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Development of Bread Leftovers-Derived Bioplastics and Its Characterisation

V. W. T. Yong[1], N. Z. Z. M. Zailani[2], N. A. A. Aziz[3]*

[1] *Sri Pengkalan Binaan Sdn Bhd, 75300 Melaka, MALAYSIA*
[2] *Faculty of Civil Engineering and Built Environment,*
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA
[3] *Micropollutant Research Centre, Institute for Integrated Engineering,*
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA

*Corresponding Author: nuradila@uthm.edu.my

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Abstract

Bioplastics offer a sustainable solution to plastic pollution. This study investigated bioplastics derived from bread leftovers (BLB), characterising their mechanical and chemical properties to assess their potential as alternatives to petroleum-based plastics. BLB samples, formulated with varying amounts of bread leftovers (5g, 10g, 15g), were tested for their moisture content, solubility, biodegradability, tensile strength, Young's modulus, elongation at break, shape memory recovery, surface morphology, and elemental composition. Results showed insignificant variations in moisture content (25.3-28.9%) and water solubility (42.6-48.6%). However, increasing bread leftover content improved alcohol resistance, with the 15g BLB sample exhibiting the lowest alcohol solubility (10.6%). Notably, BLB samples demonstrated superior biodegradability, degrading within seven days, unlike conventional plastics. The 15g BLB formulation exhibited the most promising mechanical properties, including a Young's modulus of 2.884 ± 0.127 MPa, a tensile strength of 1.46 ± 0.10 MPa, and an elongation at break of 53.75 ± 6.646%, suggesting its potential to replace low-density polyethene (LDPE). While the low melting point hindered shape memory recovery, elemental analysis revealed a composition of 63% carbon and 36% oxygen, contributing to its biodegradability. Overall, 15 g of BLB shows significant potential as a biodegradable material for plastic production, offering a viable path to reducing non-biodegradable waste.

1. Introduction

According to the World Bank Group [1], the plastic manufacturing sector in Malaysia experienced rapid growth, contributing to the encouraging economic performance in 2018. The Malaysia Plastics Sustainability Roadmap 2010-2030 confirms that plastics manufacturing has experienced a significant surge, resulting in an annual production of 370 million tonnes in 2019. Undoubtedly, plastic has become a primary environmental concern due to its non-biodegradable nature and damaging impact on ecosystems, despite its practicality. Inefficient plastic waste management puts landfill sustainability at risk.

A large amount of non-biodegradable plastic waste is disposed of in landfills due to inadequate separation procedures and insufficient recycling provisions. As a result, additional land must be allocated to establish a landfill where waste can be disposed of. Besides, non-biodegradable plastics often introduce significant harm since they never fully break down and accumulate in natural environments for hundreds to thousands of years. It can also leach harmful chemicals, such as bisphenol A (BPA) and phthalates, and further break down into microplastics, which can be harmful to humans and animals that ingest them [2]. This highlights the importance of eliminating plastic waste and establishing long-term alternatives to replace single-use plastics. To combat environmental pollution, researchers are focusing heavily on developing environmentally friendly, biodegradable polymers to replace those based on petroleum [3].

The bioplastic sector recently expanded its research into non-food crops and waste products. Agricultural products, such as corn and sugarcane, were initially used as bioplastic ingredients [4]. On the other hand, households that create significant volumes of organic garbage, including food scraps and biodegradable materials, also become a critical environmental burden in contemporary society. As a result, organic materials account for 45% of Malaysia's overall waste generation [5]. Poor waste disposal management often results in the accumulation of waste in landfills, where it decomposes anaerobically and emits detrimental greenhouse gases, such as methane. To worsen the situation, leachate, a liquid resulting from the decomposition of solid waste, will be produced. This liquid can seep into the ground and pollute groundwater, adversely affecting its quality.

Additionally, leachate can also harm soil properties, causing further environmental damage. Moreover, bread leftovers, particularly those containing starch, are composed of a natural polysaccharide, which is a combination of amylose and amylopectin that can be plasticised with water and other additives, such as glycerol [6]. Additionally, starch-based bioplastics are inherently biodegradable and can be readily broken down by microorganisms in various environments.

Therefore, this study aims to develop biodegradable plastic derived from the selected kitchen waste (bread leftovers) and to evaluate its feasibility as one of the sustainable materials in plastic production as an alternative to conventional non-biodegradable plastic materials by characterising its moisture content, solubility in water, solubility in alcohol, biodegradability, tensile strength, Young's modulus, elongation at break, shape memory recovery (thermal cyclic test method), and surface morphology and elemental composition (using the SEM-EDX).

2. Materials and Methods

2.1 Materials

Bread leftovers (BL) were supplied from a bakery shop in Parit Raja, Batu Pahat, Johor, Malaysia. USP-grade vegetable glycerin with a purity of 99.7% and gelatin powder with a bloom of 150 were purchased from Dchemie Malaysia in Johor and Trans Standard International Malaysia, respectively.

