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Development of a Lux Meter for the Identification of Liquids in Post-Consumer Polyethylene Terephthalate Bottles for Collection Centers in Mexico

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Abstract: This article aims to enhance technological advancements in the classification of polyethylene terephthalate (PET) bottle plastic, positively impacting sustainable development and providing effective solutions for collection centers (CC) in Mexico. Three experimental designs and machine learning tools for data processing were developed. The experiments considered three factors: bottle size, liquid volume, and bottle labels. The first experiment focused on determining the sensor distance from post-consumer PET bottles. The second experiment aimed to evaluate the sensor's detection ability with varying liquid levels, while the third experiment assessed its detection capability for bottle labels. A digital lux meter integrated with a microcontroller was developed to monitor illuminance in post-consumer PET bottles containing liquid as they moved through a conveyor belt at an average rate of three bottles per second. The implemented methodology successfully detected liquids inside transparent PET bottles when they contained beverages ranging from 25% to 100% of their capacity. This study highlights the feasibility of implementing an affordable design for identifying bottles with liquids at CC.

Keywords: PET; recycling; lux meter; classification; ANOVA; machine learning; automation; illuminance; municipal solid waste

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1. Introduction

Every year, millions of metric tons of plastic are produced worldwide, leading to significant challenges in managing urban and industrial solid waste. Initiatives promoting a recycling culture have been developed globally to reduce waste generation [1]. For successful recycling, polymers must possess specific quality characteristics [2]. In [3], they revealed that it is possible to make significant improvements in terms of sorting recovered plastic waste. In the United Mexican States, over 86,343 tons of solid and organic waste are collected daily from homes, buildings, streets, avenues, parks, and gardens. More than half of these generated materials nationwide are organized in seven states. Unfortunately, less than 11% of the collected waste is separated daily in Mexico [4]. The country has CC for urban solid waste. In the various CC where recyclable materials are purchased, users bring bottles to be paid at a reasonable price. However, these bottles are often internally and externally contaminated with liquids or organic substances. Mexico has 501 CC that collect various materials, with paper, cardboard, PET, and glass accounting for 65% of the collected waste. The states with the most CC are Ciudad de México with 411, Estado de México with 17, Hidalgo with 15, Quintana Roo with 15, and Aguascalientes with 11 [5]. While 87 out of 100 people in Mexico express interest in environmental conservation, only 31% practice it [5,6]. Implementing efficient waste separation and recovery measures can significantly reduce the amount of waste sent to landfills [7]. Therefore, promoting and facilitating reuse and recycling practices can profoundly impact the environment. It is crucial to take viable actions to transfer value to the end consumer and minimize the environmental impact of solid urban waste. In Mexico and Latin America, leading companies provide direct employment to approximately 98,000 individuals and generate over one million indirect jobs in recycling plastic materials [8]. Daily, CC buy recyclable materials including polymers, ferrous and non-ferrous metals, and electrical and electronic materials. Proper separation is essential to restore market value to recyclable materials, ensuring that polymers are not mixed with other materials, liquids, oils, or polymers. To increase recycling, personnel who can identify material that could still be used again are required. The identification of recyclable bottles is primarily performed manually at CC, resulting in delays in classification and increased losses due to the inability to detect contaminated bottles. Bottles with higher levels of contamination, particularly liquids, contribute to increased weight. Therefore, it is crucial to identify bottles with significant liquid or other contaminants. Accurate classification of recyclable materials in CC, mainly polymers, supports the circular economy and provides employment opportunities. Modernizing CC can enhance productivity and improve plastic waste management in developing countries [4]. This project proposes a potential solution for micro-enterprises functioning as CC, enabling them to estimate the liquid content rather than relying solely on plastic weight. The development and design of a digital lux meter aims to monitor the reflectance in post-consumer PET bottles when liquids are present. Existing commercial lux meters may not be suitable for the specific purpose described in this context. To address this issue, this paper proposes developing an affordable alternative to effectively measure illuminance and provide the advantage of generating actions based on a predefined illuminance value.

- This paper aims to develop an automatic liquid identification system for recyclable polyethylene terephthalate bottles with an affordable design.
- A new methodology is developed and implemented to identify dark liquids.
- In conclusion, it is possible to quantify the number of dark liquids that post-consumer PET bottles may contain by implementing an affordable design.

1.1. Post-Consumer PET Bottles

Recyclable plastics (thermoplastics) are defined as polymers that can be melted and shaped almost indefinitely. When exposed to heat, they undergo a phase change, melting into a malleable state, and solidify again upon cooling. However, if frozen, thermoplastics can break, just like glass. The reversible nature of their melting and solidification processes allows thermoplastics to be repeatedly heated, shaped, and cooled without a significant loss in their material properties. This characteristic is integral to their name and distinguishes them from other plastics [9]. There are more than one hundred types of plastics, but six of them are particularly common and widely used [10]. Polypropylene, polyethylene, polyvinyl chloride, polystyrene, polyethylene terephthalate, and polycarbonate [11]. These plastics are frequently recycled due to their widespread use. They are identified by a number within a triangle to aid in their identification. They were codified by the Plastics Industrial Society in 1980 [12]. There are various presentations of PET bottles; see Figure 1.

Figure 1. Different presentations of PET bottles in the Mexican market.

PET bottles are identified by the number one within a triangular symbol often engraved on the bottom of the bottle. One million plastic bottles are sold worldwide every minute, and 60 million metric tons of PET are produced yearly. For soft drink manufacturers Coca-Cola and PepsiCo, the production of PET bottles from 250 mL to 600 mL constitutes 50% of annual sales. Bottling represents 30% of world PET production, amounting to 20 million metric tons. The annual consumption was estimated to exceed half a billion in 2021 [13]. Once the PET has been collected and classified, it represents a raw material for the recovery processing lines. The recovery involves washing the materials, mainly bottles, and conditioning the plastics to be processed as resin [14]. Because PET is food safe, it is used throughout the food delivery system. Out of total plastic production, 50% is for single-use products [13]. Plastic waste has physical characteristics that comprise only 7% to 9% by weight and 20% to 30% by volume. This means that a lot of energy is required to store, move, and process the waste polymers [15]. Recycling PET is a profitable endeavor, as it can be transformed into various products, such as fibers for carpets, clothing, 3D printer filaments, bags, toys, and new bottles. In Mexico, Coca-Cola has already introduced 100% recycled bottles to the market. While recycling is essential for maintaining an economic cycle, it also has environmental implications. For instance, PET bottles in landfills can release over 1108 tons of antimony into the hydrosphere, pedosphere, and atmosphere, potentially causing developmental disorders in children [16].

1.1.1. Physical Characteristics of Post-Consumer PET Bottles

To ensure the suitability of post-consumer PET bottles for mechanical recycling, specific criteria must be met, and knowledge of the plastic's origin is essential to ensure the purity of the resulting resin. Plastics primarily originate from the mass of urban solid waste from two prominent sources. These sources can be further divided into three classes: those that have been classified and separated from other classes, or mixed waste; those of the same class but of a different color of cap or bottle; and mixed plastic waste combined with other debris, such as paper, cardboard, metal, etc., including plastics found in electronic waste. Among these different types of bottles, the plastic used in PET bottles differs from the plastic used for the screw caps used to seal them. Lids are made of high-density polyethylene or foamed polypropylene, while the bottom of the lid is polypropylene. This plastic is more rigid than PET [13].

1.1.2. Reducing the Problem to an Empirical Level

The global population growth and the impact of the COVID-19 pandemic increased the use of single-use plastics and solid waste, particularly in cities [17]. There are at least 23 different presentations of PET bottles in Mexico, and their storage capacity ranges from 100 mL to more than 10 L. Therefore, more efficient systems and methods are required to collect, classify, store, and process solids after having finished their life cycle. Solid waste collection and sorting of post-consumer recyclable materials require many resources and human resources. Developing automated systems that perform these activities reduces the requirements for resources and labor. CC buy materials to be separated, classified, or treated for reuse. See in [5] the type of material and amount separated in 2018. The modernization of CC in managing urban solid waste represents an economic, social, technological, and ecological opportunity. This research work was carried out using the methods of observation and statistical analysis. The study contemplates only the characteristics of post-consumer PET bottles collected and taken to a collection center for purchase. The study and data collection were conducted in Querétaro, in a collection center called Recyclable Materials Ángeles located north of the town. The data acquisition period was 7 March 2021. The analysis ended 6 May 2023. To estimate the number of liquids in the post-consumer PET bottles, a manual classification process was conducted by three individuals who had prior knowledge of the characteristics required for PET polymer to be recyclable. This classification process aimed to identify the bottles that contained liquids. A sample of 100 kg of post-consumer PET bottles was selected from a collection center to approximate the number of liquids present. The sample consisted of a total of 4959 post-consumer PET bottles. The bottles were unsorted and of various sizes and colors.

2. Methodology

Figure 2 summarizes the implemented methodology; the results of each stage are used for the final proposal.

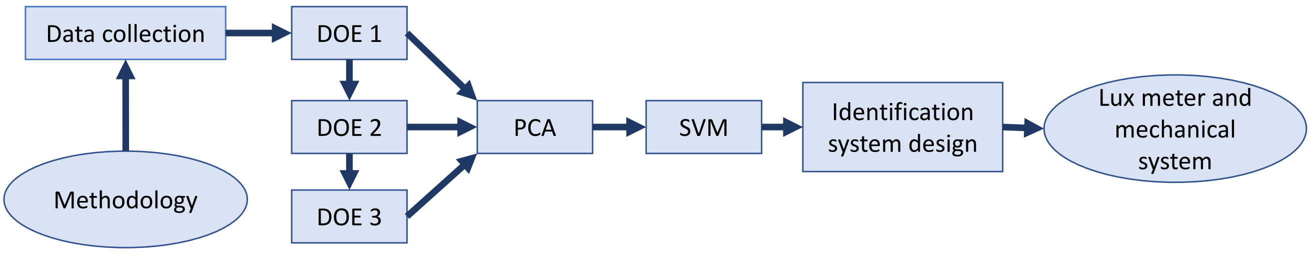

Figure 2. Diagram of the new methodology for designing and developing the liquid identification system.

2.1. Materials

Various materials were used to automate the experiment and minimize the variation in the data, thus avoiding external factors such as the environment, etc.

2.1.1. Mechanical Design Parameters

For experimentation, a mechanical system was developed to transport bottles of different sizes. The design parameters can be seen in Table 1. A conveyor belt and a mobile structure were used to determine the best position for data acquisition to assemble the lux meter. The conveyor belt has a geared motor with 1750 revolutions per minute and a reducer of one hundred to one, equivalent to making eighteen turns in one minute.

Table 1. Conveyor belt design parameters.

