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Sustainability Indicators Model Applied to Waste Management in Brazil Using the DPSIR Framework

Eduardo Santos [1], Fernando Fonseca [2], Aníbal Santiago [3] and Daniel Rodrigues [2,*]

[1] Department of the Waste Management of the National Secretariat for Urban Environment and Environmental Quality, Ministry of Environment and Climate Change, Esplanada dos Ministérios Bloco B sala 736, Brasília 70068-900, Brazil; edurochasantos@gmail.com
[2] CTAC (Centre for Territory, Environment and Construction), University of Minho, 4800-058 Guimarães, Portugal; ffonseca@civil.uminho.pt
[3] Department of Civil Engineering, Federal University of Ouro Preto, Morro do Cruzeiro, Ouro Preto 35402-163, Brazil; anibal@ufop.edu.br
* Correspondence: dsr@civil.uminho.pt; Tel.: +351-253-510-200

Abstract: Municipal solid waste is a chronic problem in many developing countries like Brazil. Addressing the challenges of waste management requires robust frameworks for assessing the policies' impacts. In this context, sustainability indicators may help decision-makers in adopting more efficient waste policies. The main goal of this study is to propose a framework for identifying and classifying indicators related to waste management within Brazilian public policies. This evaluation was based on extensive legislative surveys aimed at identifying goals, targets, and obligations outlined in these policies. A comprehensive Driving Force–Pressure–State–Impact–Response (DPSIR) framework was employed to identify and classify the usefulness of these indicators in the context of waste management. A total of 151 indicators were identified, alongside 283 waste goals, targets, and obligations, which were primarily related to municipal waste and were mostly sourced from plans, laws, presidential decrees, and collegiate resolutions. Within the framework, 66 indicators, mostly related to waste collection and recycling, were deemed useful, comprising 34 classified as Responses, 14 as Pressures, six as Driving Forces, four as States, two as Impacts, and six as Pressure/Responses. The challenges associated with the DPSIR framework and strategies to enhance the efficiency of public waste policies in Brazil are also discussed.

Keywords: urban solid waste; recycling; waste policies; circular economy; planning

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1. Introduction

Waste generated from human activities has a wide range of environmental, social, and economic implications. Sustainability indicators provide information on human–environment dynamics, detecting environmental changes over time based on pre-established parameters [1]. They could be used to measure the performance and efficiency of waste management practices, from the stage of waste collection to the generation of greenhouse gas emissions [2–5], at different spatial levels from the local to a national scale [6–9]. The application of waste indicators spans various dimensions and is crucial for monitoring and assessing public policies [10–14]. Various types of waste, such as municipal, construction and demolition, healthcare, and waste from electrical and electronic equipment, lead to a diverse array of flows and disposal methods involving numerous processes and stakeholders in waste management [15]. Therefore, identifying the waste types, rules, standards, and flows is critical to understanding the limitations and contexts of the entire waste management chain.

Waste management is a critical issue globally, but it poses unique challenges in developing countries [16] due to factors such as population and urbanization growth, limited resources and infrastructure, lack of local expertise, and inadequate regulatory frameworks, among others. In Brazil, the situation regarding solid waste management demands greater attention [17]. Brazil is the largest South American country, covering an area of 8,515,767 km^2, with a population of 203 million inhabitants [18], contributing to 2.4% of the global GDP [19,20]. The Brazilian territory comprises 5570 municipalities, 27 federation units, and five macro-regions [20]. Recent data shows that the collected municipal solid waste (MSW) generated in Brazil is about 76 million tons, positioning the country as the fourth-largest generator of waste [21,22]. Of this MSW, around 2% is recycled, and about 40% is sent to improper locations, including open dumps, a practice that has been a source of health and environmental problems [22,23]. Estimates from the period 2016 to 2021 suggest that the health problems associated with the waste deposition in these inadequate locations cost 1.8 billion USD. Further, Brazil's solid waste is estimated to account for 16% (over three million tons) of total methane emissions from decomposing trash and to produce the equivalent of over 47 million tons of CO_2 [23]. Additionally, improper disposal of recyclable waste in landfills results in an annual loss estimated at approximately 2.5 billion USD [23].

In Brazil, waste management is primarily overseen by the public sector [24], with government policies playing a significant role in shaping waste management practices. Regulatory frameworks have been established, and incentives have been provided to address waste management challenges. Notably, the National Solid Waste Policy (PNRS in Portuguese), published in 2010, is the most comprehensive framework, emphasizing waste reduction, recycling programs, and the closure of open dumps. Under this federal law, municipalities are required to develop solid waste management plans to access financial resources from the federal government [17]. However, limited progress has been made in addressing these key issues [25]. Due to insufficient political instruments, 40% of urban solid waste is still directed to final disposal systems prohibited by law [21], and only 24% of Brazilian municipalities have implemented selective collection, which may help explain the country's low recycling rate (2%). Moreover, waste generation varies depending on geographical region, income level, and municipality size [25,26]. For example, less developed regions of the country tend to have lower collection coverage compared to the Southeast and South regions [21]. In April 2022, the Brazilian Government enacted the National Solid Waste Plan (Decree No. 11.043), defining new targets for solid waste management in Brazil over the next 20 years, which include, for example, increase recycling rates up to 48% by 2040 and close the nearly 2600 dumpsites and uncontrolled landfills in operation in Brazil [23].

In recent years, research on waste management in Brazil has increased, driven by the urgent need to address environmental challenges and optimize resource utilization. Much of the waste management literature in Brazil is focused on MSW, reflecting the substantial challenges faced by municipalities in meeting the requirements outlined in the PNRS of 2010. For example, Rebehy et al. [26] studied the variables that influence the recovery of solid waste and best practices of efficient municipalities in Brazil; Paes et al. [25] focused on the main enablers of innovations in solid waste management in four municipalities and the respective actions between circular economy and climate change; Silva et al. [27] investigated the potential of utilizing MSW as refuse-derived fuel and the respective energy and greenhouse gas emissions impacts in Brasília; Jucá et al. [28] assessed the management of MSW in Recife through sustainability indicators across social, environmental, economic, and institutional dimensions; Fuss et al. [29] analyzed the development of a framework to evaluate MSW in Belo Horizonte, integrating economic, environmental, and social dimensions; Miranda et al. [30] studied the integration of recycling cooperatives in a medium-sized municipality (Londrina), aiming to assess their contributions within a circular economy structure and identify benchmarking options for similar cooperatives; and Alfaia et al. [17] and Lino et al. [22] carried out comprehensive reviews of MSW in Brazil. Other topics less explored in the literature include the management of specific types of waste, such as e-waste [31,32] and construction and demolition waste [33], waste characterization in Brazil [34], the impacts of the COVID-19 pandemic on solid waste generation in the country [35], public perceptions, residents' awareness and attitudes toward waste management practices in specific Brazilian cities [36], and bibliometric studies on the impact of PNRS on Brazilian scientific production [37].

The literature indicates that applying reliable and accurate sustainable indicators in developing countries like Brazil poses a significant challenge related to the quality and availability of waste data [38–43]. In these countries, waste data are often dispersed among numerous government agencies and in different formats. Other issues include gaps in data provision, low transparency, the activities performed by informal entities that are not fully captured in official data, and many entities lack adequate infrastructure, technical expertise, and funds for data collection and management [21,44]. These problems result in the lack of reliable waste data, making it difficult to compile consistent datasets, mainly at a national level [45–47], and limiting the application of sustainability indicators to the waste sector [29,48]. For example, due to the unavailability of waste data in three Brazilian cities, Silva et al. [48] only applied 11 indicators from a total of 49 initially identified.

