PROPOSAL FOR A SANITARY LANDFILL CLOSURE PLAN MODEL USING MULTI-CRITERIA DECISION SUPPORT TOOL

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ABSTRACT

The closure of sanitary landfills is a critical issue due to the environmental and social impacts they generate. This study proposes a closure plan based on a multicriteria decision support tool, considering environmental, economic, and social criteria. The methodology includes identifying relevant criteria, defining alternatives, applying the multicriteria tool, and selecting the best strategy. The approach seeks to minimize impacts, promote public safety, and address local demands, contributing to more sustainable practices in solid waste management. The study employed a descriptive, explanatory, and exploratory methodology, consulting experts to validate the steps of the closure process. Using the SNOWBALL technique, 10 specialists from various fields, including environmental engineering, biology, and governmental agencies, were selected. The results highlighted a consensus among university professors and the diverse perceptions of professionals from academic and industrial sectors. The participation of an environmental engineer linked to an industrial construction company brought a practical perspective, connecting academic theory to private sector needs. The proposed plan model follows guidelines covering phases from diagnosis to post-closure maintenance, focusing on rehabilitating the area and integrating it into the community. Continuous monitoring reinforces environmental responsibility, ensuring the process's sustainability. Thus, the study offers a strategic model for the closure of sanitary landfills, aligned with contemporary demands for responsible and efficient environmental management.

Keywords: *Waste Management, Decision-Making Model, Sustainability, Environmental Impact, Resource Recovery*

I. INTRODUCTION

The increasingly accentuated consumption patterns, coupled with changes in production methods and the growth of urban centers, have led to a significant increase in the generation of Municipal Solid Waste (MSW). In this context, it is necessary to find alternatives to minimize the negative impacts, particularly regarding the improper final disposal of such waste.

According to the Brazilian Association of Public Cleaning Companies – ABRELPE (2020), between 2010 and 2019, Brazil generated approximately 79 million tons of MSW per year, with a per capita generation of 379 kg/year. Solid waste production increased by about 1%, reaching a total of 216,629 tons of MSW per day in the country. This rate exceeds the population growth rate of 0.77% over the same period.

The National Solid Waste Policy (PNRS), Law No. 12,305 of August 2, 2010, establishes principles, objectives, and instruments, as well as guidelines for integrated management and solid waste management. Among other provisions, it determines that the environmentally appropriate final disposal

of waste must occur through the orderly disposal of residues in sanitary landfills, following specific operational standards to avoid risks to public health and safety and to minimize adverse environmental impacts (Brazil, 1998).

Although the PNRS states that sanitary landfills should be the environmentally correct final disposal for domestic waste, the reality remains far from this goal. In most Brazilian cities, final disposal still occurs through open dumps, which involve the uncontrolled disposal of waste, posing risks to the environment and human health.

According to the National Sanitation Information System (SNIS), in its Urban Solid Waste Management Diagnosis (2021), Brazil collected about 92.7 million tons of solid waste in 2020, but only 48.2 million tons were adequately disposed of in sanitary landfills. The remaining 44.5 million tons were sent to open dumps, controlled landfills, and other unrecorded destinations.

Despite the existing challenges in complying with current legislation and pursuing sustainable development in solid waste management, the presence of sanitary landfills is essential for proper final disposal. When used by the government or private sector for this purpose, specific operational rules must be followed, from the landfill's initial operation to its closure when its useful life reaches its limit. High-tech procedures must be in place before, during, and after the landfill's closure to prevent harm to public health and the environment. Efficient disposal requires well-managed projects from site selection to environmental monitoring actions during the closure and post-closure period.

Sanitary landfill projects must anticipate their useful life during initial planning to avoid environmental and social harm. The useful life of a landfill ends when the maximum volume of waste specified in the initial project is reached. According to Gurjão et al. (2019), one factor influencing the useful life of landfills is the composition of materials in Municipal Solid Waste. When a landfill reaches the end of its operational period, closure processes must begin.

According to ABNT NBR 13,896 standards, the deactivation of a sanitary landfill must be preceded by a series of plans and actions. It is necessary to conduct studies on the steps to follow during closure, ensuring quality and efficiency in all procedures involved. Poorly executed processes can result in significant short- and long-term negative impacts (ABNT, 1997).

Therefore, there is a clear need to define these closure processes to develop well-structured models with properly ranked actions based on current legislation and bibliographies on the subject. These models can then be applied to the diverse realities of sanitary landfill closure processes.