No.	Name	Parameter	Expression	Value
1	Band base width	bandBaseWidth	90 cm	90.0
2	Long band base	LongBandBase	200 cm	200.0
3	Band leg base	BandLegBase	10 cm	10.0
4	Table base width	TableBaseWidth	bandBaseWidth + (BandLegBase*4)	130.0
5	Long table base	LongTableBase	70 cm	70.0
6	High table base	HighTableBase	2 cm	2.0
7	Wide leg base	WideLegBase	70 mm	70.0
8	Long leg base	LongLegBase	150 mm	150.0
9	High leg base	HighLegBase	10 mm	10.0
10	Wide leg	WideLeg	35 mm	35.0
11	Long leg	LongLeg	100 mm	100.0
12	High leg	HighLeg	70 cm	70.0
13	Table plan	TablePlan	HighLeg + HighLegBase	101.0
14	Bottom box width	BottomBoxWidth	TableBaseWidth—10 cm	120.0
15	Long box base	LongBoxBase	LongTableBase—2 cm	68.0
16	Base box thickness	BaseBoxThickness	2 cm	2.0

Table 1. *Cont.*

No.	Name	Parameter	Expression	Value
17	High box base	HighBoxBase	60 cm	60.0
18	Height tab	HeightTab	HighBoxBase/1.5	40.0
19	Base rail width	BaseRailWidth	4.5 cm	4.5
20	Base long rail	BaseLongRail	30 cm	30.0
21	Base rail thickness	BaseRailThickness	1.3 cm	1.3
22	Base chamber width	BaseChamberWidth	TableBaseWidth—20 cm	110.0
23	Base chamber length	BaseChamberLength	LongTableBase—10 cm	60.0

2.1.2. Electronic Card

Table 2 shows some of the materials used to develop the lux meter.

Table 2. The material used for the printed circuit board (PCB) of the lux meter.

No.	Material	Type	Volume
1	LIQUID-CRYSTAL DISPLAY (LCD)	16X2	1
2	MICROCONTROLLER	18F4550	1
3	SENSOR	bpw21r	1
4	CONNECTOR	MOLEX	3
5	POTENTIOMETER	1M	1
6	POTENTIOMETER	5k	1
7	RESISTOR	1K	6
8	RESISTOR	10K	8
9	RESISTOR	220	4
10	CAPACITOR	470n	3
11	CAPACITOR	15p	4
12	CAPACITOR	0.1u	2
13	CAPACITOR	1u	2
14	CAPACITOR	0.33u	2
15	LIGHT-EMITTING DIODE (LED)	RED	3
16	CRYSTAL	20M	1
17	DIL40	40 PINS	1
18	PINS	MALE	1
19	PINS	FEMALE	1
20	PHENOLIC BOARD	COPPER	1
21	ACID	FeCl3	1
22	USB CONNECTOR	B	1
23	TEL CONNECTOR	4 HILOS	1
24	SWICH 1	POLO 2	2
25	HOUSING	BLACK	1
26	BUTTON	NC	1

2.2. Description of the Manual Bottle Classification Process

Figure 3 describes the process used in the study to discriminate post-consumer PET bottles. The experiment began in the collection center Recyclable Materials Ángeles. The material purchased was mixed, so it was inspected to find out what conditions it was in. If the bottle had a label, it was removed depending on whether it covered the entire bottle; then, the bottle was classified according to the color. Finally, it was compacted and stored.

From the 100 kg sample, it was expected to observe at least 23 different types of post-consumer PET bottles, considering liquid storage capacity as the main differentiator. Bottles ranged from 100 mL to 10 L. To verify that the sample was representative, we used the information provided by the soft drink manufacturers Coca-Cola and PepsiCo [13].

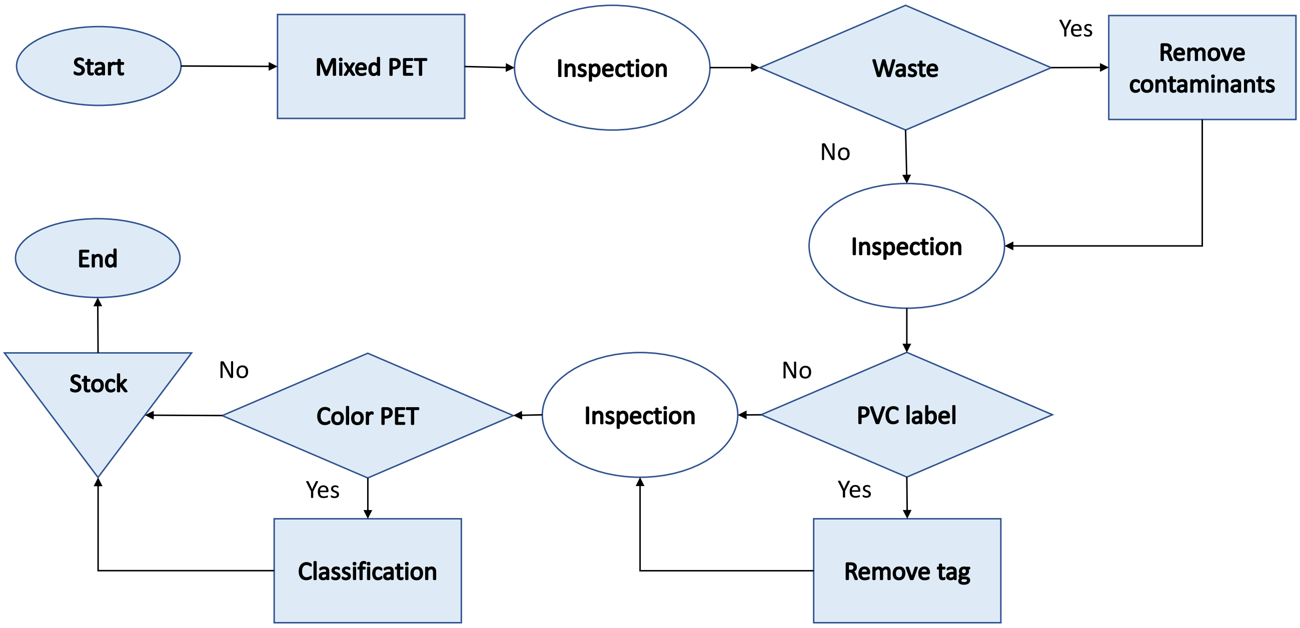

Figure 3. Flowchart of the manual sorting process for PET bottles.

2.3. Design of Experiments for Variable Identification

Design of experiments (DOE) is a practical statistical tool for design and testing. DOE provides a sequential strategy to find a region containing the optimum settings of the variables. Suppose many variables can affect the performance of a system, but only a relatively small number of them are essential. In that case, a screening experiment can be conducted to identify the critical variables [18]. Three DOEs were developed, two with two factors and the other with only one factor. The distance, the size of the bottle, and the label of the bottles are factors that were considered to affect the illuminance measurement. See Table 3.

Table 3. General guidelines for conducting DOE.

Objective DOE 1	**Identify Important Factors from Many Potential Factors**
Response	Iluminance
Factor and Levels	Distance and three levels
Factor and Levels	Bottle size and nine levels
Objective DOE 2	Identify important factors from many potential factors
Response	Illuminance
Factor and Levels	Percentage of liquids inside the bottle and three levels
Factor and Levels	Bottle size and nine levels
Objective DOE 3	Identify important factor
Response	Illuminance
Factor and Levels	Types of labels on bottles

2.3.1. Design of Experiments to Determine the Distance and Working Range of the Lux Meter

To determine the position of the lux meter, a DOE was developed that helped obtain readings that represent the amount of liquid inside the bottles. Figure 4 illustrates the causality diagram with the considered factors. See Table 4.

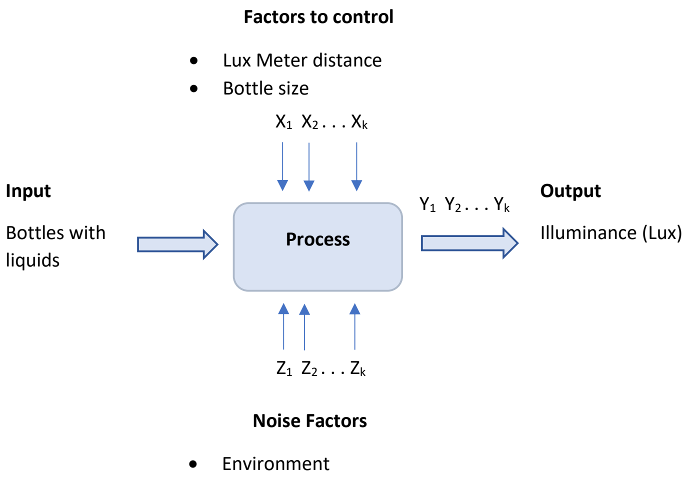

Figure 4. Factors and variables of the first design of experiments.

Table 4. Approach to the design of experiments for the position of the lux meter considering two factors.

	Lux Meter Distance (cm) (A)			
Bottle Size (mL) (B)	**15**	**20**	**25**	**Sum**
200	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
300	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
355	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
500	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
600	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
1000	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
1350	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j

Table 4. *Cont.*

	Lux Meter Distance (cm) (A)			
Bottle Size (mL) (B)	**15**	**20**	**25**	**Sum**
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
2000	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
3000	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
Sum Total	$SumT_i$	$SumT_i$	$SumT_i$	$SumT$

The position of the bottle was established vertically in the direction of the conveyor belt. It is essential to highlight that other positions were not considered. The experimentation was carried out with dark liquids. See Figure 5 to know the interaction of the distance factor [19]. With the data obtained, the significant distance was determined to specify the operating range of the lux meter.

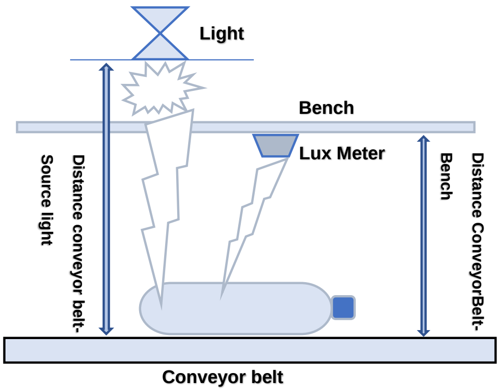

Figure 5. Discrimination system for the detection of liquids in PET bottles by their illuminance.

Table 5 summarizes the results of the variation sources of the preparation of the analysis of variance (ANOVA) of two factors.

Table 5. Summary of the first two-way ANOVA.

Source	SS	gl	MS	F
Distance (A)	SSA	$a-1$	MSA = SSA/$(a-1)$	MSA/MSE
Bottle (B)	SSB	$b-1$	MSB = SSB/$(b-1)$	MSB/MSE
AB	SSAB	$a-1$	MSAB = SSAB/$(a-1)$	MSAB/MSE
Error	SSE	$N-a-b-1$	MSE = SSE/$(N-a-b-1)$	
Total	SST	$N-1$		

2.3.2. Design of Experiments to Identify the Minimum Amount of Liquids inside the Bottle

The distance was considered a fixed factor once the results of the first DOE were obtained. The second DOE was developed to obtain readings representing the minimum amount of liquid inside the bottles. See Table 6. The position of the bottle was maintained as in the first DOE. See Figure 6.

