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# A Quantitative Assessment Approach to Implement Pneumatic Waste Collection System Using a New Expert Decision Matrix Related to UN SDGs

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**Abstract:** An innovative decision matrix has been developed to guide the selection and implementation of Pneumatic Urban Solid Waste Collection Systems (PUSWCS) in smart city projects. This study comprehensively collects and analyzes data on the advantages and disadvantages of pneumatic collection systems from technical, economic, and social perspectives. A decision-making tool was created to address the complexities of evaluating the desirability of incorporating PUSWCS in municipalities or specific areas, using a holistic approach. The tool assesses the technical, economic, and social feasibility of implementing PUSWCS, aligning it with the United Nations' Sustainable Development Goals (SDGs). Specific variables are measured to assess compliance with the SDGs, distinguishing technical aspects from economic and social aspects. The methodology includes surveys of system users and technicians, expert assessments, and the development of a decision matrix that cross-references study variables and SDGs. The matrix assigns numerical values to the Magnitude (M) and Impact (I) of each variable, enabling quantitative interpretation. This holistic approach accommodates the complexities of waste management and diverse stakeholder perspectives. The results demonstrate the matrix's effectiveness in accurately assessing the desirability of implementing PUSWCS. This confirms the matrix's ability to optimally integrate with innovative smart city concepts and align with long-term sustainability goals. The study concludes that the design of the decision matrix allows the collection of information from experts, users, and stakeholders about economic, social, and environmental variables and relates them to the SDGs, to obtain a numerical result that allows to decide whether in a given urban environment it is advisable to implement a PUSWCS.

**Keywords:** pneumatic urban solid waste collection systems; PUSWCS; waste management; smart city projects; decision matrix; sustainable development goals

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## 1. Introduction

The approach a society takes to collect its waste significantly impacts its environmental sustainability. Therefore, municipal solid waste management (MSWM) [1–4] is a critical challenge for smart cities [5,6]. Addressing this challenge is crucial for achieving sustainability. As urban areas continue to grow and since waste collection and transportation emissions are largely correlated with waste volumes [7], innovative solutions are needed to effectively collect and process waste while aligning with environmental, economic, recycling [8], mobility [9], and social goals. Other constraints must be considered, such as in old city centers, where traditional municipal solid waste collection represents a difficult problem to solve. An integrated system for waste reduction, collection, composting, recycling, and disposal is required to tackle the growing challenge of municipal solid waste management [10]. Integrated Solid Waste Management (ISWM) involves various decision-making processes [11]. The main disadvantage of conventional collection and transportation of municipal solid waste (container-garbage truck) is the release of greenhouse gases into the atmosphere of the city (methane, ammonia, sulfur compounds, etc.). This problem can be eliminated by pneumatic transportation, which collects and moves waste using an airflow in an underground pipeline [12].

Pneumatic Urban Solid Waste Collection Systems (PUSWCS) [13] have emerged as an alternative method that can outperform conventional collection systems due to lower space requirements, higher efficiency in handling, and other benefits [14]. This method integrates seamlessly with smart city concepts. Pneumatic collection is presented as an alternative to conventional trucking systems, reducing noise and odor effects, minimizing greenhouse effect gas emissions, presenting potential space savings, increasing pedestrian areas, and decreasing resource consumption [10]. According to hygiene and health criteria, pneumatic waste collection is positioned as a technological alternative to waste collection. However, the decision to implement such systems [3,10] is complex, requiring a comprehensive evaluation of technical, financial, and social factors [12]. In this way, the energy assessment of door-to-door and pneumatic collection, focusing on the biodegradable fraction collection and its subsequent recycling by anaerobic digestion indicated that, when the organic fraction is collected separately, the pneumatic collection could be a suitable alternative because the energy requirements are balanced with the savings from the anaerobic digestion process [10].

Some studies indicate that the door-to-door collection system is economically almost six times more superior. The dominant cost factor is the large investment cost of the pneumatic system [15].

Other studies indicate that, analyzing the environmental effects of a mobile pneumatic system, mobile pneumatic systems are inferior in terms of environmental effects when compared to a multi-container or a door-to-door waste collection system [16–18]. The results demonstrate that local geographic, demographic, and operational conditions play a decisive role in determining whether the pneumatic collection will reduce energy requirements, produce more or fewer greenhouse gas emissions, and cost over the long-term criteria. Miller et al. [19] stated that the initial capital costs of installing and operating a Pneumatic Urban Solid Waste Collection System (PUSWCS) are significantly higher than those of conventional collection systems. According to data from Envac Iberia SA, Ref. [20] a global leader in implementing these systems, the initial capital costs vary due to different configurations and layouts across municipalities, ranging between 12 and 18 million euros. These costs are higher than those of conventional systems, leading to greater total costs (including operations and debt service) for pneumatic systems, despite their lower labor requirements. The higher costs are mainly due to the extensive civil engineering efforts needed to install the infrastructure, especially in urban areas where complex trenches must be constructed. However, in new developments, these costs are lower as they are distributed among various required infrastructures.

Despite the high implementation costs, PUSWCS require fewer personnel and vehicles for waste transportation [1]. Farré et al. [21] highlighted that these systems offer a modern and efficient method of waste collection, improving urban aesthetics, optimizing selective collection at the source, reducing the cost per ton collected compared to conventional systems, and providing an intelligent service 24 h a day, 365 days a year.

Although there is a general reduction in truck kilometers traveled, overall energy use, and greenhouse gas (GHG) emissions associated with the system, a detailed analysis is required to determine if these are lower compared to conventional methods. Additionally, to labor savings, pneumatic collection may allow space that would otherwise be required for waste storage, staging, and collection to be used for other beneficial purposes, thus producing savings or additional revenues. When conducting a life-cycle analysis that includes the energy use and GHG emissions associated with a pneumatic facility's fixed infrastructure, the overall carbon footprint for a pneumatic system is significantly greater than if only the energy use and greenhouse emissions associated with ongoing operations are considered. Finally, although these effects have nowhere been quantified in any inclusive way, all analysts thus far have assumed some degree of externality benefits regarding pneumatic systems (e.g., quality-of-life and public-health improvements) that may have monetary value.

Given that pneumatic systems have greater external benefits due to their sustainability, it seems apparent that determining the most suitable pneumatic waste collection system for our city should be a priority. Hence, from here arises our research question: Would the use of a decision matrix facilitate the selection of the Pneumatic Urban Waste Collection System, optimizing its suitability for smart city projects?

Based on this question, the main objective of the paper will be to develop an innovative decision matrix to guide the selection of a Pneumatic Urban Solid Waste Collection System (PUSWCS), optimizing its integration into smart city projects. This decision matrix, used as a system assessment tool, will include a management information system, decision support system, expert system, scenario development, material flow analysis, life cycle assessment, risk assessment, socioeconomic assessment, and sustainable assessment [4].

To achieve this objective, we will conduct comprehensive data collection related to pneumatic waste collection systems, considering technical, economic, and social aspects as explained.

The literature suggests using multi-criteria decision-making (MCDM) methods to address this problem because these methods provide a structured approach to evaluate and prioritize multiple conflicting criteria [22]. MCDM techniques commonly require decision-makers to assign weightings of importance to the decision criteria based on which the available technologies are ranked. This structured approach ensures that all relevant factors are considered and balanced, leading to more informed and objective decision-making. Other authors introduce a hierarchical network decision structure and apply the analytic network process super-matrix approach to measure the relative desirability of disposal alternatives using value judgments as the input of the various stakeholders. That analytic network process enables decision-makers to find the best possible solution to complex problems by breaking down a problem into a systematic network of inter-relationships among the various levels and attributes [23].