2.2 Preparation of Bioplastic Film Samples

The preparation of bread leftover-derived bioplastic (BLB) from selected kitchen waste was adapted from Ashfaq et al. [7] with specific alterations to suit the materials chosen for the study. First, BL was dehydrated in the oven for about 30 minutes at 200°C. After that, it was removed from the oven and left to cool to room temperature. Then, it was transferred into a desiccator for at least 30 minutes. Then, it was transferred into a blender in batches to grind into a fine powder approximately 0.5 - 5 mm in size. Then, the powdered BL was stored in a container for further usage.

The preparation of the BLB film samples was initiated by adding 100 mL of distilled water to a glass beaker, followed by the addition of the desired mass (5 g, 10 g, or 15 g) of the BL, 10 mL of glycerin, and 10 g of gelatin. The mixture was heated on a hot plate at 200°C with constant stirring until the mixture became viscous. The mixture is then transferred to a stainless-steel mould and left to dry at room temperature for 24 hours, until the film is hardened and forms a plastic-like sheet.

2.3 Moisture Content

The study of moisture content was conducted in a laboratory setting using a methodology described by Shafqat et al. [8], with certain modifications applied. The prepared BLB samples were carefully cut into pieces measuring 1.5 cm × 1.5 cm each. The samples have been weighed accurately using an analytical balance. Then, the samples were transferred to the oven for drying at a set temperature of 85°C for 24 hours to remove moisture. After drying, the samples were reweighed to determine the final weight. The moisture content was calculated using Eq. (1), where W_1 is the initial weight of the sample and W_2 is the final weight of the sample [8].

$$\text{Moisture content }(\%) = \frac{W_1 - W_2}{W} \times 100 \tag{1}$$

2.4 Solubility in Water

In this test, the prepared BLB samples were carefully cut into pieces of 1.5 cm × 1.5 cm each. The BLB samples were weighed using an analytical balance. Then, the samples were transferred into an oven at 85°C for 24 hours to remove the moisture. The samples were then immersed in 50 mL of distilled water in a beaker at room temperature for 24 hours. After 24 hours, the BLB samples were collected by filtering the water and then dried in an oven at 85°C for 24 hours. The BLB samples were reweighed to determine the final weight. The solubility in water was calculated using Eq. (2), where W_1 is the initial dry weight of the sample and W_2 is the final dry weight of the sample [8].

$$\text{Solubility in water }(\%)=\frac{W_1-W_2}{W}\times 100 \tag{2}$$

2.5 Solubility in Alcohol

In this test, the prepared BLB samples were carefully cut into pieces with BLB sample sizes of 1.5 cm x 1.5 cm each. The BLB samples were weighed using an analytical balance before being dried in an oven at 85°C for 24 hours to remove moisture. Then, the samples were immersed in a beaker filled with 50 mL of ethanol and left at room temperature for 24 hours. After 24 hours, the BLB samples were collected by filtering the water, and then they were dried again in the oven at 85°C for 24 hours. The samples were reweighed to determine the final weight. The solubility in alcohol was calculated using Eq. (3), where W_1 is the initial dry weight of the sample and W_2 is the final dry weight of the sample [8].

$$\text{Solubility in alcohol }(\%)=\frac{W_1-W_2}{W}\times 100 \tag{3}$$

2.6 Biodegradability (Soil Buried) Test

The prepared BLB samples were carefully cut into pieces measuring 2 cm × 2 cm each. Three samples of each with the same BLB composition were then individually buried in cylindrical plastic containers with a height of 10 cm and a diameter of 4 cm, filled with garden soil to a depth of 5 cm [9]. The soil-buried samples were left in an open area in the laboratory at a temperature range of 24°C to 26°C for 14 days. The BLB samples were observed for size, shape and colour changes throughout the biodegradability test.

2.7 Young's Modulus, Tensile Strength, And Elongation at Break Tests

Young's modulus, tensile strength and elongation at break testings were conducted using a Universal Testing Machine (UCT-ST) at Universiti Tun Hussein Onn Malaysia, Johor, Malaysia, to investigate the mechanical properties of the produced BLS samples. The tests were carried out in triplicate, following the standard method for tensile properties of thin plastic sheeting (ASTM D882-18) [10]. In this test, the BLB samples were cut into 100 mm × 15 mm sizes with both ends clamped by the machine gripper. The gauge separation length was set to 60 mm, and the test was conducted at a crosshead speed of 30 mm/min [11].

2.8 Shape Memory-Recovery Test

The shape memory recovery of BLB samples was evaluated using the procedure employed by Tsujimoto et al. [12]. The method started by testing the shape memory of BLB samples. This involved coiling, flattening, and measuring its length to determine strain fixity (SF) and shape recovery (SR). For precise results, all BLB film samples were prepared as uniform rectangles (5 cm × 1 cm) as temporary shapes. Then, each sample was loaded with the preset strain, cooled and off-loaded at 20°C after being dipped in distilled water. This process left an unloading strain after instantaneously recovering. Finally, the samples were immersed in distilled water at 80°C to allow them to regain their original strain, resulting in a recovery strain. Due to the difference in terms of the nature of the materials applied in this study (BLB) and the polymeric materials applied (epoxidised soybean oil and polycaprolactone) for the adopted test method, the SF and SR were not able to be calculated due to the condition that the BLB samples were dissolved into the distilled water during the heating process, making it hard for the quantification of SF and SR. Thus, the qualitative result was reported instead of the quantitative result, as discussed in Section 3.6.