The difficulty in using sustainable indicators in the waste field reinforces the importance of developing creative and sensitive assessment models that incorporate reliable indicators for countries like Brazil [49]. In this context, the present study describes a comprehensive framework of sustainability indicators that incorporates both qualitative and quantitative aspects to improve waste management in Brazil. Indicators were sourced from documents published by Brazilian government institutions. The proposed framework is based on the Driving Force–Pressure–State–Impact–Response (DPSIR) method, which has been widely used in the field of waste management. The framework described in this study has four main goals. The first goal is to identify practical and relevant indicators included in Brazilian public policies related to waste management, along with their respective domains of intervention. The second goal is to address the regional and institutional dispersion of waste data by compiling the information into a single framework. The third goal aims to provide public institutions with a tool enabling them to select, assess, and implement sustainability indicators, thereby enhancing and streamlining waste management practices toward sustainability. Finally, the fourth goal is to address the lack of waste information studies in developing countries, particularly in Brazil [16,43,50]. Thus, the study serves not only theoretical goals related to data compilation aimed at addressing gaps in the literature but also offers practical contributions that may assist public institutions in adopting more efficient waste policies.

After this introduction, Section 2 details the methods and data utilized in this study. The findings are then presented and discussed in Section 3. Finally, the concluding remarks are presented in Section 4.

2. Materials and Methods

This section first describes the framework chosen for performing the environmental evaluation and then presents the methodological steps taken to select sustainability indicators.

2.1. Evaluation Framework

In this study, the framework chosen for performing the environmental evaluation was the DPSIR approach. The goal of the DPSIR framework is to provide a comprehensive description of a system through the use of appropriate indicators [51]. This tool has been widely employed in sustainability and environmental studies [51–54]. It was developed by the European Environment Agency (EEA) in the late 1990s which optimizes the DSR (Driving force–State–Response) and PSR (Pressure–State–Response) models. The evaluation system is composed of Driving forces, Pressures, States, Impacts, and Responses. Driving forces are underlying factors, such as industrial development, that influence human activities, leading to environmental changes. Pressures are human activities that directly affect the environment, such as pollution and habitat destruction. State refers to the current condition of the environment (air, water, soil, ecosystem quality) in response to the pressures exerted on it. Impacts represent the consequences of the environmental changes on ecosystems, human health, economies, and society as a whole. Responses are the actions taken to address or mitigate the impacts on the environment through political, economic, or behavioral changes [55–57]. In the field of waste management, the DPSIR framework may offer a broad and integrated perspective of the entire chain, facilitating the examination of interactions between human activities and the environment [54]. Therefore, DPSIR provides a holistic approach that may aid in identifying practical and relevant sustainability indicators and intervention domains intended by Brazilian waste policies.

2.2. Selection of Sustainability Indicators

The methodology adopted to select national-scale sustainability indicators was based on an exploratory approach, utilizing both qualitative and quantitative analyses within the field of waste management. The work involved conducting legislative surveys on the official websites of Brazilian government agencies at the national level. Figure 1 illustrates the methodology followed, highlighting the macro-scale approach.

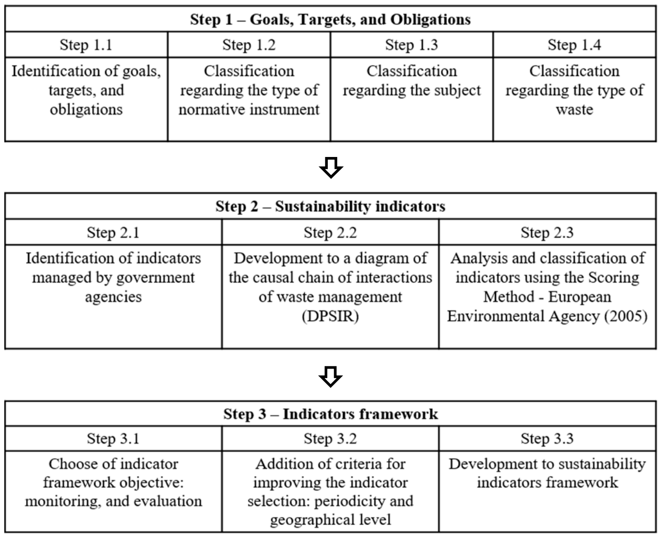


Figure 1. Methodological steps adopted in the study.

The first methodological step involved identifying the goals, targets, and obligations outlined in Brazilian legislation. Firstly, a legislative survey was conducted, and the retrieved documents were organized according to the type of legislation. Subsequently, legislative waste recommendations were extracted, and the wastes were classified according to international guidelines [58]. The second step entailed identifying sustainability indicators in waste legislation based on the DPSIR framework. These indicators were then assessed for their usefulness using the scoring method of the EEA [59]. Finally, in the last step, the sustainability indicators deemed useful were analyzed within the DPSIR framework to understand whether they functioned as Driving forces, Pressures, States, Impacts, or Responses to specific waste problems.

2.2.1. Step 1: Goals, Targets, and Obligations

The first methodological step entailed identifying the goals, targets, and obligations outlined in Brazilian waste legislation. Goals refer to statements within the legislation that articulate its purpose or explicitly mention the terms “goal” or “objective” [60]. Targets encompass quotes outlining specific objectives within a defined timeframe (e.g., days, months, years). Obligations consist of quotations from the legislation containing imperative determinations. After defining the scope, a structured legislative survey was conducted to systematically collect and analyze Brazilian legal documents related to waste. The survey spanned a significant period from 1967 to 2022 to mitigate data fragmentation and ensure a comprehensive understanding of Brazilian waste legislation over time. A comprehensive search strategy was then implemented to identify relevant legal documents.

Government websites and online databases of key public institutions were targeted for the search, including the Institute of Environment and Renewable Natural Resources (IBAMA), Livestock and Food Supply (MAPA), National Health Regulatory Agency (ANVISA), National Civil Aviation Agency (ANAC), Minister of Environment, Minister of Agriculture, Minister of Health, Minister of the Economy, Minister of Regional Development, Minister of Mines and Energy, Minister of Tourism, Presidency of the Republic, and Federal Senate. The following keywords were searched in the databases of these institutions: "solid waste", "waste", "waste management", "garbage", "unserviceable", "reverse logistics", "packaging", "recycling", "uncontrolled disposal", "landfill", "dumpsite", "composting", "incineration", "energy recovery", "sustainable consumption", "sustainable production", "waste pickers", "sanitation", "public consortia", "green public bidding", and "environmental control". The retrieved legal documents were collected and stored for subsequent analysis. In the second step, the documents were systematically organized based on their normative type, which included agreements, collegiate resolutions, court decisions, international conventions, legislative decrees, ministerial ordinances, national laws, national or sector plans, normative instructions, presidential decrees, and terms of commitment. International conventions were included due to their incorporation into national legislation. In the third step, these documents were analyzed and classified based on their significance in public policies, such as recycling, treatment, or disposal, following Bardin's method [61]. Finally, in step 1.4, the goals, targets, and obligations were classified according to the waste types defined by the EU Commission Notice on Technical Guidance on the Classification of Waste [58]. Applying the EU Commission Notice to Brazil could pose challenges due to differences in waste management practices and regulatory frameworks. Nonetheless, the aim was to provide referential support for classifying various types of waste, thereby organizing information into categories and facilitating the interpretation of waste data. Therefore, the classification included municipal waste, which, according to the EU list [58], includes household waste and similar commercial, industrial and institutional wastes, as well as construction and demolition waste, healthcare waste, and other types of waste.