The decision support system is considered as a decision model that requires information about all possible costs, technical, normative, and environmental issues, specifically pollution, and impacts induced by the ISWM system. Some decision variables used in the decision model are binary and others are continuous [24].

In this way, a multi-criteria method was used to address the best system for the disposal of solid waste municipal residues choosing among biological treatment, thermal treatment, and landfilling [25].

Subsequently, we will analyze the advantages and disadvantages of pneumatic collection systems, incorporating perspectives from experts in municipal waste management systems and feedback from users who have interacted with such systems.

The decision-making process for an efficient Municipal Solid Waste Management (MSWM) requires the consideration of a significant number of mutually conflicting criteria to come up with the optimal solution. Decision-makers must select from a wide spectrum of available alternatives. Nevertheless, balancing social, economic, and environmental perspectives in MSWM is difficult due to the inevitable conflict of objectives related to the three pillars of sustainability [26]. For MSWM to be sustainable, it requires to be economically reasonable, environmentally friendly, and socially acceptable; that is, a sustainable approach with a sound technical, environmental, and economic assessment along with public participation, consultation, and stakeholder dialogue on the proposed solutions. The social dimension of MSWM involves the participation of the society and community in their consumption and disposal attitude towards minimizing MSW generation along with involvement and relevance in the decision-making process [11].

Finally, we will conceive and develop a decision-making tool to address the complexity of assessing the suitability of incorporating pneumatic municipal solid waste collection systems in municipalities or specific areas, based on a holistic approach.

Through the developed decision matrix, we intend to assess the technical, economic, and social feasibility of implementing a pneumatic urban solid waste collection system, aligning it with the Sustainable Development Goals (SDGs) established by the United Nations [27]. We will measure the degree of compliance with the SDGs through specific variables, allowing a comprehensive assessment that separates the technical aspects of the environment from the economic and social aspects.

To achieve the proposed objectives, we will employ extensive data collection from municipalities already utilizing PUSWCS, including surveys [28,29] and statistical calculations of system users, technicians, and waste management experts. Additionally, considering our aim to optimize implementation in smart cities, we will analyze technical parameters such as implementation costs, operational efficiency, environmental impact, and health conditions, including the challenges posed by COVID-19 where automatic systems are gaining prominence. These technical considerations will be examined alongside social factors like waste management, quality of life, citizen acceptance, and resilience to disruptions.

Therefore, it is intended that the resulting decision matrix assigns numerical values to the magnitude and impact of each variable, enabling quantitative interpretation. Furthermore, in pursuit of alignment with the Sustainable Development Goals (SDGs), the matrix's calculation algorithms seamlessly integrate the sustainability pillars encompassing economic, social, and environmental aspects [30], thereby aligning the decision process with the overarching SDG framework. Through the development of this decision support tool, the research endeavors to empower municipalities to effectively integrate PUSWCS into their smart city initiatives while prioritizing sustainable development. The matrix will provide a holistic approach, accommodating the complexities of waste management and the diverse stakeholder perspectives involved.

## 2. Materials and Methods

To achieve the stated goals, a holistic methodology was chosen. This holistic approach provides the researcher with a thorough understanding of the various stages of the research, from data collection to data interpretation, integrating each phase in a coherent manner. This approach not only addresses data collection but also extends to the deployment of simplified analysis algorithms. The versatility of this process is highlighted by its ability to generate accurate and relevant knowledge, demonstrating its practical applicability. The results obtained through this methodology are significant in terms of contributing to informed decision-making and consolidating the tool developed as a valuable resource for effectively assessing and applying technologies in a variety of contexts [24].

As this research aims to develop a decision matrix to guide municipalities in assessing the desirability of adopting PUSWCS, the matrix should cross-reference variables related to pneumatic waste collection against the United Nations Sustainable Development Goals (SDGs) [27]. By quantifying the magnitude and impact of each variable [31], the tool will provide a data-driven approach to support informed decision-making [11].

To achieve this, we will first select the sample upon which the study will be conducted. The sample size will determine the number of surveys needed to ensure that the data collected has adequate statistical reliability. After determining the sample size, the next step involves choosing the variables to be analyzed in our survey. Following the selection of variables, we designed the survey to collect relevant data effectively. Finally, we developed the decision matrix based on the collected data to assess the desirability of implementing PUSWCS.

### *2.1. Population Sample and Sample Size Determination*

With the purpose of addressing our research question, the first step is to select the sample upon which the study will be conducted. To do so, the municipalities from which data will be collected were initially chosen. It was established as a criterion that these municipalities should be those where data collection would be straightforward, leading to the decision to select municipalities in the north of Spain due to their proximity, specifically those where pneumatic urban waste collection systems coexist with traditional truck collection. Ultimately, the chosen municipalities were San Vicente de Barakaldo and Portugalete, each with two facilities, and Bilbao, Galdakao, and Llodio, each with one facility, totaling 7 facilities serving 56,000 people.

According to the Spanish National Institute of Statistics (INE), the average number of individuals per household, on 1 January 2023, is 2.48; however, in the Basque Country, the average is 2.36 people per dwelling, slightly lower than the Spanish average. Given that the studied municipalities are located in the Basque Country, the total number of users served by pneumatic urban waste collection is 132,160.

Based on this average household size of Spanish households provided by the INE, the necessary sample size was then determined to achieve a confidence level of 95%, while maintaining an 8% margin of error. The methodology utilized for this calculation considers the statistical Equation (1) to obtain a required sample within a finite population.

$$\text{Sample Size} = \frac{\frac{z^2 \cdot p \cdot (1-p)}{e^2}}{1 + \left(\frac{z^2 \cdot p \cdot (1-p)}{e^2 \cdot N}\right)} \tag{1}$$

where

z = standard deviation of the normal distribution used to determine the desired confidence level in the study.

p = probability that the event under study DOES occur.

$1 - p$ = probability that the studied event will NOT occur (50%).

e = margin of error assumed in the study representing the uncertainty of the results.

N = total population size.

Based on experimentation, the standard deviation value z based on the desired confidence level is shown in Table 1. It can be seen that the z value, which represents the standard deviation of the normal distribution used to determine the desired confidence level in the study, for a confidence level of 95% is 1.96. The probability p that the event under study does occur is 50% and that it does not occur is also 50%. The margin of error e assumed in the study representing the uncertainty of the results is 8% and the population size N is 132,160 users. Therefore, the sample size and the minimum number of surveys to be conducted to obtain data with adequate statistical reliability will be 150 individuals.

**Table 1.** Standard deviation value based on Desired Confidence Level.

| Desired Confidence Level | Standard Deviation z |
|---|---|
| 80% | 1.28 |
| 85% | 1.44 |
| 90% | 1.65 |
| 95% | 1.96 |
| 99% | 2.58 |

Therefore, to obtain an updated assessment of the magnitude of the variable under study and to verify the correlation between satisfaction with the systems and evaluations on the convenience of their implementation, it was decided to conduct a number of surveys greater than this, targeting users with experience in collection systems, and some of them focused on technicians specialized in the operation of the most representative systems for urban waste management. As the minimum number of surveys required was 150, 166 surveys were carried out. Of this total, 151 surveys were aimed at users with experience in collection systems, and 15 focused on technicians specialized in the operation of the most representative systems for urban waste management.

