Preliminary Testing of a Color-based Test Kit Detector for Bioplastics

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Abstract. Plastic was invented in 1907 by Leo Baekeland who is a Belgian-American Chemist. Since then, his creation has paved the way for the future of polymers. Nowadays, plastics come in different types with multitude of uses ranging from household storage purpose to medical packaging means. However, it also has a negative impact on humanity as well, particularly on the environment and bioplastics is noticeably would be the way forward to achieve a sustainable environment. Bioplastics is synthesized from biomass or other natural material as the new alternative to plastic as it degrades much faster. Eventually, a bioplastic testing kit will be necessary, especially in the market where the use of plastic will be regulated. A prototype test kit based on Arduino and a color sensor was developed to distinguish different plastic types based on their distinct color reactions to specific chemical reagents. The fundamental question was how to create a feasible way to distinguish between cellulose-based, starch-based, biodegradable, and conventional plastics and deal with the accompanying challenges. The reagents applied to the samples included iodine, iodine-CaCl2, and Schultze reagents. Notably, the cellulose-based and starch-based straw samples exhibited a dark purple color change with iodine and dark blue with iodine-CaCl2 and Schultze reagent. In contrast, starch-based singlet bags exhibited brown transforming into purple with iodine and Schultze reagents. Besides, biodegradable, and conventional plastics displayed no color changes with any reagents. The test kit has shown a promising way to assist consumers to make a more informed decision through a simple test.

Keywords: Bioplastics, Test Kit, Reagents.

1 Introduction

1.1 Bioplastics

Over the last decades, the market has developed various materials within various manufacturing fields; overtaking wood, glass, ceramic and metal, plastics have become an essential material in the manufacturing environment [1]. There is also an increasing impetus for bioplastics manufacturing, growing demand and the introduction of more complicated applications and products. The worldwide bioplastics manufacturing capacity is predicted to increase dramatically from 2.2 million tonnes in 2022 to over 6.3 million tonnes in 2027 [2]. Bioplastics refers to bio-based plastics, which comprise biogenic materials, such as crop-based feedstock [3] or organic waste [4, 5].

1.2 Bioplastics as Alternative to Plastics

Verma and Fortunati [6] stated that bioplastics have emerged as a viable candidate with the potential as an alternative to petroleum-based plastics due to their biodegradability. Alternative materials regarded bioplastics as promising because their feedstocks are renewable and, in theory, can be composed and recycled. Besides, their manufacturing method might be more energy efficient, abundant, and inexpensive than petroleum-based ones [7, 8, 9].

According to the World Economic Forum [10], in 2014 alone, the sector produced 311 million metric tons and is predicted to triple by 2050, yet less than 15% of it gets recycled. These are the primary reasons behind the recent transition to bio-based plastics and significant growth in polymer production.

1.3 Needs for Testing Option

However, there is currently a lack of standardized and reliable methods for evaluating the biodegradability of bioplastics, which is crucial for developing and implementing more sustainable and environmentally friendly products. As a result, there is a gap in the market for an accurate and accessible biodegradability testing option.

2 Relevant Research

2.1 Biodegradability Testing

Koh and Khor [11] provided an overview of the current state and potential future advancements in the sensors used for assessing the biodegradability of polymers and sensors made from biodegradable polymers. The research concentrated on standard tests, analytical processes for biodegradability testing, and sensors for assessing biodegradable organic matter. They examined various methods and techniques for evaluating biodegradation, including gravimetric analysis, microbial tests, spectroscopy, and electrochemical sensors.

Chowdhury et al. [12] studied the development and characterization of tamarind seeds, berry seeds, and licorice roots to produce bioplastic materials. The researchers synthesized the bioplastic material and conducted various characteristics to evaluate its properties. In this paper, laboratory-based techniques were applied to test the biodegradability of bioplastic materials. Techniques such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and mechanical testing were employed to assess the bioplastics' surface morphology, thermal stability, and tensile strength. The results indicated that the bioplastics derived from these natural sources exhibited favorable properties. Interestingly, the bioplastics produced without licorice root showed superior biodegradability and had improved mechanical, morphological, thermal, and antibacterial characteristics.

