International Journal of Innovative Research and Scientific Studies, 8(1) 2025, pages: 1979-1986

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

Innovative technologies in plastic waste management in educational institutions

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Abstract

One of the pressing global problems in recent years is environmental pollution and inefficient waste management. In this regard, smart bins with automatic waste separation are increasingly being created and introduced, which facilitate recycling and reduce the burden on the environment. The introduction of such bins and simple devices for recycling plastic in educational institutions will not only ensure cleanliness and reduce the amount of waste but will also contribute to the formation of environmental awareness in the younger generation, nurturing in them a sense of responsibility for the environment. The aim of this research is to develop, within the framework of a student startup, and experimentally test smart waste bins with automatic separation of plastic waste and a device for recycling it for secondary use for educational purposes without transportation and additional costs. Based on modern IoT and AI technologies, a smart waste bin with automatic waste separation and a device for recycling collected plastic and creating threads for a 3D printer were developed, implemented in an educational institution, and experimentally tested. Their influence on the formation of environmental awareness among students was confirmed during a survey conducted among students of Abai Kazakh National Pedagogical University (Kazakhstan).

Keywords: Ecology, Educational institutions, Innovations, IoT and AI technologies, Separate waste collection, Smart waste bins, STEAM, Sustainable development.

DOI: 10.53894/ijirss.v8i1.4841
Funding: This research is supported by the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant number: IRN AP23490844).
History: Received: 7 January 2025/**Revised:** 14 February 2025/**Accepted:** 17 February 2025/**Published:** 21 February 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Publisher: Innovative Research Publishing

1. Introduction

Separate waste collection is a modern trend that has already been implemented in many large cities and organizations, including educational institutions. In these institutions, such innovations are intended not only to maintain cleanliness but also to provide a good opportunity to foster environmental awareness in the younger generation and cultivate a sense of responsibility for the environment.

Using traditional garbage containers of different colors for different types of waste, as practice shows, is insufficient and not always effective. There are many reasons for this. First of all, these are ingrained habits and stereotypes of throwing everything into one container. In addition, not everyone still understands the importance of separate waste collection and its impact on the environment. In smart bins, implemented based on modern IoT and AI technologies, the waste sorting process is automated and carried out without direct human participation.

The introduction of such bins and simple waste recycling devices in educational institutions contributes to the achievement of the global sustainable development goal aimed at reducing waste and increasing resource efficiency [1].

Smart bins with automatic waste separation allow for more efficient use of resources and a reduction in the amount of waste sent to landfills. Waste recycling devices, particularly for plastic waste, which is mainly in the form of packaging material for food and goods—of which there is a lot in educational institutions—transform plastic waste into a valuable secondary resource, reducing the need for new plastic. Installing a sign next to the bin with information on specific volumes of plastic waste and new products obtained as a result of their recycling draws the attention of students to the problem of waste and the importance of sorting it, influencing the formation of their environmental awareness.

Such bins and devices used for waste recycling can also serve as a demonstration teaching tool and be utilized in classes across various disciplines: ecology and sustainable development, the basics of IoT, and programming, particularly when implementing the STEAM approach in education, etc. [2, 3]. Along with fostering environmental awareness, studying their design, capabilities, and operating principles will contribute to the development of students' digital competencies and stimulate their creative interest [4].

Due to the relevance of the topic and the availability of Internet of Things and artificial intelligence technologies, many studies have been conducted in recent years in the field of automation of waste sorting, particularly plastic, which constitutes a significant portion of the total volume of all waste [5]. With a long degradation rate, plastic materials accumulate, pollute the environment, and lead to negative health effects [6]. Therefore, special attention is given to their recycling.

Plastic is a critical component of a circular economy with ambitious recycling targets [7]. For example, European Union (EU) Member States aim to achieve recycling targets of 65% for packaging waste and 50% for plastic packaging waste by 2025, with both targets set to be increased by a further 5% by 2030 [8].