2.9 Surface Morphology and Chemical Element Composition Analyses

Surface morphology and elemental composition of BLB were analysed using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX) at the Environmental Analysis Laboratory in

UTHM, Johor, Malaysia, by following the standard practice for characterisation of particles (ASTM F1877-16) [13]. The model of the instrument used was a ZEISS EVO 10, manufactured in Germany. Before the SEM analysis, the samples were fixed to the sample holder using carbon tape without coating. The samples were tested at various magnifications, ranging from ×250 to ×1.0K.

3. Results and Discussions

3.1 Moisture Content

Conducting the moisture content test on BL is essential to guarantee water absorption quality, stability and suitability. Moisture acts as a plasticiser in many bioplastics, especially those based on starch. Controlling moisture content is a delicate balance in bioplastic production. While some moisture is essential for processing, the final product typically requires a low moisture content to ensure optimal mechanical stability and prevent premature degradation and excessive water absorption, which could limit its applications. The moisture content in bioplastics varies depending on their composition and the additives used. For instance, bioplastics made from cocoa pod husks showed moisture contents ranging from about 5.89% to 20.89%, with lower moisture content improving stability and reducing water absorption [14]. Water absorption increases with higher moisture content, which can weaken the material by disrupting hydrogen bonds, leading to reduced tensile strength and elasticity [15]. This process aids in managing the mechanical properties of the materials and minimises the risk of degradation. Fig. 1 shows the appearance of BLB with 5 g, 10 g, and 15 g BL samples after oven-drying at 85 °C for 24 hours.

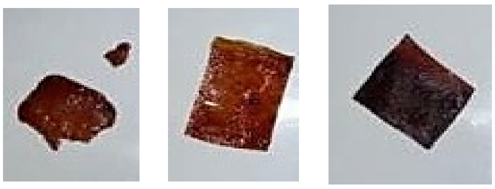

(a) (b) (c)

Fig. 1 *BLB with (a) 5 g BL; (b) 10 g BL; and (c) 15 g BL after oven-drying at 85 ℃ for 24 hours*

The findings (see Fig. 2) reveal that the highest moisture content was recorded for BLB with 5 g BL (28.9%), followed by BLB with 10 g BL (28.2%) and 15 g BL (25.3%). Shafqat et al. [8] also found that the moisture content of banana peel starch bioplastic was in the range of 5.5 to 37.63% and 4.65 to 35.52% for composite bioplastic made up of banana peel starch, cornstarch and rice starch. A slight reduction in moisture content was observed when the amount of BL increased from 5 g to 15 g. This could be attributed to the inherent moisture content within the starch component of the BL. The presence of water induces degradation in certain polymers within the bioplastic matrix. This degradation results in alterations to the overall characteristics of bioplastics, such as mechanical, physical, and thermal properties. Besides, a combination of glycerin and gelatin can also contribute to the moisture content percentage in BLB itself, while the hydroxyl in glycerin functions as a bond breaker throughout the breakdown process. Conducting the moisture content test on BL is essential to ensure the quality, stability, and suitability of water absorption for applications such as packaging and coating products.

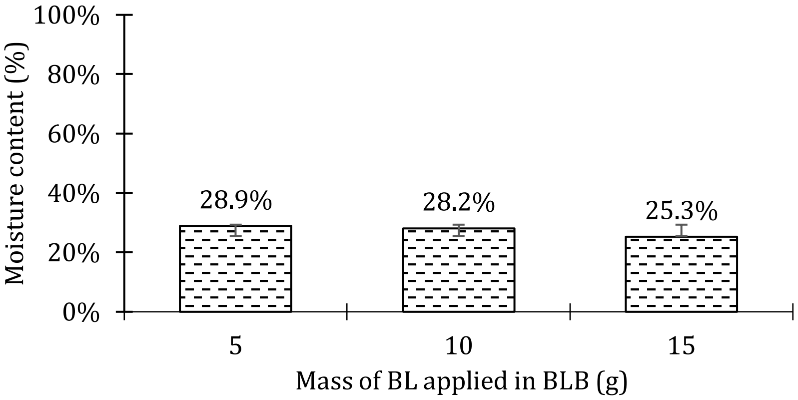


Fig. 2 *Percentages of moisture content for BLB with 5 g, 10 g and 15 g of BL*

3.2 Solubility in Water

The solubility in water test aims to confirm the water solubility of BLB and enhance the biodegradability of the materials. BL is rich in starch, which is a hydrophilic substance that readily dissolves in water, particularly at higher temperatures. Fig. 3 shows the appearance of BLB samples after being soaked in distilled water at room temperature for 24 hours. The BLB with 5 g BL shrank more than the other two samples of BLB with 10 g and 1g BL. The reason is due to the findings that demonstrated that the BLB films in solubility in water test values decreased as the material amount increased from 5 g, 10 g and 15 g, as shown in Fig. 4. The data indicates that the BLB with 5 g BL has the highest solubility in water (48.5%), followed by BLB with 15 g BL (46.3%) and the BLB with 10 g BL (42.6%). In this study, it is evident that solubility does not decrease uniformly with increasing amounts of BL.