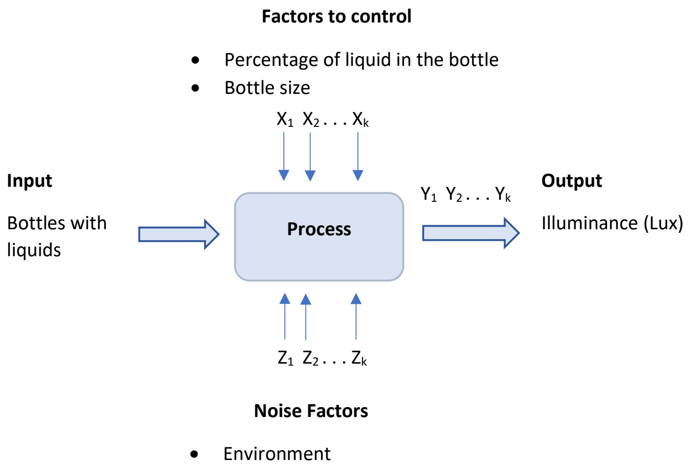

Figure 6. Factors and variables in the second design of experiments.

Table 6. Approach to the design of experiments to identify the percentage of liquid in the bottles.

	Percentage of Liquid in the Bottle (A)			
Bottle Size (mL) (B)	**50%**	**25%**	**0%**	**Sum**
200	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
300	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
355	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
500	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
600	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
1000	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
1350	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
2000	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
3000	y_{ij} y_{ij}	y_{ij} y_{ij}	y_{ij} y_{ij}	Sum_j
Sum	Sum_{ij}	Sum_{ij}	Sum_{ij}	
Sum Total	$SumT_i$	$SumT_i$	$SumT_i$	$SumT$

The minimum amount of liquids the lux meter could identify was determined with the data obtained. With the results of the two DOEs, the minimum characteristics that the lux meter must have were established.

2.3.3. Design of Experiments to Determine Label Illuminance

A one-factor DOE was performed to identify the reflectance of the labels on the bottles. A recommendation to determine the number of replicates (n) is that the degrees of freedom of the error are at least 20 or 25. According to this recommendation, we used the double $N = a + 50$, where $n = N/a$, where a is the number of levels of factor A. For this example, considering a minimum of 50 degrees of freedom in error and $N = 10 + 50$, $n = 60/10$, six replicates were performed. See Table 7 [20].

Table 7. Approach to the design of experiments to identify the variability with the labels.

	Replicas								
Bottle Size (mL) (A)	**1**	**2**	**3**	**4**	**5**	**6**	**Sum**	y	s^2
3000	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
2000	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
1350	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
1000	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
600	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
500	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
355	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
300	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
250	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2
200	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	y_{ij}	Sum_j	y_j	s_j^2

Table 8 summarizes the results of the sources of variation of the elaboration of the ANOVA of a fixed factor.

Table 8. Summary of the third ANOVA with one factor.

Source of Variation	SS	gl	MS	F
Treatments (t)	SSt	$a - 1$	MSt = SSt/$(a - 1)$	MSt/MSE
Error	SSE	$N - a$	MSE = SSE/$(N - a)$	
Total	SST	$N - 1$		

Once the three DOEs were finished, their results were processed using principal component analysis. The results will help us identify and approximate the amount of liquids inside the bottle.

2.4. Principal Component Analysis

Principal component analysis (PCA) is a numerical research method. Its main objective is to explain the maximum variance with the least number of components. PCA can analyze the main elements of multiple characteristics, expose their nature by highlighting the main features, and shorten the data dimensions to help diagnose complex problems. The first component represents the most significant percentage of the total variation in the data. The second component represents the second largest percentage of the total data variation, and so on [21,22]. Minitab 17 Statistical Software was used for this analysis. The PCA was used to describe the variation between the DOE results and their correlation, reducing the complexity and aiding data interpretation.

2.5. Support Vector Machine

A support vector machine (SVM) has robust classification capabilities considering statistical learning theory and the principle of minimum structural risk. An SVM effectively solves small-sample, high-dimensional, nonlinear learning problems and overcomes the shortcomings of artificial neural network learning in determining the rational structure. An SVM improves the generalizability of learning methods [21,23]. In general, an SVM is a linear classifier for two data types, one of which is labeled as follows: (x_1, y_1), ..., (x_l, y_l), where $x_i \in R^N$ is a feature vector and $y_i \in \{-1, 1\}$ is a label belonging to a class. An SVM constructs an optimal hyperplane as a surface decision to separate data points of two classes. The hyperplane margin is defined as the minimum distance from the hyperplane training points [24]. The learning problem of an SVM is to search for the optimal hyperplane once the data set is obtained, and find the values of w and b such that they satisfy the condition $y_i(w^t x_i + b) \geq 1; i{=}1, 2, \ldots, l$ [25].

2.6. Development of the Lux Meter and Liquid Identification System

2.6.1. Definition of the Measurand for the Measurement of Illuminance

A system that works in the visible spectrum was developed for the illuminance measurement; it can identify if there is liquid inside the plastic bottle (see Figure 7). At this stage, a lux meter was developed that identifies a bottle with no deformation and a label [26].

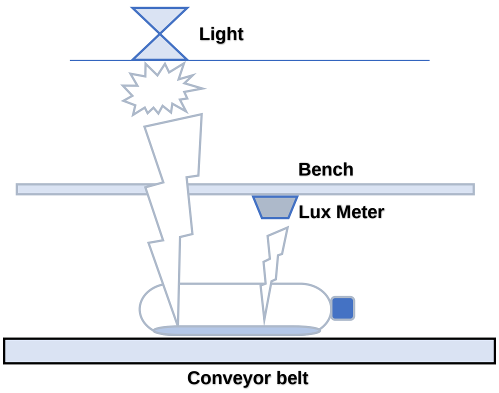

Figure 7. Detection system for liquids in PET bottles due to their illuminance.

The measurand is the electric current that passes through a silicon photodiode for illuminance measurement. The measure is indirectly due to the properties of the sensor that changes its resistance when the illuminance varies in the photodiode [27]. If the relationship between V and I is linear, we are in the presence of an ohmic material or component. The relationship that describes this behavior is known as the law of Ohm, $I = \frac{V}{R}$. By varying the resistance of the photodiode due to the change in illuminance and the induced V, the I will change. Depending on this variation, the illuminance can be calculated. To illustrate the behavior of the sensor, the manufacturer provides information represented in [27], and the scale is logarithmic–logarithmic.

2.6.2. Ambient Light Sensor BPW21R

Illuminance measures the intensity of light incident on a surface and can be correlated to the brightness perceived by the human eye. In the visible range, it is measured in units called lux. Ambient light sensors detect light or brightness like the human eye. A standard silicon photodetector is more sensitive to infrared than visible light. Using BPW21R ambient light sensors solves this problem because they are most sensitive to the visible part of the spectrum. On the other hand, there is a strictly logarithmic correlation between the open circuit voltage and the illumination over the same range. BPW21R is a planar PN silicon photodiode specially designed for high-precision linear applications. Due to its extremely high resistance to darkness, the short-circuit photocurrent is linear over seven decades of illumination levels. The device has a flat glass window built with a color correction filter, approximating the human eye spectral response. A standard silicon photodetector is much more sensitive to infrared than visible light. By contrast, BPW21R is sensitive to the visible part of the spectrum [27,28]. This work has reduced incandescent light and sunlight for the exact lux measurement.

3. Results

This work considered that the plastics came from homes, apartments, condominiums, and commercial areas generated by retail businesses, offices, and hotels because the bottles presented less than 1% loss and dirt. It should be noted that it was decided to round their value for the data capture of certain bottles that were very close in storage capacity. For example, the 1.75 L bottles were added to the 2 L bottles.

3.1. Sample Results of the Classification Process Manually

Four thousand, nine hundred and fifty-nine post-consumer PET bottles were analyzed, representing over 100 kg. The results can be seen in Table 9. The bottle that presented the most was the 600 milliliter bottle (26.35%). On the other hand, eight types of bottles represented 94% of the variation found in the twenty-three bottle types in the sample.

Table 9. Results of a 100 kg sample of post-consumer PET.

Bottles That Were Repeated the Most.				
Number	**Bottle (Liter)**	**Frequency**	**Frequency (%)**	**Accumulated (%)**
1	0.6	1307	26.356	26.356
2	1.0	837	16.878	43.234
3	1.5	653	13.167	56.402
4	2.0	642	12.946	69.348
5	3.0	382	7.703	77.051
6	0.5	346	6.977	84.029
7	0.35	294	5.928	89.957
8	0.25	205	4.133	94.091

With the results, the characteristics of the 0.25 L, 0.35 L, 0.6 L, 0.5 L, 1 L, 1.5 L, 2 L, and 3 L PET bottles were considered in the next stage. This means that by basing the experimentation on eight types of bottles, we could obtain an approximation of other kinds of bottles with similar characteristics.

3.2. Design of Experiments for Variable Identification

3.2.1. Design of Experiments to Determine the Distance and Working Range of the Lux Meter

The experiment designs with three different distances with zero speed on the conveyor belt were developed. The design experiments were carried out with a commercial lux meter to identify the distance the lux meter should have to identify liquids inside the bottles.

- A: Distance from the lux meter to the conveyor belt (20, 25, 30 cm).
- B: Bottle Size (200, 300, 355, 500, 600, 1000, 1500, 2000, 3000 mL).

The initial conditions to start the experiment were to take the reading of the lux meter when the light source was off, and the results were 0.3–0.4 lux. Subsequently, the light source was turned on, and the light reflected from the conveyor belt was between 13.8 and 14.5 lux. For replicates and not repetitions to be considered in this experiment, measurements were taken at different times and on other days. The DOE implementation is shown in Table 10, and the results are in Table 11. In [20] it is stated that for the case of two factors, the minimum sample size should be $N = a + b + (a-1)(b-1) + 24$. See Equation (1)

$$N = a + b + (a-1)(b-1) + 24 = 3 + 9 + (3-1)(9-1+24) = 52 \quad (1)$$

The number of replicates per cell is N/ab, where a and b are, respectively, the number of levels of factors A and B. For this design, N is considered to be 54

$$n = N/ab = 54/(3)(9) = 2. \quad (2)$$

Table 10. Information from the first ANOVA of two factors.