Chemical and physical differences make efficient recycling of plastic waste challenging. The quality of the waste as a raw material also influences the efficiency of recycling. Proper separation of waste will improve the efficiency of recycling for reuse [9].

The New Plastics Economy Global Commitment, a coalition of more than 500 organizations, sets a goal for 100% of plastic packaging to be reusable, recyclable, or compostable by 2025 [10].

Currently, various solutions have been proposed to the problem of waste sorting, including the separation of plastic for recycling and secondary use. The most common approaches involve waste sorting and separation using various Internet of Things (IoT) technologies, employing all kinds of sensors as well as webcams based on machine learning algorithms. Additionally, there is the possibility of combining these approaches to improve the accuracy of sorting [11].

A portable NIR spectrometer [12] or an ultrasonic sensor can also be used for automatic separation of plastic at the source. Technologies such as tracer-based sorting, sorting using digital watermarks, and others can also be noted [13]. However, among all the technologies that can automate and optimize waste sorting and recycling processes, modern video object recognition technologies based on artificial intelligence [14] still stand out. A wide range of machine learning models, such as artificial neural networks (ANN), Random Forest (RF), eXtreme Gradient Boosting (XGBoost), k Nearest Neighbour (kNN), decision tree (DT), Support Vector Machine (SVM), adaptive neuro-fuzzy inference system (ANFIS), etc., are successfully used to solve waste separation automation problems. Compared to many other algorithms, the CNN model has been shown in studies to be one of the most effective in classifying garbage, achieving 89% accuracy [15, 16].

The work by Xia, et al. [17] also noted the high efficiency of convolutional neural networks (CNNs) in image recognition tasks. However, the process of training a CNN model is quite labor-intensive [18]. To achieve high accuracy, it is necessary to train it on large sets of images, which requires significant computing power and, in some cases, limits its application [19].

Good accuracy was also demonstrated using a webcam in combination with an improved YOLO model that separates objects based on visual attributes [20].

In the work Dokl, et al. [16], the most common models, including CNN and YOLO models, used in waste sorting and separation are compared; the dataset sizes and testing accuracies of the trained models are reported. It is noted that many studies propose a combination of different approaches to improve the accuracy of waste sorting and separation [21]. For example, a combined approach, including NIR spectroscopy and a CNN model [22], was proposed to successfully separate plastic into five polymer classes under different conditions (dry, wet, scratched, and dirty). Similarly, a combined approach was used to improve the separation efficiency of weathered polymer samples [23]. In another study, Xia, et al. [24] used a combined approach to analyze 159 plastic samples, half of which were black. Various spectroscopic methods, such as near-infrared spectroscopy combined with deep learning (DL), have also demonstrated high accuracy in separating plastic components [25].

This study proposes a simple and effective method for sorting waste in educational institution waste bins using a regular webcam and a compact Raspberry Pi computer. Based on OpenCV, TensorFlow, and CNN libraries, an intelligent system is created that can accurately identify plastic packaging materials and separate them directly in the bin for further processing and recycling. A device is proposed for processing this plastic and obtaining filaments for a 3D printer from it, which can be used in the educational process.

The concept of developing smart waste bins and devices for recycling collected plastic waste without transportation and additional costs emerged as part of a research project on the IoT transformation of an educational institution and served as the topic of a startup for students.

2. Materials and Methods

The study included an analysis of scientific literature on modern technologies for the separation and recycling of plastic waste, as well as a study of the practical experience of creating and implementing smart waste bins with automatic waste separation and management in various institutions to identify the most accessible, effective, and promising solutions.

