Article

Smart Ecological Points, a Strategy to Face the New Challenges in Solid Waste Management in Colombia

Juan Carlos Vesga Ferreira *, Faver Adrian Amorocho Sepulveda and Harold Esneider Perez Waltero

School of Basic Sciences, Technology and Engineering (ECBTI), Telecommunications Engineering Program,
Universidad Nacional Abierta y a Distancia, Bogotá 111321, Colombia; faver.amorocho@unad.edu.co (F.A.A.S.);
harold.perez@unad.edu.co (H.E.P.W.)

Abstract: Around the world, managing and classifying solid waste is one of the most important challenges to sustaining economic growth and preserving the environment. The objective of this paper is to propose the use of Smart Ecological Points as a strategy to address the problem of solid waste management systems at the source, which has become one of the biggest problems globally, and Colombia is no exception. This article describes the current state of the problem in the country and presents a prototype of a low-cost Smart Ecological Point supported by the use of an experimental capacitive sensor and machine learning algorithms, which will reduce the time necessary for the classification of recyclable and non-recyclable waste, increasing the percentage of waste that can be reused and minimizing health risks by reducing the probability of being contaminated at the source, an aspect that is very common when waste is sorted manually. According to the results obtained, it is evident that the proposed prototype made an adequate classification of waste, generating the possibility of it being manufactured with existing technology in order to promote adequate waste classification at the source.

Keywords: solid waste management; waste classification; capacitive sensor; machine learning; ecological point

1. Introduction

Currently, solid waste management is one of the most important problems in the world. The generation of solid waste increases day by day as a result of rapid population growth, rapid industrialization, and economic development, causing the emergence of various social problems related mainly to health and the environment [1]. Solid waste management is made up of an entire chain of processes, among which we can mention waste collection from the point of generation (homes, companies, shopping centers, etc.), transportation, treatment, segregation, and final disposal [2]. Municipal solid waste management is one of the main functions of local institutions in developing countries, and its optimal performance depends mainly on the level of knowledge that organizations have in relation to the production of solid waste.

The segregation or classification of solid waste is considered by many researchers to be one of the most important pillars of solid waste management systems [3]. Solid waste consists of a series of materials that, in most cases, are recyclable and could be reused in various industrial processes, such as paper, cardboard, glass, plastic, rubber, and ferrous and non-ferrous metals. Additionally, organic waste can be treated to generate biogas and biofertilizers. However, due to poor waste management and inadequate collection practices that are currently present in most cities, solid waste causes serious social, health, and environmental problems, as well as economic, resource, and energy losses [4]. Additionally, as a result of poor waste management, the recycling percentage is minimal, and the amount of waste that reaches landfills or areas established for landfills exceeds their capacities, generating a negative impact on society and the world that surrounds us.
Within the wide spectrum of problems related to environmental protection, solid waste management occupies one of the most important places. The main objective of environmental management policies is to establish mechanisms that allow this process to be carried out in an efficient manner compatible with environmental and public health [5]. Waste sorting has become crucial to sustaining global economic growth, reducing poverty levels, and preserving the environment. For this reason, it is very important to have efficient solid waste classification processes to improve environmental and health conditions, job creation, the emergence of new services, and the economic level of many families that depend on the current economic activities related to the sector.

Given this situation, there is a need to develop an effective system that allows the possibility of making significant changes in the solid waste classification process at the source to minimize the problem. Currently, every government in the world is planning to build smart cities or trying to transform existing cities into smart cities [6]. The collection and classification of solid waste is a crucial point for the environment and its impact on society, which is why the use of technologies such as the Internet of Things (IoT) and artificial intelligence could help implement solutions that allow the provision of services related to this problem. There are a large number of developments related to the classification of materials and/or waste through image recognition from convolutional neural networks and optical and spectrophotometry techniques, among other related techniques, such as those proposed by [7–12]. However, despite being efficient in the classification process, these require cameras and robust hardware, generating a higher implementation cost compared to the method proposed in this article. Moreover, in most cases, they may not be suitable for the dirty conditions to which any ecological point will be subjected.

In view of the above, this article presents a demonstration of the development of a prototype of an ecological point that carries out a basic waste separation process through the design of a capacitive sensor with low manufacturing cost and sufficient capacity and sensitivity to facilitate the classification of various types of solid waste, such as glass, plastic, metal, and organic waste, at the source through the use of machine learning algorithms in order to optimize the separation processes of recyclable and non-recyclable waste. In Colombia, it is regulated by Resolution 2184 of the Ministry of Environment and Sustainable Development of 26 December 2019 [13].

