Clean Technologies and Environmental Policy (2022) 24:2547–2562
https://doi.org/10.1007/s10098-022-02333-x

ORIGINAL PAPER

A combined approach to improve municipal solid waste management in upper-middle-income countries: the case of Sabana Centro, Colombia

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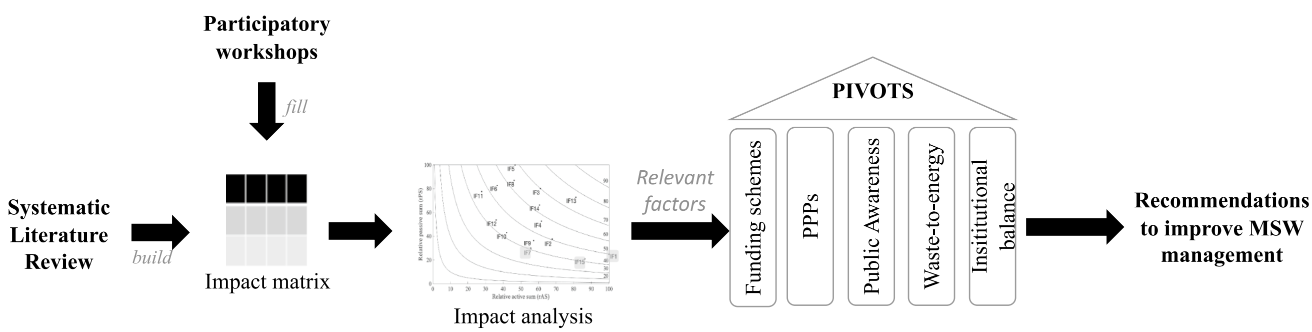
Received: 15 December 2021 / Accepted: 30 April 2022 / Published online: 28 May 2022

Abstract
In developing countries, the lack of specific knowledge of the local context and complex interactions among variables influence effective solid waste management. As a result, the formulation of effective strategies to improve waste management is still a challenge. This study draws on the principle that an adequate formulation of recommendations can be achieved through deep knowledge of the context of implementation, specific for each country. This research designs and applies a novel impact analysis combined with participatory workshops to formulate recommendations to enhance municipal solid waste management. The approach includes four components: (i) a systematic literature review to identify the factors that affect municipal solid waste management in upper-middle-income countries; (ii) participatory workshops to collect information directly from relevant stakeholders; (iii) an impact matrix to systematize valuable information obtained from (i) and (ii), and (iv) an impact analysis to classify the obtained information and develop recommendations to improve municipal solid waste management. The combined approach can be applied to upper-middle-income countries. This was exemplified using a region in Colombia (Sabana Centro), which is composed by 11 municipalities, as a case study. Key recommendations to improve sustainable waste management in Sabana Centro emerged from this study, i.e., the need for multiple funding schemes and new public–private partnerships, the promotion of waste treatment technologies, the encouragement of public involvement in source separation activities, and the alignment of local waste management plans in Sabana Centro and with the national waste management policy.

Graphical abstract



Keywords Municipal solid waste · Upper-middle-income countries · Impact analysis · Participatory workshops · Waste management

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Introduction

Municipal solid waste (MSW) is a consequence of human daily life, and its proper management is a starting point for a healthier urban society (Inglezakis et al. 2018). Inappropriate management of MSW has been associated with hazardous chemicals release, deforestation, affectations to human health, land degradation, among other environmental, social, and economic impacts (Ferronato and Torretta 2019). According to the World Bank, the solid waste generated from urban areas globally is expected to increase from 3.5 million tons per day to 6.1 million tons per day by 2025 (Makarichi et al. 2018). This increasing pace has exceeded the handling capacity of municipalities, especially in developing countries (Anwar et al. 2018), where solid waste management is inefficient due to a lack of proper administrative, infrastructure and adequate resource utilization (Tsai et al. 2020). Nowadays, waste management not only aims to reduce volumes of waste but to incorporate concepts of waste prevention, recycling and waste to energy (WtE) (Abushammala and Qazi 2021). Scientists and policymakers are dedicating efforts to find more sustainable means of disposal and to develop technologies that utilize MSW as a resource in energy production.

Colombia is one of the most important economies in South America. An accelerated economic growth has promoted an increase in consumption levels and the generation of more waste. At the same time, increased consumption has led to higher energy demand. However, few efforts are in place to take full advantage of the energy content of MSW. Colombia produces an average of 0.63 kg of municipal solid waste per person per day (Superintendencia de Servicios Públicos Domiciliarios 2019), waste production is growing every year, and the recycling rate is only 17% of total waste (Superintendencia de Servicios Públicos Domiciliarios 2019). Even though few municipalities recycle inorganic materials such as plastics or metals, there is no generalized intention to prevent waste generation, reuse is not encouraged, and the use of urban waste for energy generation is not implemented yet. It is important to keep in mind that effective waste management is expensive, often comprising a large portion of the very restricted municipal budgets.

The formulation of MSW management strategies requires a deep knowledge of regulations, the selection of an appropriate conversion technology, and the understanding of the challenges inherent with new technology adoption (Coventry et al. 2016). Several studies for developing countries have highlighted the relevance of understanding local factors to guide the decision-making processes in the assertive development of policies and strategies to support sustainable solid waste management. Batista et al. (2021) proposed a framework for sustainable integrated MSW management in developing countries considering the barriers and critical factors to achieve it. Similarly, Qing et al. (2010) analyzed the problems and challenges of MSW management in China and several recommendations were made to improve the system (Qing et al. 2010). Circular economy in waste management has been also promoted by the identification of critical factors (Salmenperä et al. 2021) and a combined systematic review and SWOT analysis (Bertolucci Paes et al. 2019).

Due to the high complexity in these systems, systemic approaches that consider the specific location and the dynamics of the technical and institutional structures in particular contexts must be developed and tested. Knowledge of the relationships and interactions between different factors is necessary to understand the behavior of the system and support the decision-making process to adopt the adequate transformations. Impact analysis is a well-recognized method to scrutinize different types of systems. Its application can help to identify the variables that play a significant role in the evolution of the system (Guertler and Spinler 2015). Vester (2007) proposed an impact matrix initially for forecasting purposes (Vester 2007). The matrix has been used in different contexts to study the interrelationships among the system variables (Krieger et al. 2017). Later, Linss and Fried (2009) developed the Advanced Impact Analysis (ADVIAN®) classification method based on the impact analysis to study indirect relationships among variables and calculate supplementary indices for a better understanding of the system (Guertler and Spinler 2015; Linss and Fried 2010). Participatory approaches have been developed for business and modeling. However, few approaches have been applied in the waste management field (Martins et al. 2018).