The research involved modeling the functional logic of a smart waste bin and plastic recycling device and developing prototypes based on readily available materials and components. The body of the waste bin and containers for waste sorting are made of plastic using 3D printing. To identify waste types, a video camera equipped with infrared illumination is integrated into the bin to ensure high-quality imaging in low-light conditions. A Raspberry Pi microcomputer was used to process the resulting images, where waste was classified using a pre-trained neural network. A dataset of 2,500 images of various types of waste found in the educational institution was used to train the machine learning model. These are mainly paper, metal, plastic, and non-recyclable mixed waste. To transmit messages about the basket being full, a Wi-Fi module is integrated into it. To study the attitude of students toward the idea of installing smart waste bins and devices for recycling plastic bottles and reusing them for educational purposes, and to assess the impact of these innovations on the environmental awareness of students, a survey was conducted among 347 students of the pedagogical university.

3. Results and Discussion

The problem of environmental pollution has become increasingly urgent in recent years. Educational institutions, as centers of education and upbringing, play an important role in shaping environmental awareness among the younger generation. The introduction of innovative technologies, such as smart bins and waste recycling devices, can be a significant step in solving this problem.

A smart bin is a modern waste collection device equipped with various sensors, video cameras, and the ability to independently determine the degree of fullness of the waste bin, transmit messages to a special server about the need to empty the bin, as well as sort and separate waste, which facilitates recycling and reduces the burden on the environment. The introduction of such technologies in educational institutions will not only automate the waste disposal process but also educate students to be mindful of the environment and foster their environmental awareness. In addition, it demonstrates the social responsibility of the educational institution and its commitment to sustainable development.

Functionality, ease of use, and ease of maintenance are key factors when choosing a waste bin. It is important that they not only perform their direct functions but also fit harmoniously into any interior. Modern technologies provide ample opportunities for creating bins with unique designs and a wide range of functions.

Modern design and innovative technologies are harmoniously combined in the smart waste bin presented in the work [26]. It combines aesthetic appeal and practicality, offering convenient and functional solutions for waste separation.

Similar design and waste sorting technologies are utilized to create a smart waste bin for an educational institution in this study. The bin comprises four rotating containers for different types of waste. The principle of its operation is quite simple:

- Waste is thrown into the bin.
- The video camera captures an image of the thrown object, which is then processed on the Raspberry Pi using the OpenCV and TensorFlow libraries, along with CNN neural networks, to determine the type of object.
- The stepper motor driver activates the rotation mechanism.
- Depending on the type of recognized waste, the servo drive opens or closes the flap to dump it into the container if it is located above the required compartment; otherwise, the stepper motor moves it to another compartment.
- After closing the compartment, the system returns to its original position.
- Data on the occupancy of the compartments is transmitted to the cloud for monitoring and analysis.
- When the compartments are full, the system sends notifications to the mobile application.

For the body of such a smart basket for an educational institution, transparent plastic is more attractive; however, metal or wood can also be used. It is important that it is durable, waterproof, easy to clean, and has an appealing design.

Inside, such a basket is equipped with a video camera for recognizing the type of waste with a resolution of 5 MP and a viewing angle of at least 120 degrees. It consists of several rotating sections with removable containers for separate waste collection (paper, plastic, metal, and non-recyclable waste of mixed composition), each of which must be equipped with ultrasonic or infrared weight sensors to determine their level of filling. Thanks to these sensors, the basket is emptied only when necessary, which increases the efficiency of the technical staff. The rotating sections make the disposal process more convenient and hygienic, as they do not require constant opening and closing of the lid.

To implement such a basket, the following components are also required:

- Stepper motor for moving waste into a specific container.
- Automated flaps that open depending on the type of waste above the corresponding container in the basket and direct the waste into it.
- Special turning mechanisms (gears, etc.) are required to rotate the sections.
- Miniature servo drives are required to control the valves and compartments.