2. Materials and Methods
2.1. Ecological Point

An ecological point is defined as a special area or space, clearly delimited and marked, composed of containers of different colors, that aims to raise awareness and encourage people to act responsibly in the solid waste separation process [14]. An ecological point facilitates the classification of solid waste because it has special containers to properly dispose of the different recyclable materials and organic waste. It is important to mention that the use of color in recycling containers is considered a mechanism that helps guide people in the correct identification and classification of the type of waste that should be deposited in each of them.

Although manual classification of solid waste is the most used method worldwide, there are other methods supported by the use of technology that seek to carry out the same process. These methods are classified as direct and indirect and are used in various sectors according to the need for classification [15]. Direct methods make use of the physical properties of the waste, such as electrical conductivity, magnetic susceptibility, or density. These methods seek to separate heavy waste from organic waste, as well as ferrous metals from non-ferrous metals. Normally, this method is used in the first stage of solid waste classification. Indirect methods are related to the use of sensors for the identification and classification of the different types of materials that make up the solid waste resulting from the direct separation process. These methods are used in a later stage of the process since, at this stage, more specialized identification of materials is required [16].
The implementation of a technological solution for the classification of solid waste in Colombia is essential for several reasons. Firstly, inadequate waste management has generated serious environmental and public health problems in the country. A technological solution would allow optimizing and streamlining of the waste separation process, increasing management efficiency and facilitating the identification of recyclable, organic, and non-recyclable materials. This would help reduce environmental pollution and promote a more effective and sustainable recycling culture.

Furthermore, a technological solution can be scalable and adaptable to different environments, making it more accessible and practical to implement on a large scale in various Colombian communities. Using technologies such as artificial intelligence, sensors, or mobile applications, education about waste management could be improved by offering real-time information on proper classification, thus encouraging more responsible habits. This technological solution not only represents an effective short-term measure but also lays the foundations for long-term cultural and educational change, promoting environmental awareness in Colombian society.

In view of the above, promoting the design and implementation of Smart Ecological Points could be considered a great contribution to the Comprehensive Solid Waste Management Plans (PGIRS) that each municipality in Colombia is committed to developing and continuing to strengthen. The formulation of projects for the use of solid waste and development of separation programs at the source (homes, companies, commercial environments, etc.) through the companies that provide collection, use, and treatment services for the public cleaning service aim to improve environmental and health conditions, the generation of employment, the emergence of new services, and the economic level of many families that currently depend on economic activities related to the sector, thereby generating the possibility of contributing to the implementation of measures necessary for the economic and social reactivation of the country, derived from the pandemic and post-pandemic context, and in turn contributing to sustainable development.

Additionally, the proposed technological solution would allow, in the short-, medium-, and long-term, to optimize the logistics processes of the route and frequency of waste collection at ecological points, taking into account that the system could have the capacity to send information on the current status of each container to the cloud via GRPS or WiFi, allowing us to identify when each ecological point has reached its storage capacity and in this way, the company can schedule the collection at each ecological point along its route. In turn, through the use of the Internet of Things (IoT), an updated record could be kept in the cloud, with statistics on the weight, types of waste, place, day of the week, and times of day when there is greater generation of waste, among other parameters, in such a way that through the use of data analytics and machine learning algorithms, it is possible to generate new knowledge and identify patterns related to this social dynamic, which will allow in the not too distant future the creation of new development programs of more efficient environmental culture [6]. These aspects will be addressed in greater detail in future manuscripts.

2.2. Current Situation of the Colombian Context in the Classification of Solid Waste

In the particular case of Colombia, according to the Ministry of Environment, the generation of estimated solid waste derived from domestic activities is close to 26,975 tons/day. The total accumulated in one year, adding industrial and commercial waste, is around 11.6 million tons per year [17]. In Figure 1, it is possible to see that most of the departmental distribution of the country’s waste disposal (51.41%) is concentrated in the Capital District and three departments, Bogotá, DC (6366.24 Ton/day, 20.55%), Valle del Cauca (3592.68 Ton/day, 11.60%), Antioquia (3575.26 Ton/day, 11.54%), and Atlántico (2387.50 Ton/day 7.71%). In accordance with the trend exposed for the 2017 period in the 2017 Final Disposal Report, it can be seen that these three departments and the Capital District also had the highest concentration of disposed waste. Although awareness campaigns, environmental education programs, and legislative documents have been carried out in
this regard for years, it is estimated that the recycling percentage only reaches 17%. In the particular case of plastic, it is stated that only 7% is recycled [14].