The performance of waste management systems is influenced by financial, environmental, social and political aspects (Mmereki et al. 2016). The relevance of each aspect and the interactions among them depend on specific dynamics of the local context that differ among countries. As a result, methods that can help on decision-making processes must consider the local context and its dynamics. While there have been studies to identify barriers, challenges, and opportunities to sustainable waste management in developing countries, there is no study that combines impact analysis and participatory approaches to enhance MSW management in developing countries. To fill this gap, this paper aims to propose an innovative approach that combines an impact analysis with participatory workshops to develop recommendations to improve MSW management in upper-middle-income countries. The combined approach considered participatory workshops as part of the impact analysis to gain understanding of the context. This will translate in

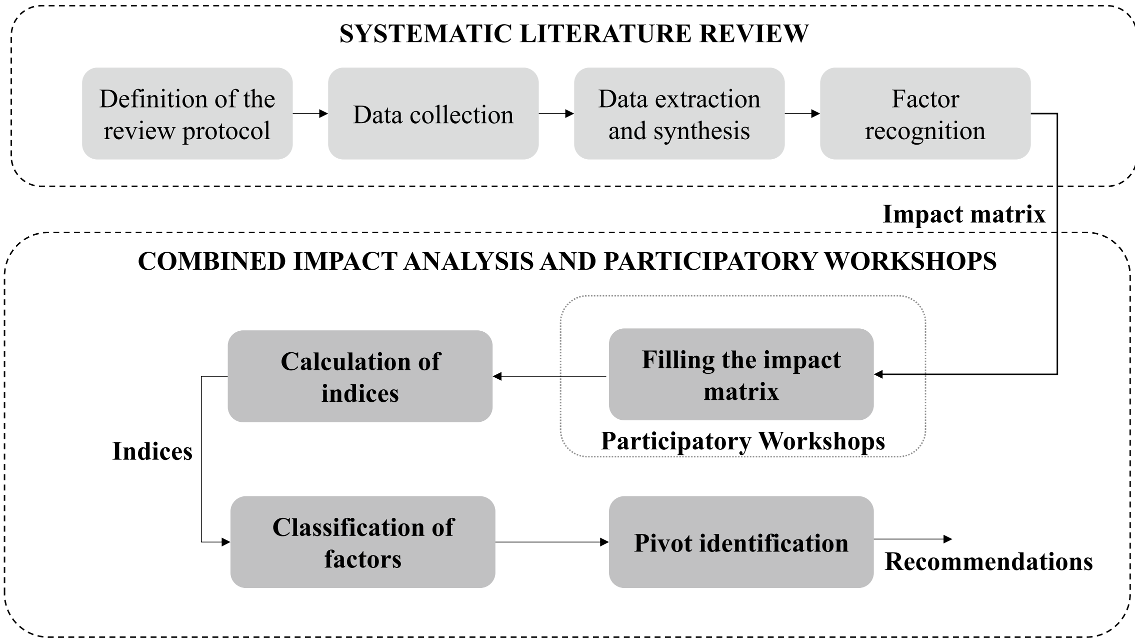

Fig. 1 Methodological approach for municipal solid waste management assessment

positive results in MSW management through the development of recommendations based in the specific behavior of the local context. This approach was applied to Sabana Centro, a region in Colombia composed by 11 municipalities, as a case study with the idea of providing an example of its application, which can be reproduced in upper-middle-income countries.

Methodological approach

This research proposes the combination of two methods to formulate recommendations to improve MSW management in upper-middle-income countries. The World Bank classifies the world's economies into four income groups based on the Gross National Income (GNI) per capita: low, lower-middle, upper-middle and high-income countries. Colombia is classified as an upper-middle-income country (GNI 4096–12,695 USD) (The World Bank 2021a). The approach is presented in Fig. 1. To illustrate the application of the approach, a case study was performed for Sabana Centro Province in Colombia.

Systematic literature review: impact factor recognition

A systematic literature review was performed to build the impact matrix used for the combined analysis. This impact matrix can be applied in upper-middle-income countries and is used as starting point to perform the combined analysis proposed in the present study. The review protocol consisted of a primary study research using a search string composed by the terms representing the population: solid waste management, municipal solid waste, and indicators: barriers, challenges, recommendations, strategies. The search string captured 23,846 publications. Then, inclusion and exclusion criteria were applied. Inclusion criteria considered the following databases: Science Direct, Latindex, Scielo, Google Scholar, and local publications and regulations considering a timeframe from 2010 to 2020, documents in English and Spanish, only studies applied in upper-middle-income countries and developing countries in general, and journals classified as Q1/Q2. Exclusion criteria contemplated: short length publications with less than 5 pages, workshop articles or conference papers, tech reports and articles not directly related to waste management. After the implementation of inclusion and exclusion criteria, only 49 publications were left for detailed screening. After performing a quality assessment, 32 studies were selected for data extraction and synthesis. Finally, the backward snowball technique was applied (Wohlin 2014), and 9 more studies were included. A total of 41 publications were chosen for data synthesis and extraction of data.

For the purpose of this study, impact factors (IF) are a set of variables that describe MSW management systems. Vester (2007) recommends a range between 20 and 40 for the IFs (Vester 2007). However, the number of IFs selected for the present study was purposely reduced, because filling the impact matrix for more than 15 factors would have been a very long process during participatory workshops.

As a result, some variables were combined. These IFs were classified as financial, social, regulatory, institutional and technical. Based on the impact factors, an impact matrix that describes MSW management in upper-middle-income countries was built.

The combined impact analysis and participatory workshops

Filling the impact matrix: participatory workshops

The combined approach proposed in the present study considered participatory workshops. Participatory workshops were applied since they bring a group of people together with the aim of seeking opinions, knowledge with a creative and collaborative view (Jisc 2012). In our approach, the workshops provided the basis to build the impact matrix. The impact matrix is the starting point of the impact analysis. The rows of the impact matrix contain the impact strengths of a considered IF on the system of IFs arranged in the columns, and the main diagonal is filled with 0 because there is no impact from a factor on itself (Linss and Fried 2009). The active sum (AS) is the sum of the values in the rows, and the passive sum (PS) is the sum of the values in the columns. AS indicates how strongly a factor is affecting the system and the PS represents the sensitivity of a factor to changes within the system (Schianetz and Kavanagh 2008).