An applicable tool for this purpose is multicriteria analysis, which, according to Francisco et al. (2007, p.13), is a method of analyzing alternatives to solve problems using multiple criteria related to the study object. It allows for identifying priority alternatives for the considered object.

II. OBJECTIVES

2.1. General Objective

Develop a model for a sanitary landfill closure plan using the multicriteria decision support tool.

2.2. Specific Objectives

- Conduct a diagnosis regarding the final disposal of municipal solid waste in Brazil;
- Conduct a diagnosis regarding the closure of sanitary landfills in Brazil;
- Provide an overview of the number of sanitary landfills in Brazil, with emphasis on the Northeast region and the state of Ceará;

- Select the most commonly used processes for closing sanitary landfills in Brazil, ranking them in order of importance, using a decision-making method with the multicriteria analysis tool.

III. METHODOLOGY

This study follows a descriptive, explanatory, and exploratory research methodology that aims to consult experts and subsequently validate, through a decision-making software tool, the most appropriate order of steps to be followed in the sanitary landfill closure process. This will allow for the development of a Sanitary Landfill Closure Plan based on the results found.

Figure (eg, Figure 1) presents, in the form of a methodological flowchart, the steps followed in this research, including literature review, selection of criteria and alternatives for each phase of the landfill closure process, questionnaire development, application of the questionnaire to experts, use of the PROMETHEE method, and the creation of the Sanitary Landfill Closure Plan model.

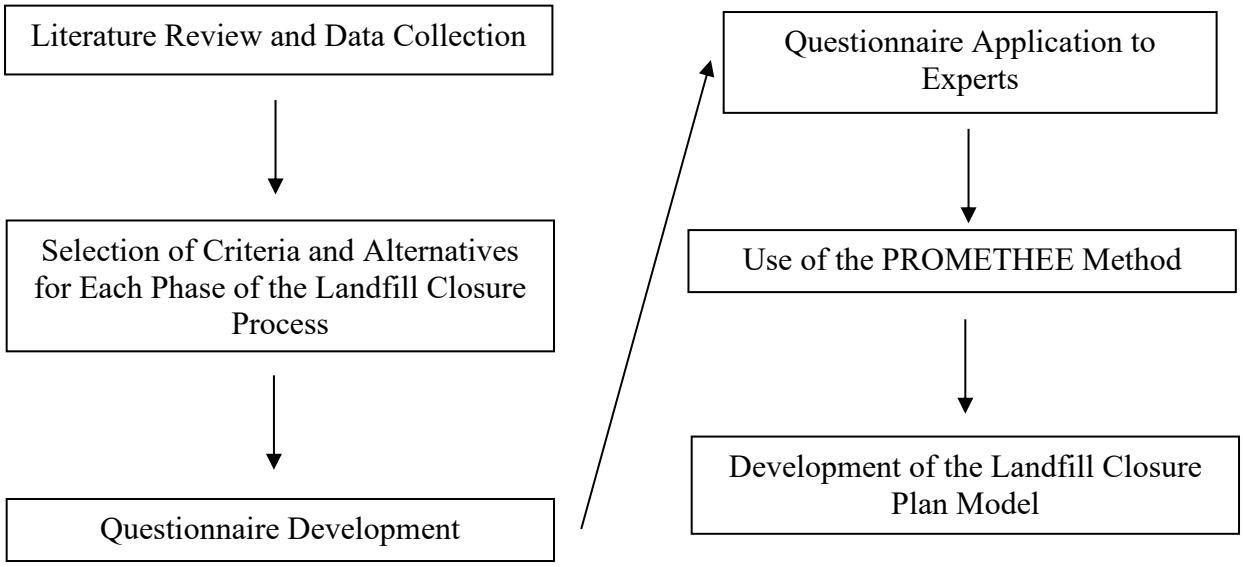

Figure 1. Methodological flowchart of the research

IV. RESULTS AND DISCUSSIONS

4.1. Results of the application of the questionnaire to the experts

The research involved the participation of 10 specialists, each identified by their profession and affiliated institution. The results provided a comprehensive view of these professionals' perceptions. In this diagnostic phase of data analysis, the research included a wide diversity of participants in terms of their professions.

Thus, the specialists represent a variety of professions, including academics, environmental agencies, and consultancies. There was consistency in the responses, and an initial analysis reveals consistency in the responses from university professors, indicating a possible alignment of perspectives within the academic environment.