2.2.2. Step 2: Sustainability Indicators in Waste Management

The second methodological step aimed to identify sustainability indicators in waste management. The process began by pinpointing indicators directly related to waste, as well as economic, environmental, health, or demographic data indirectly associated with waste. Indicators were sourced from documents published over the last ten years to ensure that all considered data are up-to-date and aligned with the recommendations of the PNRS. This law has supported various national and municipal plans, as well as sectoral agreements, over the last decade. Sustainability indicators data were gathered from publications issued by more than 20 Brazilian government institutions, including the Institute of Environment and Renewable Natural Resources (IBAMA), the National Sanitation Information System (SNIS), the National Information System on Waste Management (SINIR), the National Institute of Metrology, the National Health Regulatory Agency, the National Health Regulatory Agency (ANVISA), the National Civil Aviation Agency (ANAC), among others. A detailed overview of the searched institutions can be found in Supplementary Table S1. The extensive number of Brazilian institutions publishing waste-related data highlights the significant dispersion of data across multiple entities, each with distinct roles. For example, while the Ministry of Environment and the Brazilian Institute of Environment and Renewable Natural Resources establish regulatory frameworks, policies, and guidelines for waste management, regional and local entities, such as municipalities, are responsible for implementing these national directives in their daily waste management operations. A comprehensive overview of the institutions and documents surveyed can be found in the Supplementary Table S3.

Afterward, the conceptual causal chain of waste management interactions was analyzed using the DPSIR framework [62]. Finally, following previous studies [59,63], the indicator's attributes were firstly selected, and subsequently scored using the method proposed by the EEA [59], which was originally designed for scoring agri-environmental indicators in the EU. Despite differences in socio-economic contexts between the EU and Brazil and the scope of application, this classification method was selected for three main reasons: (i) it serves an explicit environmental purpose; (ii) the method is based on a DPSIR framework; and (iii) the indicators contribute significantly to environmental reporting, offering valuable insights into the strengths and weaknesses of various waste indicators. The indicator's attributes, their rational, and corresponding scores utilized in this study are outlined in Table 1. In this approach, the description of the attributes was fully adjusted to address the challenges associated with waste management (see Table 1). This approach ensured the study's relevance by assessing the extent to which an indicator provides useful information for policy action/decision, accounting for its potential utility and data constraints, including the lack of sufficient and accurate waste data.

Table 1. Method used to define and score the sustainability indicator's attributes.

Indicator's Attributes	Description	Scoring
Analytical soundness	Is the indicator derived from direct or does it rely on indirect, or modeled waste data?	Indirect (0) Modeled (1) Direct (2)
	Is the indicator based on well-founded technical and scientific waste statistics or data?	Low-quality data (0) Medium quality data (1) High-quality data (2)
	What are the causal links with other indicators within the DPSIR framework?	Weak or no link (0) Qualitative link (1) Quantitative link (2)
Cost-effectiveness	Is the indicator based on existing waste statistics and data sets?	No (0) Yes (1)
	Are the waste statistics or data needed for compilation easily accessible?	No (0) Yes, but requires lengthy processing (1) Yes (2)
Data availability and measurability	Does the indicator have good geographical coverage?	Only case studies (0) National (1) National and regional (2)
	Are waste data available in regular time series?	No (0) Occasional data source (1) Regular data source with at least 10 years (2)
Ease of interpretation	Are the key messages easy to seize, clear, simple and unambiguous?	Not clear (0) Fairly clear (1) Very clear (2)
Policy relevance	Is the indicator linked to national waste policy goals, targets, or obligations?	No (0) Yes, indirectly (1) Yes, directly (2)
	Could the indicator provide waste-related information valuable for policy actions or decisions?	Not useful (0) Fairly useful (1) Very useful (2)
Responsiveness	Is the indicator sensitive to changes in the field of waste management?	Slow, delayed response (0) Fast, immediate response (1)

Sources: [59,63].

Figure 2 illustrates the flowchart employed for the classification of indicators as "useful", "potentially useful", or "not useful". Following the methodology defined by the EEA [59], each indicator was individually evaluated, and the seven reported attributes (policy relevance, responsiveness, analytical soundness, data availability, measurability, ease of interpretation, and cost-effectiveness) were scored. The final score is the sum of all attribute scores, with the maximum attainable value being 20 points. Subsequently, an indicator is designated as "useful" if its final score is not less than 15. Following the EEA method [59], three key attributes should have minimum specific scores: policy relevance (not less than 2), analytical soundness (not less than 4), and either data availability or measurability (not less than 3). If any of these conditions are not met, or if the final score falls within the range of 8 to 14, the indicator is categorized as "potentially useful". Conversely, indicators are classified as "not useful" if their score is 7 or less.

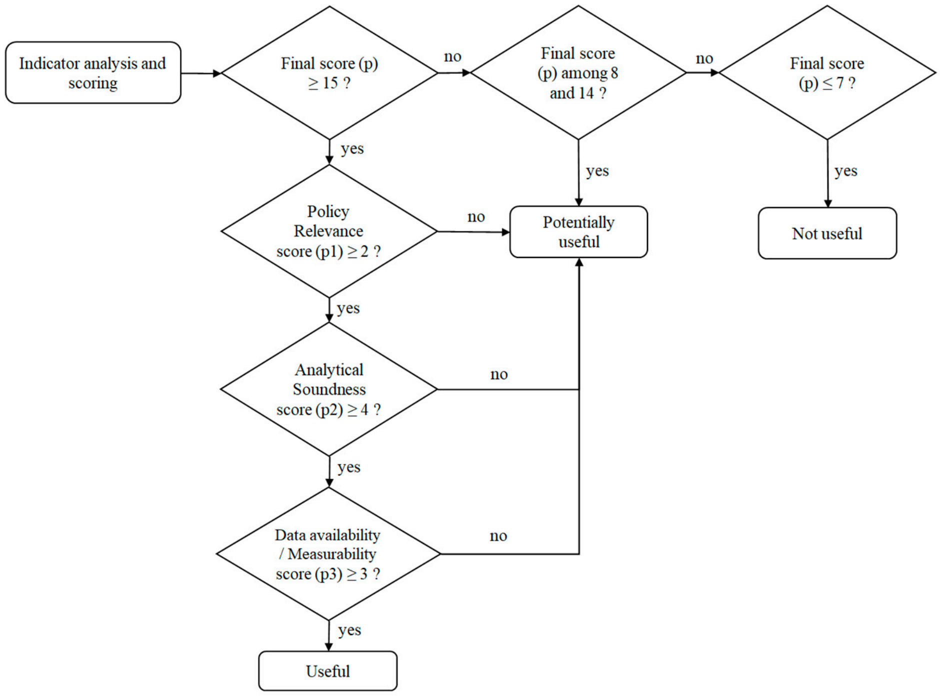


Figure 2. Flowchart describing the scoring process.