The aim of the workshops was to gather insights to fill the impact matrix as the first step of the impact analysis. Through the workshops, knowledge of the interactions among the IF is gained through different points of view of the stakeholders. In each workshop, participants rated the impact of one factor on the others, using a template of the impact matrix (Fig. 2). Facilitators of the workshops were trained in the moderation of group discussion and the process of building the matrix. The question which was addressed to the participants and used for to rate the impact was: "if variable A changes, how will variable B change in the Colombian waste management system?". Influence was categorized by the following system: (0) no influence "change of factor A causes no/very weak change of B or change of factor A causes change of B after a significant time delay," (1) weak influence "strong change of factor A causes small change of B," (2) moderate influence "change of factor A results in similar change of B" and (3) strong influence "small change of indicator A causes strong change of B." Results from each workshop were computed into a Microsoft Excel application specifically designed for the analysis. To the authors' knowledge, there are no other studies with the aim of understanding complex waste management systems in upper-middle-income countries using participatory workshops.

During the present study, the case of small cities in upper-middle-income countries was evaluated by performing participatory workshops in Sabana Centro region. Sabana Centro is a Colombian region founded in 1998 located in the Department of Cundinamarca. It is formed by eleven municipalities: Cajicá, Chía, Cogua, Cota, Gachancipá, Nemocón, Sopó, Tabio, Tenjo, Tocancipá and Zipaquirá. The region of Sabana Centro plays an essential role in the development and growth of Bogotá (the capital of Colombia) and the Department of Cundinamarca. As a result, Sabana Centro is suitable for the development of infrastructure, housing, education and health projects (Rojas et al. 2020). Sabana Centro generates around 127,258 tons of municipal solid waste (MSW) per year and treats 4288 tons per year (around 3.4% of total MSW). The municipality of Cajicá is the national leader in recycling and treating the putrescible organic fraction of municipal solid waste. In total, 2989 tons of waste per year are composted, and this represents a recycling rate of 17% for Cajicá and 70% of total waste treated in Sabana Centro. This success is due to a transition of more than 15 years to source separation policies to promote recycling and treating of waste. Cajicá is an example for the remaining ten municipalities of Sabana Centro.

As part of the impact analysis, three participatory workshops were performed with participation of stakeholders in Cajicá, Chía and Zipaquirá, the biggest municipalities in Sabana Centro, representing about 64% of its population. Lastly, a final workshop was applied with a team of researchers. Selection of the cities for the application of the workshops was made considering the following aspects: Cajicá is a small city near Bogotá and is the leader of the country in recycling and treating waste. Chía and Zipaquirá are also implementing source separation policies and treating the organic fraction of MSW. Zipaquirá, Chia and Cajicá represent more than 60% of total urban area of Sabana Centro and generate more than 65% of total waste generation in Sabana Centro (Rojas et al. 2020). According to R.M Sebastian et al. (2020), relevant stakeholders in the waste management are waste generators, national and local governmental bodies, non-governmental organizations and private organizations (Sebastian et al. 2020). The participants of each workshop were: one participant of environmental entities, the director of the public service company, the director of local waste collector associations, the local solid waste management plan (PGIRS[1]) coordinator and a representative of the community. The last workshop was developed with support from a team of five researchers, providing insights from an academic perspective.

[1] In Spanish, *Plan de Gestión Integral de Resiudos Sólidos*.

ID	Variable (Factor)	P1 Cost of Investment	P2 Public Resources	P3 Legal Framework	P4 SWM institutions	P5 Policy implementation	P6 Public involvement	P7 Risk of investment	P8 Institutional coordination	P9 SWM Infrastructure	P10 Technical capacity	P11 Waste collectors	P12 Research and Development	P13 Fossil-fuel based economy	P14 Local and national level balance	P15 waste-to-energy technologies
P1	Cost of Investment	**0**														
P2	Public Resources		**0**													
P3	Legal Framework			**0**												
P4	SWM institutions				**0**											
P5	Policy implementation					**0**										
P6	Public involvement						**0**									
P7	Risk of investment							**0**								
P8	Institutional coordination								**0**							
P9	SWM Infrastructure									**0**						
P10	Technical capacity										**0**					
P11	Waste collectors											**0**				
P12	Research and Development												**0**			
P13	Fossil-fuel based economy													**0**		
P14	Local and national level balance														**0**	
P15	waste-to-energy technologies															**0**

Fig. 2 Impact matrix composed by the impact factors obtained during the systematic literature review

Table 1 Indices calculated as part of the proposed approach

Index	Description	Method
Direct active sum d(AS)	Indicates how strongly a factor is affecting the system Sum of the values in the rows	The impact matrix (Vester 2007)
Direct passive sum d(PS)	Represents the sensitivity of a factor to changes within the system Sum of the values in the columns	
Indirect active sum i(AS)	Indirect relationships of the factors obtained by a matrix multiplication method	The ADVIAN® method (Linss and Fried 2010)
Indirect passive sum i(PS)	Indirect relationships of the factors obtained by a matrix multiplication method	
Criticality (C)	Heavily influenced by other IFs and have a strong impact on other factors in the system Geometric mean of iAS and iPS	
Stability (S)	Indicates that the system is highly interconnected Arithmetic mean of iAS and iPS	
Integration (I)	Harmonic mean of indirect iAS and iPS which is subtracted from 100	

Table 2 Pivot identification based on the proposed classification rules

Class	Selection rule	Classification rules
First class Suitable	Low/neutral C, high S high/neutral dAS, low dPS Neutral C, low/neutral S, high dAS, low dPS	Suitable for extrinsic actions to improve performance of the whole system
Second class Positive	Low/neutral C, high dPS Low dAS and neutral PS	Positively affected by the system
Third class Neutral	Neutral C and S, PS and AS low/ neutral	Neutral factors, no negative effects

AS direct active sum, *PS* direct passive sum, *C* criticality, *S* stability

Calculation of indices

During the present study, relevant indices were calculated to classify the factors (Table 1). The idea was to identify the factors that can be suitable for immediate changes, causing positive effects on the system and formulate recommendations to improve the whole MSW system. This will help local authorities in the decision-making process. Direct active and passive sums were calculated as proposed by the impact analysis (Vester 2007). Then, supplementary indices were calculated by a matrix multiplication method as reported by the ADVIAN® classification method (Linss and Fried 2010). Through the application of the matrix multiplication method, indirect relationships among factors can be contemplated. These indices were calculated in a Microsoft Excel application specially developed for the study.

