local Management Capacity, Cooperation with other Governmental Levels and MSWMS based on local strengths and potentials, are key elements in stakeholder mobilization, changes in the population-level behavior and good medium- and long-term MSWMS performance; iv) these enablers and technological routes can generate significant economic and environmental benefits (such as GHG reduction) for municipalities.

These changes involve rethinking the current global economic growth model, shaped so far by a linear economic system, with manufacturing processes based (in the first order) on profit, high consumption, and energy waste. This rethink favors a more sustainable model, recalibrated by the vision of the Circular Economy, which will generate more autonomous, self-sufficient, and self-sustainable systems and locations.

CRediT authorship contribution statement

Michel Xocaira Paes: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jose A. Puppim de Oliveira:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sandro Donnini Mancini:** Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Joan Rieradevall:** Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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.

Acknowledgment

We would like to express our gratitude to FAPESP (São Paulo Research Foundation) for the postdoctoral fellowship awarded to Dr. Paes (Grant #2018/16542–0 and Grant #2023/09744–4) and Grant 2017/50425-9. Additional support to was provided by the Coordination for the Improvement of Higher Education Personnel (CAPES), process number 88887.310379/2018–00, and the National Council for Scientific and Technological Development (CNPq), process numbers 311282/2016–4 and 303117/2022–2.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.habitatint.2023.102990.

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