	Lux Meter Distance (cm) (A)			
Bottle Size (mL) (B)	**15**	**20**	**25**	**Sum**
200	13.4 12.7	14.9 14.5	16.5 16	88
Sum	26.1	29.4	32.5	
300	12.4 13.1	14.4 12.7	16.7 16.6	85.9
Sum	25.5	27.1	33.3	
355	13 13.9	15.2 14.9	16.2 16.2	89.4
Sum	26.9	30.1	32.4	
500	13.6 13.3	13.9 13.6	14.8 15	84.2
Sum	26.9	27.5	29.8	
600	12.5 13.1	13.9 12.7	15 15.4	82.6
Sum	25.6	26.6	30.4	
1000	13.9 13.1	14 14.7	15.1 15	85.8
Sum	27	28.7	30.1	
1350	15.6 13.4	15.2 16.5	16.4 15.5	92.6
Sum	29	31.7	31.9	
2000	10.7 9	16.8 17.5	14.3 14.9	83.2
Sum	19.7	34.3	29.2	
3000	5.2 3.9	19.3 18.5	17 16	79.9
Sum	9.1	37.8	33	
Sum Total	215.8	273.2	282.6	771.6

The following Equations (3)–(7) shows the elaboration of the ANOVA of two factors. The sum of squares and degrees of freedom were calculated as follows.

$$SST = \sum\sum y_{ij}^2 - \frac{(\sum\sum y_{ij})^2}{N} = (13.4)^2 + \cdots + (16)^2 - \frac{771.6}{54} = 371.0533 \quad (3)$$

$$SSA = \frac{\sum TotalSum_i^2}{bn} - \frac{(\sum\sum y_{ij})^2}{N} = \frac{(215.8)^2 + (273.2)^2 + (282.6)^2}{18} - \frac{(771.6)^2}{54} = 145.2844 \quad (4)$$

$$SSB = \frac{\sum TotalSum_j^2}{an} - \frac{(\sum\sum y_{ij})^2}{N} = \frac{(88)^2 + \cdots + (79.9)^2}{6} - \frac{(771.6)^2}{54} = 19.73 \quad (5)$$

$$SSAB = \frac{\sum Sum_{ij}^2}{2} - \frac{(\sum\sum y_{ij})^2}{N} - SSA - SSB = \frac{(26.1)^2 + \cdots + (33)^2}{2} - \frac{(771.6)^2}{54} - 145.2844 - 19.73 = 194.5788 \quad (6)$$

$$SSE = SST - SSA - SSB - SSAB = 371.0533 - 145.2844 - 19.73 - 194.5788 = 11.46 \quad (7)$$

Table 11. ANOVA of the first experiment. * Factor affecting variability.

Source	SS	gl	MS	F
Distance (A)	145.2844	2	72.6422	259.8892 *
Bottle (B)	19.73	8	2.4662	8.8234 *
AB	194.5788	2	97.2894	348.0686 *
Error	11.46	41	0.2795	
Total	371.0533	53		

With the ANOVA we seek to know if the factors are significant and if there is an interaction. Interaction is defined as a dependency relationship between the value of the response and the levels of two or more variables. The response graphs are presented in Figure 8. The calculations are

$$\bar{Y}_{A1} = \frac{215.8}{18} = 11.98 \qquad \bar{Y}_{A2} = \frac{273.2}{18} = 15.17 \qquad \bar{Y}_{A3} = \frac{282.6}{18} = 15.7$$

$$\bar{Y}_{B1} = \frac{88}{6} = 14.66 \qquad \bar{Y}_{B2} = \frac{85.9}{6} = 14.31 \qquad \bar{Y}_{B3} = \frac{89.4}{6} = 14.9$$

$$\bar{Y}_{B4} = \frac{84.2}{6} = 14.03 \qquad \bar{Y}_{B5} = \frac{82.6}{6} = 13.76 \qquad \bar{Y}_{B6} = \frac{85.8}{6} = 14.3$$

$$\bar{Y}_{B7} = \frac{92.6}{6} = 15.43 \qquad \bar{Y}_{B8} = \frac{83.2}{6} = 13.86 \qquad \bar{Y}_{B9} = \frac{79.9}{6} = 13.31$$

$$\bar{Y}_{A1B1} = \frac{26.1}{2} = 13.05 \qquad \bar{Y}_{A1B2} = \frac{25.5}{2} = 12.75 \qquad \bar{Y}_{A1B3} = \frac{26.9}{2} = 13.45$$

$$\bar{Y}_{A1B4} = \frac{26.9}{2} = 13.45 \qquad \bar{Y}_{A1B5} = \frac{25.6}{2} = 12.8 \qquad \bar{Y}_{A1B6} = \frac{27}{2} = 13.5$$

$$\bar{Y}_{A1B7} = \frac{29}{2} = 14.5 \qquad \bar{Y}_{A1B8} = \frac{19.7}{2} = 9.85 \qquad \bar{Y}_{A1B9} = \frac{9.1}{2} = 4.55$$

$$\bar{Y}_{A2B1} = \frac{29.4}{2} = 14.7 \qquad \bar{Y}_{A2B2} = \frac{27.1}{2} = 13.55 \qquad \bar{Y}_{A2B3} = \frac{30.1}{2} = 15.05$$

$$\bar{Y}_{A2B4} = \frac{27.5}{2} = 13.75 \qquad \bar{Y}_{A2B5} = \frac{26.6}{2} = 13.3 \qquad \bar{Y}_{A2B6} = \frac{28.7}{2} = 14.35$$

$$\bar{Y}_{A2B7} = \frac{31.7}{2} = 15.85 \qquad \bar{Y}_{A2B8} = \frac{34.3}{2} = 17.15 \qquad \bar{Y}_{A2B9} = \frac{37.8}{2} = 18.9$$

$$\bar{Y}_{A3B1} = \frac{32.5}{2} = 16.25 \qquad \bar{Y}_{A3B2} = \frac{33.3}{2} = 16.65 \qquad \bar{Y}_{A3B3} = \frac{32.4}{2} = 16.2$$

$$\bar{Y}_{A3B4} = \frac{29.8}{2} = 14.9 \qquad \bar{Y}_{A3B5} = \frac{30.4}{2} = 15.2 \qquad \bar{Y}_{A3B6} = \frac{30.1}{2} = 15.05$$

$$\bar{Y}_{A3B7} = \frac{31.9}{2} = 15.95 \qquad \bar{Y}_{A3B8} = \frac{29.2}{2} = 14.6 \qquad \bar{Y}_{A3B9} = \frac{33}{2} = 16.5$$

At a closer distance, the larger-capacity bottles reflected less, and at a greater distance, the reflectance seemed to stay between 14.7 and 16.5 lux. When comparing the initial conditions when there was no bottle on the conveyor belt, the range was between 13.8 and 14.5. Therefore, it indicates that the illuminance increased when a bottle with liquid was between 0.9 and 2 lux.

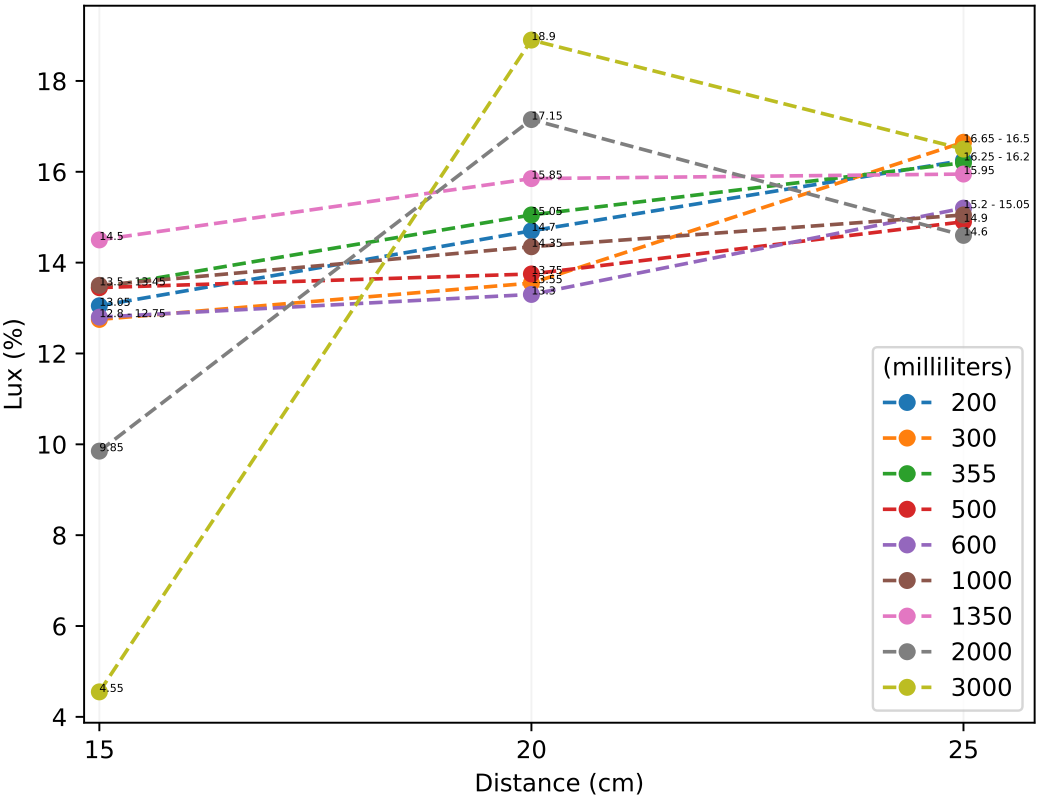

Figure 8. Response graph with the interaction of factors A and B.

The significant distance to obtain the illuminance was determined with the data obtained. Figure 9 shows the optimal distance between the meter and the conveyor belt and between the light source and the conveyor belt.

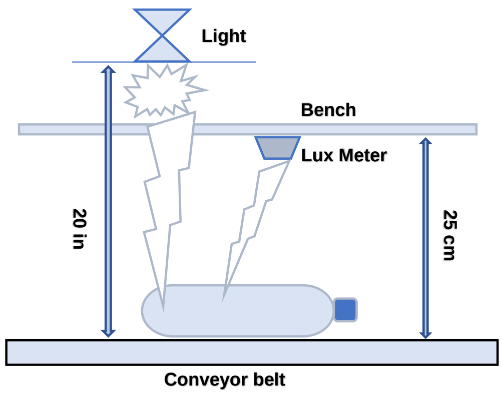

Figure 9. Discrimination system for liquid detection.

3.2.2. Design of Experiments to Identify the Minimum Amount of Liquid Inside the Bottle

For the initial conditions to start the experiment, the lux meter readings were taken when the light source was off, and the readings were between 0.7 and 0.8 lux. With the light source on, the reflection was between 15.6 and 17.8 lux. These were taken at different times and on other days so that replicates and not repetitions were considered in this experiment. The conveyor belt was cleaned, which caused an increase in reflectance. See Tables 12 and 13.