Regarding the environmental focus, it is notable that professionals with backgrounds in environmental engineering and biology are present, signaling a multidisciplinary approach in the responses, which may enrich the discussions on the topic.

Concerning the contribution of the industry, the presence of an environmental engineer linked to an industrial construction company specializing in landfills adds a practical perspective to the dataset,

indicating a connection between academia and the private sector. The agreement among professors from different universities suggests academic consensus on certain aspects, which may indicate a solid knowledge base in the field.

There is an interconnection between theory and practice, with the presence of professionals active in the industry highlighting the importance of this connection, emphasizing the relevance of academic research for real-world challenges.

The interdisciplinary approach, with a combination of biologists and environmental engineers, highlights the need for interdisciplinary approaches in addressing complex environmental issues. The diversity of profiles also emphasizes the challenges and opportunities faced by professionals in different sectors, providing valuable insights for future research and collaborations.

These results offer an initial understanding of the landscape of opinions among the specialists, providing a solid foundation for deeper analyses and meaningful contributions to the field in question.

4.1.1 Diagnostic Phase of Condition

In the first approach of the form, during the phase called the Diagnostic Phase of Condition, the specialists were invited to assign a weight value (from 1 to 5) to each criterion based on their own evaluation and considerations.

When assigning these weights, the specialists took into account the impact each criterion has on the final decision. Thus, they filled it out in such a way that a criterion with a higher weight had a more significant impact on the evaluation than a criterion with a lower weight.

Therefore, during the Diagnostic Phase of Condition, the specialists indicated which criterion was of greatest importance, assigning it a value of 5. Among the others, they indicated which had the least importance, consequently assigning a value lower than 5. In this way, at this initial stage, they followed this procedure until all criteria had values assigned.

Continuing with the questionnaire, the specialists responded regarding the relevance of each criterion, but now based on the alternatives presented. In other words, the relevance degrees were used to assess and compare the alternatives in relation to each specific criterion.

For the first alternative in the Diagnostic Phase of Condition, called "Topographic survey of the site". This resulted in highlights where most of the specialists defined the criteria C2, defined as "Execution time," and C5, defined as "Negative environmental impacts," as less relevant. On the other hand, the criterion C3, defined as "Need for specialized labor," stood out as the most relevant for this alternative, receiving the highest number of choices.

For the second alternative, called "Provision of a drainage system for gases and liquids". This resulted in highlights where most of the specialists defined the criterion C5, defined as "Negative environmental impacts," as very relevant, with 5 selections, and the criterion C1, defined as "Financial feasibility," also as relevant, with 5 selections. For the majority, C3, defined as "Need for specialized labor," was considered "moderately relevant" for the alternative in question.

For the three alternative called "Planning a drainage system to prevent water riots (water mines) in the surrounding area" was presented. In this context, C1, named Financial Viability, was chosen by most of the experts as "relevant," while C5, related to negative impacts, was considered "highly relevant.

For the fourth alternative in this phase, titled "Design a monitoring system for visual, chemical, and environmental analysis of soil and water," the experts mostly attributed the following relevance levels:

for Financial Viability (C1), it was considered "relevant"; for Execution Timeline (C2), it was considered "slightly relevant"; for the Need for Specialized Labor (C3), the relevance levels "moderately relevant" and "relevant" stood out, with three selections each; for the Technologies Used (C4), the majority classified it as "highly relevant"; and for Negative Environmental Impacts (C5), with three selections each, the relevance levels were "moderately relevant" and "highly relevant.

Regarding the fifth alternative in this phase, titled "Collection of basic information on the type, composition, consistency, volume of release, and characterization of existing waste," the experts mostly attributed the following relevance levels: for Financial Viability (C1), the relevance levels "slightly relevant" and "relevant" were selected, each with four marks. For Execution Timeline (C2), the majority selected "slightly relevant"; for the Need for Specialized Labor (C3), the relevance level "moderately relevant" stood out, with four selections; for the Technologies Used (C4), the majority classified it as "moderately relevant" and "relevant"; and for Negative Environmental Impacts (C5), the relevance levels "moderately relevant" and "highly relevant" were selected, each with three marks.