Classification of factors and identification of pivots

The estimation of integration, criticality and stability gives an idea of the behavior of the system. However, to formulate recommendations a final classification based on all the indices that describe the system (direct and indirect effects) was proposed. The criteria established to perform the final classification are presented in Table 2. First class: factors suitable for changes, second class: positive factors and third class: neutral factors. This classification has the aim to identify factors that can be used to formulate recommendations. Also, factors with negative impacts were not classified. Lastly, based on the classified factors, opportunities to improve the system were considered as pivots to develop recommendations. For the purpose of this study, a pivot is a point that can be considered as support to promote a change or turn on the waste management system.

Results

Systematic literature review: impact factor recognition for upper-middle-income countries

The systematic literature review allowed to build an impact matrix based on the understanding of the barriers, challenges and opportunities to improve MSW management. The performed systematic literature review resulted in 15 IFs (Table 3) initially classified as: financial, social, regulatory, institutional and technical. The most cited factors were cost of investment, public involvement and institutional coordination.

The impact matrix built is presented in Fig. 2. The systematic literature review considered only upper-middle-income countries as an inclusion factor. As a result, the identified relevant factors are a representation of waste management systems in upper-middle-income countries. This impact matrix can be used by researchers as input to apply the combined analysis proposed. In the present study, the combined approach was applied to Sabana Centro Province in Colombia as a case study.

The combined impact analysis and participatory approach: a case study for Sabana Centro, Colombia

To illustrate the application of the combined approach, this section presents the results of the case study applied to Sabana Centro, Colombia.

Filling the impact matrix: participatory workshops

A compilation of the matrices filled during participatory workshops was performed, and the matrix multiplication

Table 3 List of impact factors and their definitions

	Impact factor	Classification	Definition	References
IF1	Cost of investment	Financial	Cost of investment of waste management projects	Batista et al. (2021), Bertolucci Paes et al. (2019), Ferronato et al. (2019), Marshall and Farahbakhsh (2013), Nevzorova and Kutcherov (2019), Pan et al. (2015), Salmenperä et al. (2021), Santagata et al. (2021), UPME and BID (2015) and Zhang et al. (2019)
IF2	Public resources	Financial	Public resources assigned to waste management	Bertolucci Paes et al. (2019), Fiksel et al. (2021), Marshall and Farahbakhsh (2013) and Nevzorova and Kutcherov (2019)
IF3	Legal framework	Regulatory	Legal framework in waste management, policies and existing regulations	Batista et al. (2021), Bertolucci Paes et al. (2019), Fiksel et al. 2021) and Yukalang et al. (2017)
IF4	SWM institutions	Institutional	Number of institutions dedicated exclusively to solid waste management	Marshall and Farahbakhsh (2013)
IF5	Policy implementation	Regulatory	Existing strategies to ensure the adequate implementation of solid waste management policies	Batista et al. (2021) and De Sousa Jabbour et al. (2014)
IF6	Public involvement	Social	Public involvement and cooperation in source separation	Bertolucci Paes et al. (2019), Fiksel et al. (2021), Nevzorova and Kutcherov (2019), Salmenperä et al. (2021), Santagata et al. (2021) and Zhang et al. (2019)
IF7	Risk of investment	Financial	Risk of investment in waste management projects that can be unattractive due to its dependence on local conditions of implementation	Ezeah and Roberts (2012) and Ferronato et al. (2019)
IF8	Institutional coordination	Institutional	Coordination among sectors: academic public industries	De Sousa Jabbour et al. (2014), Luiz Bufoni et al. (2016), Marshall and Farahbakhsh (2013), Nevzorova and Kutcherov (2019) and Zhang et al. (2019)
IF9	SWM infrastructure	Technical	Infrastructure, facilities, vehicles, alternatives for disposal, waste-collecting points and space for new plants	Fiksel et al. (2021) Patinvoh and Taherzadeh (2019)
IF10	Technical capacity	Technical	Technological maturity and infrastructure in waste management	Bertolucci Paes et al. (2019), Ferronato et al. (2019) and Yukalang et al. (2017)
IF11	Waste collectors	Social	Inclusion of waste collectors in the solid waste management system	Ferronato et al. (2019) and Fiksel et al. (2021)
IF12	Research and development (R&D)	Technical	Number of R&D projects in waste management and waste to energy	Chand Malav et al. (2020), Nevzorova and Kutcherov (2019), Salmenperä et al. (2021) and UPME and BID (2015)
IF13	Fossil fuel-based economy	Financial	Dependence on fossil fuels due to low prices and technological maturity	Bößner et al. (2019), Marshall and Farahbakhsh (2013) and Nevzorova and Kutcherov (2019)
IF14	Local and national-level balance	Institutional	Cooperation and communication among national and local development plans, policies and PGIRS	Marshall and Farahbakhsh (2013) and Qing et al. (2010)
IF15	Waste-to-energy technologies	Financial Technical	Implementation of WtE technologies	Bößner et al. (2019), Pan et al. (2015) and Salmenperä et al. (2021)

Table 4 Results of the indices calculated for the case study

IFs	rd(AS)	rd(PS)	ri(AS)	ri(PS)	I	C	S
1. Cost of investment	100.0	29.6	100.0	24.8	62.4	49.8	60.3
2. Public resources	70.4	4.4	67.8	37.5	52.7	50.4	51.7
3. Legal framework	66.7	85.2	61.1	80.1	70.6	69.9	30.7
4. Waste management institutions	63.0	51.9	61.7	52.6	57.1	56.7	43.2
5. Policy implementation	48.1	85.2	46.7	100.0	73.4	68.4	36.3
6. Public involvement	37.0	74.1	36.5	82.8	59.6	54.9	49.4
7. Investment risk	63.0	29.6	55.7	30.0	42.8	40.9	61.0
8. Institutional coordination	51.8	70.4	46.2	87.1	66.7	63.4	39.6
9. Waste management infrastructure	59.3	55.6	57.2	36.3	46.8	45.6	55.6
10. Technical capacity	37.0	63.0	41.9	43.0	42.4	42.4	57.6
11. Waste collectors	25.9	51.9	27.7	77.5	52.6	46.3	59.2
12. Research and development	33.3	66.7	36.0	53.7	44.9	44.0	56.9
13. Fossil fuel-based economy	62.9	70.4	81.2	72.8	77.0	76.9	23.2
14. Local and national-level balance	62.9	44.4	60.6	66.2	63.4	63.36	36.7
15. Waste-to-energy technologies	70.4	29.6	86.3	20.9	53.6	42.46	66.4

Measures for system behavior: (rd(AS)): relative direct active sum, (rd(PS)) relative indirect passive sum, (ri(AS)) relative indirect active sum, (ri(PS)) relative indirect passive sum, (I) integration, (C) criticality and (S) stability

method was applied in the Microsoft Excel application. Table 4 presents the results of the indices calculated during the application of the approach to Sabana Centro, Colombia, as a case study.