- A: Percentage of liquids in the bottle (50, 25, 0%).
- B: Bottle Size (200, 300, 355, 500, 600, 1000, 1500, 2000, 3000 mL).

Table 12. Information from the second two-way ANOVA.

	Liquid (%) in the Bottle (A)			
Bottle Size (mL) (B)	**50**	**25**	**0**	**Sum**
200	13.3 14.4	14.3 13.3	15 15.2	85.5
Sum	27.7	27.6	30.2	
300	14.7 14.5	14.8 14.4	15 15.3	88.7
Sum	29.2	29.2	30.3	
355	16.5 14.7	16.3 15.2	15.5 16	94.2
Sum	31.2	31.5	31.5	
500	14.5 14	14.5 14.1	14.5 15.4	87
Sum	28.5	28.6	29.9	
600	15.1 14.3	14 13.7	14 15	86.1
Sum	29.4	27.7	29	
1000	12.2 13.9	14.2 13.6	13.5 15.2	82.6
Sum	26.1	27.8	28.7	
1350	14.5 13.4	14.4 13.4	13.4 15	84.1
Sum	27.9	27.8	28.4	
2000	15.1 13.8	13.7 13.3	13.4 16	85.3
Sum	28.9	27	29.4	
3000	15.2 13.7	13.2 12.7	12.2 15.3	82.3
Sum	28.9	25.9	27.5	
Sum Total	257.8	253.1	264.9	775.8

Table 13. Results of the ANOVA of the second experiment. * Factor affecting variability.

Source	SS	gl	MS	F
% Liquid (A)	3.921	2	1.9605	3.8442 *
Bottle (B)	17.4633	8	2.1829	4.2802 *
AB	5.7855	2	2.8927	5.6721 *
Error	20.91	41	0.51	
Total	48.08	53		

Figure 10 shows an interaction between the factors. It describes that when there is less liquid inside the bottle, the amount of illuminance increases depending on the bottle size. This means that the operating range is between 13.75 and 15.75 lux and that the variation in illuminance is between 1.85 and 2.05 lux.

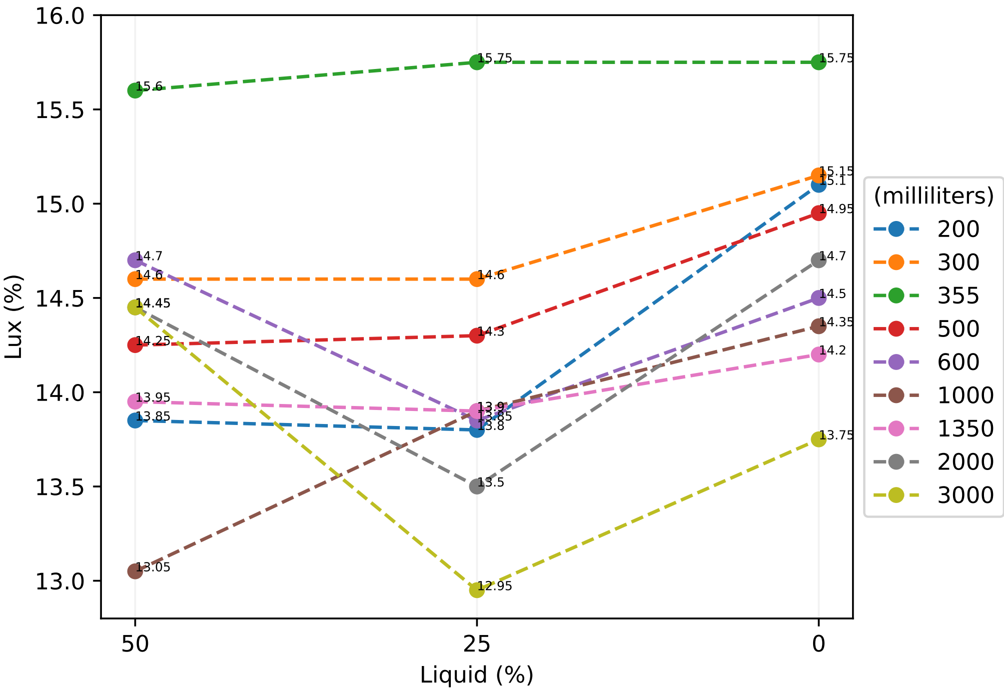

Figure 10. Response graph with the interaction of the second experiment.

3.2.3. Design of Experiments to Determine the Illuminance of the Labels

In the third DOE, the label of each bottle is not uniform, so depending on its position, it would give a different reading, see Table 14.

Table 14. Results design of experiments to identify the variability with the labels.

	Replicas								
Bottle Size (mL) (A)	**1**	**2**	**3**	**4**	**5**	**6**	**Sum**	y	s^2
3000	30.00	28.10	25.20	24.10	26.00	29.80	163.20	27.20	6.092
2000	26.5	26.4	24.5	23.4	22.1	21.6	144.5	24.08	4.38
1350	22	26.7	25.7	25.8	27	28.4	155.6	25.93	4.67
1000	20.8	21.1	21.3	20.3	19.8	19.4	122.7	20.45	0.563
600	18.2	18.4	18.2	18.5	18.3	18.3	109.9	18.32	0.013
500	18.2	18.5	18.9	19.1	19	18.8	112.5	18.75	0.115
355	18.4	18.5	18.5	19.1	18.3	18	110.8	18.47	0.13
300	18	17.5	17.8	17.5	18.2	17.9	106.9	17.82	0.07
250	17.9	18.1	17.9	18.4	18.5	17.9	108.7	18.12	0.073
200	16.6	17.8	17.3	17.8	17.9	18	105.4	17.57	0.282

The calculation of the sums of squares and degrees of freedom for a factor is performed as follows:

$$SST = \sum\sum y_{ij}^2 - \frac{(\sum\sum y_{ij})^2}{N} = (30)^2 + \cdots + (18)^2 - \frac{(1240.20)^2}{60} = 804.526 \quad (8)$$

$$SSt = \frac{\sum Sum_j^2}{n} - \frac{(\sum\sum y_{ij})^2}{N} = \frac{(163.20)^2 + \cdots + (105.4)^2}{6} - \frac{(1240.20)^2}{60} = 722.48 \quad (9)$$

$$SSE = SST - SSt = 804.526 - 722.48 = 82.046 \quad (10)$$

$$gl(SST) = N - 1 = 60 - 1 = 59 \quad (11)$$

$$gl(SSt) = a - 1 = 10 - 1 = 9 \quad (12)$$

$$gl(SSE) = gl(SST) - gl(SSt) = N - a = 60 - 10 = 50 \quad (13)$$

The results of the sums of squares and degrees of freedom calculations are shown in Table 15. With the results obtained, 48.92 is more significant than 2.07, and the equality of means is rejected. The size of the label affects the illuminance.

Table 15. One -way ANOVA of the third experiment. * Factor affecting variability.

Source of Variation	SS	gl	MS	F
Treatments (t)	722.48	9	80.27	48.92 *
Error	82.04	50	1.64	
Total	804.52	59		

The experiment was carried out by modifying the bottle in different positions to obtain the most significant variation between replicates. In Figure 11, it is shown that as the size of the label on the bottle decreases, the illuminance decreases. However, the illuminance increases when the bottle has a label; this occurs when the brand has white letters.

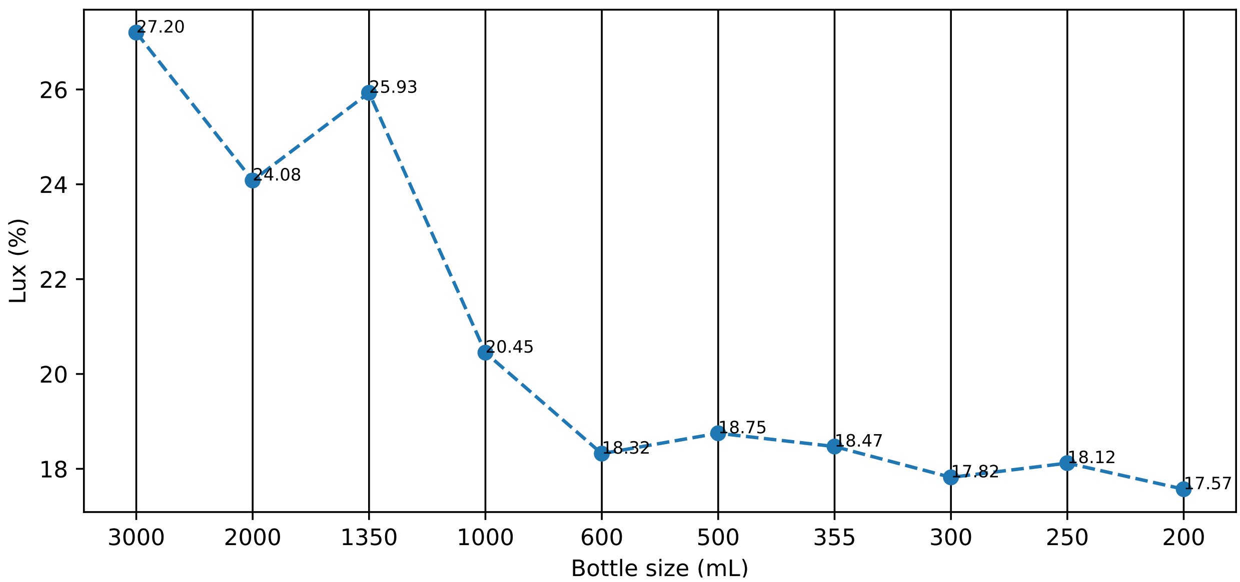

Figure 11. Response plot of the third experiment.

3.3. Principal Component Analysis

Finally, principal component analysis was used to identify the number of liquids in the bottles. Data were entered into the Minitab software, and the data and results are shown in Table 16.

Table 16. Data and results of the PCA.

Bottle Size (mL)	Liquid (100%)	Liquid (50%)	Liquid (25%)	Label	PC1	PC2
3000	16.50	14.45	12.95	27.20	−1.34137	1.99768
2000	14.60	14.45	13.50	24.08	−1.16713	−0.41555
1350	15.95	13.95	13.90	25.93	−0.96440	0.83528
1000	15.05	13.05	13.90	20.45	−1.25152	−1.28753
600	15.20	14.70	13.85	18.32	0.26894	−0.64694
500	14.90	14.25	14.30	18.75	0.14066	−1.18554
355	16.20	15.60	15.75	18.47	2.84955	0.37889
300	16.65	14.60	14.60	17.82	1.39885	0.47160
200	16.25	13.85	13.80	17.57	0.06642	−0.14789

Transforming the data with the following formula, $x_{ij} = \frac{x_{ij} - \bar{x}_j}{\sigma_j}$, the two principal components represent 76.8% of the variation in the data. The results are shown in Figure 12. The graph shows that the 3000 and 1350 bottles have the most illuminance, mainly due to their type of label. This result is due to the manufacturing design. The bottles 2000 and 1000 have high illuminance when they have a label. When they contain liquids, their illuminance is much lower than the other bottles. The 500 and 600 bottles have slight label variations but are more significant when the amount of liquids decreases. The 200 bottle is the most difficult to detect by its label and if it has liquids. The 300 and 355 bottles are similar concerning the label when they have liquids inside the bottle. The 355 and 300 bottles with liquid contents between 75 and 177 mL have the most variation at a distance of 25 cm from the conveyor belt.