The biodegradability of bioplastics is often evaluated using standard test methods. According to Ashter [13], ASTM D6866 is a standardized test technique created by the American Society for Testing and Materials (ASTM) to assess bio-based content. The test technique is based on determining the quantity of radiocarbon (carbon-14) in the sample, as bio-based materials include carbon generated from modern renewable sources and will contain a higher percentage of carbon-14 than fossil-based materials. The ASTM D6866 test applies to many goods, including plastics, coatings, adhesives, lubricants, fuels, and other materials. It provides a reliable method of assessing bio-based content, allowing consumers and the industry to make educated decisions regarding the environmental impact and sustainability of the goods they use.

2.2 Research Activities on Testing

Film-based Testing Analysis. Pucci et al. [14] applied this to monitor the deformation of polymer produced by film manufacturing or any structural alteration of plastic material using a luminescence mechanochromic sensor. The melt processing technique was used to create films made of poly(propylene) (PP) with varied concentrations of bis(benzoxazolyl)stilbene (BBS). During the observation, the films noticed a change, with the emission shifting from blue to green. Subsequently, the tensile deformation detection in PP films confirmed and demonstrated the existence of the polymer’s properties.

Another approach by Pucci et al. [15] focused on using the BBS compounds as luminescent sensors to measure temperature and deformation in biodegradable polybutylene succinate (PBS) films. The BBS molecules dispersed in a PBS matrix to achieve changes in emission properties. The concentration of BBS in films influences the emission color, with lower concentrations exhibiting blue emission from isolated BBS molecules and higher concentrations showing green emission from supramolecular aggregates called excimers. In the case of the tested PLA, the monomer band (representing blue light) exhibited a significant presence during tensile stress. In contrast, the emission band (indicating green light) showed notable prominence under thermal stress.

Capacitance Testing Analysis. Schusser et al. [16] introduce the idea of real-time and monitoring of the degrading process of biopolymers using capacitive field-effect sensors comprising electrolyte-insulator-semiconductor (EIS). Their research findings demonstrated the practicality of capacitive field-effect sensors for evaluating polymer biodegradation under the influence of pH and enzymes. However, the research was deemed unsuitable for examining the degradation of bulk polymers due to the enzymes’ size, which hindered their ability to penetrate the polymer. Hence, for future research, they suggest the formulation of a more detailed model of the sensor for a precise description of the degradation process.

Inductance Testing Analysis. Salpavaara et al. [17] proposed a technique for detecting biodegradable polymer changes during hydrolysis using an inductively coupled resonance sensor. The sensor, equipped using capacitive sensing elements digital, was utilized to track modifications in two biodegradable poly(lactide-co-glycolide)s (PLGs) over an eight week testing period. However, this approach solely offers a qualitative evaluation of the biodegradability of the tested polymers, lacking quantitative data like the biodegradation rate, which cannot be deduced. Hence, for future research, it was suggested in this paper that the sensor encapsulation techniques should be improved.

Mechanical Testing Analysis. Karthiani et al. [18] signified the development and characterization of biodegradable algae-based bioplastics based on alginate derived from brown seaweeds of Sargassum sp. One of the crucial variables during the research is the mechanical testing of synthesized bioplastics to determine tensile strength and elongation at break. The results demonstrated that bioplastics mixed with inverted sugar improved the properties of the bioplastics by making them more flexible, as opposed to the control bioplastics, which were fragile. Then, with good mechanical properties, a soil burial test was performed, resulting in bioplastics with 6% alginate and 5% inverted sugar having a rapid degradation within four days.