![Figure 1. Average daily tons presented to the public sanitation service by department and for the Capital District vs. number of people in each department. Source: SUI, SSPD Calculations, DANE 2018 Census.](image)

Through progress made in Colombia in the organization of people who literally live off garbage, an expression that since 1986 has been changing to “solid waste recyclers”, the creation of trade union organizations has been achieved. There are cooperatives and NGOs in the main cities and, at the national level, representations such as the National Association of Recyclers (ANR) [18]. These entities report that there are between 50 and 60 thousand families who make a daily living from the job of collecting recyclable waste in the country, highlighting that this activity has become a family dynamic because children must help their parents in this work, or if they are very young, their parents must accompany them at night, given the insecurity of leaving them alone in the house. This work is regularly carried out between 6:00 am and 10:00 pm and generates an income of COP 200 to 300 thousand per month, equivalent to approximately USD 44 to 66 [19].

Although recycling is a very important activity for the environmental sustainability of the country, it continues to present very low income. It can be mentioned as an example that, in 2019, only 1.3 million tons of waste were reused out of about 30 million produced [20]. One of the main reasons why recyclers have low economic income, despite the high volume of products that could be collected, is the inadequate classification process at the source, which generates contamination between the waste and the inadequate disposal of the same. This means that the material has to be discarded due to its contamination and, consequently, causes an economic loss as well as the opportunity to reuse it [14].

It is evident that to improve indicators such as SDG 12—Responsible production and consumption, as well as SDG 1—End poverty in all its forms throughout the world, it is necessary to engineer and develop innovative technological solutions with the capacity to carry out the solid waste classification process at the source in an efficient and systematized manner, through so-called “Smart Ecological Points”, which would be consistent (in the case of
Colombia), with Resolution 2184 of the Ministry of Environment and Sustainable Development of 26 December 2019, which came into force as of 1 January 2021, in which it is determined that, to carry out the separation of solid waste at the source, from now on, only three colors will be implemented for the classification of solid waste, as can be seen in Figure 2 [13].

![Figure 2. Color assignment for container or bag according to the type of waste. Source: Resolution 2184 of the Ministry of Environment and Sustainable Development of 26 December 2019.](image)

On the other hand, in decree 349 of 2014, which regulates the imposition and application of the Environmental Comparative in the Capital District, the following is expressed: “Culture of waste reduction and separation at the source”. It is oriented towards training and raising awareness among citizens who use sanitation services through massive campaigns on the benefits of recycling, separation at the source, and the differentiated disposal of solid waste. Differentiated interventions are included according to the type of user: schools and universities, homes, residential complexes, businesses and commercial premises, and industries [21]. Although the pedagogical nature of the construction of environmental culture is highlighted in the responsibility of separation at the source, this is not currently applied by society. That is why paragraph 2 of article 94 of Law 1801 of 2016, better known as the Police Code, which established three types of fines (16 SMDLV) for people or institutions that do not separate at the source or do so incorrectly, must be kept in mind.

It is very important to mention that solid waste management is a fairly broad field that includes the following processes: waste collection from the point of generation, waste transportation, waste treatment, waste classification, and finally, waste disposal [22]. When talking about the correct way to separate waste, the best-known method implemented by institutions and at the domestic level is the manual classification method, which consists of depositing the waste in different containers based on their material; this method is supported by pedagogy programs that instruct people on the subject [23].

2.3. The Trash

There are wastes that do not have a commercial value and require special treatment for their final disposal. These generate disposal costs that cannot be reincorporated into the economic–productive cycle [24]. These wastes create negative environmental impacts, which is why they must be minimized. Figure 3 shows the general solid waste classification scheme.
2.4. Recycling

Recycling is the process of collecting and processing materials that would otherwise be discarded as garbage and turning them into new products. Recycling is a process that benefits the community and the environment. There are two general types of recycling operations: internal and external [25]. Internal recycling is the reuse in a manufacturing process of materials that are a waste product of that process. Internal recycling is common in the metals industry, for example. The manufacturing of copper tubes results in a certain amount of waste in the form of tube ends and trimmings. This material is melted again to give it another use. Another form of internal recycling is seen in the distillation industry, where, after distillation, spent grain mash is dried and processed into edible livestock feed. External recycling corresponds to the recovery of materials from a product that has worn out or has become obsolete. An example of external recycling is the collection of old newspapers and magazines to make new paper products.

2.5. Current Regulations for Ecological Points Colombia

Table 1 presents a list of the most relevant regulations related to the treatment and collection of solid waste.