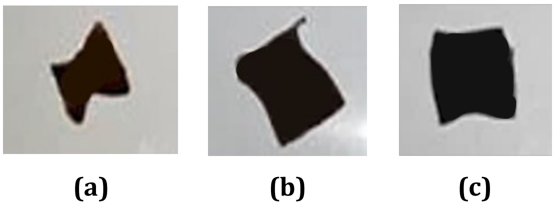


Fig. 3 *BLB with (a) 5 g BL; (b) 10 g BL; and (c) 15 g BL samples after being soaked in distilled water at room temperature for 24 hours*

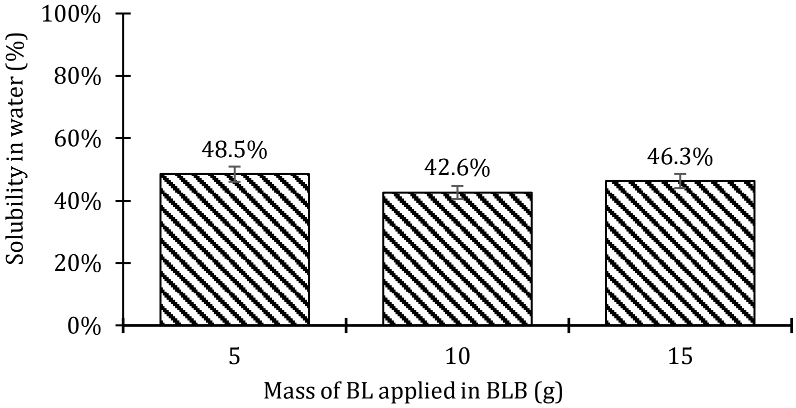


Fig. 4 *Percentages of solubility in water for BLB with 5 g, 10 g and 15 g of BL*

According to Shafqat et al. [8], the solubility of starch-based bioplastic (banana peel starch bioplastic (BPSB) and composite bioplastic from banana peel starch, cornstarch and rice starch (COM)) in water was influenced by the addition of plasticisers with their solubility in water were recorded in the ranges of 25.35-85.57% (for BPSB) and 10.53-65.57% (for COM). For their study, they used glycerol and sorbitol as plasticisers and found that the solubility in water of the produced bioplastics increased when these plasticisers were added. However, in our study, only glycerin with a fixed amount of 10 mL was used in the BLB matrix, so that the solubility of BLB in water did not significantly change upon increasing the BL amount in the BLB samples from 5 g to 15 g.

3.3 Solubility in Alcohol

The ability of BLB to dissolve in alcohol is known as the solubility of alcohol in BLB. The characterisation has significant implications for the use, production and recycling of BLB. Observing alcohol solubility can indicate whether certain plasticisers or other additives used in the bioplastic formulation are leaching out or if the polymer chains are interacting in a way that allows alcohol penetration and partial dissolution. This is crucial for understanding the stability of the bioplastic over time and its potential to leach undesirable compounds into packaged food or drinks [15]. In this test, ethanol is commonly employed for bioplastic tests, and it is frequently utilised to investigate and advance bioplastics due to its distinctive properties that can impact bioplastics. Fig. 5 shows that the BLB solubility in alcohol was highest (41.4%), with the least BL applied in the BLB (5 g BL). The decreases in BLB solubility in alcohol were observed for BLB with 10 g BL (36.6%) and BLB with 15 g BL (10.6%), indicating increased resistance to alcohol as the BL amount increases. This signifies that the increase in BL quantities makes BLB more resistant to alcohol. Even though BL has more soluble components at a lower applied amount, the higher amount of BL applied in BLB samples may also contribute to a denser and more cross-linked matrix, making them less permeable to alcohol and reducing their capacity to dissolve. The observed reduction in solubility in alcohol with increasing BL amount could be linked to the BLB structure properties and composition. This finding is supported by a previous study on the bioplastic films made from bread particles, which exhibit lower hygroscopicity and reduced solubility compared to flour films, attributed to these molecular rearrangements and the formation of insoluble cell wall residues and gluten networks [16].