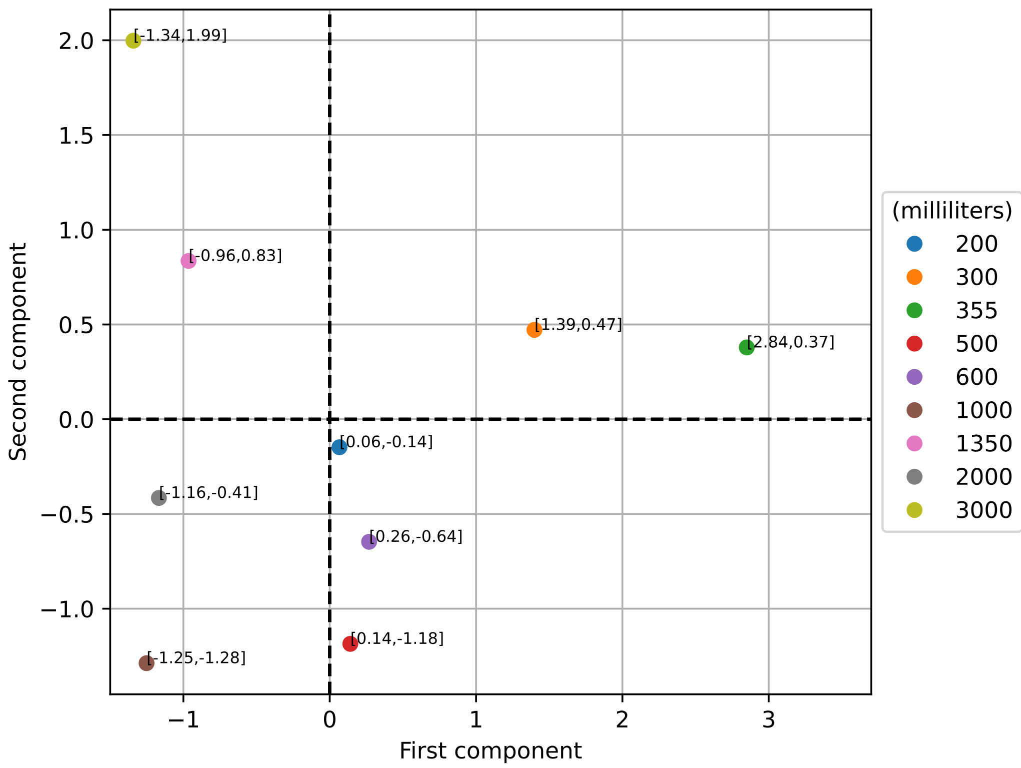

Figure 12. The plot of scores for the two principal components.

In conclusion, the first component is the amount of variation in the bottles affecting the detection of liquids. The second component was interpreted as the variation in bottle labels. With these results, at least two classes can be identified to determine the amount of liquid inside the bottles.

3.4. Support Vector Machine

In Table 17, the bottles were classified according to their different sizes and the amount of liquid inside them.

Table 17. Classes for parsing SVM.

	Class	1		Class	2
Liquid (%)	**Liquid**	**Illuminance**	**Liquid (%)**	**Liquid**	**Illuminance**
100	355	16.20	100	1000	15.05
100	300	16.65	100	600	15.2
100	200	16.25	100	500	14.9
50	177.5	15.60	50	500	13.05
50	150	14.60	100	3000	16.50
50	100	13.85	100	2000	14.60
25	88.75	15.75	100	1350	15.95
25	75	14.60	50	1500	14.45
25	50	13.80	50	1000	14.45
50	300	14.7	50	675	13.95
50	250	14.25	25	750	12.95
25	250	13.9	25	500	13.50
25	150	13.85			
25	125	14.3			
25	337.5	13.9			

The development of the SVM used a program in Matlab that can be consulted in Listing A1. Figure 13 shows that two classes were determined, one for bottles with liquids less than 337.5 mL and class two for bottles with more than 500 mL.

The SVM results help us determine the operating range to detect the bottle size and the amount of liquid inside it. As the number of classes increases in this analysis, the amount of liquid inside the bottles can be determined better at an affordable cost of implementation.

3.5. Development of the Lux Meter and the Liquid Identification System

A system was developed that works in the visible spectrum. By measuring the luminous intensity, it is possible to identify if there is liquid inside the plastic bottle. At this stage, a lux meter was developed to be activated by identifying a bottle with no deformation. See Figure 14. Activation was performed manually.

Infrared spectroscopy was used to detect the absorption of different light wavelengths in PET and labels. In the first stage of this configuration, work was carried out with an infrared photodiode that detects wavelengths in the range of 800 nm to 1100 nm, suitable for differentiating between transparent and colored PET and labels with different sizes and colors. A light source was installed to help the sensor better detect the type of plastic and to obtain the data. With the results of the three DOEs and with statistical evidence, the working range was designed for optimal operating conditions and detection of wavelengths [29,30].

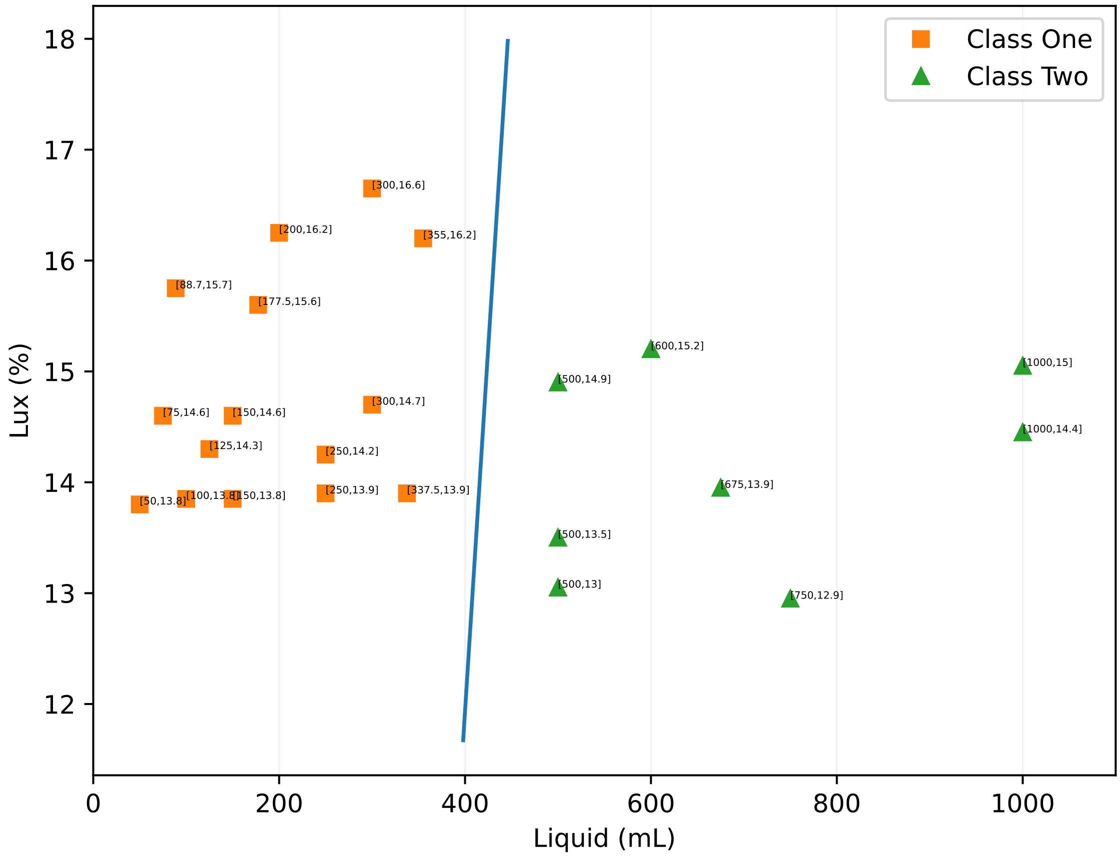

Figure 13. SVM graph to identify the amount of liquid in PET bottles.

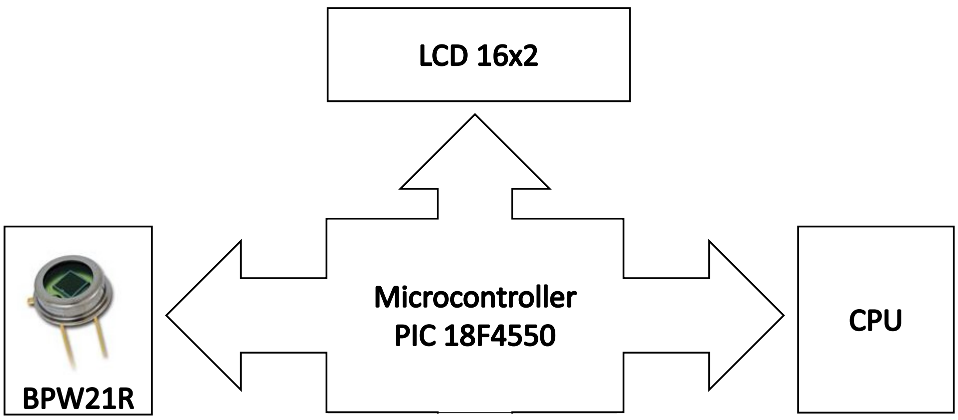

Figure 14. Block diagram of the lux meter data acquisition system.

3.5.1. Functions to Estimate the Illuminance on the Sensor

The value of the measurand was estimated, and the law of Ohm was applied (see Equation (14)), and 18 linear equations were calculated to obtain the electrical resistance in the entire working range of the photodiode. See Figure 15.

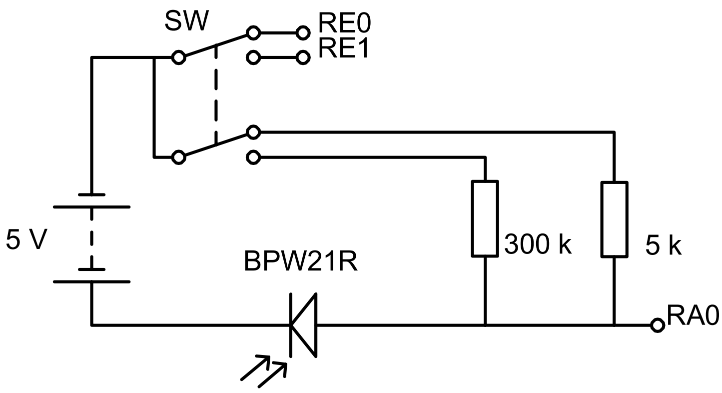

Figure 15. Sensor data reading system circuit.