### *2.2. Selection of Variables of the Study*

After selecting the sample size, the next step involved choosing the variables we intended to analyze in our survey. These variables are consistent across all selected municipalities in accordance with key international agreements and may be updated based on regional particularities and/or new technological and environmental developments.

The variables to be analyzed include the following:

- Cost and inconvenience of implementation.
- Evaluate the cost of the service in operation and its operability due to inclement weather (snow, rain, etc.).
- Quality of the selective residue based on characterizations.
- $CO_2$ and greenhouse gas emissions.
- Circular economy.
- Impact of collection systems on mobility and transit in cities (Transit Oriented Development, TOD). Reduction in heavy traffic.
- Noise levels produced.
- Quality of service, as well as inconvenience due to implementation and operation.
- Quality of life, security, and citizen service.
- Odor emissions, leachates released, public roads, and environmental cleanliness.
- Effect on employment.
- Information and monitoring of waste in real time (weighing, user, habit, etc.) with the possibility of implementing Pay as you throw.
- Integration of collection systems in SMART CITIES. Sensorization and digitalization in the operation of systems.
- 24/7/365 system availability.
- Resilience of collection systems to strikes.
- Citizen acceptance.
- Vandalism.
- Sustainable development and its basic pillars (environmental, social, and economic).
- Occupation of public roads.
- Human contact with waste fractions.

In terms of ethical considerations, data collection had to prioritize safeguarding the privacy and anonymity of the participants. Data collection was performed with the informed consent of the participants, ensuring their confidentiality and anonymity. The informed consent provided comprehensive details on the procedures, as well as the significance and aims of the research concerning the confidentiality of gathered information and its potential applications.

### *2.3. Survey Design and Data Collection*

A survey is a systematic method for gathering information. Surveys are conducted to collect information that reflects the attitudes, behaviors, opinions, and beliefs of the population that cannot be observed directly. Therefore, the survey questions must address our research question. The success of research using a survey depends on how closely the answers people provide to survey questions match how they think and really act. This methodological approach allows us to obtain a precise and contextualized representation of reality within the population sample. Thus, the survey design [28,29] plays a crucial role in our research, as it serves as a foundation to support the reference values used in the decision matrix being developed.

It was decided to design the survey using a Likert scale as it allows to know the opinion of the individuals surveyed through a questionnaire containing specific, multiple-choice questions that facilitate data measurement and are easy to interpret using statistical methods [32]. This tool indicates the degree of satisfaction or agreement with the statements given on a scale composed, in our case, of five levels.

Due to the type of data to be collected, the survey was sent to competent municipal technicians who know the waste management systems in the cities and to users of these systems. The survey was divided into three blocks.

The first section of the survey comprises eight general questions designed to gather information about the participant's profile and secondly to gauge their familiarity with pneumatic solid urban waste collection systems. This section includes questions on the participant's sex, age, level of education, mobility impairment status, municipality, and job title. This section serves a dual purpose: first, to collect demographic data, providing essential context for analyzing the survey data in relation to the study variables; second, to filter out participants who lack knowledge about pneumatic collection systems. If a respondent indicates unfamiliarity with these systems, the survey is discontinued for them. Conversely, if the respondent is acquainted with these systems, the subsequent sections aim to assess their satisfaction levels with the pneumatic collection systems implemented in their municipality.

The purpose of the second block of the survey is to assess the significance attributed by the respondents to each one of the variables under study. Therefore, this section contains specific questions related to each variable listed in Table 2, which details the correlation between study variables and survey questions, ensuring alignment with the selection matrix.

**Table 2.** Correlation between study variables and survey questions.

| Selection Matrix | Survey Question No. |
|---|---|
| Cost and hassle of implementation | 9 |
| Operation cost | 25 |
| Selective quality | 15 |
| $CO_2$ and GHG emissions | 20 and 21 |
| Circular economy | 18 and 19 |
| TOD | 11 |
| Noise | 22 |
| Quality of life | 14 and 17 |
| Odors | 23 |
| Employment impact | 9, 24, and 25 |
| SMART (Tracking, Real-Time Weighing, and Pay Per Generation) | 12, 13 |
| Favorite residue fraction system | 30 |
| 24-7-365 | 14 |
| Affection strikes | 24 |
| Citizen acceptance | 8, 28, and 29 |
| Vandalism | 26 |
| Sustainability | 16 |
| Occupation of public roads | 27 |
| Direct contact with waste | 10 |

In Table 3, the questions posed in the survey are listed, where a Likert scale has been used. Respondents are asked to consider the degree of importance or satisfaction for each variable, with 1 meaning "not at all important", "very dissatisfied", or "nothing" and 5 meaning "very important", "very satisfied", or "excellent". After each question, respondents have the opportunity to write comments to provide additional context or details regarding their ratings.

The third block of the survey focuses on the interviewee's perspectives and preferences regarding pneumatic collection systems for solid urban waste. It includes questions aimed at understanding whether respondents would support exploring the implementation of pneumatic systems in municipalities that currently lack them, or if this issue is not a priority for them. Additionally, the block examines the interviewee's preference between pneumatic and traditional solid waste collection systems if they were to change their residence. It also seeks to determine which waste collection system—either a five-fraction system (packaging, paper, glass, organic, and rest) or a two-fraction system (wet for organic waste and dry for recyclables)—respondents consider most suitable for selective waste collection in their localities. These questions aim to gather insights into public opinions and preferences regarding innovative waste management technologies and practices.

**Table 3.** Survey questions to assess the importance and satisfaction of the variables considered regarding the PUSWCS.

| | Questions |
|---|---|
| 8 | Level of satisfaction with the pneumatic solid urban waste collection system |
| 9 | In pneumatic waste collection systems, do you think that a higher implementation cost compensates for a lower operating cost? |
| 10 | Reduce contact with waste for users and waste collection professionals. |
| 11 | Reduce the circulation of vehicles within cities. |
| 12 | Waste collection systems integrated with SMART cities where waste doors can be opened automatically. |
| 13 | Identification, monitoring, weighing, and invoicing in real time about waste disposed. |
| 14 | Dump the waste generated by any citizen at any time of the day, any day of the year. |
| 15 | PUSWCS improve selective waste collection. |
| 16 | PUSWCS contribute to improving sustainability and the environment. |
| 17 | PUSWCS contribute to a better quality life of people. |
| 18 | PUSWCS improve production and consumption patterns. |
| 19 | PUSWCS promote the circular economy. |
| 20 | PUSWCS lower $CO_2$ emissions. |
| 21 | PUSWCS lower greenhouse gas emissions. |
| 22 | PUSWCS generate less noise during the waste collection process. |
| 23 | PUSWCS reduce odors at waste disposal points for citizens. |
| 24 | PUSWCS are not affected by workers' strikes. |
| 25 | PUSWCS reduce operating wage costs. |
| 26 | PUSWCS are less exposed to possible vandalism acts than traditional collection systems. |
| 27 | PUSWCS reduce the occupation area for waste collection on public streets. |

### 2.4. Design of the Decision Matrix

Given our research aim of developing a decision-making tool to evaluate the implementation of pneumatic solid urban waste collection systems in municipalities, aligned with the United Nations Sustainable Development Goals (SDGs), a decision matrix was chosen. Recognized as a key tool for evaluating various alternatives considering multiple determining factors influencing the final decision, the decision matrix was selected for its effectiveness, stemming from its simplicity and speed in assessing different alternatives considering multiple relevant factors. This allows for a preliminary response to the research question effectively and efficiently, without requiring complex calculations.