<table>
<thead>
<tr>
<th>Regulation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution No. 2184 of 2019</td>
<td>Establishes the new color code (white, black, and green) for recycling bins and containers. Defines what type of waste should be deposited in each color: white (plastic, glass, paper), black (non-reusable waste), and green (organic waste).</td>
</tr>
</tbody>
</table>
### Table 1. Cont.

<table>
<thead>
<tr>
<th>Regulation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special Waste</td>
<td>Waste such as electrical equipment, batteries, used oils, tires, and expired medications, among others, must be deposited in Ecolecta, Ecopunto, Recipunto, and Blue points according to regulations.</td>
</tr>
<tr>
<td>Relevant Regulations</td>
<td>Laws, decrees, and agreements such as Law 1672 of 2013, Decree 284 of 2018, and Agreement 565 of 2014, among others, regulate the comprehensive management of specific waste such as electronic devices, used oils, and hazardous substances.</td>
</tr>
</tbody>
</table>

#### 2.6. Some Developments Related to Waste Classification in National and International Environments

Garbage classification and environmental monitoring technology have developed rapidly in recent years. The combination of the Internet of Things and environmental technology has become a trend. The growth of cities has, in turn, generated considerable growth in environmental pollution and solid waste management, causing enormous environmental and social problems [26]. Currently, urban areas commonly apply the strategy of “mixed collection, centralized transportation, centralized processing”, commonly known as three-segment management for recycling and garbage disposal, which has proven to be ineffective in treating massive waste [27]. Figure 4 presents a summary of some of the most representative works in Colombia and internationally related to the use of technologies aimed at the classification and management of solid waste that are part of the state of the art of this manuscript.

The development of a waste classification system using a low-cost capacitive sensor and machine learning algorithms entails a series of substantial benefits compared to similar solutions that have been developed and exist on the market.

![Figure 4. Some developments related to waste classification in national and international environments [15,24,25,28–47].](image-url)
In terms of cost, the proposed prototype offers an economically viable alternative, allowing even communities with limited resources to access advanced waste management technologies. This makes a notable difference compared to expensive and complex solutions that, although they may be effective, are often out of reach for areas with restricted budgets. This aspect is common in most of the solutions listed in Figure 4.

The use of a capacitive sensor for waste classification, based on the measurement of the capacitance value, marks a fundamental difference compared to conventional solutions supported by image recognition or other optical methods, taking into account that these largely depend on the visibility and visual clarity of objects, in contrast to the capacitive sensor, which focuses on the unique dielectric properties of materials, allowing waste to be identified and differentiated more easily, without being affected by external factors such as lighting, shadows, or changes in the color and shape of the waste. This independence from visual conditions makes the capacitive sensor a more robust and reliable option for accurate waste sorting in a wide range of environments and situations.

In terms of efficiency, the developed prototype offers adequate levels of waste classification supported by the use of machine learning algorithms, allowing its adaptation and greater adjustment over time, taking into account that its learning is supported by the amount of waste that was taken as a reference during training campaigns. This aspect not only simplifies sorting processes but also guarantees more effective and precise waste management, resulting in a lower environmental impact and greater efficiency in recycling and reuse processes.

Simplicity of implementation is another essential aspect. Often, existing solutions on the market may require complex installations, specialized technical knowledge, or special conditions for their operation, which are aspects that limit their application in diverse environments. However, this prototype, based on an experimental capacitive sensor and machine learning algorithms, offers an accessible and easy-to-implement alternative, reducing the barriers to its adoption and promoting its use in a wider variety of contexts, from urban areas to rural environments.

Finally, the innovation that this proposal represents goes beyond the technology itself. By facilitating accurate waste sorting, we encourage a cultural shift towards more sustainable practices. Education and awareness about waste management are reinforced, potentially leading to more responsible communities committed to reducing their environmental impact. This combination of economic benefits, improved efficiency, ease of implementation, and positive effects on environmental awareness highlights the crucial importance of this innovative approach in waste management.