The input signal to the microcontroller was not amplified because the readings were consistent. The variable resistance of the photodiode was estimated, and with it, the current of the circuit was calculated to assess the illuminance.

$$I = \frac{V}{R} = \frac{Voltage}{Resistance_{variable} + Resistance_{fixed}} \quad (14)$$

The first nine points of Table 18 were taken to obtain the equations that describe the photodiode, then Newton's interpolation was applied, and the variables were cleared.

Table 18. Data to obtain the equations of the operation of the photodiode.

No.	EA-Iluminancia (lx)	IK-Short-Circuit Current (mA)
1	0.01	0.0001
2	0.1	0.00086
3	1	0.0092696
4	10	0.09172
5	100	0.967639
6	1000	9.712874
7	10,000	96.64246
8	100,000	972.178
9	912,669	1000

Work intervals were estimated, and a function was determined using the current in the circuit. The results are the following: From 0 lux to less than 89 lux, we have the following Equations (15)–(17).

$$lux = 45 - 5\sqrt{69 - 200I} \quad (15)$$

$$lux = \frac{10}{11}(100I + 3) \quad (16)$$

$$lux = 175 - 5\sqrt{1041 - 800I} \quad (17)$$

Equation (18) from 90 to 200 lux

$$lux = 0.151515(100000495 - \sqrt{10000105600001089 - 1320000000000I}) \quad (18)$$

Equation (19) from 200 to 400 lux

$$lux = \frac{(5(21909103 - \sqrt{374223401867769.0 - 145454800000000I}))}{363637} \quad (19)$$

Equation (20) from 400 to 600 lux

$$lux = \frac{(50(\sqrt{240.0I - 359.0} - 1.0))}{3} \quad (20)$$

Equation (21) from 600 to 800 lux

$$lux = 50\sqrt{80I + 113} - 650 \quad (21)$$

Equation (22) from 800 to 1000 lux

$$lux = 1750 - 50\sqrt{1041 - 80I} \quad (22)$$

Equation (23) from 1000 to 3000 lux

$$lux = 50\sqrt{16I - 127.0} + 650 \quad (23)$$

Equation (24) from 3000 to 5000 lux

$$lux = \frac{(500(31 - \sqrt{889 - 24I}))}{3} \quad (24)$$

Equation (25) from 5000 to 7000 lux

$$lux = \frac{(1000(I + 3))}{11} \quad (25)$$

Equation (26) from 7000 to 9000 lux

$$lux = 17500 - 500\sqrt{1041 - 8I} \quad (26)$$

Equation (27) from 7000 to 20,000 lux

$$lux = 100(I - 5) \quad (27)$$

Equation (28) from 20,000 to 40,000 lux

$$lux = \frac{(500(1825757 - \sqrt{2598770771809 - 101010000001I}))}{30303} \quad (28)$$

Equation (29) from 40,000 to 60,000 lux

$$lux = \frac{(1000\sqrt{5}(\sqrt{12I - 1795} - \sqrt{5}))}{3} \quad (29)$$

Equation (30) from 60,000 to 80,000 lux

$$lux = 1000\sqrt{5}\sqrt{4I + 565} - 65,000 \quad (30)$$

Equation (31) from 80,000 to 100,000 lux

$$lux = 175000 - 1000\sqrt{5}\sqrt{5205 - 4I} \quad (31)$$

Equation (32) greater than 100,000 lux

$$lux = 1000\sqrt{4I - 3175} + 65000 \quad (32)$$

3.5.2. Lux Meter

The above equations were programmed on a microcontroller and a PCB designed for implementation on the conveyor belt. The conveyor belt was designed so that the system would analyze three bottles per second. It can move forward and backward and be controlled by pulses through a programmable logic controller (PLC) interface with a web page. The lux meter design can send the information through the USB port, and the data can be processed to identify liquids inside the bottles. Figure 16 shows the connections for the implementation and acquisition of the data.

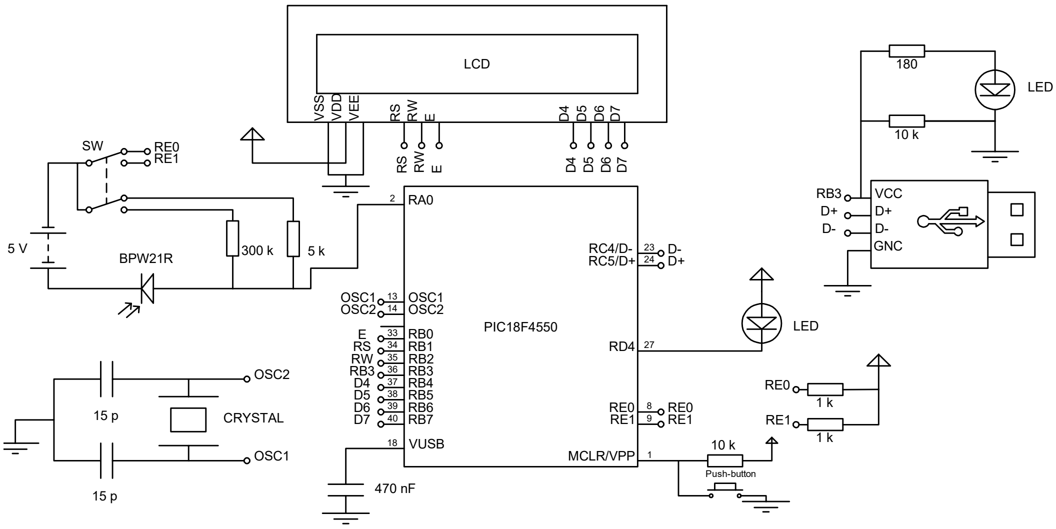

Figure 16. Circuit diagram and data acquisition.

Figure 17, shows the conveyor belt where the commercial lux meter and the proposed lux meter were installed. To detect the bottles, the conveyor belt starts and stops depending on the bottle when it passes entirely through the lux meter. The results coincide with the experimentation already mentioned above.

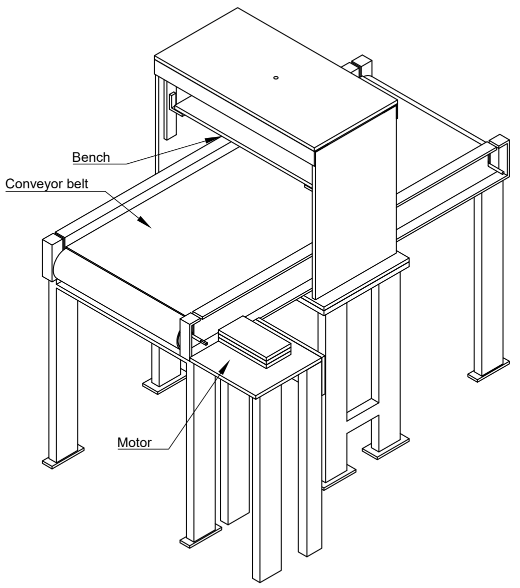

Figure 17. Conveyor belt.

Listings A2 to A4, shows the code used to program the digital lux meter. Figure A1 shows evidence of the lux meter design.

4. Discussion

Based on the results obtained from the three experiments, it was possible to determine the distance at which the lux meter should operate to identify if the bottles contain liquids and approximate the amount of liquid in a ton of bottles. The results from the SVM also demonstrated that estimating the amount of liquid in a bottle is feasible. By increasing the dimensions of the support vector machine, it would be possible to optimize the system further using the available data. To enhance the accuracy of the liquid approximation, the research proposes the implementation of a video camera to identify the size of the bottle. This additional information can be used to optimize the performance of the lux meter in estimating the liquid content more effectively. Another objective of this work is to publish the results of developing an automated system for polymer identification CC in Mexico. The experimentation focused solely on bottles aligned with the conveyor belt. Incorporating a camera system can help minimize variations caused by the bottle's orientation. To simplify the proposed idea, the research will conduct at least three experimental designs to analyze the factors that impact real-time image processing in a test bed. These experiments aim to generate insights for designing and developing an affordable classification system within the academic field. Overall, the work presented in this section represents a part of a larger project, and by combining the vision system, lux meter, and additional experimental designs, the research aims to achieve better results in developing an automated system for identifying polymers in recycling centers.

5. Conclusions

This work integrates classification technologies to demonstrate advances in the modern recycling of urban solid materials. It is necessary to emphasize that Mexico needs to develop techniques to increase the productivity of collection centers for recyclable materials and face the challenges that recycling implies.

- It is possible to develop an automatic liquid identification system for recyclable polyethylene terephthalate bottles with an affordable design.
- It was possible to develop a new methodology to be implemented to identify dark liquids.
- It is possible to quantify the amount of dark liquid that post-consumer PET bottles contain by implementing an affordable design.

This work has provided a solution for modernizing collection centers to increase the classification of post-consumer PET bottles. We can assume with this work that it is possible to approximate the weight represented by liquids in post-consumer PET bottles by applying an identification system with machine learning instead of using a scale and then empirically estimating the weight of the liquid in bottles.