- To collect and process data from sensors and a video camera, control servo drives, and manage all functions of the basket, a microcontroller is required; for example, an Arduino Uno or a compact Raspberry Pi computer, which is more powerful for complex functions.
- Software for writing code that controls the operation of a microcomputer.
- To collect data on the amount of recycled waste and send notifications regarding the status of the bin, remote control and software updates, communication modules (Wi-Fi or Bluetooth) are required to provide a connection to the Internet.
- To control the operation of the basket and receive notifications regarding its functionality, it is necessary to create a mobile application.
- To display information and interact with the user, as well as to present data on the amount of waste disposed of to motivate students, it is desirable to have a display.

The functional and logical diagram of such a smart waste bin is illustrated in Figure 1.

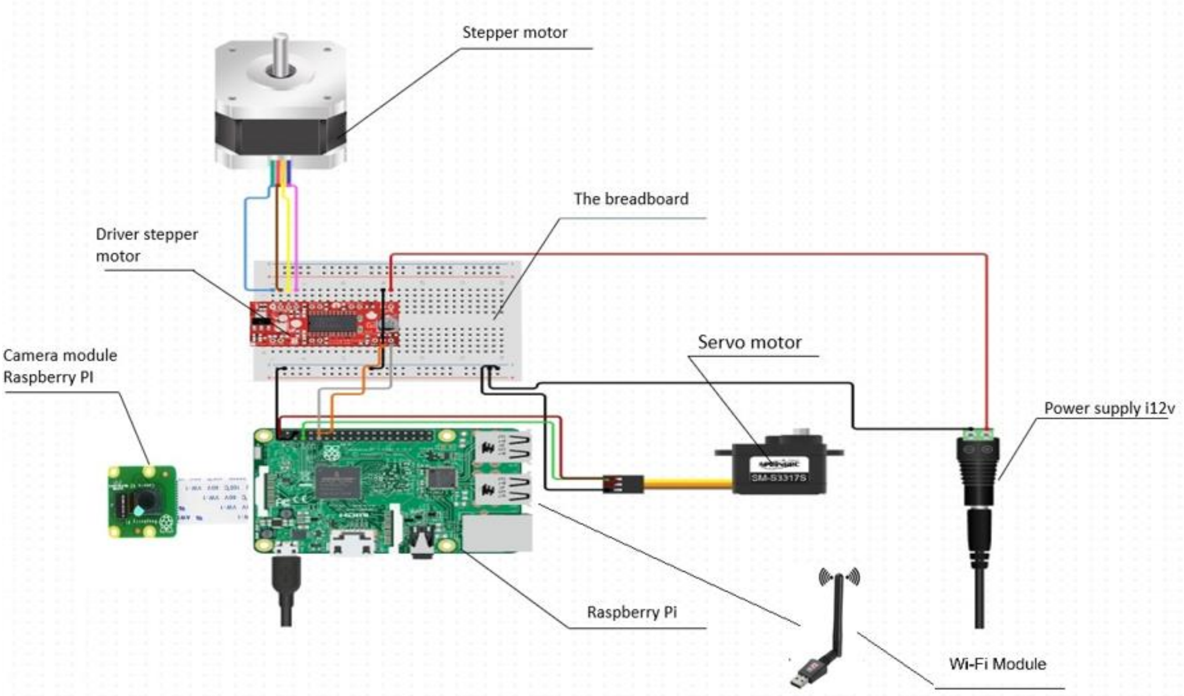

Figure 1.
Functional and logical diagram of a smart trash can.

This diagram provides a general idea of how a smart trash can might function.
Let's highlight the main advantages of the waste bin created based on this concept:

- Hygiene: Minimizing hand contact with waste.
- Efficiency: Precise waste sorting.
- Convenience: Intuitive interface;
- Environmental friendliness: Reduction of the volume of waste sent to landfills.
- Intelligence: The ability to integrate with other smart campus systems.

A prototype of a smart trash can created based on it was tested in the educational building of the Faculty of Mathematics, Physics, and Computer Science of the Kazakh National Pedagogical University (KazNPU) named after Abai.