The purpose of this matrix is to assess, through a numerical evaluation, the suitability of implementing a pneumatic municipal solid waste collection system in a specific municipality or area within it. Its construction involves the cross-referencing of information between the study variables and the Sustainable Development Goals (SDGs) established by the United Nations. This strategy not only allows the precise visualization of the relationship between the two entities but also enables their quantification. This relationship is supported by surveys of system users and technicians responsible for the logistics of municipal cleaning systems.

The development of relevant assessments involves the participation of experts in waste collection systems and associated logistics. The opinions of these experts, based on experience and knowledge, will be collected using fixed-value scales. This technical procedure will facilitate the quantitative interpretation of the variables.

Each variable in the study has been associated with two different values: Magnitude (M) and Impact (I). Figure 1 represents each cell of the decision matrix corresponding to a specific variable and its relationship to various Sustainable Development Goals (SDGs). Magnitude (M), derived from the survey results, is represented in the upper left corner of each cell, while Impact (I), which indicates the significance of this magnitude in relation to the SDGs, is represented in the lower right corner of each cell.

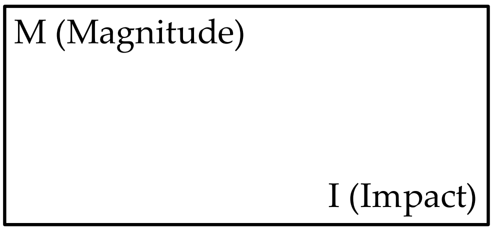


**Figure 1.** Cell of the Decision Matrix designed: Magnitude of the variable and its Impact on the SDG against which it is measured.

The first component, Magnitude (M), represents the extent of the variable and is derived from the evaluations conducted by technicians specialized in cleaning procedures in the areas under consideration for potential implementation of the pneumatic urban waste collection system. The magnitude takes a value between 1 and 5, as assigned by the competent technicians' values that are verified based on the survey.

The second value, Impact (I), reflects the importance assigned to the Sustainable Development Goals (SDGs) in accordance with United Nations guidelines. According to a survey conducted by "El Ágora, Diario del Agua" [33], this value will be calculated according to the overall relevance given to the SDGs. The survey asks the question: "Which of the 17 UN SDGs seems most important to you?". To summarize, the impact value will determine the level of influence of the variable under study, regardless of its extent, which is determined by the value assigned to the magnitude. Impact is categorized as Low, Significant, or High, assigning numerical values 1, 2, and 3, respectively.

This rigorous and structured approach ensures a robust and evidence-based assessment, supporting informed decision-making.

## 3. Results

This section shows how the decision matrix is constructed through the opinion of the surveyed sample. This considers the variables "Magnitude" and "Impact", similar to other multivariate decision matrices such as those used for environmental impact assessment. The "Magnitude" considers the opinions of experts as well as other stakeholders. The "Impact" correlates with the importance of the different SDGs for society.

Finally, the values of the matrix are presented in order to decide whether or not the implementation of a pneumatic municipal solid waste collection system is appropriate in this particular place.

### *3.1. Results of the Magnitude (M) of the Variable in the Decision Matrix*

The Magnitude (M) reflects the extent of the variable according to the perception of the professionals in charge of deciding whether or not to implement a pneumatic urban waste collection system. It takes values between 1 and 5, where 1 indicates the lowest magnitude and 5 the highest, with a positive value if it is favorable and a negative if it is unfavorable. Neutral values 3 and $-3$, after calculations in the decision matrix, will help to establish a dividing line to determine the desirability of implementing the system.

Although user evaluations provide valuable information, greater decision weight will be given to the analysis of those surveys directed at competent technicians, due to their ability to discern between pneumatic and traditional collection systems and because they will be the ones in charge of completing the final decision-making matrix based on their knowledge of the unique idiosyncrasies of their municipalities and respective localities. These results are shown in Figure 2, representing the level of satisfaction of the competent technicians with respect to the PUSWCS. The data obtained reinforce the convenience decision hypothesis through the dividing line established with the magnitude rating 3, where more than 50% of the qualified technicians gave the highest score to satisfaction with the pneumatic collection systems, while the rest gave a high rating of 4. This population group, which coexists with the preeminent waste collection systems and, at the same time, in charge of the logistics of their operation, places significant trust in the pneumatic collection systems. Given their position, the opinion of these professionals, both in terms of importance and knowledge of the systems under study, is crucial for the evaluation of the magnitude to be introduced in the matrix of the potential municipality under investigation.

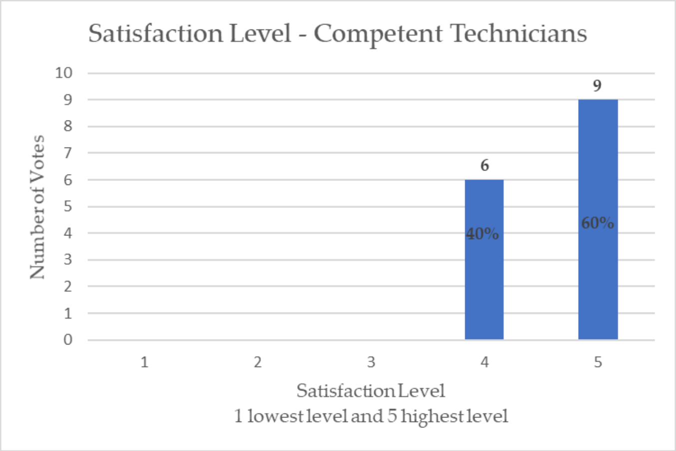


**Figure 2.** PUSWCS satisfaction rating for competent technicians.

Figure 3 shows the satisfaction level of the population group in the study corresponding to the users of the systems with respect to the PUSWCS, assigning the value 1 to "Very Dissatisfied", while the value 5 represents "Very Satisfied". The analysis of the rating given by the users of the systems is aligned with the technician's perception, with more than half assigning the highest rating to pneumatic collection systems, 27.81% assigning a high rating, while 14.57% providing an indifferent rating and only a very small percentage of 3.31% assigning a poor rating to the systems. In this case, reliance continues to be placed on the dividing line between the desirability of implementation or not, which is marked by the value 3 in the decision matrix.

In Figure 4, which represents the level of satisfaction of both, the competent technicians and the users of the systems with respect to the PUSWCS, all the samples were aggregated to spread the inequalities among the population groups so that the results are not negatively affected by lack of knowledge of the collection systems by people who have not interacted sufficiently with them.