Calculation of indices: the impact analysis

The calculation indices must be followed by the identification of the ones with the highest criticality, integration and stability and contrast them with the local context to understand how they can help in the formulation of recommendations. Integration and criticality is presented in Fig. 3a, b. High integration and criticality was found for IF13 (fossil fuel-based economy), IF5 (policy implementation) and IF3 (legal framework). Highly integrative factors are the ones related to the complete system, and changes in these factors can cause effects of large magnitude on the system and result in feedback connections (Guertler and Spinler 2015). The most critical factors strongly influence the system but are also influenced by it, and the reaction of the system to changes cannot be foreseen. As a result, recommendations should not be formulated based on these three factors. To analyze the relevance of this result, an analysis of the Colombian context regarding these factors was performed.

In Colombia, fossil fuels (IF13) are determinant for financial stability and economic development of the country. In fact, oil, natural gas and their by-products represented 55% of the total exports in 2013. Additionally, private investments in infrastructure in the sector during the last decade have been around 5% of total GDP, far above from other relevant sectors such as communications and transport which do not exceed 0.7% (UPME 2015). According to the Mining-Energetic Planning Unit[2] (UPME), financial support for fossil fuels in Colombia increased up to $5 million in 2014. Only the first 8 months of 2014, these subsidies reached $500,000 (Semana 2015). This situation is not expected to change in the next 30 years.

According to the Energy National Plan[3] (PEN) 2020–2050, considering a disruptive scenario in which innovation to develop renewable technologies is the pillar, Colombia will be strongly dependent on fossil fuels by 2050. This means that, even under the most innovative scenario, the country foresees a very high dependence on fossil fuels. While oil, natural gas and coal will still represent more than 55% of total energy supply by 2050, opportunities for biogas development will represent less than 12% (UPME (Unidad de Planeación Minero Energética) 2020). This scenario is supported by a strong legal framework for fossil fuels (IF3) considering royalties for the exploitation of non-renewable resources (Law 2056 of 2020). As a result, the marketplace in Colombia implies, for other waste treatment technologies, a strong competition with more established fossil fuel and hydropower. Based on this reasoning, direct changes in non-renewable resources actual legal framework are not recommended. On the other hand, legal framework for solid waste management in Colombia is based on CONPES 3874 with clear milestones and goals. However, even though there is a national policy, the strategies for its implementation are

[2] In Spanish, *Unidad de Planeación Minero-energética*.

[3] In Spanish, *Plan Energético Nacional*.

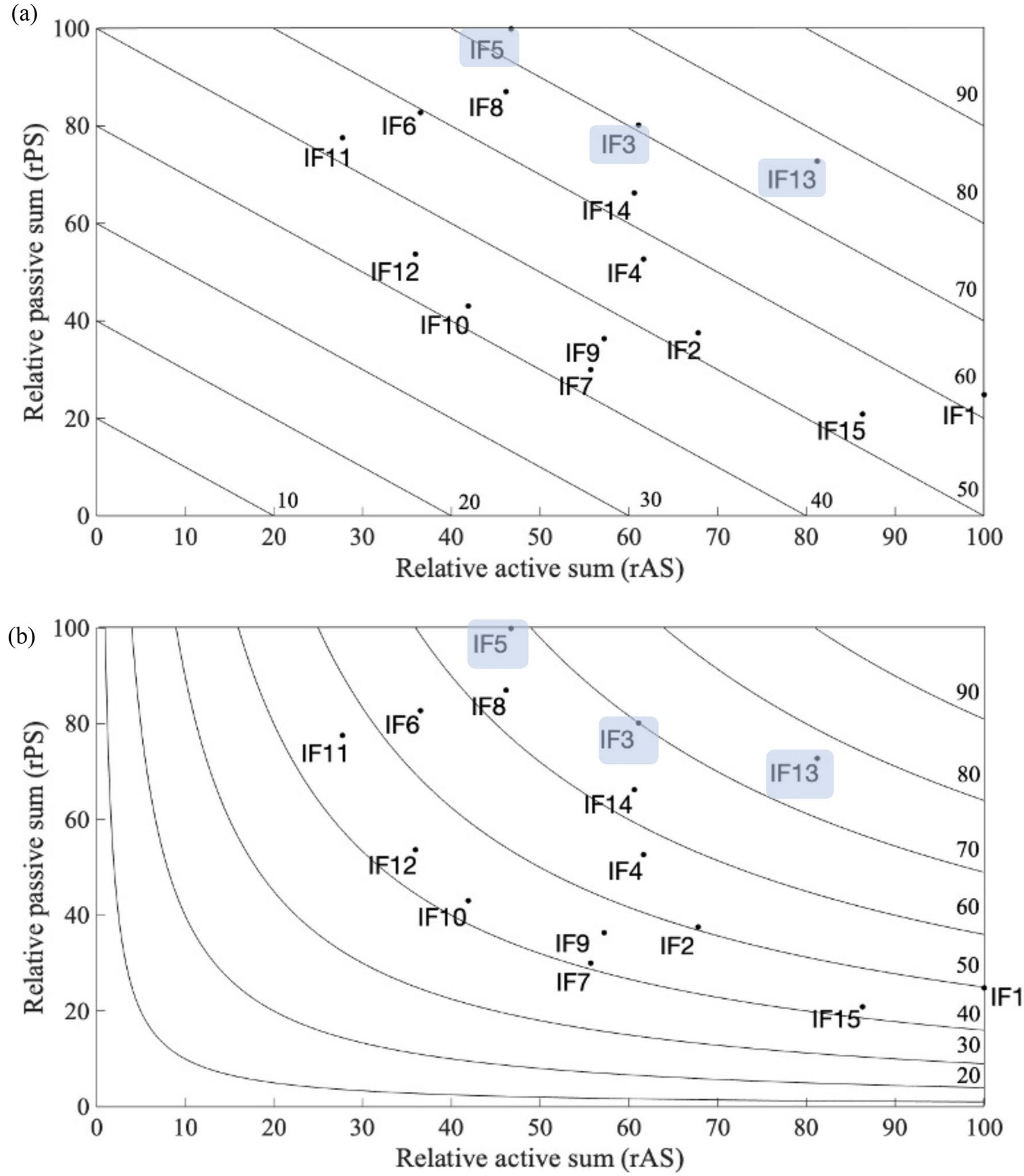

Fig. 3 Factors highly **a** integrative and **b** critical in Sabana Centro, Colombia. IFs: (1) cost of investment, (2) public resources, (3) legal framework, (4) waste management institutions, (5) policy implementation, (6) public involvement, (7) investment risk (8), institutional coordination, (9) waste management infrastructure, (10) technical capacity, (11) waste collectors, (12) research and development, (13) fossil fuel-based economy, (14) local and national-level balance and (15) waste to energy