3. Results

Below is a description of the results obtained during the design and implementation process of the Smart Ecological Point prototype as a strategy for waste classification at the source through the use of a low-cost experimental capacitive sensor articulated with machine learning algorithms. The first section provides a general description of the hardware architecture of the ecological point, the elements that compose it, and the function it will perform. The second section describes the design of the experimental capacitive sensor and the characterization of the capacitance value for each class of waste used during the sampling campaign. The third section describes the analysis of the data obtained experimentally from a statistical and correlational point of view. In the fourth section, an analysis of the machine learning models proposed for waste classification is carried out, accompanied by the evaluative metrics in order to identify the model that best fits the established requirements. Finally, in the fifth section, an analysis is made of the results obtained when carrying out the integration process of the entire system to evaluate the behavior of the developed prototype of the Smart Ecological Point during the classification process of various types of waste.
3.1. Architecture of the Smart Ecological Point Prototype

An ecological point is an infrastructure designed for the correct disposal of solid waste, with a special focus on its classification and efficient management. These points play an essential role in promoting sustainable practices and reducing environmental pollution. One of the key components in waste management is proper separation, and eco-points make this task easier by providing specific containers for different types of waste.

The ecological point prototype developed using Raspberry Pi is an outstanding example of the technology applied to waste management. This system mainly consists of two containers: one for organic waste and the other for reusable waste. Most impressive is the integration of a capacitive sensor connected to a rotating platform controlled by a servo motor. After reading the capacitance of the introduced residue, the platform rotates clockwise or counterclockwise, depending on the result of the classification carried out by a machine learning algorithm. This allows the waste to be deposited in the corresponding container in an automated and precise manner. Figure 5 shows the diagram that describes the prototype of the ecological point that was developed.

In addition, the system incorporates two HC-SR04 ultrasound sensors that function as waste-level detectors in each container. Also included are two XS-112 load cells with a capacity of up to 50 kg each, connected to HX711 modules. This allows the measurement of the weight of the containers, providing information on their fill level. All of this complex infrastructure is managed by a Raspberry Pi, which not only reads the capacitance and controls the rotating platform but also records and monitors the weight and level of each container to identify when they are full. This prototype demonstrates that it is possible to play a fundamental role in the efficient management of solid waste with existing technology, thus promoting more sustainable and environmentally friendly practices.

![Diagram of the developed Smart Ecological Point prototype.](image)

Figure 5. Diagram of the developed Smart Ecological Point prototype.

The prototype of the Smart Ecological Point developed can be considered a low-cost solution, considering that the total value related to the manufacturing materials was approximately USD 137, of which USD 20 corresponds to the cost related to the experimental capacitive sensor, ultrasound sensors, weight sensors and servo motor of the rotating platform, USD 50 for the Raspberry Pi and USD 67 for the metal structure, waste containers, and complementary hardware. At the same time, its manufacturing cost is very close to that of traditional ecological points that can be found on the market, which do not
have any type of electronic system for waste classification. This is an aspect that can be considered of great importance when it comes to whether the prototype can be marketed in the medium term.

3.2. Design of the Proposed Capacitive Sensor

For the construction of the proposed capacitive sensor, the use of aluminum sheets made from beer cans was considered, taking into account the ease of having this resource as a reusable material and in coherence with the general objective of the project. It is very important to mention that beer or soda cans can be made from steel or aluminum, depending on the application and the region in which it is manufactured, where one type of metal or another may be more common. In most cases, cans are made from aluminum (as in this particular case) because this material helps keep drinks fresh and protected from air, light, and safety hazards (bacteria, viruses, chemicals, and physical hazards), as well as guarantees their quality levels [50].

For this particular case, a non-traditional capacitive sensor (MNT) was proposed, which is made up of two E-shaped plates, which is inspired by the shape of a resistive humidity sensor, where the area of the plates \( A = A_1 = A_2 \) and the number of slots that interlock between the plates is the same, separated from each other by a distance \( d \). Figure 6 presents the proposed diagram for the MNT sensor, which is given by the dimensions \( a, b, c, \) and \( d \). Additionally, the way in which the positive and negative electric charges are distributed on the plates that are part of the capacitive sensor, the electric field lines, and their similarity from an analytical point of view with a parallel plate capacitor of area \( A \) and separation \( d \).

![Schematic of the MNT capacitive sensor.](image)

For the development of the experiment, a digital capacitance and inductance meter (LCR) brand UNI-T series UT603 was used, which has a tolerance percentage of 1%, through which the capacitance measurement in pF was carried out for each of the proposed sensors, under each of the established conditions, according to the type of material or waste for subsequent identification and classification. In turn, an Electronic SF-400 series digital scale was used, which has a maximum capacity of 5 kg and a sensitivity level of 1 g.

It is important to mention that the MNT sensor was covered with a layer of plastic (polypropylene) during the manufacturing and design stage in order to protect the sensor from the environment to which it will be subjected and, at the same time, maintain a constant separation distance between the plates, without any type of contact between them. In view of the above, a value of \( \varepsilon_r = 2.6 \) was considered to estimate the capacitance value.