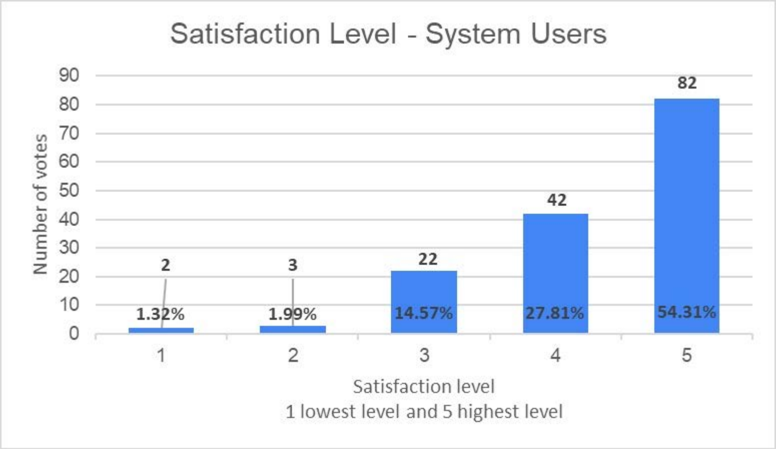


**Figure 3.** PUSWCS satisfaction rating for system users.

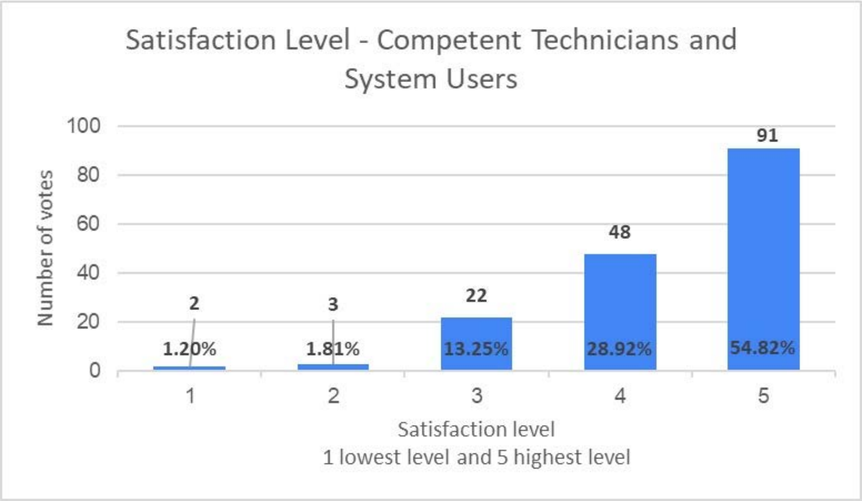


**Figure 4.** Satisfaction with the PUSWCS for both, competent technicians and users of the systems combined.

A detailed analysis of the surveys informs that the larger the population group of individuals who do not interact with the systems, the lower the maximum rating offered, but it helps not to be optimistic and ensures that the dividing line established with the value 3 serves as the first approach of whether the systems should be implemented.

From a statistical point of view, it has been demonstrated that those places where pneumatic collection has been implemented enjoy a high degree of satisfaction in all the population groups analyzed and, therefore, increase the desirability of implementation. This supports the initial hypothesis of establishing a threshold where the magnitude value is 3 for each variable in the decision matrix calculation, with the resulting value determining the convenience of implementation.

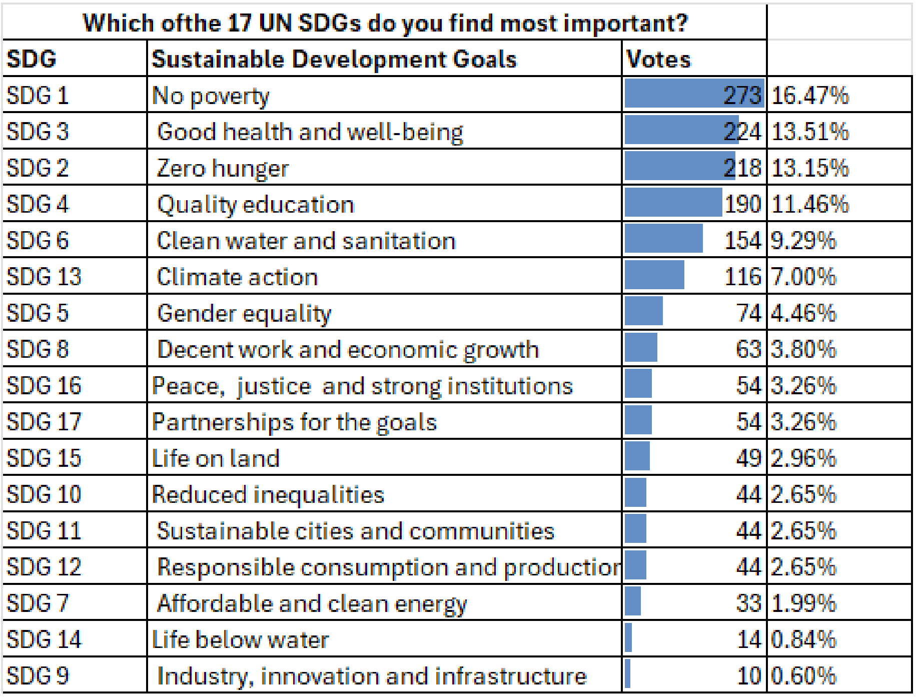
Although this study does not focus on the COVID-19 pandemic, it is noteworthy that several respondents highlighted the benefits of touchless interaction systems in their comments. They expressed appreciation for the ability to manipulate systems without physical contact, citing the recent pandemic as a significant factor. This feedback underscores the importance of touchless technology in enhancing user satisfaction and addressing health concerns in a post-pandemic world.

### *3.2. Results of the Impact (I) of the Variable with Respect to the SDG in the Decision Matrix*

Impact (I) reflects the relevance given to the SDG in question, so the value of this parameter is constant for a given SDG regardless of the variable analyzed. The impact assessment is only not applicable when there is no direct relationship between the SDG and the variable assessed. In cases where such a relationship does exist, an impact assessment criterion categorized as Low, Significant, or High will be established, assigning numerical values 1, 2, and 3, respectively. Thus, the absence of correlation between the SDG and the variable implies zero impact. A rating of 1 indicates the presence of the impact, a rating of 2 doubles the impact, and a rating of 3 triples the magnitude of the impact.

To determine the value of the impact provided by the SDG under study, the results of the survey conducted by “El Ágora, diario del agua” [33], an independent media for the dissemination of information and knowledge on the use and consumption of water and compliance with the United Nations Sustainable Development Goals, are used.

Once the results of the “El Ágora, diario del agua” [33] survey have been collected in Figure 5, a categorization regarding the SDGs is carried out to facilitate analysis. This categorization will apply the importance of the respondents to the SDGs by dividing the responses from the votes cast into three segments according to the 33% and 66% percentiles, which will allow the SDGs to be categorized into the three important groups: Low, Significant, and High.



| Which ofthe 17 UN SDGs do you find most important? | | | |
|---|---|---|---|
| **SDG** | **Sustainable Development Goals** | **Votes** | |
| SDG 1 | No poverty | 273 | 16.47% |
| SDG 3 | Good health and well-being | 224 | 13.51% |
| SDG 2 | Zero hunger | 218 | 13.15% |
| SDG 4 | Quality education | 190 | 11.46% |
| SDG 6 | Clean water and sanitation | 154 | 9.29% |
| SDG 13 | Climate action | 116 | 7.00% |
| SDG 5 | Gender equality | 74 | 4.46% |
| SDG 8 | Decent work and economic growth | 63 | 3.80% |
| SDG 16 | Peace, justice and strong institutions | 54 | 3.26% |
| SDG 17 | Partnerships for the goals | 54 | 3.26% |
| SDG 15 | Life on land | 49 | 2.96% |
| SDG 10 | Reduced inequalities | 44 | 2.65% |
| SDG 11 | Sustainable cities and communities | 44 | 2.65% |
| SDG 12 | Responsible consumption and productior | 44 | 2.65% |
| SDG 7 | Affordable and clean energy | 33 | 1.99% |
| SDG 14 | Life below water | 14 | 0.84% |
| SDG 9 | Industry, innovation and infrastructure | 10 | 0.60% |

**Figure 5.** Results of the votes conducted in the survey carried out by the media "El Ágora, Diario del Agua" [33] on the importance of the SDGs.