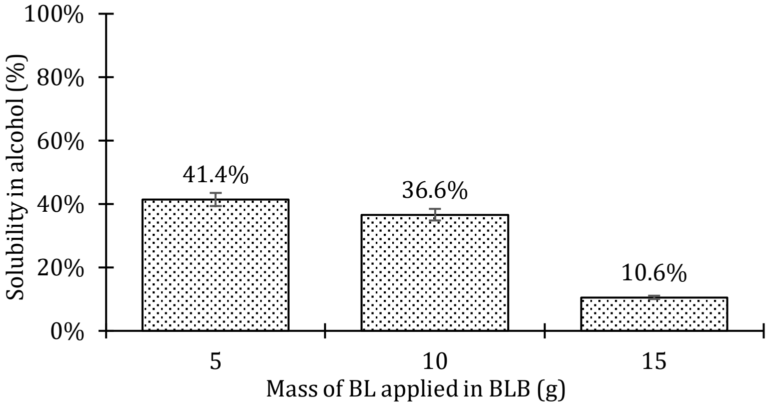
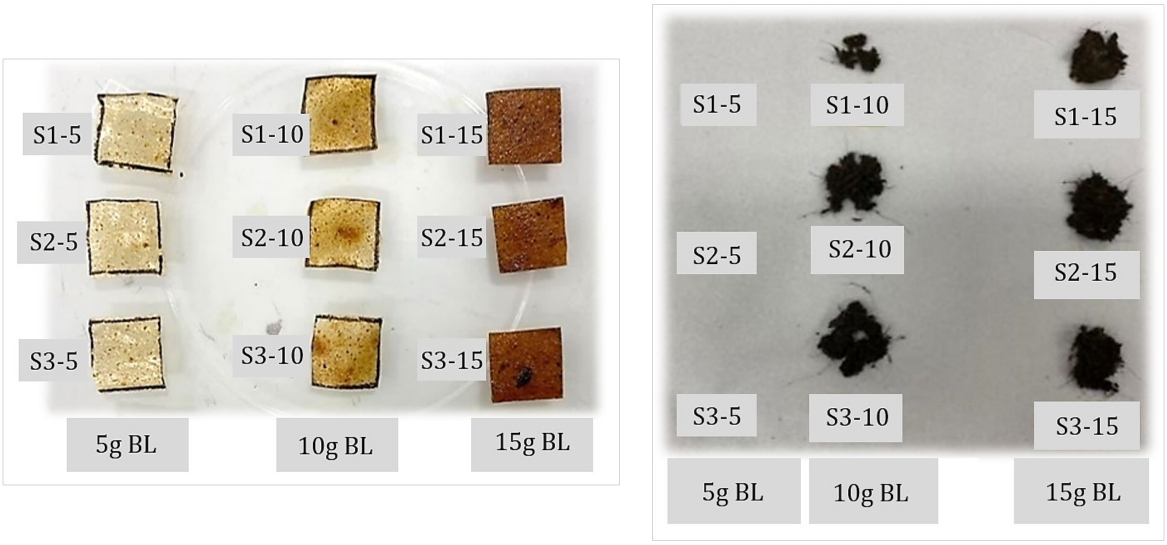


Fig. 5 *Percentages of solubility in alcohol for BLB with 5 g, 10 g and 15 g of BL*

Besides, the structural integrity in BLB with a higher BL amount applied can contribute to a higher concentration of cross-linking agents or stabilisers, which improves their resistance to breakdown in alcohol. Understanding the solubility behaviour in different media helps the strategic design of BLB to meet specific functional needs in various industrial and environmental settings.

3.4 Biodegradability

Before conducting the soil burial test, the colour and surface roughness of the BLB were recorded. The produced BLB had a smooth surface, but it is still incomparable to the surface appearance of petroleum-based plastic (PBP), which is very smooth. The colour of BLB became darker when the mass of BL increased from 5 g to 15 g, as seen in Fig. 6(a). Initially, the present study aimed to observe the changes in the colour, shape, and size of BLB during the biodegradability test and compare these physical characteristics with those of PBP over a 14-day period. However, after seven days of soil burial, the BLB samples became soft, brittle and shrank in size, as shown in Fig. 6(b). A similar observation was reported by Noorjahan et al. [17] for banana peel.



(a) **(b)**

Fig. 6 *Physical appearance of BLB samples on (a) Day 1; and (b) Day 7*

As can be seen in Fig. 6(b), the BLB films were broken into smaller pieces because the glycerin was contained in the BLB. It plays an important role in biodegradability, as it is a natural, non-toxic additive, which makes the produced BLB more environmentally friendly and biodegradable compared to its original appearance (Fig. 6(a)). The hydroxyl group (-OH) in glycerin is a bond breaker throughout the breakdown process [18]. This is because a hydrophilic plasticiser loosens the hydrogen bonding in the polymer chain [19]. Even though common plasticisers such as phthalates are used in making typical PBP, they usually perform better, offering great flexibility and resistance to ultraviolet rays, oils, and other chemicals, while also raising health concerns. These concerns make them undesirable for producing eco-friendly products.

At the same time, it was also discovered that there are white particles spotted on BLB films, which are believed to be microorganisms growing on the surface of all samples, which are clearly illustrated in Fig. 7. Additionally, soil microbes like bacteria and fungi in the soil consume the decaying BLB samples and boost the degradation rate.

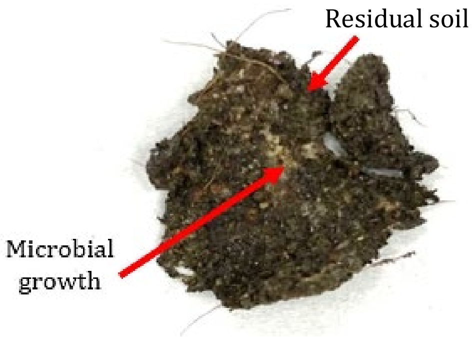


Fig. 7 *Microbial growth on the BLB samples*

Furthermore, the starch content in the bread is also vital in promoting microbial growth because it serves as a readily available food source that quickly decomposes by microorganisms. The physical characteristics of the PBP remain the same after 14 days. These findings indicate that BLB samples were effectively degraded and decomposed in the soil environment within only seven days compared to PBP.