2.2.3. Step 3: Indicators Framework

The third methodological step involved defining the sustainability indicators. The process began by selecting indicators aligned with the framework's objectives, primarily focusing on monitoring and evaluating waste management at a national scale. Similar-meaning indicators were excluded if deemed not useful, retaining only those with the highest scores. In cases where indicators had identical scores and definitions, preference was given to those with the largest available data sample. The analysis resulted in a comprehensive set of indicators at the national scale, organized according to waste type.

The described methodology aimed to provide a comprehensive and integrated understanding of the factors influencing waste monitoring in Brazil. By employing these procedures, the study assessed how public policies respond to Driving forces, Pressures, changes in the environment's State, and the Impacts of waste management. Figure 3 illustrates the complete generic methodology for selecting and scoring sustainability indicators. It also graphically shows the legislation searched, the sources and criteria adopted for scoring the indicators, and the overall organization of the framework. Horizontal grey arrows denote intersections between legislative requirements and indicators employed by institutions. The smaller horizontal white arrows delineate the flow of analysis for indicator classification. Vertical grey arrows illustrate the sequential steps in this work.

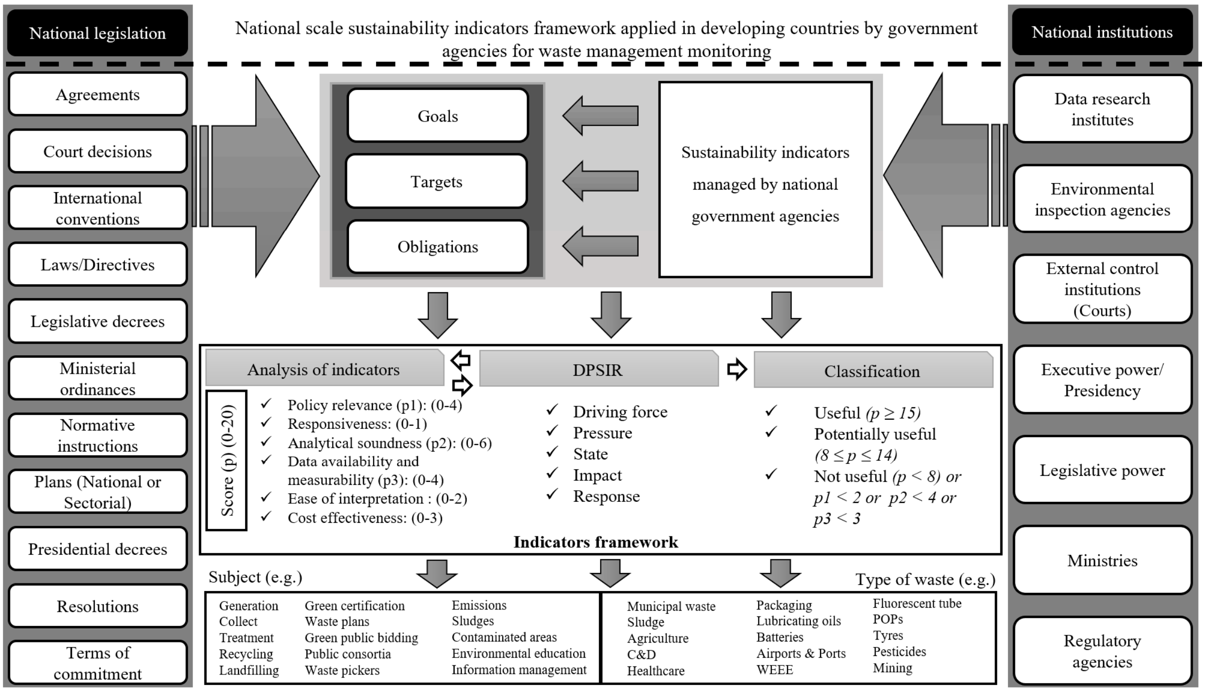


Figure 3. Proposed sustainability indicator framework.

3. Results and Discussion

This section presents and discusses the primary findings of the research, organized in accordance with the methodological steps outlined in Section 2.

3.1. Goals, Targets, and Obligations

3.1.1. Identification of Goals, Targets, and Obligations

A total of 283 goals, targets, and obligations were identified in the Brazilian waste legislation published between 1967 and 2022 [64,65], including presidential decrees, international conventions, legislative decrees, collegiate resolutions, national plans, normative instructions, ministerial ordinances, agreements, terms of commitment, and court decisions. The search revealed that prior to the 2000s, waste legislation was limited (more details can be found in Supplementary Table S1). Before the early 2000s, in the absence of national waste policies, guidelines were primarily established by the Brazilian Association of Technical Standards (ABNT in Portuguese). The first waste standard series was published in 1987 [66], aiming to provide technical standards for waste engineering projects. This set of standards followed the international scenario on waste management, led by the International Organization for Standardization (ISO), which published a series of guidelines for environmental projects and waste classification [67,68]. Between 2000 and 2010, operating under a normative vacuum due to the absence of a national legal framework, the Brazilian National Environment Council (CONAMA in Portuguese) published 10 waste management resolutions. Additionally, other entities, such as the National Civil Aviation Agency, issued security rules for waste management, addressing the risks posed by birds near airports attracted by organic waste. The National Health Regulatory Agency also established resolutions focusing on healthcare waste, particularly hazardous waste. In this period, other initiatives were published, such as federal sanitation guidelines and public consortia legislation.

The year 2010 marked a turning point with the publication of the PNRS (Law No. 12.305), which played a crucial role in shaping waste management practices by providing a comprehensive legal framework and promoting sustainable waste practices and targets. The main goals of PNRS included reducing waste generation, increasing recycling, and reducing disposal in improper locations to enhance sanitary safety and environmental protection. Following this, waste management received more comprehensive attention, and new legal instruments, including sectoral agreements for reverse logistics, were implemented, containing a significant number of targets and obligations for both the public and private sectors.

This finding aligns with Silva et al. [69], who demonstrated that national waste legislation gained strength with the publication of the PNRS and gradually evolved within the Brazilian regulatory framework. The PNRS also promoted the creation of relevant instruments for managing waste data, such as the National Information System on Waste Management (SINIR in Portuguese). The goal of SINIR is to collect, analyze, and provide waste data to help the operationalization and implementation of waste management plans. This instrument has helped various public entities to provide waste data efficiently, thus promoting greater transparency and public responsibility for waste management across the country [70,71].

As emphasized by Alfaia et al. [17], the PNRS improved municipal solid waste management in Brazil compared to the early years of the century, but progress fell short of expectations. As explained in the Introduction, around 40% of urban solid waste is still disposed of in locations prohibited by law (open dumps), and recycling rates remain low. The National Waste Management Plan, introduced in 2022 as part of the PNRS, aims to address these challenges and set new goals for the medium term (2024 to 2040). These goals include, for example, ensuring that by 2040, 90% of municipalities provide separate collection services and have Integrated Waste Management contracts, and by 2024, all municipalities must close down all dumps.

3.1.2. Goals, Targets, and Obligations Regarding the Type of Normative Instrument

As illustrated in Figure 4, the search indicated that, in general, targets were mostly included in plans, while goals were primarily included in plans and laws. In turn, obligations were disseminated among presidential decrees, collegiate resolutions, and laws. The other normative instruments were much less representative in defining goals, targets, and obligations. More specifically, the PNRS contained 24% of the total identified goals, being the most relevant normative instrument; the Presidential Decree No 7.404, 2010, contained 28 obligations of national scope, being the most relevant instrument in this category; and the National Waste Plan holds 32% of the targets on this topic.