During the analysis of the waste obtained, it was found that the waste mainly consists of plastic used in the food industry. These are primarily PET (polyethylene terephthalate) bottles of various configurations. This is an extremely useful material, usually derived from petrochemical raw materials; it can be melted and molded and possesses incredible strength. This served as a reason to search for cost-effective and environmentally safe methods of recycling and reusing plastic waste in an educational institution without the need for transportation, benefiting both human health and the environment.

One of the options for processing is to obtain plastic threads for 3D printing, which are in demand for educational purposes. Students of the Faculty of Mathematics, Physics, and Computer Science at the Abai Kazakh National Pedagogical University, as part of their work on the startup, developed a device that allows for the recycling and reuse of plastic bottles, along with a smart trash bin with automated waste separation. The functional and logical diagram of this device is presented in Figure 2.

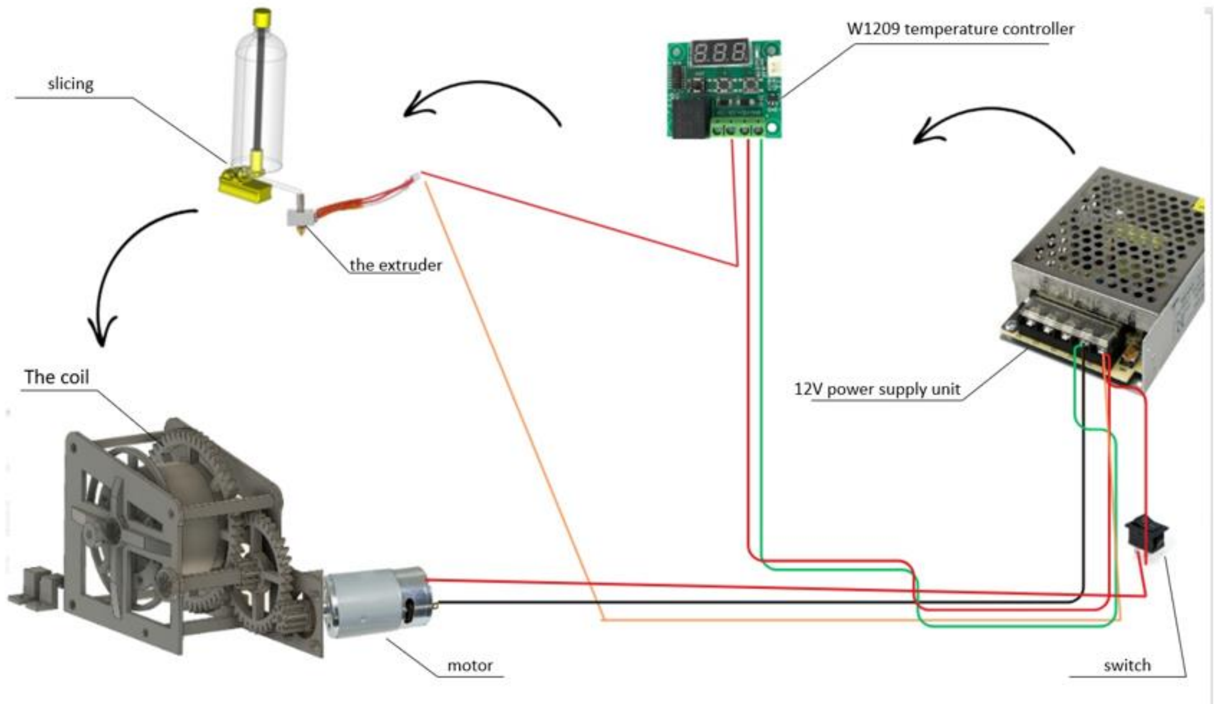

Figure 2.
Functional and logical diagram of the device for recycling plastic waste.