3.5 Young's Modulus, Tensile Strength and Elongation at Break

Fig. 8 depicts that the higher the amount of BL applied, the higher the tensile strength can be achieved. This finding is consistent with a previous study by Nasir et al. [20], which found that the highest starch content applied resulted in the highest tensile strength. The BLB comprising 15 g BL achieved the ultimate tensile strength at 1.46±0.10 MPa compared to the tensile strengths achieved by 5 g and 10 g of BL. Meanwhile, BLB with 15 g BL achieved the highest Young's modulus of 2.884±0.127 MPa compared to the lower BL mass applied. This shows that the higher amount of BL used resulted in a higher Young's modulus. On the other hand, BLB with 10 g and 15 g of BL exhibited notable mechanical properties, as the results obtained were closer to the standard value of a moderate-grade bioplastic [20].

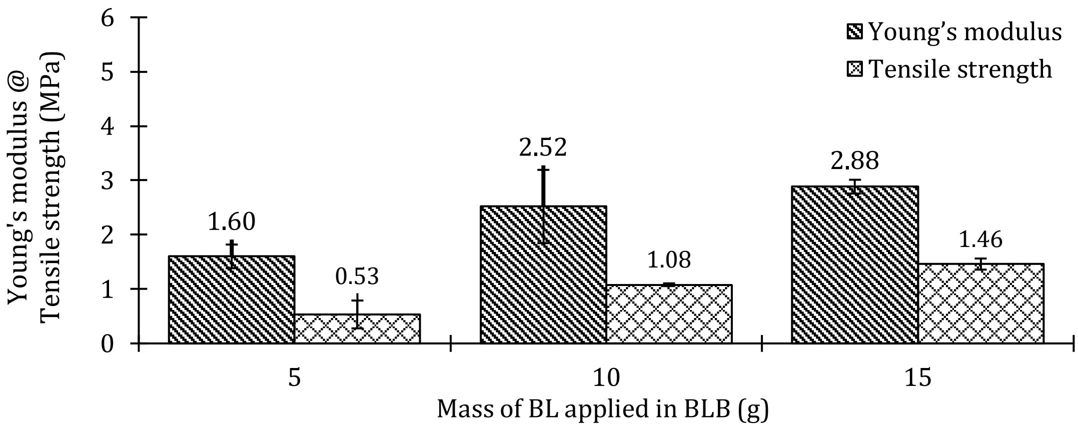


Fig. 8 *Young's modulus and tensile strength of BLB with 5 g, 10 g and 15 g of BL*

As reflected in Fig. 8, Young's modulus increased when the amount of BL increased, which aligns with the previous study that has also observed a correlation between Young's modulus and tensile strength [20]. Table 1 shows the detailed result of the mechanical properties of BLB. Furthermore, the elongation at the break of BLB is shown in Fig. 9. It was observed that increasing the amount of BL increased the elongation of the break. The highest elongation (53.75 ± 6.646 %) was observed for 15 g of BL applied. This is because the flexibility of the polymer chain caused an increase in the material's elasticity [21].

Table 1 *Mechanical properties of BLB*

Mass of BL applied in BLB (g)	Young's modulus (MPa) (*N*=3)	Tensile strength (MPa) (*N*=3)	Elongation at break (%) (*N*=3)
5	1.601±0.218	0.533±0.256	36.20±13.029
10	2.519±0.674	1.080±0.0251	51.35±7.197
15	2.884±0.127	1.460±0.1020	53.75±6.646

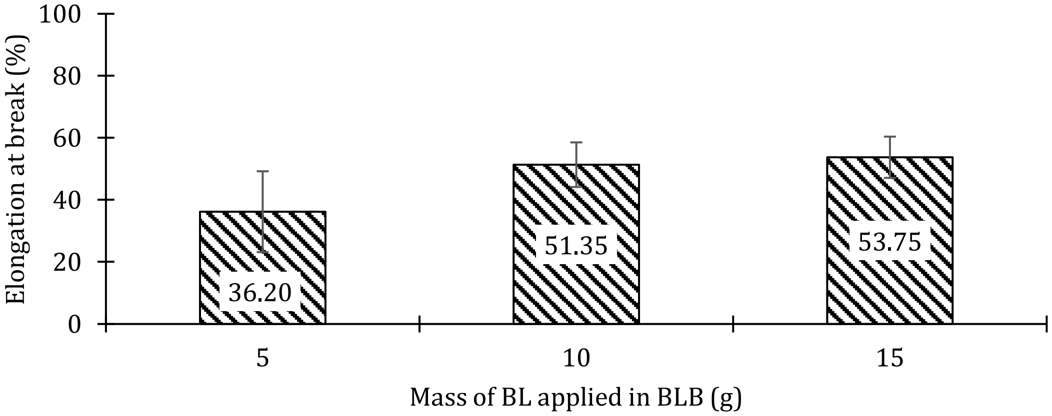


Fig. 9 *Elongation at break of BLB with 5 g, 10 g and 15 g of BL*

3.6 Shape Memory Recovery

For this test, the BLB samples were dissolved in distilled water after being immersed at 80°C (Fig. 10). The results indicate that the produced BLB cannot be examined according to the recommended procedure for its shape memory characteristic. This is due to the melting point of the BLB being significantly lower than the employed temperature.