Regarding the sixth alternative in this phase, titled "Evaluation of site risks," the experts mostly attributed the relevance of "relevant" for Financial Viability (C1), with four selections. For Execution Timeline (C2), the majority selected "slightly relevant"; for the Need for Specialized Labor (C3), there was a balance, with three selections each for the relevance levels "moderately relevant," "relevant," and "highly relevant." Regarding the criterion Technologies Used (C4), the majority classified it as "highly relevant," and for Negative Environmental Impacts (C5), the relevance level "highly relevant" was selected by the majority, with six selections.

For the seventh alternative in this phase, titled "Preparation of the Preliminary Environmental Report (RAP), based on the information collected earlier," the experts mostly attributed a relevance of "relevant" for Financial Viability (C1), with five selections. For Execution Timeline (C2), the majority selected "relevant." Regarding the Need for Specialized Labor (C3), there was a balance, with two selections each for the relevance levels "relevant" and "highly relevant." In relation to the criterion Technologies Used (C4), there was also a balance between the relevance levels "Irrelevant," "Moderately relevant," and "relevant," each with three selections. For Negative Environmental Impacts (C5), the majority selected "highly relevant," with four selections.

For the eighth alternative in this phase, titled "Development of a green belt project in the area, in the 20% waste disposal strip," the experts mostly attributed a relevance of "slightly relevant" for Financial Viability (C1), with four selections. For Execution Timeline (C2), the majority selected "moderately relevant." Regarding the Need for Specialized Labor (C3), the majority selected the relevance level "relevant." In relation to the criterion Technologies Used (C4), there was a balance between the most selected relevance levels, "Irrelevant" and "moderately relevant," each with three selections. For Negative Environmental Impacts (C5), the majority selected "highly relevant," with four selections.

Regarding the ninth alternative in this phase, titled "Identification of the sequence for closing unstable structural operations used on the site," the experts mostly assigned a relevance of "relevant" for Financial Viability (C1), with five selections. For Execution Timeline (C2), the majority selected "relevant." Regarding the Need for Specialized Labor (C3), the majority selected the relevance level "relevant." In relation to the criterion Technologies Used (C4), the most selected relevance level was "moderately relevant," with five selections. For Negative Environmental Impacts (C5), the majority selected "highly relevant," with four selections.

For the tenth alternative in this phase, titled "Documentary Evaluation Related to the Sanitary Landfill," the experts mostly assigned a "slightly relevant" degree of relevance for Financial Viability (C1), with four selections. For Execution Timeline (C2), the majority selected "relevant." Regarding the Need for Specialized Labor (C3), the majority selected the relevance level "moderately relevant." In relation to the criterion Technologies Used (C4), the relevance levels "slightly relevant" and "moderately relevant"

were balanced, each with three selections. For Negative Environmental Impacts (C5), the relevance levels "slightly relevant" and "highly relevant" were also balanced, each with three selections.

For the last alternative in this phase, titled "Mitigation and Compensation Approach for the Surrounding Community of the Landfill and for the Landfill Workers," the experts mostly assigned a "relevant" degree of relevance for Financial Viability (C1), with four selections. For Execution Timeline (C2), the majority selected "relevant." Regarding the Need for Specialized Labor (C3), the majority selected the relevance level "relevant." In relation to the criterion Technologies Used (C4), the relevance levels "moderately relevant" and "relevant" were balanced, each with three selections. For Negative Environmental Impacts (C5), the relevance level "highly relevant" stood out, with six selections.

4.1.2 Phase of Action Initiation

For the first alternative in this phase, titled "Review of the closure plan with a focus on eliminating potential failures," the specialists predominantly assigned the "moderately relevant" relevance to Financial Feasibility (C1), with "relevant" being selected three times as well. For Execution Time (C2), the majority selected "slightly relevant." Regarding the Need for Specialized Labor (C3), the majority chose "highly relevant." In terms of the Technologies Used (C4), the relevance levels "moderately relevant" and "highly relevant" were balanced, each receiving three selections. For Negative Environmental Impacts (C5), the most selected relevance was "relevant," with five votes from the specialists.

For the second alternative in this phase, titled "Defining a specific closure date," the specialists predominantly assigned the "moderately relevant" relevance to Financial Feasibility (C1), with three selections. For Execution Time (C2), the majority selected "highly relevant." Regarding the Need for Specialized Labor (C3), the majority chose "irrelevant." In terms of the Technologies Used (C4), most specialists selected the relevance level "slightly relevant." For Negative Environmental Impacts (C5), the relevances "irrelevant" and "slightly relevant" were balanced, each receiving three selections from the specialists.