ambiguous (IF5). These strategies are still unclear due to a missing link with the private sector and the existing institutions dedicated to waste management. Energy service companies (ESCOs) are dedicated to design, build and arrange financing for projects that reduce energy costs. The creation of ESCOs in Colombia can help in building waste treatment capacity.

Stability is presented in Fig. 4 for Sabana Centro, Colombia. IFs with high stability have the highest contribution to balance of the system and can hardly be changed by the system. According to the results, the most stable factors are waste-to-energy technologies (IF15), investment risk (IF7) and cost of investment (IF1). As a result, recommendations for Sabana Centro must be based on these factors.

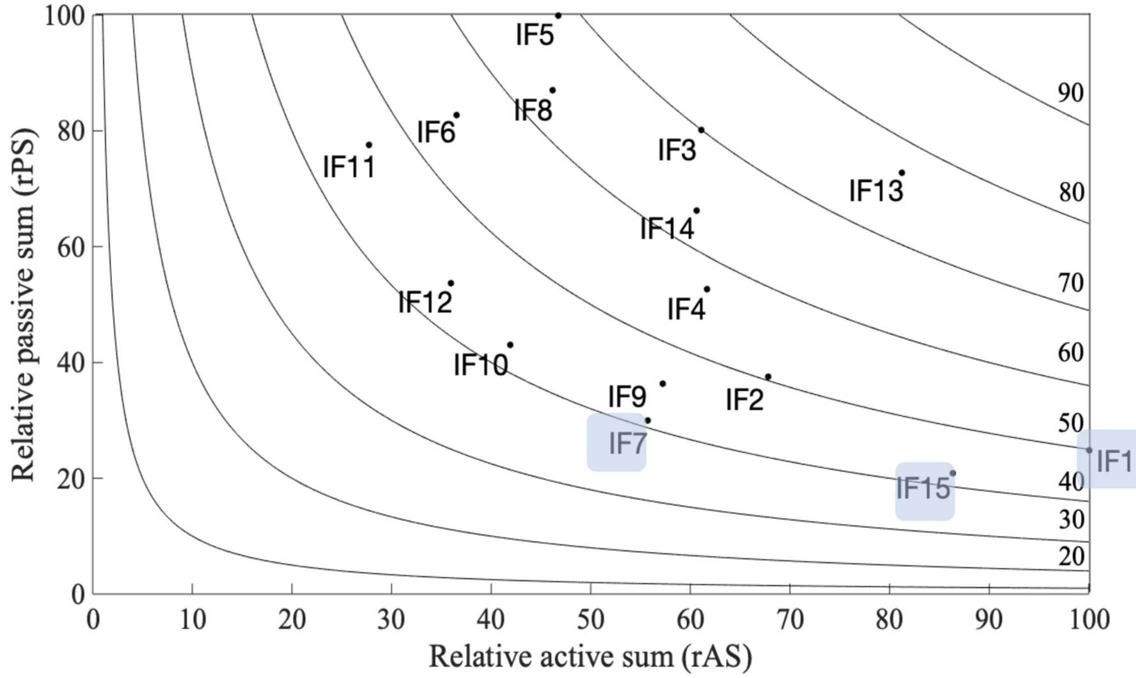

Fig. 4 Stability of impact factors in Sabana Centro, Colombia. IFs: (1) cost of investment, (2) public resources, (3) legal framework, (4) waste management institutions, (5) policy implementation, (6) public involvement, (7) investment risk (8), institutional coordination, (9) waste management infrastructure, (10) technical capacity, (11) waste collectors, (12) research and development, (13) fossil fuel-based economy, (14) local and national-level balance and (15) waste to energy

WtE technologies are processes such as gasification, anaerobic digestion, combustion, pyrolysis or landfill gas recovery that recover energy from non-recyclable wastes and produce heat, electricity or fuel (Shareefdeen et al. 2015). Nowadays, WtE is the preferred treatment option for waste that cannot be recycled (Van Caneghem et al. 2019). As a result, WtE technologies have a critical role in the improvement of MSW in developing countries. For instance, several countries around the world have reported advances in MSW management through the promotion of WtE (Chen et al. 2010; Patinvoh and Taherzadeh 2019; Surendra et al. 2014).

In Colombia, these technologies are not successfully implemented yet. The law 1715 issued in 2014 regulates financial incentives for private investments regarding NCRE. To receive benefits such as a 50% annual reduction of total investment, an exemption of added value taxes, and import tariffs, and an accelerated depreciation, private companies must receive an approval from the UPME and the Ministry of the Environment. Article 10 of the law 1715 regulates the creation of a "Non-conventional Renewable Energy and Efficient Energy Management Fund," FENOGE,[4] supervised by the Ministry of Energy and Mining. FENOGE has the aim of financing, management and executing programs and projects aligned with NCRE. To apply for funding, private companies and governmental institutions must present a technical and financial proposal, this proposal is evaluated by FENOGE, and they decide if the project is qualified for partially or full refundable financing or partially or full non-refundable financing (FENOGE 2021). These incentives are the only ones existing today in Colombia. As a result, additional financing sources are necessary in Colombia. These strategies have worked in different countries such as Sweden, China and Indonesia. Multiple financial schemes are essential to reduce risk and cost of investment associated with MSW management.

According to the results of criticality, stability and integration for Sabana Centro, recommendations must be developed based on the factors: WtE technologies (IF15), investment risk (IF7) and cost of investment (IF1). However, an extensive classification of the factors is proposed in the following section to provide insights for specific recommendations that can help Sabana Centro in its way toward sustainable waste management systems implementation.

[4] In Spanish, *Fondo de Energías no Convencionales y Gestión Eficiente de la Energía*.