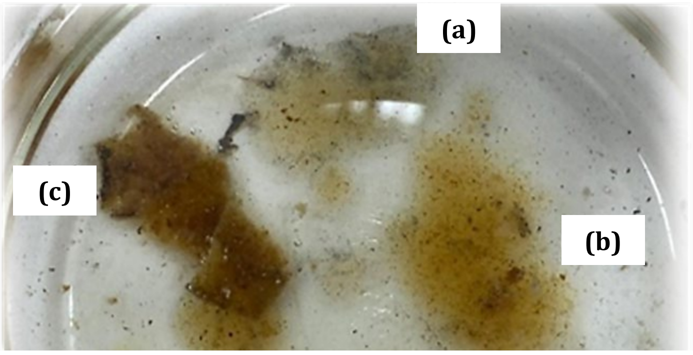
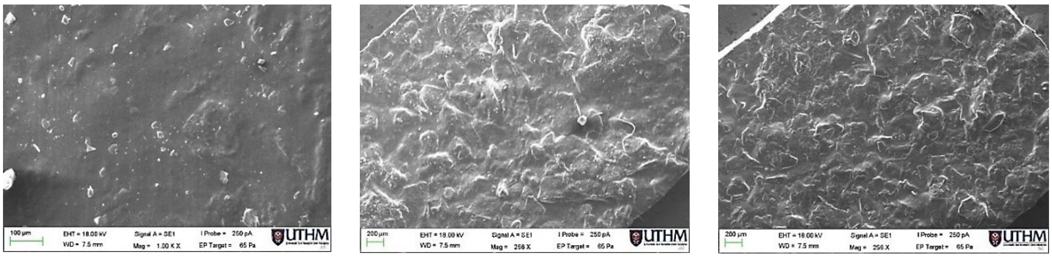


Fig. 10 *Physical appearance of BLB samples with (a) 5 g; (b) 10 g; and (c) 15 g of BL after soaking in distilled water at 80°C for the shape memory recovery test*

In this case, gelatin provides a medium level of strength and stiffness to the BLB. The maximum melting point for this medium gelatin concentration is less than 40°C, as declared by Yang et al. [22]. Thus, less energy is needed to melt the produced BLB in the water because weak intermolecular forces are present between the molecules. In short, the strength of the intermolecular forces determines the energy required to change the solid into a liquid state and affects its melting point [23]. Synthetic plastics do not possess this property; they only exist when specifically designed [24]. For future tests, it is suggested that using a lower temperature, around 25-35°C, might be more appropriate for the initial trials. Alternatively, the composition of BLB could be modified to increase its higher melting point. This would involve increasing the starch content, reinforcing it with fillers, or introducing non-toxic cross-linking agents such as citric acid to create stronger chemical bonds.

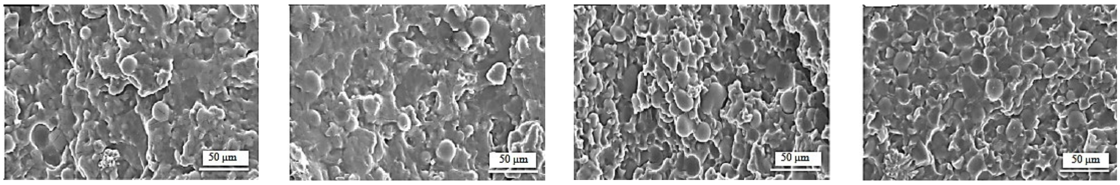
3.7 Surface Morphology and Elemental Composition Analyses

The results of the SEM analysis are displayed in Fig. 11(a) to Fig. 11(c), which show the surface morphology of the produced BLB. The BLB with 5 g BL appears to have a smoother surface than the BLB with 15 g of BL, and there appears to be some porosity in the BLB, especially for the BLB with 15 g of BL. The images of the BLB produced by the SEM analysis show a wavy and non-homogeneous structure, which may result from the BL powder being mixed inconsistently with the solution [25]. This is because the powder may not dissolve in the solution during the formation process, potentially forming residual particles on the surface of the films [26]. It can be concluded that the higher the BL amount applied in BLB, the wavier the surface morphology of the BLB becomes. This statement was supported by Dawam Abdu et al. [27], where similar results were obtained for sweet potato starch, as illustrated in Fig. 12(a) to Fig. 12(d).