This device allows you to cut a PET bottle into thin strips using a blade and a stepper motor. Next, the tape enters the input funnel of the hotend molder, where it is heated in the range of 75 to 80 degrees and twisted into a tube, and then squeezed through the hotend molder using a winch into a thread with a diameter of 1.6 to 1.75 mm. Then, the thread is wound onto a reel using a gearbox on a stepper motor, which can be used in 3D printers to print various objects.

At such a low temperature, plastic does not emit an odor. Moreover, unlike industrial installations for obtaining plastic, this recycling technology does not require expensive equipment and consumes significantly less electricity.

This is a fairly accessible, simple, environmentally friendly solution for recycling plastic bottles without harming the environment. This method of recycling plastic bottles is not only environmentally friendly but also economically advantageous. It allows you to create new products from available raw materials that do not require additional costs for transportation and processing.

The idea of creating a 3D printing filament from plastic is not new and is already being studied by scientists around the world [27]. The method of recycling bottles proposed in this paper allows educational institutions to independently address the problem of plastic waste, giving it a second life in the form of useful products.

The developed device for recycling plastic, along with the created prototype of a smart waste bin, was tested in the educational building of the pedagogical university with the aim of.

- Determining the reliability of the sorting mechanisms, notifications about the need to empty the basket, mobile application, and other system components.
- Identifying users' opinions on the necessity of introducing smart waste bins and plastic recycling devices in educational institutions;
- Assessment of the environmental impact over a certain period.

Such testing in an educational building is an important step in assessing the potential of the created devices and improving their functionality.

In general, the results of using the basket during the trial period (3 weeks) were quite good, without any particular technical failures. However, there were cases of incorrect waste sorting. Errors occurred when determining the type of waste in the presence of contamination and severe deformations. Thus, for the entire period, 24 (5%) of 478 bottles were incorrectly identified.

The device allows for the processing of all types of PET containers available in retail today.

- Five-liter water bottles (16-17 meters of plastic from one bottle) (blue, light blue, transparent, turquoise);
- 1-2 liter bottles (8-9 meters of plastic);
- 0.5-1 L bottles (2-4 meters of plastic).

Accumulate plastic threads on different spools and sort the threads by color.

A standard reel contains 300 meters of plastic. Thus, one reel will require 150 half-liter PET bottles.

In order to determine the need and possibility of introducing smart waste bins in educational institutions and recycling plastic bottles for secondary use for educational purposes, as well as their impact on increasing the environmental awareness of students, a user survey was conducted using a 5-point Likert scale (Table 1). A total of 347 students from the Pedagogical University in Almaty, Kazakhstan, participated in the survey.

Table 1.
Questions to identify key aspects of the "smart audience" functionality and survey results on them.

No.	Survey questions
1.	Installing smart waste bins in an educational institution will enhance cleanliness and hygiene.
2.	Smart bins allow you to effectively separate waste into different categories.
3.	Smart trash bins could help reduce pollution.
4.	Smart urns require complex maintenance and repair.
5.	Having a smart bin would make waste disposal more convenient and hygienic.
6.	Do you believe that recycling plastic bottles is an important contribution to environmental protection?
7.	The educational institution has all the necessary conditions for organizing the process of collecting and recycling plastic bottles.
8.	The introduction of a smart trash can and a device for recycling plastic bottles in an educational institution is a pressing task in the context of the transition to environmentally sustainable development.
9.	I would support the initiative to install smart bins and devices for recycling plastic waste in our educational institution and in the organization where I will work in the future.
10.	I am prepared to participate in events aimed at addressing the issue of plastic and other waste in educational institutions.

Before the implementation of these technologies, a survey of the same students was also conducted at the educational institution. The results are shown in Figure 3, where the numbers from 1 to 10 on the horizontal axis correspond to the survey question numbers from Table 1. The survey revealed that more than 80% (280) of respondents did not have a full understanding of the functional capabilities of smart waste bins and expressed doubts about the effectiveness of their use. Additionally, 94% (325) of respondents had no idea about the possibilities of recycling plastic bottles and their secondary use for educational purposes without transporting bottles and incurring special costs for this. Furthermore, 89% (309) of students did not consider personal participation in solving environmental problems.