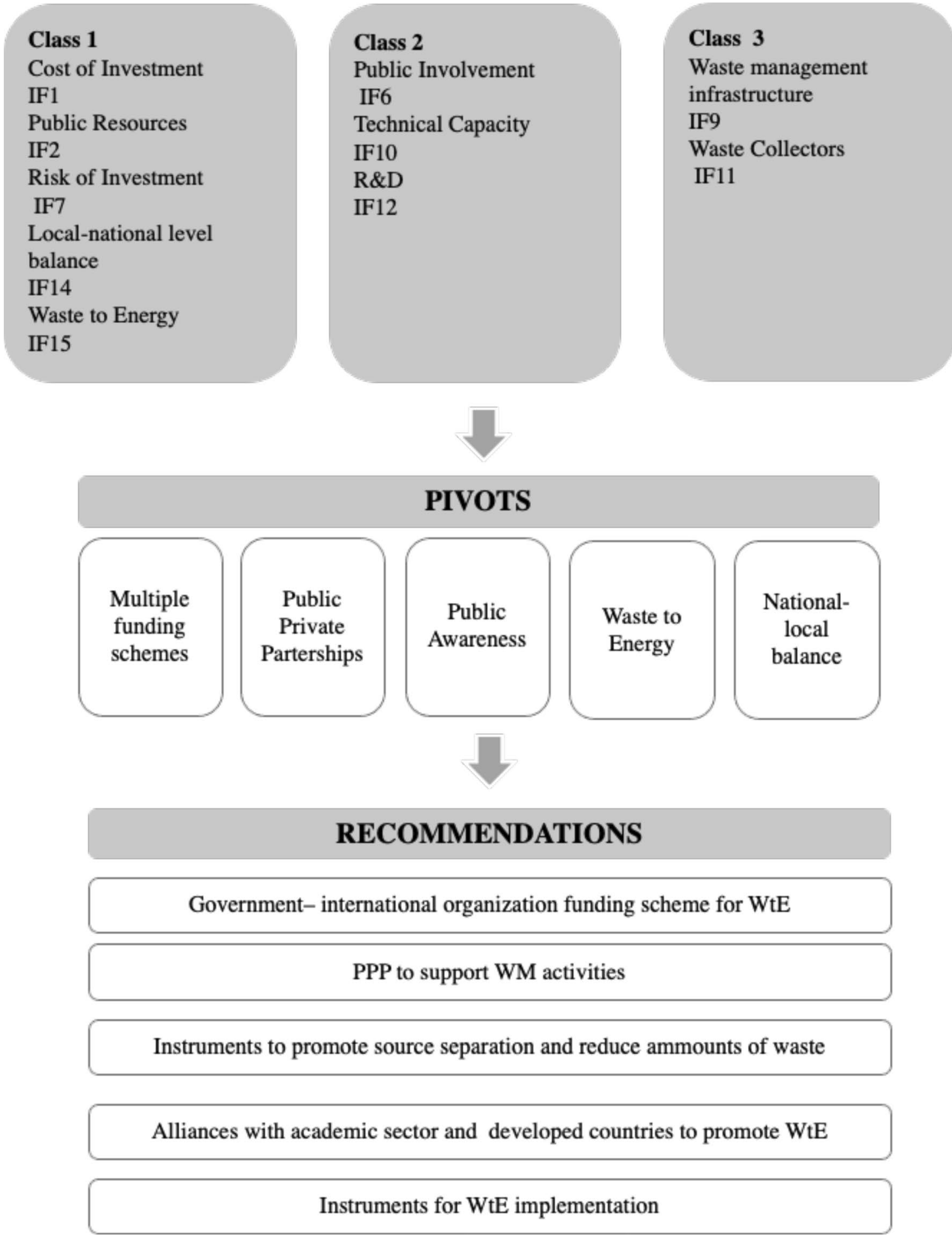

Fig. 5 Recommendations for based on the proposed classification

Classification of factors: development of recommendations for Sabana Centro

Figure 5 shows a framework to improve MSW management in Sabana Centro based on the results of the combined approach. First, the classification of factors according to Table 2 is discussed. These factors are the ones suitable for changes. Then, based on these factors, 5 pivots were identified: multiple funding schemes, public–private partnerships, public awareness, waste to energy and national–local-level balance. The application of the combined approach enabled the identification of pivots and the development of recommendations specifically formulated for Sabana Centro, Colombia. The pivots are the starting point for changes that can result in positive effects to improve how MSW is currently managed in Sabana Centro. By analyzing the local context, this study led to know the real situation of the region. This ensures that the recommendations developed could potentially be used as a base for decision makers to develop MSW management policies.

Multiple funding schemes are needed to promote waste treatment technologies: Waste treatment technologies, such as WtE, are more commonly applied in developed countries (Mmereki et al. 2016). In developing countries these technologies are not viable due to their high capital investment. For instance, biological treatments are applied at small scales and some existing facilities present incompatibilities in terms of process design and characteristics of the waste (Mmereki et al. 2016). Feasibility of WtE depends on waste-related and demographic factors, while financial viability is based on financial resources and potential revenues (Abdallah et al. 2020). Government funding, the private sector inclusion in waste management and the financial support of international organizations are needed to boost the implementation of waste treatment technologies, especially in developing countries where primitive treatment technologies and disposal methods are still in place (Mmereki et al. 2016). Sabana Centro is not the exception, even though municipalities have the intention to implement treatment technologies and avoid disposing MSW in sanitary landfills, and lack of funding to support these projects is identified as a main barrier to this transition. FENOGE is a successful case of a government funding program in Colombia. By 2020, the law 1715 of 2014 and the creation of FENOGE have promoted 294 renewable energy projects, represented mainly by solar and wind energy (Alfonso López Suárez 202AD). The government of Colombia needs to dedicate efforts to develop programs in collaboration with the private sector to reduce the high cost and risk of investment of waste treatment technologies. It is important to consider that in Colombia and other developing countries, MSW management activities are not given higher priority by planners, and there are other issues which may take precedence, such as health and education (Mmereki et al. 2016). As a result, a multiple funding scheme could help in the development of waste treatment projects in Sabana Centro, reducing the risk and cost of investment associated with these kinds of projects that nowadays must be covered by municipalities.