2.3 Color-sensing Analysis

Due to the lack of research regarding color-based testing analysis for biodegradability, this section explains the color-sensing approach, which will detect the color of the prospective object. Seelye et al. [19] developed an automated technique for determining the color of plant leaves using low-cost color sensors. The research focused on calibrating and validating the TCS3200 sensor to provide accurate plant leaf red, green, and blue (RGB) readings. Integrating the sensor with a proximity sensor and a robotic arm enabled autonomous and fixed-height color measurements. The study, however, was limited to calibrating the sensor for a particular range of green-yellow colors, focusing just on plant leaves. Future research opportunities include broadening the sensor's applicability, combining it with other sensors, and developing image processing approaches to optimize plant development based on color information.

Mogi et al. [20] presented a study focused on developing a method to detect insertion errors in electronic boards by utilizing the hue, saturation, and value (HSV) color format. The notion of using HSV format instead of RGB format is due to its benefits in identifying color, simplicity of conversion, and resemblance to human color perception. This paper described extracting regions based on hue values and detecting regions using borderline tracing. Experimental results demonstrated the effectiveness of the HSV-based recognition method compared to RGB. However, the limitations showed the computational complexity and sensitivity to lighting conditions. These outcomes acknowledge improvement areas, such as utilizing machine learning and Bayesian detection theory for more intelligent and efficient recognition.

Feng et al. [21] proposed a novel detection for identifying rare colored capsules (RCC) mixed with regular-colored capsules in pharmaceutical manufacturing. The method utilizes RGB and HSV color spaces to detect accurately and efficiently. The histogram-based approach to extracting RGB values speeds up detection while reducing data processing. Based on the results, the proposed method outperforms the conventional HSV algorithms in terms of time and accuracy. The method's effectiveness may be affected by lighting and camera setting variations, necessitating further research against image noise and variances.

Malkurthi et al. [22] developed an automated color detection system to analyze liquid reagents qualitatively. The system was designed to be simple and cost-effective, utilizing a light-emitting diode (LED) and a light-dependent resistor (LDR), which was compared to a camera-based system (ESP32-CAM, OV2640 camera). As a result, the LED-LDR system outperformed the camera-based module, with a maximum error was less than 8%. However, the LDR is subject to influence from outside light, necessitating an opaque enclosure. They suggested fabricating a single substrate, LED-LDR pair, for future studies to produce a small real-time color detection on a monolithic system-on-chip.

A trichromatic-color-sensing (TCS) metasurface featuring reprogrammable electromagnetic functions was proposed by Chen et al. [23]. The design incorporated a photodiode sensor (TCS3200) to recognize the color of light in the environment and a one-bit programmable device to control the reflected phase response using the field-programmable gate array (FPGA) hardware system. This system allowed the detection and conversion of RGB colors into desired metasurface scattering patterns. Although, the TCS metasurface may require considerable light intensity to activate the matching patterns, which might cause unwanted interference. Future research on integrating photodiode sensors with metasurfaces can be extended to sensor arrays for material characterization or strain sensing.

Panuganti et al. [24] proposed an embedded color segregation system using Arduino with a multi-rate sensor and color identification for various applications, such as waste management and fruit and vegetable packing. The sensor measurements were collected from the TCS34725 RGB sensor, which will detect and organize color according to its category. The significant benefits from the approach showed that the accuracy is above 95% with a response time of fewer than 3 ms. Despite this, the research did not specify the system's effectiveness under difficult lighting conditions or the categories of items that can be effectively categorized based on color. Future studies might improve the color classification system to handle a greater variety of colors.

Therefore, the applications of color detection for determining bioplastics and non-bioplastics in the prototype test kit will be described in the next section.

3 Test Kit Development

3.1 System Architecture

The color detection will be implemented using three main components: (i) microcontroller as the program control; (ii) color sensor; and (iii) LCD display to fulfil the bioplastic test kit requirements. Fig. 1 and shows the block diagram of the proposed project. The color sensor will detect the color of the solution formed from mixing the reagent with the test substrate (bioplastic or non-bioplastic material). Next, the microcontroller algorithm will process the sensed color to detect the present color. An external power supply will power the microcontroller. After the processing, the information in bioplastic or non-bioplastic will be displayed on the LCD screen.