Each respondent had the opportunity to allocate between 1 and 3 votes, indicating the order of importance assigned to each Sustainable Development Goal (SDG). Out of the 727 respondents, a total of 1658 votes were cast. This initial dataset offers a preliminary insight into the SDGs, revealing both the highest and lowest rankings.

Remarkably, the SDG rated with the lowest importance received only 10 votes (1%), corresponding to SDG number 9, which pertains to Industry, Innovation, and Infrastructure. Conversely, the most highly ranked SDG garnered 273 votes (16%), correlating with SDG number 1 related to the End of Poverty. This outcome aligns with expectations, considering that this SDG ranked highest in respondents' preferences.

To establish a comprehensive understanding of the significance attributed to each SDG, a vote range is calculated based on a maximum of 273 votes and a minimum of 10 votes, resulting in a range of 263 votes. Subsequently, this range is segmented using the 33% and 66% percentiles. SDGs receiving votes below the 33% percentile are categorized as Low Importance, those falling between the 33% and 66% percentiles are deemed of Significant Importance, and SDGs with votes exceeding the 66% percentile are considered of High Importance.

Table 4 presents the resulting ranking derived from this criterion, where the impact outcome is evaluated on a scale of 1 to 3. Specifically, a rating of 1 indicates Low Impact, 2 signifies Significant Impact, and 3 denotes High Impact. Additionally, the table delineates the categorization of the impact of the SDGs based on the 33% and 66% percentiles of the range of votes cast according to the survey results conducted by "El Agora, Diario del Agua" [33].

Once the Magnitude (M) and Impact (I) values have been quantified, the baseline decision matrix is developed.

**Table 4.** Distribution of SDGs by level of importance according to the results of the survey carried out by "El Agora, Diario del Agua" [33].

| SDG | No. Votes | SDG Impact | SDG Assessment |
|---|---|---|---|
| 1 | 273 | High impact | 3 |
| 2 | 218 | High impact | 3 |
| 3 | 224 | High impact | 3 |
| 4 | 190 | High impact | 3 |
| 5 | 74 | Significant impact | 2 |
| 6 | 154 | High impact | 3 |
| 7 | 33 | Low impact | 1 |
| 8 | 63 | Significant impact | 2 |
| 9 | 10 | Low impact | 1 |
| 10 | 44 | Low impact | 1 |
| 11 | 44 | Low impact | 1 |
| 12 | 44 | Low impact | 1 |
| 13 | 116 | High impact | 3 |
| 14 | 14 | Low impact | 1 |
| 15 | 49 | Significant impact | 2 |
| 16 | 54 | Significant impact | 2 |
| 17 | 54 | Significant impact | 2 |

### *3.3. Calculation of the Decision Matrix*

To determine the feasibility of implementing a pneumatic municipal solid waste collection system, a reference calculation matrix has been developed based on technical, economic, and environmental parameters. This matrix allows for estimating the costs and benefits associated with the installation of this type of system and serves as a decision support to determine the feasibility of the project. A value of magnitude 3 or $-3$ has been considered for all those variables that are related to an SDG. This intermediate value whose positive value will be applied in those cases where the variable offers a favorable impact on the SDG and a negative one when the impact is unfavorable. Figure 6 illustrates with a graph the boundary between the suitability and unsuitability of implementing a Pneumatic Waste Collection System (PUSWCS). As for the impact, its value is applied according to the 33% and 66% percentiles calculated by the number of votes cast according to the survey conducted by the independent media El Ágora Diario [33].

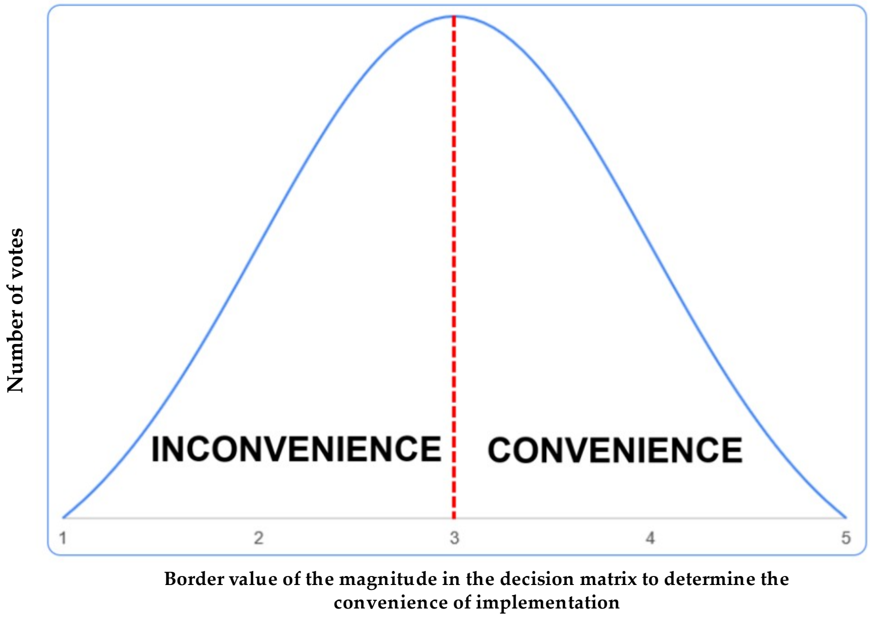


**Figure 6.** Proposed operational limit for the implementation of a PUSWCS.

### 3.4. Calculation Algorithms

Prior to the calculation process, the sign that the magnitude (M) will have been determined will depend on the variable with which it is measured. For this purpose, it has been decided that the variables that contribute value to sustainability will have a positive sign, while those that detract value from sustainability will have a negative sign. Sustainability is understood as those variables that combine any of the three basic pillars: economic, social, and environmental.

The variables with positive magnitude are as follows:

- Quality of the selective residue based on characterizations.
- $CO_2$ and greenhouse gas emissions.
- Circular economy.
- Impact of collection systems on mobility and transit in cities (TOD). Reduction in heavy traffic.
- Noise levels produced.
- Quality of service, as well as inconvenience due to implementation and operation.
- Quality of life, security, and citizen service.
- Emission of odors, leachates released, public roads, and environmental cleanliness.
- Affect on employment.
- Information and monitoring of waste in real time (weighing, user, habit, etc.) with the possibility of implementing Pay as you throw.
- Integration of collection systems in Smart Cities. Sensorization and digitalization in the operation of the systems.
- 24/7/365 system availability.
- Resilience of collection systems to strikes.
- Citizen acceptance.
- Vandalism.
- Sustainable development and its basic pillars (environmental, social, and economic).
- Human contact with waste fractions.