Figure 7 presents a capacitance value \( C_{MNT}' = 28 \) pF that the LCR delivers for the prototype that was implemented for the MNT sensor when it is free of residue, accompanied by the proposed diagram. From Equation (1), the capacitance value \( C_{MNT} \) is calculated according to the sensor dimensions that were considered at the discretion of the researchers for its construction \((a = 5 \text{ cm}, b = 0.9 \text{ cm}, c = 1.5 \text{ cm}, \text{ and } d = 0.1 \text{ cm})\).
The capacitance value for the MNT capacitive sensor ($C_{MNT}$) can be calculated from Equation (1):

$$C_{MNT} = \frac{\varepsilon A}{d} = \frac{\varepsilon_0 \varepsilon_r A}{d} = 24.5 \text{ pF}$$  \hspace{1cm} (1)

$$\varepsilon_{abs} = C'_MNT - C_{MNT} = 3.49 \times 10^{-12}$$  \hspace{1cm} (2)

$$\varepsilon_r = \frac{C'_MNT - C_{MNT}}{C_{MNT}} = 0.143$$  \hspace{1cm} (3)

In Equations (2) and (3), the result of this process is presented accompanied by the absolute error ($\varepsilon_{abs}$) and the relative error ($\varepsilon_r$) in contrast with the result obtained experimentally, where it can be seen that the theoretical value and the one obtained experimentally, as in the previous case, are very similar to each other, with low absolute and relative error levels. In view of the above, it could be said that the mathematical expression proposed for the type of sensor is consistent with the results obtained experimentally, thereby allowing us to establish a reference point of great importance for future research in which we wish to use the proposed model or make some variation in terms of design or dimensions.

Figure 8 presents some of the results obtained during the measurement campaigns in the presence of reusable waste, such as plastic, glass, and metal, as well as various types of organic waste. For the sampling campaign, 100 samples were established and distributed into 25 records for each of the four types of waste or materials (plastic, glass, metal, and organic). In Tables 2 and 3, the mean, standard deviation, and confidence intervals are presented for each characteristic according to the type of material or waste used during the sampling campaign.

Table 2. Statistical results of measurements with MNT Sensor.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Confidence Interval (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic</td>
<td>34,680</td>
<td>1574</td>
<td>(34,063–35,297)</td>
</tr>
<tr>
<td>Glass</td>
<td>34,880</td>
<td>1666</td>
<td>(34,227–35,533)</td>
</tr>
<tr>
<td>Metal</td>
<td>31,960</td>
<td>0.934</td>
<td>(31,593–32,326)</td>
</tr>
<tr>
<td>Organic</td>
<td>680,960</td>
<td>324,396</td>
<td>(553,799–808,120)</td>
</tr>
</tbody>
</table>
Table 2. Statistical results of measurements with MNT Sensor.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Confidence Interval (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic</td>
<td>34,680</td>
<td>1574</td>
<td>(34,063–35,297)</td>
</tr>
<tr>
<td>Glass</td>
<td>34,880</td>
<td>1666</td>
<td>(34,227–35,533)</td>
</tr>
<tr>
<td>Metal</td>
<td>31,960</td>
<td>0.934</td>
<td>(31,593–32,326)</td>
</tr>
<tr>
<td>Organic</td>
<td>680,960</td>
<td>324,396</td>
<td>(553,799–808,120)</td>
</tr>
</tbody>
</table>

Table 3. Statistics related to the weight of each sample.

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight [g]</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Confidence Interval (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic</td>
<td>95,920</td>
<td>23,184</td>
<td></td>
<td>(86,832–105,008)</td>
</tr>
<tr>
<td>Glass</td>
<td>98,320</td>
<td>27,018</td>
<td></td>
<td>(87,729–108,911)</td>
</tr>
<tr>
<td>Metal</td>
<td>102,560</td>
<td>28,649</td>
<td></td>
<td>(91,330–113,790)</td>
</tr>
<tr>
<td>Organic</td>
<td>135,360</td>
<td>46,473</td>
<td></td>
<td>(117,143–153,577)</td>
</tr>
</tbody>
</table>

3.3. Classification of Solid Waste with MNT Sensor Using Machine Learning Algorithms

For the training and evaluation of the different processes related to data analytics, training, testing, and validation of the proposed model, use was made of the cluster of libraries (sklearn, matplotlib, pandas, numpy, and scipy, mainly) and other resources in Python that are available in the Anaconda tool—Jupyter Notebook version 6.5.4. To carry out adequate conditioning of the data in order to minimize biases during the model training process, a process of adjustment and normalization of the data was carried out using the “RobustScaler” technique, which is part of the sklearn library. Additionally, for the training and testing process of each of the proposed classification models, the “train_test_split” function was used.