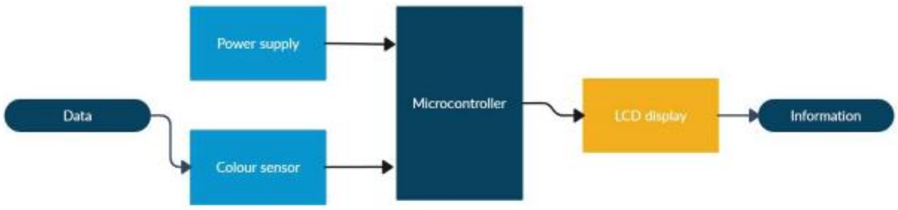


Fig. 1. Block Diagram of the System

The flowchart in Fig. 2 represents the more detailed processing of the block diagram. The LCD and the color sensor will be initially initialized. Once the reagent has been poured onto the test material, color change in the form of purple (Reagent 1 – iodine) or blue color (Reagent 2 – iodine-$CaCl_2$ and Schultze solution) will be detected and if these colors are present, it will indicate as “bioplastics” else, it is “not bioplastics” on the LCD. Each of the components will be explained in detail in the following sub-sections.

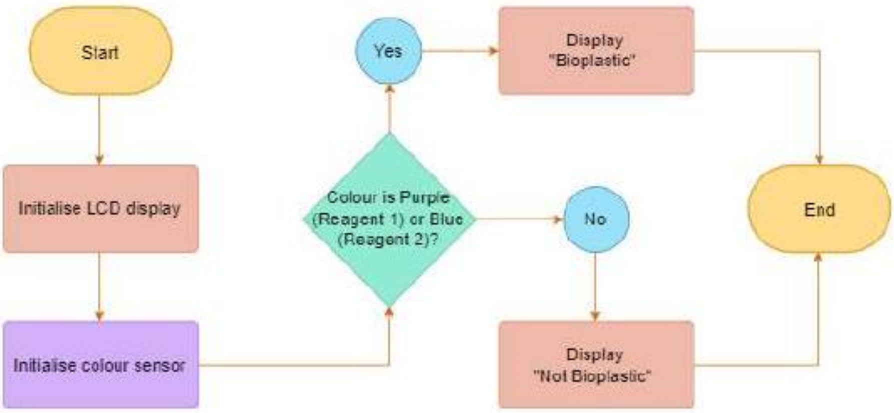
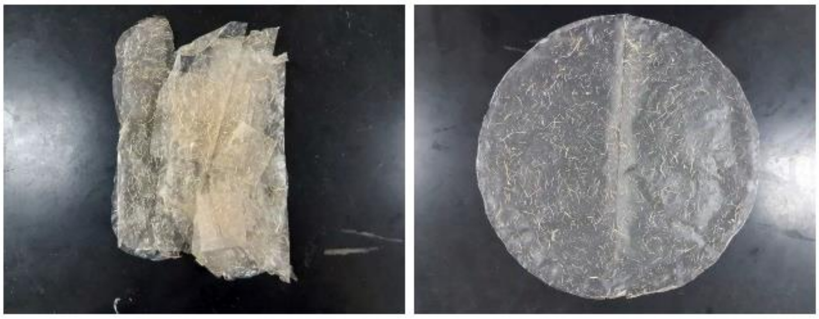


Fig. 2. Flowchart of the System

3.2 Test Samples

Cellulose-based Bioplastic. A laboratory-made bioplastics shown in Fig. 3 was produced using tapioca starch and contained 20g and 30g of cellulose extracted from palm empty fruit respectively were used as test samples.