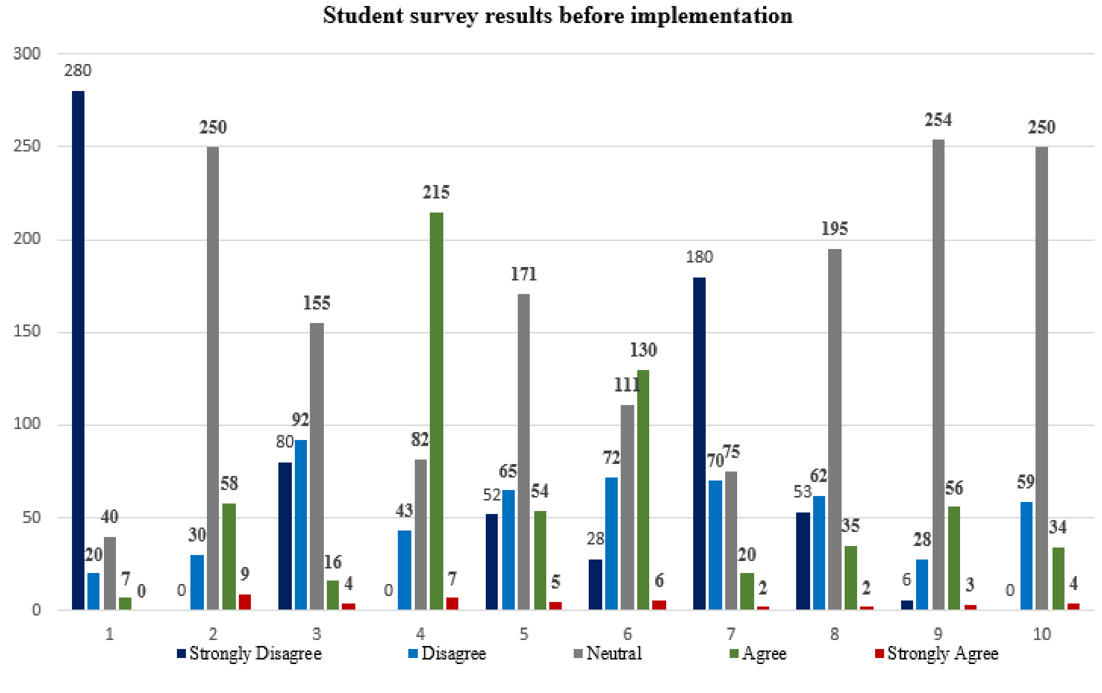

Figure 3.
Results of the survey of students before the introduction of innovations in plastic waste management in an educational institution.

But after their implementation and use during a short trial period (3 weeks), where students watched with interest the information about the number of collected plastic bottles and the filament spools for the 3D printer obtained from them, in parallel with mastering courses on ecology and the basics of IoT, in integrated disciplines when implementing the STEAM approach, where these devices were used as visual aids in training, the overwhelming majority of them changed their understanding of both smart bins and the possibility of recycling used plastic bottles. The survey results are presented in Figure 4, where the numbers from 1 to 10 on the horizontal axis correspond to the survey question number from Table 1.