For the third alternative in this phase, titled "Notifying the regulatory body about the procedures adopted," the specialists predominantly assigned the relevance level "slightly relevant" to Financial Feasibility (C1), with four selections. For Execution Time (C2), the majority selected "moderately relevant." Regarding the Need for Specialized Labor (C3), the majority chose "relevant." In terms of the Technologies Used (C4), most specialists selected the relevance level "slightly relevant." For Negative Environmental Impacts (C5) of this alternative, the specialists predominantly selected the relevance level "highly relevant."

For the fourth alternative in this phase, titled "Development of an action plan regarding the closure of activities," the specialists predominantly assigned the relevance level "moderately relevant" to Financial Feasibility (C1), with four selections. For Execution Time (C2), the majority selected "highly relevant." Regarding the Need for Specialized Labor (C3), the majority chose "highly relevant," with six selections. In terms of Technologies Used (C4), most specialists selected the relevance level "relevant." For Negative Environmental Impacts (C5) of this alternative, the specialists predominantly selected "irrelevant" and "slightly relevant," each with three selections.

For the fifth alternative in this phase, titled "Definition of performance indicators for the technical part and processes," the specialists predominantly assigned relevance levels of "irrelevant" and "slightly relevant" to Financial Feasibility (C1), each with three selections. For Execution Time (C2), the majority selected "slightly relevant" and "relevant," each with three selections. Regarding the Need for Specialized Labor (C3), the majority selected "moderately relevant," "relevant," and "highly relevant," each with three selections. In terms of Technologies Used (C4), most specialists selected "relevant." For Negative Environmental Impacts (C5) of this alternative, the specialists predominantly selected "highly relevant," with four selections.

For the sixth alternative in this phase, titled "Development of a communication plan," the specialists predominantly assigned a "relevant" relevance level to Financial Feasibility (C1), with four selections. For Execution Time (C2), the majority selected "slightly relevant." Regarding the Need for Specialized Labor (C3), the majority selected "highly relevant" with six selections. In terms of Technologies Used (C4), most specialists selected "moderately relevant." For Negative Environmental Impacts (C5) of this alternative, the specialists predominantly selected "irrelevant" with five selections.

For the seventh and final alternative in this phase, titled "Obtaining necessary approvals and authorizations," the specialists predominantly assigned a "relevant" relevance level to Financial Feasibility (C1), with four selections. For Execution Time (C2), the majority selected "highly relevant." Regarding the Need for Specialized Labor (C3), the majority selected both "moderately relevant" and "relevant," with three selections each. In terms of Technologies Used (C4), most specialists selected "irrelevant." For Negative Environmental Impacts (C5) of this alternative, the specialists predominantly selected "moderately relevant" with four selections.

4.1.3 Landfill closure phase

In the first alternative of this phase, titled “Install fences or other appropriate structures to prevent unauthorized access,” the experts mostly assigned a relevance degree of "relevant" for Financial Viability (C1) with 5 selections. For Execution Timeline (C2), the majority selected "moderately relevant." Regarding the Need for specialized labor (C3), most experts chose the relevance degree "irrelevant" with 4 selections. In the Technologies used (C4) criterion, the majority of experts selected "slightly relevant." As for the Negative Environmental Impacts (C5) of this alternative, the majority of experts selected "moderately relevant" with 3 selections.

In the second alternative of this phase, titled “Collect all remaining trash or debris and place it in the disposal area for disposal,” the experts mostly assigned relevance degrees of "slightly relevant" and "very relevant" for Financial Viability (C1), with 3 selections each. For Execution Timeline (C2), the majority selected "moderately relevant." Regarding the Need for specialized labor (C3), most experts chose "irrelevant" with 4 selections. In the Technologies used (C4) criterion, the majority of experts selected "slightly relevant." For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected "moderately relevant" and "very relevant" with 3 selections each.

In the third alternative of this phase, titled “Cover all waste that might be exposed,” the experts mostly assigned a relevance degree of "slightly relevant" for Financial Viability (C1), with 4 selections. For Execution Timeline (C2), the majority selected "very relevant." Regarding the Need for specialized labor (C3), most experts chose "irrelevant" with 4 selections. In the Technologies used (C4) criterion, the majority of experts selected "moderately relevant." For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected "very relevant" with 4 selections.