(a) (b) (c)

Fig. 11 *SEM images of BLB with (a) 5 g; (b) 10 g; (c) 15 g of BL*



(a) (b) (c) (d)

Fig. 12 *SEM images of sweet potato starch-derived bioplastics with a ratio of starch: glycerol - (a) 2.5:1; (b) 2.75:1; (c) 3:1; and (d) 3.5:1* [27]

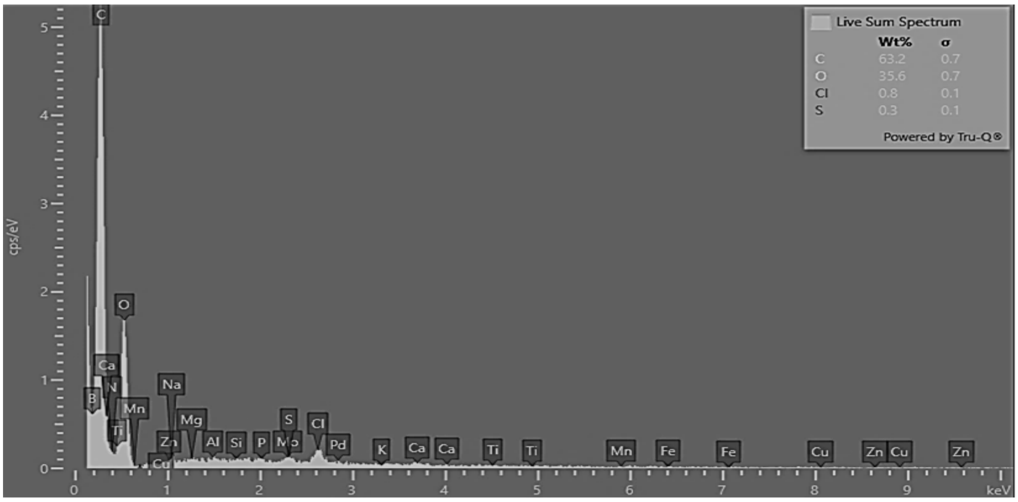


Fig. 13 *Elemental composition of the BLB sample*

On the other hand, chemical elements of the periodic table, such as carbon, oxygen, chlorine, calcium, potassium, sodium, and sulphur, were found in the BLB studied during the EDX analysis. Fig. 13 depicts that BLB constitutes high percentages of carbon (63%), followed by oxygen (36%), chlorine, calcium, potassium, sodium, and sulphur. The high carbon content primarily contributes to the high biodegradability rate of the produced BLB, which aligns with a finding from Onovo et al. [28]. Furthermore, BL is rich in carbohydrates, consisting of carbon, oxygen, and hydrogen elements that contribute to the mineral content of bioplastics [29].

4. Conclusion

In summary, bread leftovers (BL) have promising potential as raw materials for bioplastic production, contributing to a more environmentally friendly future. The moisture content of bread leftovers-derived bioplastic (BLB) varied insignificantly (25.3-28.9%), with the highest moisture content (28.9%) recorded for BLB with 5 g BL. This suggests that increasing the amount of BL in the BLB formulation may decrease the final moisture content of the material.

Furthermore, BLB samples retain considerable percentages of solubility in water (42.6-48.5%), indicating their water resistance and potential for applications requiring controlled breakdown in water. BLB solubility in alcohol decreased significantly from 41.4 to 10.6% when the amount of BL increased from 5 g to 15 g. This implies that raising the amount of BL in the BLB formulation can enhance its alcohol resistance.

On the other hand, BLB with 15 g BL had the highest Young's modulus (2.884 ± 0.127 MPa), tensile strength (1.46 ± 0.10 MPa), and elongation at break (53.75 ± 6.646%). They can potentially replace low-density polyethene (LDPE), where further enhancements can be made by adding fillers or plasticisers to enhance their mechanical characteristics. However, the produced bioplastic could not be evaluated for shape memory recovery in this study due to its substantially lower melting point than the recommended temperature (80°C) while applying the recommended thermal cycling technique.

In the surface morphology analysis, the BLB with 5 g BL appears to have a smoother surface than those with 15 g BL, which is more porous. BLB has a high carbon content (63%), followed by oxygen (36%), with additional elements including chlorine, calcium, potassium, sodium, and sulphur, resulting in excellent biodegradability of the produced BLB. BLB in the soil-buried test became brittle and softer, decreasing its size within seven days of observation, unlike the standard petroleum-based plastic (PBP), which did not degrade. Thus, it supports the notion that BLB demonstrates a better biodegradability rate than typical PBP, as it indirectly reduces waste in landfills, extends their lifespan, and promotes economic and environmental sustainability.

The study concludes that BLB is a promising alternative to PBP, and future research could explore enhancing the mechanical properties of bioplastics, especially their flexibility and strength, as well as potential applications.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

*The authors confirm their contribution to the paper as follows: **Study conception and design**: V. W. T. Yong, N. Z. Z. M. Zailani, N. A. A. A. Aziz; **Data collection**: V. W. T. Yong, N. Z. Z. M. Zailani; Analysis and interpretation of results: V. W. T. Yong, N. Z. Z. M. Zailani, N. A. A. A. Aziz; **Draft manuscript preparation**: V. W. T. Yong, N. Z. Z. M. Zailani, N. A. A. A. Aziz. All authors reviewed the results and approved the final version of the manuscript.*

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