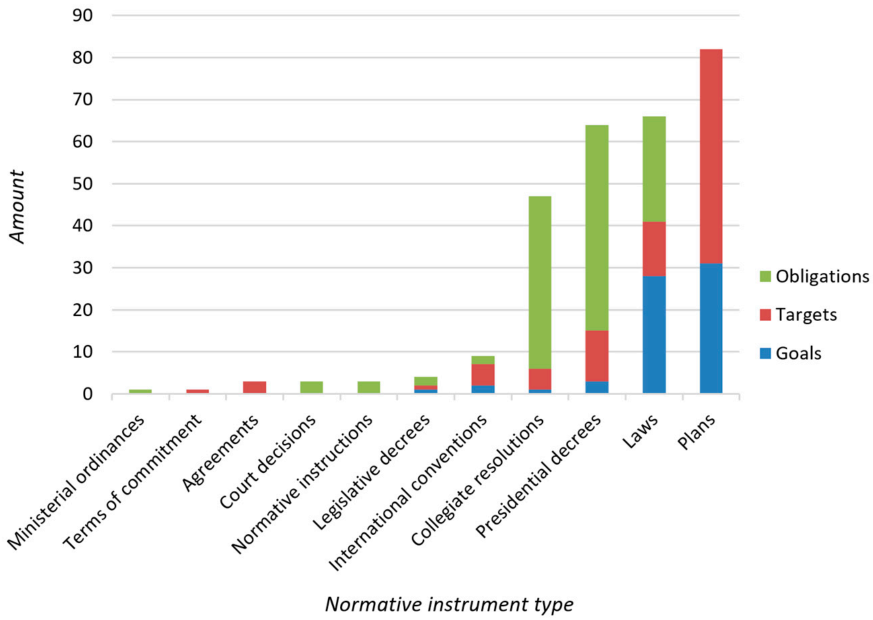


Figure 4. Number of goals, targets, and obligations by type of normative instrument.

3.1.3. Goals, Targets, and Obligations Regarding the Subject

Goals, targets, and obligations were categorized into 32 subjects, forming organized clusters of information. Figure 5 depicts the results of this classification. For a more detailed overview, refer to Supplementary Table S2. The search indicated that goals, targets, and obligations were mostly presented in waste plans, reverse logistics, waste management, and information documents. Other important subjects, such as recycling, technology, public health and environment, emissions, and energy recovery, contained a residual number of goals, targets, and obligations, indicating that these areas have been less important in the waste legislation. This finding confirms previous studies in this field [22]. Additionally, the qualitative analysis revealed that waste plan requirements extend to national, regional, and local governments, as well as private companies. Moreover, various responsibilities were assigned to national information systems such as SINIR, SNIS, and CTF/CNORP, playing a crucial role in the field of waste information management. The defined clusters may assist public managers in identifying the subject areas requiring more attention to efficiently achieve goals, targets, and obligations in waste management.

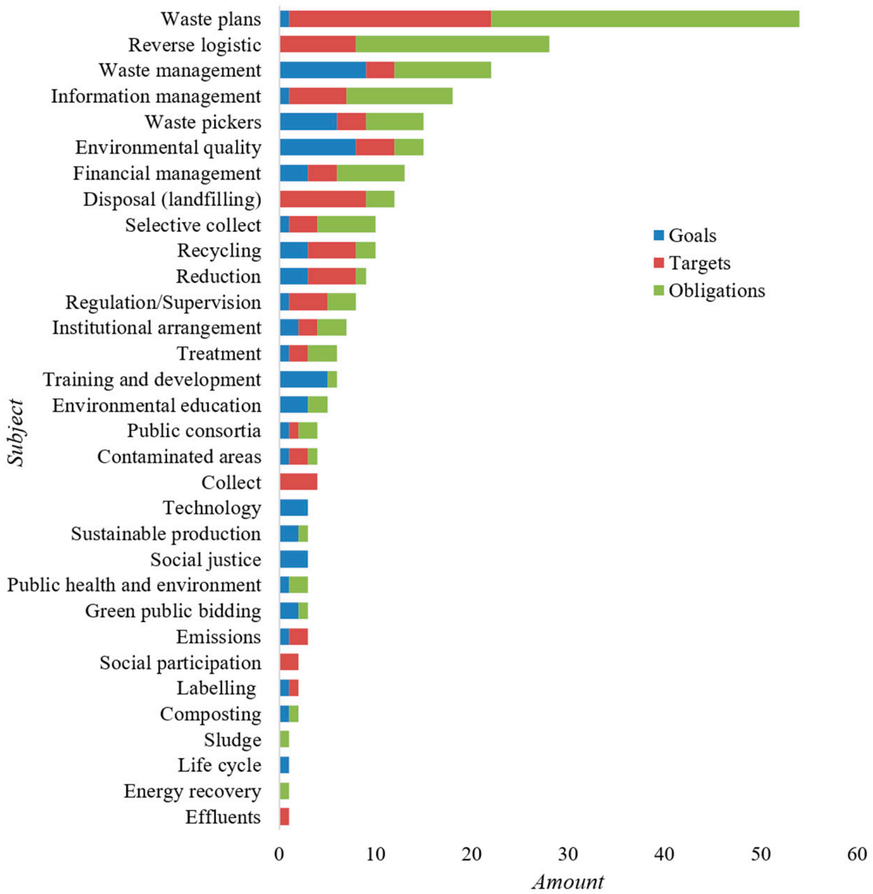


Figure 5. Goals, targets, and obligations by subject.

3.1.4. Goals, Targets, and Obligations Regarding the Type of Waste

Waste legislation in Brazil is based on international principles, particularly those followed by the EU [26]. Thus, assessing the application of the European Waste List [58] to the Brazilian context is pertinent. Figure 6 illustrates the results of the waste type classification. The classification revealed that the majority of goals, targets, and obligations were primarily related to municipal waste. This finding clearly indicates the problems associated with MSW in Brazil reported in the Introduction. Although the Brazilian legal framework for MSW is similar to that of developed countries [22], local governments face several challenges in meeting the requirements proposed by the PRNS due to financial difficulties in investing in modern infrastructure and equipment to cope with the continuously increasing MSW, resulting in a still high waste deposition in improper locations [28]. This explains why most of the targets and goals were addressed to MSW. Additionally, a strong association was found between obligations, goals, and targets. The Pearson correlation coefficient was calculated to assess this relationship, yielding a value of 0.86. The results indicate that multiple types of legislation are interrelated. For instance, the promulgation of laws may have ramifications in lower hierarchical legislation, resulting in cascading effects. Additionally, the evaluation showed that the Brazilian Waste List [72] exhibits significant similarities with the EU list [58]. This finding aligns with the perspective of Faria [73], who suggests that Europe served as a model for Brazil's national waste policy. However, some differences should be noted. For example, the Brazilian legislation focuses on waste segregation but does not consider circular economy metrics as in the EU [26].