In the fourth alternative of this phase, titled “Verify if all the goals and actions established in the diagnostic phase have been executed,” the experts mostly assigned a relevance degree of "moderately relevant" for Financial Viability (C1), with 3 selections. For Execution Timeline (C2), the majority selected "very relevant." Regarding the Need for specialized labor (C3), most experts chose "relevant" with 5 selections. In the Technologies used (C4) criterion, the majority of experts selected the relevances "slightly relevant," "relevant," and "very relevant" with 3 selections each. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the relevances "irrelevant," "relevant," and "very relevant" with 2 selections for each.

In the fifth alternative of this phase, titled “Perform gas monitoring,” the experts mostly assigned a relevance degree of "relevant" for Financial Viability (C1), with 4 selections. For Execution Timeline (C2), the majority selected "irrelevant." Regarding the Need for specialized labor (C3), most experts chose "very relevant" with 5 selections. In the Technologies used (C4) criterion, the majority of experts selected the relevance "moderately relevant" with 4 selections. For the Negative Environmental Impacts

(C5) of this alternative, the experts mostly selected the relevance degree "very relevant" with 4 selections.

In the sixth alternative of this phase, titled “Implementation of appropriate drainage systems to prevent water accumulation in the landfill,” the experts mostly assigned a relevance degree of "relevant" for Financial Viability (C1), with 5 selections. For Execution Timeline (C2), the majority selected "irrelevant." Regarding the Need for specialized labor (C3), most experts chose "moderately relevant" with 4 selections. In the Technologies used (C4) criterion, the majority of experts selected the relevances "moderately relevant," "relevant," and "very relevant" with 3 selections each. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the relevance degree "very relevant" with 4 selections.

In the eighth alternative of this phase, titled “Groundwater monitoring,” the experts mostly assigned a relevance degree of "relevant" and "very relevant" for Financial Viability (C1), with 4 selections each. For Execution Timeline (C2), the majority selected "irrelevant." Regarding the Need for specialized labor (C3), most experts chose "relevant" with 4 selections. In the Technologies used (C4) criterion, the majority of experts selected the relevance degree "moderately relevant" with 4 selections. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the relevance degrees "relevant" and "very relevant," with 3 selections each.

In the ninth and final alternative of this phase, titled “Air Pollution Control,” the experts mostly assigned relevance degrees of "relevant" and "very relevant" for Financial Viability (C1), with 3 selections each. For Execution Timeline (C2), the majority selected "irrelevant." Regarding the Need for specialized labor (C3), most experts chose "relevant" with 4 selections. In the Technologies used (C4) criterion, the majority of experts selected "moderately relevant" with 4 selections. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected "very relevant" with 4 selections.

4.1.4 Post-Closure Phase

For the first alternative of this phase, titled "Technical evaluation of the conditions of the bottom layers," the experts mostly assigned a "moderately relevant" and "relevant" degree of relevance for Financial Feasibility (C1), with 3 selections each. For the Execution Timeline (C2), the relevance chosen by the majority was "irrelevant." Regarding the Need for Specialized Labor (C3), the majority selected the "highly relevant" degree of relevance, with 5 selections. For the Technologies Used (C4), the majority of experts selected the "slightly relevant" degree of relevance with 4 selections. Regarding the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the "irrelevant" and "moderately relevant" degrees of relevance, with 3 selections each.

For the second alternative of this phase, titled "Use and maintain vegetation cover over time," the experts mostly assigned a "moderately relevant" degree of relevance for Financial Feasibility (C1), with 4 selections. For the Execution Timeline (C2), the relevance selected by the majority was "highly relevant." Regarding the Need for Specialized Labor (C3), the majority selected the "moderately relevant" degree of relevance with 3 selections. For the Technologies Used (C4), the majority of experts selected the "relevant" degree of relevance with 4 selections. Regarding the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the "relevant" degree of relevance, with 3 selections.

For the third alternative of this phase, titled "Carry out necessary repairs and cleaning operations at transfer stations to keep them fully functional," the experts mostly assigned a "moderately relevant" and "relevant" degree of relevance for Financial Feasibility (C1), with 3 selections each. For the Execution Timeline (C2), the relevance selected by the majority was "moderately relevant" and "relevant." Regarding the Need for Specialized Labor (C3), the majority selected the degrees of relevance "irrelevant," "moderately relevant," and "highly relevant," with 3 selections each. For the Technologies Used (C4), the majority of experts selected the "moderately relevant" degree of relevance with 4

selections. Regarding the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the "moderately relevant" degree of relevance, with 5 selections.