The variables with negative magnitude are as follows:

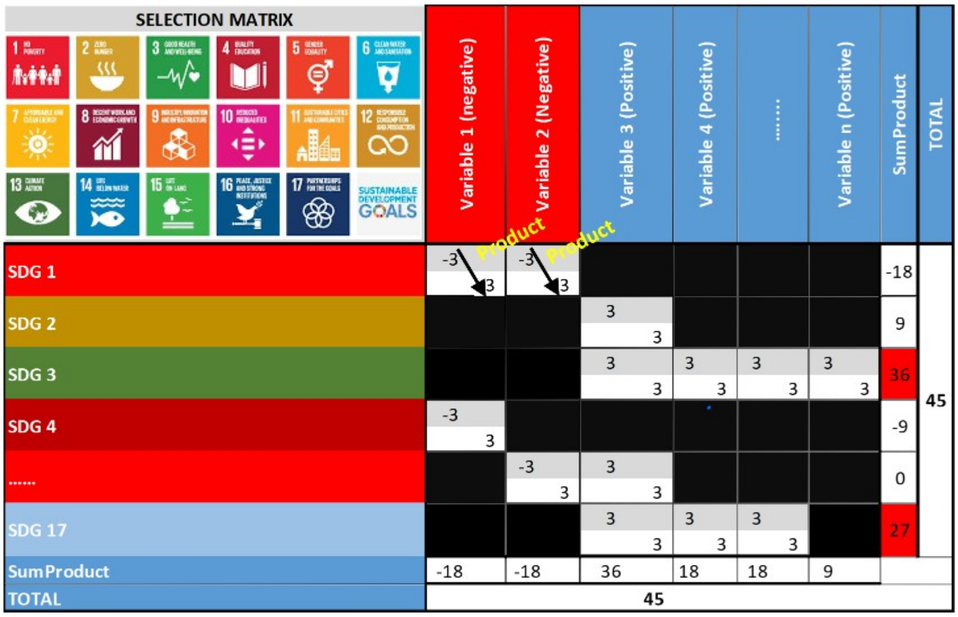
- Cost and inconvenience of implementation.
- Evaluate the cost of the service in operation and its operability due to inclement weather (snow, rain, etc.).
- Occupation of public roads.

Each variable of the research is measured with each of the SDGs established by the United Nations; in those cases where the variable is not applicable to any SDG, the value assigned for the calculation will be 0 as there is no affectation.

Each cell in the matrix (as explained in Figure 1) has a magnitude (M) with the corresponding sign according to the value contributed to any of the three basic pillars of sustainability and an Impact (I) dependent on the importance assigned to the SDG [25].

For each cell, the value of the magnitude is multiplied by the impact, and the sum of all these products of each variable within an SDG is added up. Next, all the summations of the outputs obtained in each SDG are added together to obtain the result of the matrix. To check that the calculations have been carried out correctly, the matrix is recalculated by also performing the product of the magnitude by the impact, but this time the sum of all these products is calculated within the same variable for all the SDGs, finally adding up of all these calculated sums obtain the same result for the matrix. Figure 7 illustrates, for each cell, the corresponding values of Magnitude and Impact, how these values are represented, and how they influence the overall assessment.

The result of the final decision matrix will depend on the value assigned to the magnitude by each competent technician in his locality. However, the reference matrix used in the research to determine the threshold for the implementation convenience of a PUSWCS, considering the neutral value of 3 or $-3$ for the magnitude, results in the value 537. Consequently, once the study has been carried out by the qualified technicians and the corresponding matrix to the case under study has been calculated, a result above this threshold would be in favor of the implementation of the system while a lower value would indicate the opposite.



| SELECTION MATRIX | Variable 1 (negative) | Variable 2 (Negative) | Variable 3 (Positive) | Variable 4 (Positive) | …… | Variable n (Positive) | SumProduct | TOTAL |
|---|---|---|---|---|---|---|---|---|
| SDG 1 | -3<br>3 | -3<br>3 | | | | | -18 | 45 |
| SDG 2 | | | 3<br>3 | | | | 9 | |
| SDG 3 | | | 3<br>3 | 3<br>3 | 3<br>3 | 3<br>3 | 36 | |
| SDG 4 | -3<br>3 | | | | | | -9 | |
| …… | | -3<br>3 | 3<br>3 | | | | 0 | |
| SDG 17 | | | 3<br>3 | 3<br>3 | 3<br>3 | | 27 | |
| SumProduct | -18 | -18 | 36 | 18 | 18 | 9 | | |
| TOTAL | 45 | | | | | | | |

**Figure 7.** Sum of the products of Magnitude by Impact outputs.

Although the value of the reference matrix may vary due to the inclusion of new variables or SDGs, the calculation algorithms remain constant, ensuring consistency in decision-making. The results obtained through this methodology range from 103 to 959, indicating a scale from total inconvenience of implementation to highest convenience, respectively.

This approach provides a robust and adaptable decision-making tool for the implementation of pneumatic collection systems, effectively aligning with the Sustainable Development Goals and responding to the particularities of each locality.

## 4. Discussion

Surveys conducted with users of Pneumatic Urban Solid Waste Collection Systems (PUSWCS) and competent technicians from municipalities where traditional waste collection systems coexist with pneumatic systems confirm a positive perception toward PUSWCS. Statistical analysis and decision matrix algorithms also support this positive perception as highlighted by [3,18,21]. These results align with our survey data, positioning PUSWCS as fundamental waste collection models for creating smart, sustainable, and resilient cities in the future. In municipalities where PUSWCS is implemented, users, technicians, and stakeholders express high satisfaction with the urban solid waste management system.

The choice of an urban solid waste management system, based on an objective assessment of various economic, social, and environmental variables, involves different strategies summarized in two research lines: life cycle analysis (LCA) and multi-decision matrices. In some cases, decisions are made based on short-term objectives of different variables that may be antagonistic among the various stakeholders involved in urban solid waste management. Our research selected different socioeconomic variables of the urban environment and environmental variables. To set long-term goals and minimize the urban planning constraints of the area under study, long-term objectives related to the Sustainable Development Goals (SDGs) were chosen.

Given the growing importance of waste management by governments and administrations [2,34], the good alignment of PUSWCS with the SDGs analyzed in our decision matrix highlights the fundamental role these systems play in SMART cities and sustainable cities. Implementing Pneumatic Urban Solid Waste Collection Systems (PUSWCS) can significantly impact several SDGs, particularly those related to sustainable cities, health, and responsible consumption. Table 5 illustrates the relationship between each study variable and the SDGs they interact with.

**Table 5.** Correlation between study variables and SDG with which they interact.

| Variable of the Selection Matrix | Associated SDGs |
|---|---|
| Cost and hassle of implementation | 7, 8, 9, 11 y 12 |
| Operation cost | 7, 8, 9, 11 y 12 |
| Selective quality | 3, 6, 7, 8, 9, 11, 12, 13,14 y 15 |
| $CO_2$ and GHG emissions | 3, 6, 7, 9, 11, 12, 13,14 y 15 |
| Circular economy | 3, 6, 7, 9, 11, 12, 13,14 y 15 |
| TOD | 3, 6, 7, 9, 11, 12 y 13 |
| Noise | 3, 8, 9 y 11 |
| Quality of life | 3, 7, 8, 9, 11, 12, 13, 14 y 15 |
| Odors | 3, 6, 7, 8, 9, 11, 12, 13, 14 y 15 |
| Employment impact | 3, 8, 9 y 11 |
| SMART (Tracking, Real-Time Weighing, and Pay Per Generation) | 3, 9, 11, 12 y 13 |
| Favorite residue fraction system | 3, 7, 9, 11, 12, 13, 14 y 15 |
| 24-7-365 | 3, 7, 8, 9, 11 y 12 |
| Affection strikes | 3, 8, 9 y 11 |
| Citizen acceptance | 3, 7, 8, 9, 11, 12 y 13 |
| Vandalism | 3, 8, 9, 11, 14 y 15 |
| Sustainability | 3, 6, 7, 8, 9, 11, 12, 13, 14 y 15 |
| Occupation of public roads | 3, 6 y 9 |
| Direct contact with waste | 3, 6, 8, 9 y 11 |

Looking at Table 5, we can identify which variables in our study interact with SDG 3, which focuses on good health and well-being. These variables are related to reducing the exposure of waste collectors and the public to waste-related hazards. Our findings align with those of Elsheekh et al. [35], who indicated that by reducing such exposures, Smart Non-Recyclable Urban Solid Waste Systems can contribute to better health outcomes.