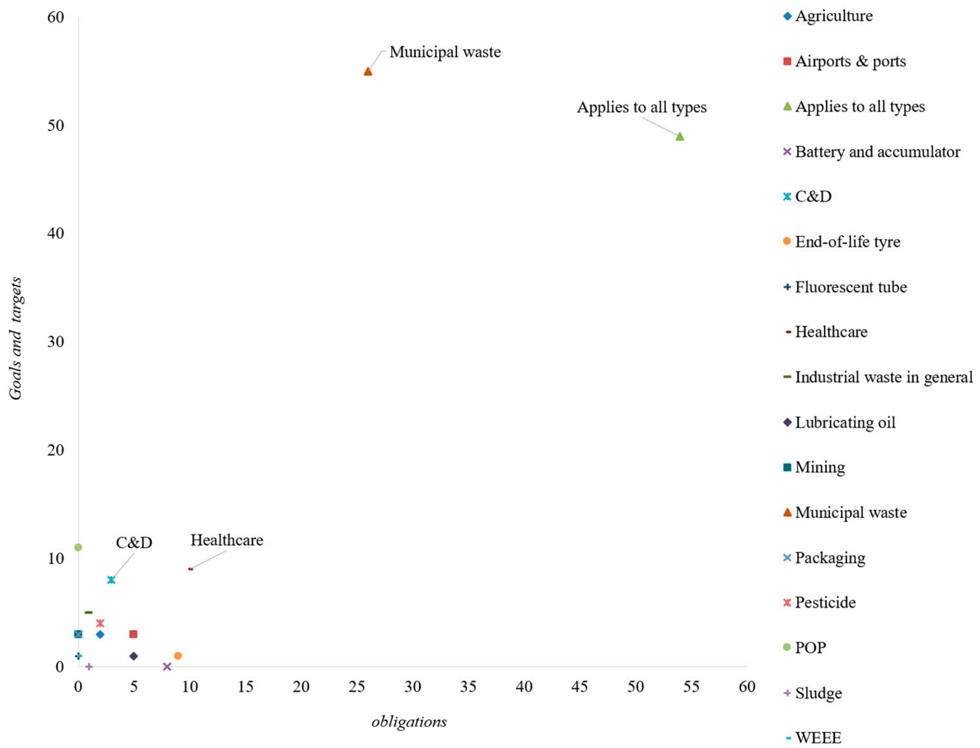
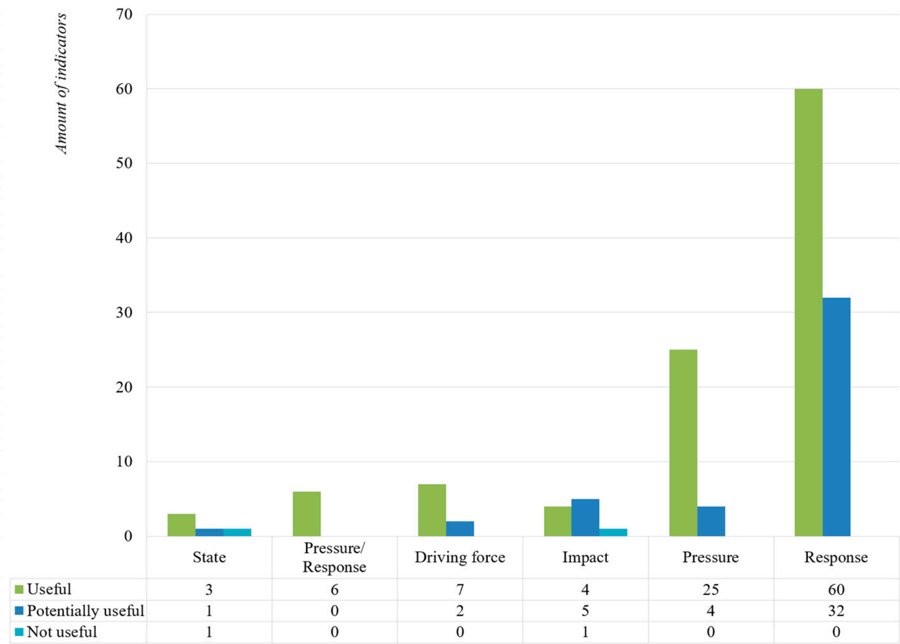


Figure 6. Goals, targets, and obligations by type of waste.

3.2. Sustainability Indicators in Waste Management

The classification of the sustainability indicators according to the DPSIR framework is summarized in Figure 7. A total of 151 indicators were identified. Of these, 61% were classified as Response type indicators, 19% as Pressure indicators, 7% as Impact indicators, 6% as Driving Force indicators, 3% as State indicators, and 4% as Pressure/Response indicators. The prevalence of Response indicators may directly reflect concerns about the outcomes of public policies and actions taken in response to environmental pressures, such as waste deposition in open dumps, the environmental consequences of these practices, or the low recycling of waste. In addition, Response indicators are typically easier to measure and track compared to indicators representing Driving forces, Pressures, or Impacts. Similar findings were reported by Cifrian et al. [74] in their study in Spain, where Response indicators were also the most representative. The analysis also showed a low percentage of Impact and State indicators, specifically related to the effects of waste disposal in improper locations, which may restrict the assessment of the environmental impacts of these waste management practices. A more detailed classification of these indicators can be found in Supplementary Tables S3 and S4.



	State	Pressure/ Response	Driving force	Impact	Pressure	Response
Useful	3	6	7	4	25	60
Potentially useful	1	0	2	5	4	32
Not useful	1	0	0	1	0	0

Figure 7. DPSIR classification of sustainability indicators related to waste.

In addition to the DPSIR classification and according to the methodological step 2.3, each indicator underwent a performance assessment and was assigned a score on a scale from 0 to 20 points to understand the extent to which indicators are useful, potentially useful, or not useful. From this evaluation, 70% of the indicators were identified as useful, 29% as potentially useful, and only 1% as not useful. Pressure indicators obtained the highest average score, with 86% deemed useful, while Response indicators exhibited the poorest performance, with only 40% classified as useful. This discrepancy can be attributed to the notable difference in the number of indicators within each category.

The classification of the seven indicator's attributes is illustrated in Figure 8. From these attributes, responsiveness obtained the highest percentage (99%), indicating that almost all indicators for this attribute scored 1. Responsiveness is of significant importance as it indicates the ability to react promptly to changes, enabling stakeholders to adapt to evolving challenges in the field of waste management. However, the scores for this attribute were limited to 0 or 1 (with no intermediary values), which restricts the analysis. The average performance of data availability and measurability was 83%, indicating a substantial amount of waste data published by national entities, including the National Sanitation Information System (SNIS). Notably, 54 indicators in this study relied on data sourced from SNIS.

In the field of waste management, analytical soundness plays a crucial role in enhancing the effectiveness of sustainability indicators, ensuring that they are supported by reliable and accurate data and methods. In our analysis, analytical soundness achieved an average performance of 73%, indicating primarily qualitative connections with the DPSIR framework, with rare quantitative links observed. While most indicators showed connections, measuring the degree of influence among them was not feasible within the scope of this study. Quantitative statistical analyses could assess this influence, but they were beyond our study's scope. However, the lack of reliable quantitative waste data may impede such analyses. The qualitative analysis helped preliminarily identify interrelated indicators, with only 1% showing a quantitative linkage. Policy relevance is another crucial attribute, reflecting the alignment of indicators with policy goals and stakeholder needs to address key waste management issues. With a performance of 71%, this attribute was deemed decisive for the final classification. The cost-effectiveness is demonstrated in proportion to the value of information derived from existing statistics and the ease of accessing the data needed for compilation [59]. The satisfactory performance of this attribute indicates that data can be easily accessed on government websites. However, effective data collection requires collaboration between national institutions and regional and municipal governments to systematize the collection and provision of waste data. Finally, the attribute ease of interpretation had the lowest performance (57%). This performance shows that at least some key messages in the legislation are not clear or easy to understand. In the study by Cifrian et al. [74], ease of interpretation was also the attribute with the lowest performance (72%).