Author Contributions: Conceptualization, L.A.Á.-H. and J.R.-R.; methodology, L.A.Á.-H.; software, L.A.Á.-H.; validation, J.R.G.-M., H.R.Z., H.T.-S. and J.R.-R.; formal analysis, L.A.Á.-H.; investigation, L.A.Á.-H.; resources, L.A.Á.-H. and J.R.-R.; data curation, L.A.Á.-H.; writing—original draft preparation, J.R.-R., J.R.G.-M., H.T.-S. and H.R.Z.; writing—review and editing, J.R.G.-M., J.R.-R., H.T.-S., S.P.S.-A. and H.R.Z.; visualization, L.A.Á.-H.; supervision, H.R.Z. and J.R.-R.; project administration, L.A.Á.-H.; funding acquisition, J.R.G.-M., L.A.Á.-H., J.R.-R. and S.P.S.-A. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of variance
CC	Collection centers
DIL40	40 PINS dual-in-line package
DOE	Design of experiments
F	F Ratio
gl	Degrees of freedom
LCD	Liquid-crystal display
LED	Light-emitting diode
MS	Mean squarese
ml	Milliliters
NC	Normally closed
No.	Number
PC1	First principal component
PC2	Second principal component
PCA	Principal component analysis
PCB	Printed circuit board
PET	Polyethylene terephthalate
PIC	Peripheral interface controller
PLC	Programmable logic controller
SVM	Support vector machine
SS	Sum of squares
USE	Universal serial bus

Appendix A

Listing A1. Code for the SVM algorithm in Matlab.

```
format~long

P1 = [337.5,13.90,1];    % -1
P2 = [355,16.2,1];       % -1
P3 = [500,14.9,1];       % +1

Figure~(1),plot(337.5,13.90,'o');
hold on;
Figure~(1),plot(355,16.2,'o');
hold on;
Figure~(1),plot(500,14.9,'x');
xlim([0,800])
ylim([12,17])

syms A1 A2 A3;
a1 = A1;
a2 = A2;
a3 = A3;

eqs=[a1*(sum(P1.*P1))+a2*(sum(P1.*P2))+a3*(sum(P1.*P3))==-1,...
a1*(sum(P1.*P2))+a2*(sum(P2.*P2))+a3*(sum(P2.*P3))==-1,...
a1*(sum(P1.*P3))+a2*(sum(P3.*P2))+a3*(sum(P3.*P3))==1];

[a1,a2,a3]=solve(eqs);

Wx=a1*P1(1)+a2*P2(1)+a3*P3(1);
Wy=a1*P1(2)+a2*P2(2)+a3*P3(2);
Wb=a1*P1(3)+a2*P2(3)+a3*P3(3);

t=[0:1:800];
y=( -Wx*t - Wb )/Wy;
hold on;
Figure~(1),plot(t,y);
```

```
    % Evaluate the results
    Dx=[600,15.2];
    res=Dx(1)*Wx+Dx(2)*Wy+Wb;

    if(res > 0)
        1
    elseif res < 0
        -1
    end
```

Appendix B

Listing A2. Code for programming the lux meter in c.

```

#include <18F4550.h>
#device adc=10
#fuses HS,NOWDT,NOPROTECT,NOLVP,NODEBUG,USBDIV,PLL5,CPUDIV2,VREGEN
#use delay(clock=20000000)
#define use_portb_lcd TRUE
#include <LCD.c>
#define USB_CON_SENSE_PIN PIN_B3
#include "usb_cdc.h"
#include <math.h>
#Byte PortA = 0xF80
#Byte PortB = 0xF81
#Byte PortC = 0xF82
#Byte PortD = 0xF83
#Byte PortE = 0xF84
void main(void){
while(TRUE){
   int16 q;
   float p,y,lux,t=0,Ts=0.5;
   int k=0,aux=0;
   char ch;
   set_tris_a(0x01);
   setup_adc_ports(AN0);
   setup_adc(ADC_CLOCK_INTERNAL);
   set_tris_e(0x03);
   lcd_init();
   printf(lcd_putc,"\f");
   bit_clear(PortB,3);
   while(TRUE){

   output_d(0x00);
   set_adc_channel(0);
   delay_us(10);
   q=read_adc();
   p=5.0*q/1024.0;

   if(bit_test(portE,0)==0){
      y=p/300000.0;
      aux=1;
   }
   if(bit_test(portE,1)==0){
      y=p/5000.0;
      aux=2;
   }
   y=y*1000000.0;
   if(bit_test(PortB,3)==1 && k==0){
            usb_cdc_init();
            usb_init();
            while(!usb_cdc_connected())
            {
            }
            k++;
   }
```

Listing A3. Code for programming the lux meter in c.

```
if(k>0 && usb_enumerated() ){
      usb_task();
     printf(usb_cdc_putc,"%f\t%f\tTs=%f\t\n",t,lux,Ts);
     t=Ts+t;
   }
   if(bit_test(PortB,3)==0 && k>0){
      k=0;
      break;
    }
      if(y>=0.1 && y<=0.3){
         lux=45.0-5.0*sqrt(69.0-200.0*y);
         p=1.0;
      }
      if(y>0.3 && y<=0.52){
         lux=(10.0/11.0)*(100.0*y+3.0);
         p=2.0;
      }
      if(y>0.52 && y<=0.75){
         lux=175.0-5.0*sqrt(1041.0-800.0*y);
         p=3.0;
      }
      if(y>0.75 && y<=0.95){
         lux=0.151515*(100000495.0-sqrt(10000105600001089.0-132000000000.0*y)
    );
         p=4.0;
      }
      if(y>0.95 && y<=2.2){
         lux=(5.0*(21909103.0-sqrt(374223401867769.0-145454800000000.0*y)))
    /363637.0;
         p=5.0;
      }
      if(y>2.2 && y<=4.1){
         lux=(50.0*(sqrt(240.0*y-359.0)-1.0))/3.0;
         p=6.0;
      }
      if(y>4.1 && y<=6.4){
         lux= 50.0*sqrt(80.0*y+113.0)-650.0;
         p=7.0;
      }
      if(y>6.4 && y<=8.5){
         lux=1750.0-50.0*sqrt(1041.0-80.0*y);
         p=8.0;
      }
      if(y>8.5 && y<=11){
         lux=50.0*sqrt(16.0*y-127.0)+650.0;
         p=9.0;
      }
      if(y>11 && y<=30){
         lux=(500.0*(31.0-sqrt(889.0-24.0*y)))/3.0;
         p=10.0;
      }
```

Listing A4. Code for programming the lux meter in c.

```
        if(y>30 && y<=52){
            lux=(1000.0*(y+3.0))/11.0;
            p=11.0;
        }
        if(y>52 && y<=75){
            lux=17500.0-500.0*sqrt(1041.0-8.0*y);
            p=12.0;
        }
        if(y>75 && y<=95){
            lux=100.0*(y-5.0);
            p=13.0;
        }
        if(y>95 && y<=220){
            lux=(500.0*(1825757.0-sqrt(2598770771809.0-10101000000.0*y)))
      /30303.0;
            p=14.0;
        }
        if(y>220 && y<=410){
            lux=(1000.0*sqrt(5.0)*(sqrt(12.0*y-1795.0)-sqrt(5.0)))/3.0;
            p=15.0;
        }
        if(y>410 && y<=640){
            lux=1000.0*sqrt(5.0)*sqrt(4.0*y+565.0)-65000.0;
            p=16.0;
        }
        if(y>640 && y<=850){
            lux=175000.0-1000.0*sqrt(5.0)*sqrt(5205.0-4.0*y);
            p=17.0;
        }
        if(y>850 && y<=1100){
            lux=1000.0*sqrt(4.0*y-3175.0)+65000.0;
            p=18.0;
        }
            if(aux==1 && y<0.1)
                printf(lcd_putc,"\fMenor a 10 lux");
            else
                printf(lcd_putc, "\fLux %1.1f(%1.0f)",lux,p); //
            if(aux==1 && y>1.1){
                printf(lcd_putc,"\fCambie Escala(2)\n");
                printf(lcd_putc," 100 lux a 100k");
            }

            if(aux==2 && y<=1.1){
                printf(lcd_putc,"\fCambie Escala(1)\n");
                printf(lcd_putc," 0 lux a 100 ");
                }
            delay_ms(250);
            aux=0;
          }
    }
}
```

Appendix C

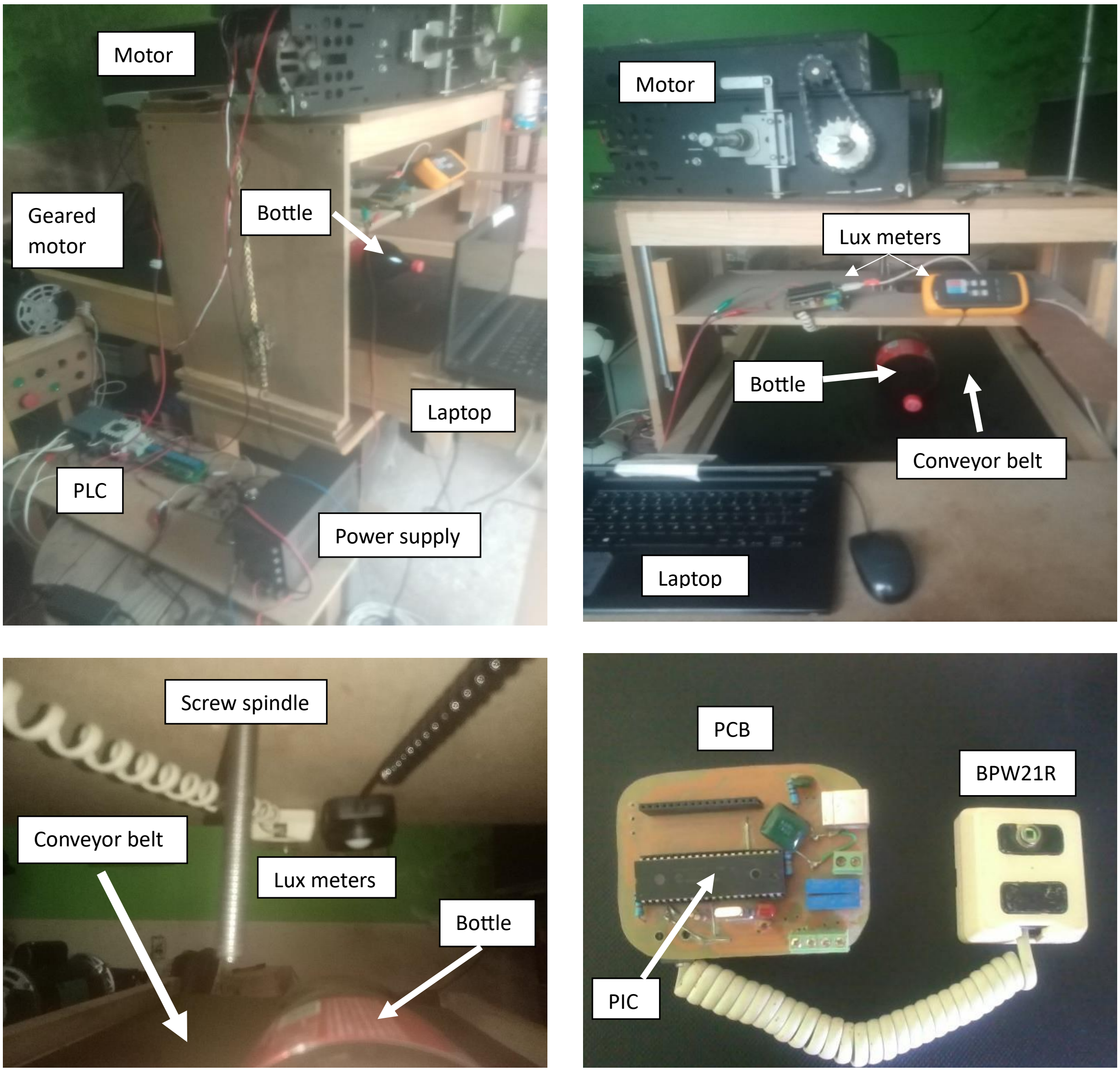

Figure A1. Photos of the experiment workbench.

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