Figure 9 shows the correlation matrix of the two characteristics under study, where it is possible to show a correlation factor of 0.44 between Weight and Capacitance. This is an aspect that can be considered relatively low, and, therefore, we can consider that the two characteristics are independent of each other, a result that is very important to consider when carrying out the classification process and analysis of the results of the proposed machine learning model.
In order to evaluate each algorithm, the confusion matrix was considered, through which it is possible to identify the number of correct or unsuccessful predictions made by the trained model and compare it with the original data through a supervised learning process. Figure 10 presents the result of the confusion matrix, where it can be seen that for the random forest, logistic regression, and neural network MLP classifier models, the number of “False Positives” and “False Negatives” was “Zero (0.0)”, thereby expressing that no data value was classified incorrectly for each of the proposed classes, accompanied by an adequate classification of each one of the categories, where it is possible to verify through the “True Negatives” and “True Positives” that of the total records that were considered, 75 of them belong to class “0” and 25 to class “1”, being “0” for reusable waste and “1” for organic waste, which is correct. An aspect that did not happen in the same way, although with very similar results for the KNN model where the number of “False Positives” and “True Positives” was 1 and 24, respectively, causing slight changes in metrics such as Accuracy, Recall, and F1. The results can be considered favorable, considering that they describe a low probability of presenting overfitting processes in accordance with the values obtained in the Precision, Recall, and F1 metrics [51]. Figure 10 presents the confusion matrix and evaluation metrics for each of the proposed models.
Weight and capacitance stand out as relevant variables for solid waste classification due to their ability to discern between different types of materials. Weight, being a direct physical measurement, allows us to distinguish the density and mass of waste, which is essential to separate heavy materials such as metals from lighter materials such as plastics or paper. On the other hand, capacitance, when evaluating the dielectric permittivity of materials, can differentiate between recyclable and non-recyclable elements, facilitating the identification of electronic components or conductive materials. These variables provide essential quantitative and qualitative information for an accurate and efficient solid waste classification process, thus contributing to improving waste management systems.

For the identification of waste or materials through the use of the proposed experimental capacitive sensor, four machine learning algorithms were used for the classification of waste (random forests, KNN, logistic regression, and MLP neural network), through which the respective training, testing, and validation process was carried out, based on the database that was prepared during the sampling campaigns for the MNT sensor, in which the measurement of two characteristics was carried out (Capacitance [pF] and Weight [g]) of each sample, for a total of 100 records, distributed in two classes (0: Reusable waste, 1: Organic waste or paper). On the other hand, capacitance, when evaluating the dielectric permittivity of materials, can differentiate between recyclable and non-recyclable elements, facilitating the identification of electronic components or conductive materials. These variables provide essential quantitative and qualitative information for an accurate and efficient solid waste classification process, thus contributing to improving waste management systems.

Figure 11 presents graphically the validation of each of the four classification models that were considered as an alternative for the separation of solid waste. It is possible to identify the straight line or reference line that was estimated by each algorithm for decision-making in relation to the class to which each type of waste belongs from a statistical point of view. In three of the four models, it can be seen that the reference line is completely horizontal, where the standardized capacitance value is less than four (4.0), each of them with a different reference threshold value, although they are very close to each other. However, in the case of the MLP neural network model, the algorithm established a linear reference level with a negative slope and a maximum value of less than five (5). In turn, it can be seen that the KNN model presents a very similar behavior in terms of metrics and
reference threshold for classification, where although they present high values in terms of metrics such as Recall, Precision, and F1 mainly, they perform an inadequate classification process, especially for values in which organic waste describes a low capacitance value and values close to those recorded for reusable waste.

On the other hand, the MLP neural network model, although from a graphical point of view it carries out an adequate classification process, accompanied by metric values of 1.0 in all cases, may present the same situation as in the case of the two previous models, because it is possible that situations may arise in which a very low weight organic waste is introduced, where according to the graph obtained it is possible to estimate that in this situation the waste will be classified as reusable waste, which is not correct. In the case of the model supported by logistic regression, it presents, like the previous models, high levels in its metrics and, at the same time, establishing a threshold level that allows carrying out an adequate classification process with the data established for its training and testing. However, it is possible to show that the threshold level established for the algorithm is very close to the record of the lowest capacitance value in the case of organic waste, a situation that could generate errors during the process of classifying some organic waste as reusable because it would present a capacitance value slightly lower than the minimum value used during the training process, which is why the logistic regression model would not be considered ideal for the waste classification process.