Additionally, variables interacting with SDG 11, as noted by Farré et al. [3,21], show that PUSWCS contribute to making cities inclusive, safe, resilient, and sustainable by reducing traffic congestion and pollution and improving waste collection efficiency in urban areas. These systems also support efficient resource management and promote waste reduction, reuse, and recycling, aligning with the goal of ensuring sustainable consumption and production patterns [35], as pursued by SDG 12. Finally, SDG 13 is highlighted in variables that show that Integrated Solid Waste Management Systems (ISWMS) can reduce greenhouse gas emissions through more efficient waste collection and transportation, contributing to climate action efforts [3,21].

The results of our study, which evaluate the satisfaction level expressed by system users and competent technicians regarding our study variables, align with previous findings by Iriarte et al. [16], Punkkinen et al. [17], and Farré et al. [3,21]. These studies, through life cycle analysis (LCA), concluded that PUSWCS offer positive environmental impacts, especially in highly populated areas. This consistency reinforces the validity of our results and suggests that the environmental benefits of PUSWCS are recognized by both users and specialized technicians. However, as Farré et al. [21] indicated in their review on the subject that literature on PUSWCS is scarce, so the analysis must be contextualized under this premise, and there is a need to expand knowledge in this field.

Although PUSWCS users lack information about the energy consumption of each waste collection system, studies by Punkkinen et al. [17], Chafer et al. [18], and Farré et al. [3,21] concluded that this variable is crucial for evaluating the environmental impact of different collection systems. Nevertheless, technicians with detailed information on the energy costs of systems in their municipalities consider this solution favorable. Additionally, energy costs from renewable sources would reduce greenhouse gas emissions. Other positive variables, well-received by system users, include convenience, hygiene, aesthetics, reduced traffic, and less dependency on collection during adverse weather conditions.

A significant disadvantage not perceived by system users but noted by competent technicians is the pipe blockages that require system interruption for maintenance and the lifespan of the pipes used for PUSWCS, as noted by Farré et al. [21]. This opens a new research avenue to increase the lifespan of pipes and reduce mechanical wear caused by waste, which could alter the projected operation and maintenance costs during the system's lifespan.

In summary, PUSWCS are well-perceived by system users and competent technicians, aligning with the SDGs analyzed in our study, making them a potential solution for municipal waste management in future cities. PUSWCS play a role in advancing the SDGs by promoting sustainable urban development, improving public health, fostering responsible waste management practices, and contributing to climate action. However, it is essential to have a tool to study whether the installation of such urban solid waste collection systems is suitable in a specific urban environment with its socioeconomic conditions, considering the specific context and design of each system to maximize its positive impact on the SDGs.

## 5. Conclusions

The pneumatic solid urban waste collection systems have been analyzed, comparing their advantages and disadvantages with respect to the Sustainable Development Goals (SDGs). Despite high implementation costs and significant challenges during the execution phase, these systems improve citizens' quality of life and enhance system management by incorporating new technologies, with citizens playing a fundamental role in its success. In short, these systems contribute to achieving the sustainable development goals set by the United Nations, which leads to greener, more sustainable cities closer to the smart cities of the future.

Historically, waste management has been a primary concern for local authorities due to its health and environmental impacts. Today, it is recognized as a systemic issue with far-reaching implications, including economic development, social and economic inequalities, community engagement, marine pollution, and other factors that shape the urban ecosystem. These implications are continuously evolving. According to the World Bank's report "What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050" [7], cities often lack adequate and suitable systems to handle changes in waste disposal. In response, this article presents a decision matrix that has helped us confirm the feasibility and effectiveness of pneumatic urban waste collection systems, providing a tool for future analyses and the planning of waste collection systems in cities.

Once the pneumatic urban solid waste collection system has been implemented, future steps should focus on long-term studies of energy savings, greenhouse gas emission reductions, and material durability. These long-term studies will provide deeper insights into the effectiveness of such systems in sustainable cities and adjust operation and maintenance costs.

A decision support matrix has been designed and has proven to be a reliable tool for assessing the implementation of a pneumatic urban waste collection system This confirms the hypothesis that pneumatic collection systems integrate optimally with smart city concepts. Pneumatic technology not only offers an efficient solution for waste management but also aligns closely with the vision of more connected and eco-efficient cities. The results support the desirability of implementation, providing evidence of its effectiveness in terms of sustainability, efficient waste management, and improving citizens' quality of life. The decision matrix could enable future comparative studies of different collection systems and their urban contexts, helping to design the best waste collection system for each urban environment.

For the design of the multi-criteria decision matrix, the opinions of technicians specialized in pneumatic waste collection systems and various stakeholders have been considered.

This opinion has been collected through surveys and the information collected, whether qualitative or quantitative, has been weighted according to the experience of the participants, following the philosophy of fuzzy logic techniques. The variables considered have technical, economic, and social impacts and are based on the SDGs, which present long-term constraints that transcend the geolocation and law and environmental regulations of each country.

The rigorous process followed in the matrix design supports the decision-making, consolidating the collection systems as an effective, sustainable, and resilient solution for waste collection management. However, this matrix could be improved by considering additional decision criteria, especially if the numerical value does not clearly indicate whether to implement a PUSWCS.

Future analyses could benefit from using Artificial Intelligence (AI) to adapt collection systems efficiently to different urban contexts. Artificial Intelligence plays a fundamental role in the evolution of PUSWCS by analyzing system usage, detecting patterns, and evaluating optimal collection routes. An AI-driven database could include solution matrices from installations with proven use, relating results to specific variables and SDGs, thus achieving highly reliable outcomes.

This matrix is adaptable to various collection systems, both existing and future ones. However, it is essential to maintain a clear relationship between the variables studied and the SDGs measured.

In the future, the decision matrix could also incorporate sociocultural context variables. This would integrate population habits and user interactions with waste collection systems, adapting different systems to provide effective and efficient responses to urban environments. It is important to note that the perception of PUSWCS users and technicians may be influenced by local factors. In such cases, the decision matrix results may need to be adjusted or new variables added for urban environments with characteristics significantly different from the studied municipalities.

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## Abbreviations

| | |
|---|---|
| GHG | Greenhouse gas |
| I | Impact |
| ISWM | Integrated solid waste management |
| LCA | Life cycle assessment |
| M | Magnitude |
| MCDM | Multi-criteria decision making |
| MSW | Municipal solid waste |
| MSWM | Municipal solid waste management |
| PUSWCS | Pneumatic urban solid waste collection systems |
| SDGs | Sustainable development goals |
| TOD | Transit-oriented development |

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