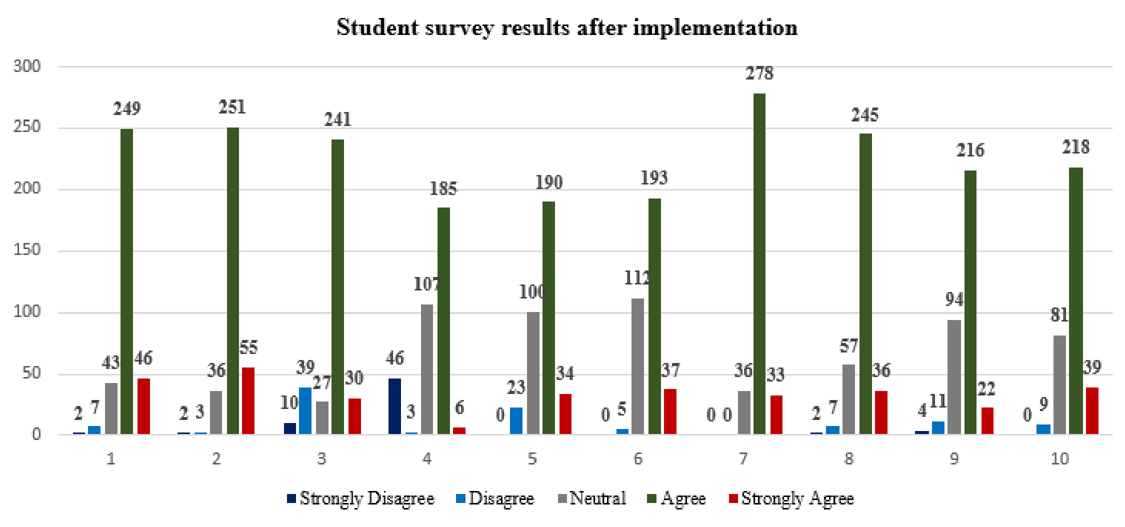

Figure 4.
Results of a survey of students after the introduction of innovations in plastic waste management in an educational institution.

Here, 85% (295) of respondents noted an increase in cleanliness in the educational building and that they followed this with interest.

The survey results showed that recycling plastic bottles is of great interest to students. Eighty-one percent (281) of respondents believe that the implementation of such innovations is a pressing issue in the context of the transition to environmentally sustainable development. Approximately seventy-four percent (257) of respondents expressed a desire to participate in a project to address the problem of environmental pollution and waste recycling.

The majority of respondents (69%) positively assessed the idea of introducing smart waste bins and devices for recycling plastic waste in educational institutions. They noted that such innovations can help improve the level of cleanliness and order and are ready to support the initiative to install smart bins in the future. A sign next to a smart bin indicating how many spools of plastic filament for a 3D printer have been received increases students' interest in them.

However, a significant number of respondents (55% (191)) still expressed concerns about possible technical problems and the need for additional maintenance.

The data obtained from the survey were analyzed to determine how accurately they reflect the true state of affairs (validity) and how stable they are across repeated measurements (reliability).

The results showed that Cronbach's alpha (α) before and after the implementation of these innovations in plastic waste management in the educational institution was 0.9634544 and 0.971925, respectively, and the square root of α, which was used to determine the validity, was 0.9816 and 0.9859, respectively. This indicates that the reliability and validity values in both cases are excellent and demonstrate very good internal consistency of the data [28].

During the discussion, teachers also praised the potential of smart waste bins and plastic recycling devices in the school, especially regarding their impact on students' environmental awareness.

4. Conclusion

The study demonstrates that the introduction of innovative technologies, such as smart waste bins with automated waste separation and devices for recycling sorted plastic, significantly increases the efficiency of plastic waste management in an educational institution.

Automation of separate waste collection and local recycling of plastic, without the need for transportation and expensive equipment thanks to self-created devices, allows for a reduction in the negative impact on the environment and conservation of resources. The minimization of human involvement and reduction of costs, along with the use of devices created through personal efforts, make such solutions even more attractive.

The students and staff of the educational institution showed great interest in the innovations. The involvement of students in the process of their design and implementation within the framework of the start-up, as well as the results of the survey, indicates an increase in their environmental awareness and readiness to take an active part in solving environmental problems.

The conducted research is only the first step towards the creation of environmentally friendly educational institutions. In the future, it is possible to expand the range of recyclable waste, as well as integrate the proposed innovations into other educational institutions and organizations.

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