For the fourth alternative of this phase, titled "Prepare comprehensive reports every 6 (six) months containing environmental, technical, and socio-economic information about an investigation involving risk assessment," the experts mostly assigned a "relevant" degree of relevance for Financial Feasibility (C1), with 4 selections. For the Execution Timeline (C2), the relevance selected by the majority was "slightly relevant." Regarding the Need for Specialized Labor (C3), the majority selected the relevance degrees "slightly relevant" and "highly relevant," with 3 selections each. In terms of Technologies Used (C4), the majority of experts selected the relevance degrees "irrelevant" and "moderately relevant," with 3 selections each. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the "slightly relevant" degree of relevance, with 4 selections.

For the fifth alternative in this phase, titled "Regular weekly inspections," the experts assigned equal relevance without a predominant grade for the majority in the Financial Feasibility (C1) criterion, with 2 selections for each degree of relevance. For the Execution Timeline (C2), the relevance selected by the majority was "irrelevant." Regarding the Need for Specialized Labor (C3), the majority selected the relevance degrees "slightly relevant" and "relevant," with 4 selections each. In terms of Technologies Used (C4), the majority of experts selected the relevance degree "moderately relevant" with 4 selections. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the "slightly relevant" degree of relevance, with 3 selections.

For the sixth alternative in this phase, titled "Maintenance of structures," the experts assigned the "very relevant" degree of relevance for the Financial Feasibility (C1) criterion with 4 selections. For the Execution Timeline (C2), the relevance selected by the majority was "irrelevant." Regarding the Need for Specialized Labor (C3), the majority selected the relevance degree "relevant" with 4 selections. In terms of Technologies Used (C4), the majority of experts selected the "relevant" degree of relevance with 5 selections. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the "moderately relevant" degree of relevance with 3 selections.

For the seventh alternative in this phase, titled "Leachate Management," the experts assigned the "very relevant" degree of relevance for the Financial Feasibility (C1) criterion with 3 selections. For the Execution Timeline (C2), the relevance selected by the majority was "irrelevant." Regarding the Need for Specialized Labor (C3), the majority selected the "very relevant" degree of relevance with 4 selections. In terms of Technologies Used (C4), the majority of experts selected the "relevant" degree of relevance with 4 selections. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the "very relevant" degree of relevance with 3 selections.

For the eighth and penultimate alternative in this phase, titled "Maintenance of Final Cover," the experts assigned the "relevant" degree of relevance for the Financial Feasibility (C1) criterion with 4 selections. For the Execution Timeline (C2), the relevance selected by the majority was "relevant." Regarding the Need for Specialized Labor (C3), the majority selected the "moderately relevant" degree of relevance with 3 selections. In terms of Technologies Used (C4), the majority of experts selected the "moderately relevant" degree of relevance with 6 selections. For the Negative Environmental Impacts (C5) of this alternative, the experts mostly selected the "relevant" degree of relevance with 4 selections.

For the ninth and final alternative in this phase, titled "Updating the Monitoring Plan," the experts assigned the "relevant" degree of relevance for the Financial Feasibility (C1) criterion with 5 selections. For the Execution Timeline (C2), the relevance selected by the majority was "slightly relevant." Regarding the Need for Specialized Labor (C3), the majority selected the "relevant" degree of relevance with 5 selections. In terms of Technologies Used (C4), the majority of experts selected the "moderately relevant" degree of relevance with 4 selections. For the Negative Environmental Impacts (C5) of this alternative, the experts assigned an equal distribution of relevance degrees, with no predominant relevance for the majority, as 2 selections were made for each degree of relevance.

4.2 Results of the use of the PROMETHEE method

As described in the methodological procedures of this study, after the data collection stage from the specialists, they were applied to the PROMETHEE method using the Visual Promethee Academic software. The software, as well as the method, provides both quantitative analysis, through numerical utilization, and qualitative analysis, using scales ranging from very low, low, medium, high, to very high. For application in the software, a correlation was made between the scales present in the software and the average scales of the weights defined by the specialists.

To do so, the average of the weights indicated by the 10 specialists was initially calculated for each alternative in each phase. After obtaining the averages for each alternative for each criterion, for later qualitative application in the software, the following interpretation scale was used, as previously described in this study:

- 1 to 1.9 – Irrelevant – Very Low
- 2 to 2.9 – Slightly Relevant – Low
- 3 to 3.9 – Moderately Relevant – Medium
- 4 to 4.9 – Relevant – High
- 5 to Very Relevant and Very High

With the averages obtained and their respective defined scales, a type of file was created for each phase in the selected software.