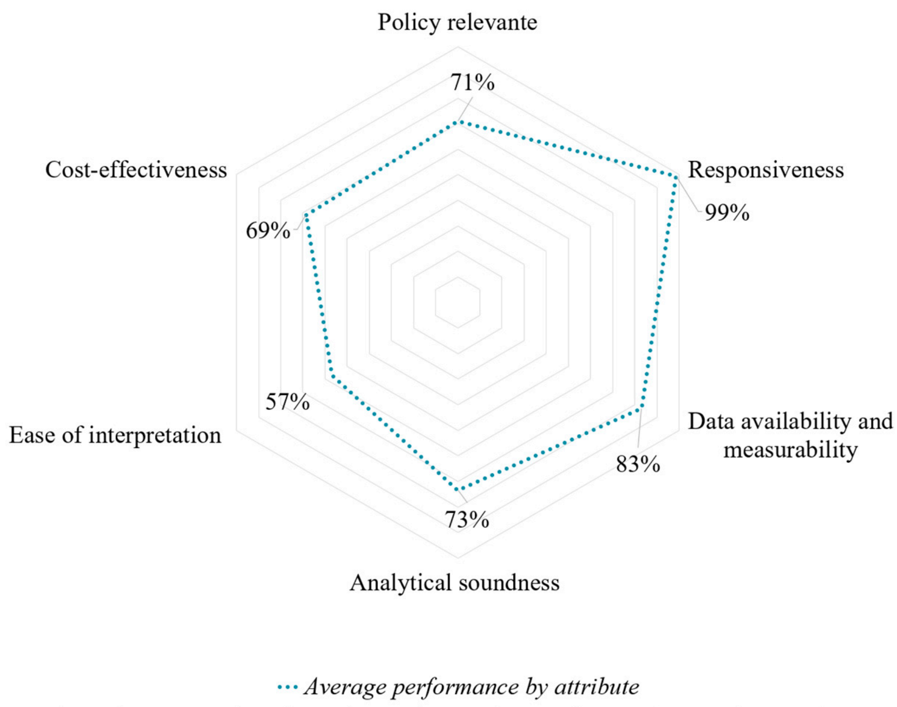


Figure 8. Performance of sustainability indicators by attribute analyzed.

In summary, the analysis of sustainability indicators' performance revealed that 70% of the data published by national institutions could be classified as useful for waste management according to the criteria outlined by EEA [59]. However, a limitation of the DPSIR framework is the lack of a direct and automatic correlation between its components, necessitating manual evaluation, which can be inefficient, subjective, and complex [51]. Another challenge in our study was the limited availability of reliable waste data for assessing various indicators. Information and Communications Technology (ICT) could play a crucial role in automating, streamlining, and enhancing the classification of information within the DPSIR framework, thereby enabling more effective environmental assessment, monitoring, and decision-making processes. Brazil is still far behind developed countries in utilizing ICT for managing environmental issues related to waste [22]. However, the use of ICT presents an opportunity to collect, organize, and manage large volumes of waste data, enabling more informed decisions and operational efficiency [75] and facilitating subsequent evaluation studies.

3.3. Indicators Framework

Figure 9 shows the DPSIR framework obtained from the legislative survey and includes the distribution of sustainability indicators across the DPSIR components and the respective waste types. The framework includes 66 sustainability indicators retrieved from various Brazilian public entities, with six classified as Driving Forces, 14 as Pressures, four as States, two as Impacts, 34 as Responses, and six as Pressure/Responses.

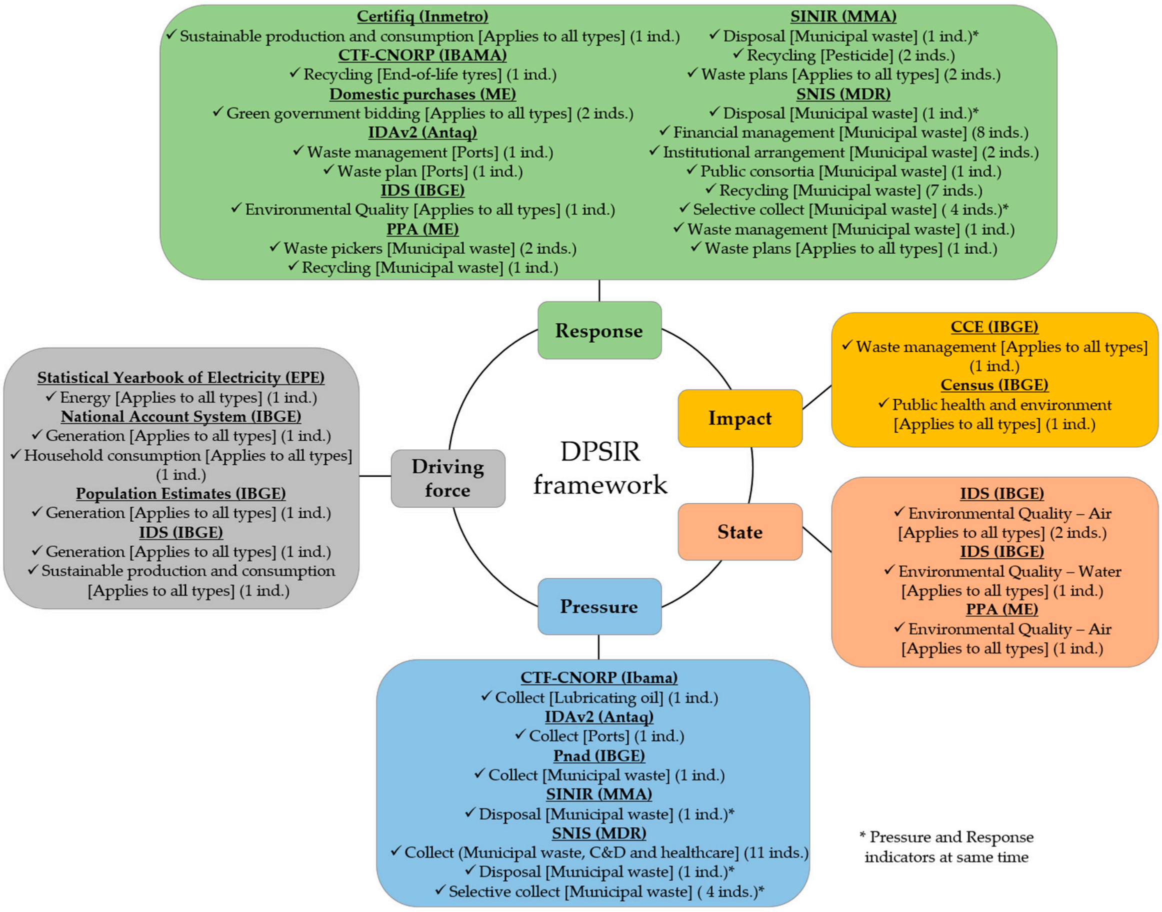


Figure 9. Proposed DPSIR framework.