(a) 20g Cellulose Bioplastics (b) 30g Cellulose Bioplastics

Fig. 3. Cellulose-based Bioplastics

Starch-based Bioplastic. Two types of starch-based plastics were used namely the bio singlet bags from Dunkin' Donuts and straws called RiceStraws manufactured by NLYTech Biotech Penang. The bio singlet bag (Fig. 4 (a)) is made from starch mixes such as cornstarch, tapioca, and sweet potato. Meanwhile, the straw (Fig. 4(b)) is made using rice flour (63%) and tapioca starch.

(a) Bio singlet Bag (b) RiceStraws

Fig. 4. Starch-based Bioplastics

Biodegradable plastic. Figure 5(a) shows the biodegradable garbage bag found in any grocery store. The ingredients to make it are unknown.

Conventional plastic. The conventional plastic used in this experiment is regular plastic found everywhere and used daily, as shown in Figure 5(b).

(a) Biodegradable Plastic (b) Conventional Plastic

Fig. 5. Biodegradable and Conventional Plastic Samples

4 Experimental Testing

The experiments were conducted through the testing of four types of samples namely cellulose-based, starch-based, biodegradable, and conventional plastic. These samples have been outlined in the previous section. The reagents applied to the samples included iodine, iodine-$CaCl_2$, and Schultze reagents. Table 1 shows the results of the experimental testing of the test kit.

Table 1. Color reaction after exposure to reagents

Samples		Reagents		
		Iodine	Iodine-$CaCl_2$	Schultze
Cellulose-based	10 g	Dark purple	Dark blue	Dark blue
	20 g	Dark purple	Dark blue	Dark blue
Starch-based	Singlet bag (corn)	Brown → purple	Slightly brown	Brown → purple
	Straws (rice)	Dark purple	Dark blue	Dark blue
Biodegradable		No change	No change	No change
Conventional		No change	No change	No change

Table 1 shows the color reaction of each sample after being exposed to the reagents. The cellulose-based samples (both 10 g and 20 g) and starch-based samples (straws) exhibit a "dark purple" color reaction after being exposed to iodine solution. Meanwhile, the starch-based sample in a singlet bag shows a "brown" color, and then changes to "purple" after a brief time.

As for the iodine-$CaCl_2$ and Schultze reagents, the reactions show a “dark blue” color reaction for the cellulose-based (both 10 g and 20 g) and starch-based (straws). However, the starch-based (singlet bag) reaction differed for both reagents. The iodine-$CaCl_2$ shows a “slightly brown” while the Schultze shows the change from “brown to purple” color reactions.

The reaction for the biodegradable and conventional plastics shows “no change” in color for all the reagents. The reaction of the biodegradable garbage bag supports the statement that not all biodegradable bioplastics are derived from bio-based sources.

5 Conclusions

A prototype test kit using Arduino and color sensors to differentiate which plastic is biodegradable, bio-based, or both, based on color reactions. The experiments demonstrated that chemical reagent-induced color changes provided a method for distinguishing between cellulose-based, starch-based, biodegradable, and conventional plastics.

However, difficulties in color sensor calibration were encountered, resulting in RGB value inaccuracies. Another limitation of the detector is that it still indicates other blue or purple conventional plastics as bioplastics if they fulfil the RGB range values. The prototype has the potential to identify plastic types, but further refinement and research are required to improve sensor calibration and accuracy. This study demonstrates the potential of using technology to address plastic identification issues, paving the way for potential applications in waste management and environmental sustainability.

For improvement, several key areas can be considered to enhance effectiveness and reliability of the developed test kit. Firstly, in terms of accuracy, it is needed to tackle the calibration challenges faced during the project. It is to ensure the consistency and accuracy of RGB readings. Exploring alternative calibration methods and sensor configurations could be done to mitigate inaccuracies. Secondly, consider incorporating a camera module and utilizing the HSV color space for color detection. By integrating a camera, the system can capture images of plastic samples and perform color analysis based on the HSV color model. This method has advantages such as higher color resolution, lower lighting sensitivity, and better color discrimination.

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