Public–private partnerships must be created to support waste management activities: Public–private partnerships (PPPs) are often capable or reducing the cost of waste management, improving service quality and making a formal link between the public and the private sector to improve efficiency (Spoann et al. 2019). In most developed countries, there are sufficient PPPs and expertise to implement waste management technologies. They have integrated and implemented policy frameworks that consider environmental, technical, institutional and financial aspects (Mmereki et al. 2016). In developing countries, the absence of technological waste treatment facilities has led local governments to create privately built MSW facilities through PPPs (Dolla and Laishram 2021). Regarding waste collection and treatment, China is another successful case of MSW management development with the support of the private sector. The private sector plays an important role in MSW management in China, specially in projects which are expensive to build and operate (Chen et al. 2010). Deus et al. (2017) proposed the creation of public consortia or the privatization of final disposal systems to promote adequate MSW disposal in small municipalities in Brazil (Deus et al. 2017). Additionally, according to the World Bank initiatives to promote micro-enterprise can help regularize the informal sector (The World Bank 2021b). Nowadays, Sabana Centro uses composting to treat the organic fraction of MSW. However, this service is provided by private companies and the municipality must cover treatment costs. PPPs in Colombia could foster the inclusion of the private sector in the construction and operation of waste treatment facilities. Additionally, municipal authorities could work with ESCOs to develop programs to support renewable energy generation.

Public involvement in source separation activities can help preparing waste for treatment technologies: In developed countries, different waste treatment technologies have been applied successfully. Thermal and biological conversion of waste through different methods have been reported. The success of these processes is due to effective source separation and recycling policies (Mmereki et al. 2016). However, high costs associated with recycling and source separation activities hinder the transition to more effective treatment technologies in developing countries. Sabana Centro have demonstrated the essential role of source separation in the effectiveness of MSW management. Cajicá is an example of source separation. Chía and Zipaquirá are currently implementing source separation policies and starting organic collection routes to send waste to compost. Even though Colombia, and even Cajicá, consider a flat rate method to charge for MSW management, Cajicá contemplates an additional charge to penalize households that do not comply with local separation policies. This has helped Cajicá in the achievement of a recycling rate higher than 70%. To improve MSW in Sabana Centro, the remaining municipalities must apply source separation policies and introduce waste management charges. This task can be achieved by encouraging public involvement with the help of television and social media, involving citizens in management activities and inclusion of solid waste management as syllabus at school level (Chand Malav et al. 2020).

Waste-to-energy technologies are essential to improve the efficiency of waste management systems: WtE technologies offer multiple benefits in terms of social and environmental aspects. They generate energy from renewable sources, reduce MSW volume and produce beneficial electricity (Chand Malav et al. 2020). In Colombia, WtE technologies can be employed to progressively substitute landfilling method, decrease the amounts of waste and reduce environmental pollution. Even though the law 1715 established tax incentives, the integration of biomass-based projects has not been stimulated, especially for anaerobic digestion of MSW. Additionally, there are still subsidies for fossil fuel-based energy generation that makes the price of renewable energy too high to be a viable energy option. It is estimated that eliminating fossil fuel subsidies globally can reduce GHG emissions by 6% and benefit the development of renewable energy (Pan et al. 2015). Nowadays, eliminating conventional subsidies and modifying legal framework on fossil fuels is not possible, and financial stability of the country depends on the incomes generated by this market. To implement waste to energy, Sabana Centro will also benefit from R&D projects with the academic sector and developed countries to increase technical capacity in waste to energy.

Clear responsibilities and roles must be assigned to ensure balance between the government and the municipalities: According to Mmereki et al. (2016), the lack of clear roles and responsibilities among stakeholders is a relevant difference between developed and developing countries. This is mainly due to the lack of proper organizational structures within municipalities and the lack of ground rules for the allocation of resources and monitoring institutions in developing countries (Mmereki et al. 2016). In Sabana Centro, some municipalities show an alignment between their PGIRS and the national solid waste management policy. For instance, the municipalities of Cajicá and Chía have presented organized schemes to separate and manage MSW. The program "caneca verde" implemented first in Cajicá and then in Chia has the aim of giving special containers to dispose organic fraction of municipal solid waste to send this fraction to be composted. The program also formulates a framework to ensure source separation of organic and recyclable waste and the public involvement through education campaigns. This program has been a success in Cajicá for many years and nowadays is starting in Chía. However, there are other municipalities that are focused only on the recovery of recyclables, such as Tocancipá. According to the PGIRS formulated in 2020 (Municipio de Tocancipá 2020), the municipality only recovers recyclables. Organics are not separated and sent to landfills. To ensure an improvement in MSW management in Sabana Centro, municipalities should develop PGIRS that must be aligned with the national policy for solid waste management CONPES 3874. Municipalities in Sabana Centro must collaborate in the formulation of their PGIRS, to ensure compliance of national policies from the lower levels. On the other hand, the government of Colombia should empower local government to manage waste more efficiently.

Conclusions

The present study aimed to propose a combined approach to identify, classify and analyze the factors that affect the management of municipal solid waste in upper-middle-income countries, specifically leading to the formulation of recommendations for Sabana Centro, Colombia, used as a case study. The combined approach considered not only an extensive literature review but also an impact analysis combined with participatory workshops to gain knowledge about local MSW management. Relevant stakeholders contributed their knowledge and helped to classify the factors and identify those with potential to facilitate immediate changes for an improved system. The approach was applied in Sabana Centro, Colombia, as case study and five recommendations were formulated. (1) Due to the lack of financial stability of small municipalities, multiple funding schemes are needed to promote waste treatment technologies. (2) Public–private partnerships must be created to support waste management activities in municipalities. (3) Public involvement in source separation activities is necessary to improve MSW management, and Cajicá is an example inside Sabana Centro. (4) The implementation of waste-to-energy technologies is essential to improve the efficiency of waste management systems, multiple funding schemes and the involvement of the private sector is necessary to start this transition. Lastly, (5) local waste management plans (PGIRS) must be aligned among municipalities and with national waste management policy. Clear responsibilities and roles must be assigned to ensure compliance from the lower levels. The proposed combined analysis can be applied in upper-middle-income countries as a tool that can support decision-making processes to improve MSW management systems.

Acknowledgements This work was supported by the Colombian Ministry of Science, Technology, and Innovation (Minciencias), the Government of Cundinamarca, the program Colombia BIO 829 [Project Number 66181] and the University of La Sabana for financial support through the Carlos Jordana Grant. The authors acknowledge the participation of The Botanical Garden of Bogotá (José Celestino Mutis). Also, the authors thank ASOCENTRO, EMSERCHIA, EPC Cajicá and Zipaquirá for their support to the project and the development of participatory methodology.

Funding The authors have not disclosed any funding.

Data availability Data sharing was not applicable to this article as no datasets were generated during the present study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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