The proposed DPSIR framework has revealed that a majority of indicators are related to waste collection and recycling. Waste collection and recycling have been longstanding global sustainability goals, featured in both the UN Millennium Development Goals and the 2030 Agenda for Sustainable Development (Goal 12) [76]. These goals may have influenced countries like Brazil to develop such indicators. However, in the SDS context, collection and recycling are not limited to municipal waste but encompass the entire collection system for each waste type (such as healthcare, construction, and demolition, among other wastes), requiring the use of multiple indicators to address these issues. Despite the prevalence of Response indicators, it should be noted that no response indices were found in the searched legislative documents. Nevertheless, as outlined by Cifrian et al. [74], the inclusion of waste response indices contributes to a more comprehensive evaluation of waste management. Further, the DPSIR framework reveals that various Brazilian institutions publish indicators with similar meanings. For instance, both MMA and MDR publish indicators related to waste disposal, raising concerns about the possibility of data duplication among national institutions.

This situation could lead to distrust if different results are presented for the same data. Moreover, the analysis revealed the presence of three indices that combine various information about a system into a single model [77,78]. These indices were GDP, the social inequality index (Gini index), and the water quality index (IQA) included within the Driving Force and State components. For instance, an increase in GDP could result in the generation of more waste. In turn, the inclusion of the Gini index could provide insights into social equity considerations across different socioeconomic groups in waste collection and recycling. This may help policymakers develop more inclusive, equitable, and sustainable waste management policies.

Our review of Brazilian institution systems and publications revealed gaps in monitoring social impacts, particularly those related to waste pickers. The most comprehensive publication on waste pickers, the PNSB, was last released in 2008 without a fixed publication schedule. Therefore, enhancing the presented DPSIR framework relies on increasing the frequency of data publication. According to Ibáñez-Forés et al. [40], these gaps hinder the understanding of the real impacts of waste management in developing countries. They proposed monitoring 12 categories of social impact through 22 indicators.

This study proposes a more comprehensive DPSIR framework for monitoring waste goals, targets, and obligations in Brazilian legislation. For example, in the literature, authors such as Cetrulo et al. [79] only utilized five Response indicators from SNIS to evaluate the effectiveness of the PNRS. Hence, the framework described stands out from existing methods by offering a more holistic and integrated perspective. It encompasses various dimensions, including environmental aspects such as air and water quality, social factors such as public health, economic considerations like energy and household consumption, and governance elements such as waste plans and institutional arrangements in waste management. Unlike existing methods that often focus on specific aspects or sectors in isolation, this comprehensive framework enables a more thorough and nuanced assessment of the effectiveness of PNRS and its limitations.

Furthermore, the alignment of the DPSIR framework with both international guidelines and Brazil's internal waste management policies enhances its applicability and relevance in the field. Its key contributions may include promoting standardization and consistency in waste management practices, integrating waste management considerations into national policies and plans, and identifying priority areas for intervention and resource allocation to achieve national and international sustainability targets.

Finally, to enhance waste data consistency and trustworthiness in evaluations like DPSIR, it is crucial to standardize methods and develop information systems. This can be achieved through the establishment of standardized guidelines, improved collaboration among stakeholders, and the adoption of common frameworks to provide updated waste data at the national level. Standardization among national institutions in waste management in Brazil is crucial for ensuring the quality and reliability of sustainability indicators. For instance, Pupin et al. [80] identified divergences between methodologies regarding waste data collection, highlighting the critical need for uniform criteria across different institutions. Thus, by establishing standardized methods, definitions, and protocols for data collection, public institutions can enhance the consistency, comparability, and accuracy of waste data. Waste data consolidation across different government levels can be achieved through solutions such as implementing standardized data collection protocols and establishing interoperable information systems. These measures facilitate the real-time sharing of waste data between government levels. Finally, the quality of the DPSIR framework could be enhanced through various improvements, particularly in terms of data quality, which is currently fragmented and insufficient to adequately describe certain attributes. Additionally, expanding the framework to incorporate more frequent and updated social and economic aspects related to waste management practices in Brazil would further improve its effectiveness.

4. Conclusions

In this study, a DPSIR framework was presented for identifying and classifying sustainability indicators related to waste management within Brazilian public policies. The framework was developed through a rigorous methodological process, which involved selecting and scoring sustainability indicators from legislative surveys conducted across various Brazilian public entities. Based on the conducted surveys, a total of 151 indicators, alongside 283 waste goals, targets, and obligations, primarily related to municipal waste, were identified. The evaluation revealed that 70% of the identified indicators met the quality criteria outlined by the EEA [59] and were classified as useful for waste management. Through distribution across the DPSIR components, 66 practical and relevant indicators were identified. These indicators, which can potentially be used for monitoring nationwide public policies related to waste management, span various domains, including sanitation, sustainable production and consumption, climate change, energy, the economy, public health, and demography.

While the methodology facilitated the integration of sustainability indicators from diverse fields, a significant challenge was encountered regarding the quality and continuity of waste data. Frequent discontinuity in data collection often hampers the continuity of historical data series. To improve the quality of waste data in Brazil, among other measures, it will be necessary to implement standardized data collection protocols, adopt interoperable information systems enabling real-time sharing of waste data between different government levels, and support municipalities in collecting and regularly publishing waste data.

This study has some limitations that should be highlighted. Our findings are primarily based on the search conducted on Brazilian legislation. Relying solely on governmental documents may introduce biases, potentially reflecting specific perspectives or political agendas. Further, the legislative survey conducted may not capture all relevant legal documents or fully represent the complexity of waste management practices across different regions and entities in Brazil. Moreover, defining indicators within the DPSIR framework, particularly for components such as Driving force and Pressure vs. State and Impact, can be complex, leading to potential inconsistencies or misinterpretations. These limitations could be addressed by incorporating complementary data sources, such as those from non-governmental organizations and scientific publications, involving stakeholders in the process utilizing data from ICT tools, among others. Utilizing these complementary sources could potentially ensure a more comprehensive and balanced understanding of waste management in Brazil.

Besides the described limitations, the framework offers novel opportunities for waste management, enabling the measurement of public policy responses and providing feedback to managers, decision-makers, politicians, and society. The framework can potentially be applied to other scales (municipal, regional, continental), requiring accurate and comparable waste data and the tailoring of sustainability indicators to local contexts. Integrating waste legislation and indicators from various governmental levels into the DPSIR framework can enhance its comprehensiveness and relevance by providing a holistic view of adopted practices. However, challenges may arise from inconsistencies in laws, data availability, and differing priorities among public entities. This needs careful coordination and alignment efforts to ensure effective integration and interpretation of diverse waste data sources within the framework. Further research is needed to test and validate the applicability of the described framework. This can be achieved by applying the methodology to various scales and case studies in Brazil and other countries to evaluate its effectiveness in analyzing waste management dynamics, identifying key drivers and pressures, assessing environmental and socioeconomic impacts, and informing policy responses. Additionally, involving waste management experts and stakeholders through workshops or focus groups to discuss the DPSIR framework could provide another avenue for validation and potentially improve the methodology.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16052192/s1, Table S1: Goals, targets, and obligations in Brazilian national legislation; Table S2: Number of goals, targets, and obligations in national legislation; Table S3: Sustainability indicators classified as suitable for use in DPSIR framework; Table S4: Others indicators.

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