Therefore, the most recommended order of action for the alternatives according to the PROMETHEE method for this phase is as follows:

1. Document evaluation related to the sanitary landfill.
2. Mitigation and compensation approach for the surrounding community of the landfill and for the landfill workers.
3. Topographical survey of the site.
4. Design a monitoring system for visual, chemical, and environmental analysis of the soil and water.
5. Provision of a drainage system for gases and liquids.
6. Identification of the sequence for closing unstable structural operations used on-site.
7. Preparation of the Preliminary Environmental Report (PER), based on the information collected previously.
8. Planning of a water drainage system to prevent waterlogging (water springs) in the surrounding area.
9. Risk assessment.
10. Collection of basic information about the type, composition, consistency, volume of release, and characterization of the existing waste.
11. Development of the green belt project in the area, covering 20% of waste disposal.

Therefore, the most recommended order of action for the alternatives according to the PROMETHEE method for this phase is as follows:

1. Definition of performance indicators for technical aspects and processes.
2. Review of the closure plan with a focus on eliminating potential flaws.
3. Notification to the regulatory body about the procedures adopted.
4. Development of an action plan regarding the closure of activities.
5. Obtaining necessary approvals and authorizations.
6. Setting a specific closure date.
7. Preparation of a communication plan.

Thus, the most recommended order of action for the alternatives according to the PROMETHEE method for this phase is as follows:

1. Verify if all the goals and actions established in the condition diagnosis phase have been executed.
2. Implementation of appropriate drainage systems to prevent water accumulation in the landfill.
3. Slope reinforcement.
4. Monitoring of groundwater.
5. Cover all exposed waste.
6. Install fences or other appropriate structures to prevent unauthorized access.
7. Collect all remaining waste or debris and place it in the disposal area for disposal.
8. Perform gas monitoring.
9. Air pollution control.

Thus, the most recommended order of action for the alternatives according to the PROMETHEE method for this phase is as follows:

1. Maintenance of structures.
2. Leachate management.
3. Maintenance of the final cover.
4. Technical assessment of the conditions of the bottom layers.
5. Use and maintain vegetation cover over time.
6. Perform necessary repairs and cleaning operations in the transfer stations to keep them fully functional.
7. Regular weekly inspections.
8. Update the monitoring plan.
9. Prepare comprehensive reports every 6 (six) months containing environmental, technical, and socioeconomic information about an investigation involving risk assessment.

V. CONCLUSIONS

The primary objective of this research was the development of a comprehensive Landfill Closure Plan model, using a multi-criteria decision support tool to address the persistent challenges in urban solid waste management within the Brazilian context. Through a meticulous and careful approach, each specific objective was thoughtfully addressed, contributing to the construction of a robust and holistic framework.

In the context of the general objective, in addition to developing the plan model, it was possible to integrate a wide range of essential criteria and variables for the efficient and sustainable management of landfills in the closure process. This approach allowed for the consideration of not only technical aspects but also socioeconomic and environmental factors, ensuring a comprehensive and balanced view.

The diagnostics conducted on the final disposal of urban solid waste and the closures of landfills already carried out in the country provided an in-depth understanding of current practices, identifying successes, challenges, and gaps. This critical analysis provided valuable insights for the formulation of future strategies and guidelines.

The panoramic analysis of the number of landfills in Brazil, with a specific focus on the northeastern region and the state of Ceará, revealed important nuances regarding the geographic distribution of these facilities and their closure needs. This regionalized context allowed for a more precise and contextualized approach in the formulation of the proposed model.

The careful selection of the most commonly used landfill closure processes, through a multi-criteria decision-making methodology, added solidity and reliability to the model. By prioritizing relevant and adaptable criteria, this approach ensured that the choices were based on objective data and aligned with the specific needs of each context.

Therefore, the model resulting from this study represents a significant contribution to advancing solid waste management in Brazil, offering a solid and comprehensive framework for the responsible and sustainable closure of landfills. Its implementation can play a key role in mitigating environmental impacts, promoting public health, and meeting sustainable development goals.

It is expected that this proposal can guide future policies and practices, driving the adoption of more effective and adaptable solutions to the dynamic needs of the national and global scenario. Additionally, the importance of involving all stakeholders and fostering interdisciplinary collaboration is emphasized to ensure the effectiveness and acceptance of the proposed model.

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