The classification model corresponding to random forests not only presents values of the ideal metrics but also establishes a threshold level in an intermediate tolerance zone between the maximum and minimum values of capacitance for reusable and organic waste, respectively, establishing a tolerance zone in which the possibility of being misclassified between the two types of waste is significantly reduced, in the presence of new records where the capacitance reading is slightly outside the limits established in the model during the training and validation process. The reason why, for the particular case, it would be considered that the model that makes use of the random forest algorithm, given the data that was used during the training, testing, and validation process, thereby generating an adequate level of confidence, both for the proposed model and for the MNT sensor designed for use in processes related to the classification of solid waste.
The results obtained in this article are the result of exhaustive research carried out by the authors, focused on the analysis and validation of the prototype of the Smart Ecological Point developed. These results strongly confirm the functionality and efficiency of the implemented system, highlighting innovative and relevant aspects that distinguish it from other solutions present in current research. In contrast to previous approaches based on image recognition techniques, microwaves, or optical methods, this prototype offers a more comprehensive and advanced perspective for solid waste classification. Its ability to integrate multiple technologies and provide accurate and effective classification is a significant advance in the field, setting the standard for more complete and efficient solutions in waste management.

The validity of the results obtained is based on the methodological rigor used during the research. The development of the Smart Eco-Point was based on a carefully planned experimental design, which included extensive and comparative tests with different types...
of solid waste. Furthermore, data collection was carried out using multiple performance metrics and cross-validation, ensuring the reliability of the results and their consistency across different scenarios. These rigorous approaches and consistency in findings support the reliability and robustness of the conclusions obtained, reinforcing the credibility of the prototype and its contributions to the field of waste management.

Finally, the experimental results obtained when using the Smart Ecological Point prototype validate its effectiveness in the classification of solid waste. These results are supported by practical tests that demonstrated a high rate of accuracy and consistency in the identification and separation of various types of waste. Tests were carried out under variable conditions, such as different textures, sizes, and compositions of waste, and showed the versatility and adaptability of the system, guaranteeing reliable and accurate classification in diverse environments. The robustness of the experimental results allowed us to confirm the viability and effectiveness of the prototype, underlining its potential to significantly improve solid waste management processes. The optimal performance of the developed prototype remained constant and efficient regardless of the lighting conditions, the physical structure of the ecological point, or other environmental factors, without affecting the classification capacity of the system. Even in the face of challenging situations, such as changes in the orientation of the waste or variable lighting conditions, the prototype maintained notable consistency in the proper classification for a wide range of waste, evidencing its robustness and adaptability in diverse environments and offering adequate levels of efficiency and reliability.

5. Conclusions

Environmental protection is a global priority today, and solid waste management plays a key role in this effort. To effectively address this challenge, it is crucial to implement environmental management policies supported by technology and artificial intelligence. The application of these tools allows for more precise monitoring and optimization of waste collection, recycling, and disposal processes, thereby reducing the ecological footprint and promoting more sustainable practices. Technology and artificial intelligence not only improve the efficiency of waste management but can also prevent pollution and promote the conservation of natural resources, paving the way to a cleaner and more sustainable future for generations to come, which is why the use of technologies such as capacitive sensors and artificial intelligence could help implement economical and efficient solutions that allow the classification of solid waste at the source, minimizing the time necessary for its classification compared to manual separation processes, reducing the health risks that may arise when working with contaminated waste, and increasing the percentage of waste that can be reused and reprocessed later thanks to the adequate separation process. According to the results obtained, it was evident that the proposed ecological point prototype, supported by the use of the MNT experimental sensor, describes adequate behavior in terms of classification, sensitivity, and coherence with the readings recorded for each type of material or test waste that was used for its evaluation, thereby facilitating not only the classification of waste articulated with the use of machine learning algorithms but is also in accordance with current regulations in Colombia, establishing a line for future projects for the classification of waste materials such as more selective ways for reusable waste such as glass, paper, plastic, and metal independently.

Funding: The authors would like to thank UNAD (PG 0501ECBTI2022) and the company Smarttic, for supporting the research carried out in this article.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References


43. Niño, M.F.; Rosales, B.; Rueda, C.M.; Cárdenas, O.Y. Caneca Inteligente de Basura; UTS: Sydney, Australia, 2017.


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.