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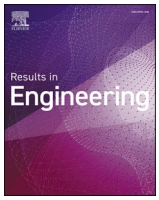

Production of bioplastic films from wild cocoyam (*Caladium bicolor*) starch

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ABSTRACT

This study tackles the pressing environmental challenges resulting from the rapid and ongoing use of conventional plastics by investigating biodegradable alternatives derived from wild cocoyam starch. The bioplastics developed from various formulations, incorporating gelatin, glycerine, vegetable oil, and vinegar, were systematically evaluated for their mechanical, chemical, microstructural and biodegradability properties. The addition of glycerine and gelatin enhanced the moisture content and flexibility of the films while vegetable oil improved water resistance, reducing water absorption. Th sample that contains 3 g of gelatin and 3 ml of glycerine exhibited the best overall performance with a tensile strength of 6.5 MPa and an elongation at break of 77 %. This sample also achieved an impressive biodegradation rate of 70 % within 7 days. Scanning Electron Microscopy revealed a uniform and smooth morphology, while Fourier Transform Infrared Spectroscopy confirmed the presence of key functional groups responsible for the material's performance. These results establish wild cocoyam starch as a promising resource for producing biodegradable bioplastics with considerable potential in various industries, particularly in packaging and agricultural applications. The excellent mechanical properties and biodegradability of the materials along with its natural abundance, offer an eco-friendly solution to the plastic waste problem. The study also opens new avenues for optimizing bioplastic formulations to enhance specific properties like thermal stability and moisture resistance, further broadening their practical applications. This research contributes to the sustainable materials landscape and represents a step toward reducing reliance on fossil-based plastics, advancing the global effort to mitigate environmental pollution.

1. Introduction

With the global increase in population, plastics have gained a stable market with its vast range of domestic, industrial, and commercial applications. Statistics show that the global population is expected to reach 9.7 billion by 2050 [1]. Alongside factors such as technological advancements and rising disposable incomes, the increase in population would increase the demand for polymer-based products. The global plastic production is expected to reach a projected value of 1.1 billion metric tons by 2050 [2] and a projection of 155–265 Mty^{-1} of mismanaged global plastic waste by 2060 [3]. The choice in the use of plastics is attributed to its relatively low cost, low weight, resistance to microbial activities, thermally and chemically insulating properties [4]. However, the world is facing a crisis due to the negative impact of plastics on people, aquatic animals and the environment at various stages involved in its lifecycle. The bulk of these plastics are currently produced as by-products of fossil fuels, particularly refined oil and gas. Gadhav et al. [5] reported that the oil used for plastic production consumes six to eight percent of the total world's oil production leading to the depletion or reduction of fossil fuels. In addition to the depletion of fossil fuels, the processes involved in the production and incineration of these plastic materials, emit dioxin, carbon dioxide and methane into

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the atmosphere. Thus, a subsequent increase in greenhouse gas emissions affects the climate [6]. Over time, due to the non-biodegradable nature of plastics, improper disposal on the land and in the ocean has fostered an increase in the rate of waste pollution and toxicity to human life and aquatic animals. A 2018 estimate indicated that Nigeria generates 42 million tonnes of solid waste annually [7]. Reports show that about 20 % of solid waste generated in the country are plastics [8]. Despite recycling operations in the country, about 70 % of these solid wastes are either dumped in unauthorised places or burned, contributing to environmental pollution and the release of harmful gases into the atmosphere [8].

As such, alternative means favorable to nature have become attractive to researchers. One of the recent and interesting alternatives is the production of bioplastics. These bioplastics are derived from renewable biomass such as plants and plant products [9] which can organically break down without harming the environment. They are eco-friendly, renewable, and non-toxic due to their botanical sources such as starch, cellulose, proteins, lipids and so on [10]. Also, they are advantageous because they reduce non-biodegradable waste, contain no health damaging additives, and save energy during production [11]. It is believed that bioplastics have the potential to contribute significantly in reducing plastic pollution in the environment [12]. Research shows that bioplastics can reduce carbon dioxide emissions by 30–70 % [13]. In 2018, the global bioplastic plastics was valued at 3.02 billion USD and is expected to rise to 12.4 billion USD by 2027 [14]. One of the key drivers in terms of application for biodegradable plastics is packaging. The adoption of these biodegradable plastics for packaging is supported by consumer preference for eco-friendly options [14]. Thus, biodegradable plastics find applications in trays, food containers, bags, bottle, and so on.

Statistics show that approximately fifty percent of bioplastics are produced from starch [15]. However, starch-based bioplastics have drawbacks such as brittleness, increased tendency for water absorption and so on. which tends to limit its applications. To improve its properties, additives such as acids (citric acid, vinegar), plasticizers (castor oil, glycerine, sorbitol), and thickening agents (chitosan, gelatine) can be used.

Hasan et al. [16] produced various samples of bioplastics from chitosan and yellow pumpkin starch using castor oil as a plasticizer. The highest values of tensile strength, elongation at break and Young's modulus for the sample were 6.787 MPa, 13.451 % and 6.093 MPa, respectively. This was attributed to the formation of hydrogen bonds with stronger starch molecules. The rate of biodegradability of the produced bioplastics in a culture medium of *Pseudomonas aeruginosa* was also determined. It was recorded that at the end of 30 days, the bioplastic was completely degraded. The bioplastic sample with the highest starch content degraded faster and this was attributed to the presence of glycosidic bonds in the amylopectin and amylose content of the starch.

[17] made investigations on the optimisation of the production of biodegradable plastic from starch and cassava peel flour using response surface methodology. One of the objectives was to determine the effect of varying drying temperatures (40 ° C, 50 ° C and 60 ° C) and drying times (4, 5 and 6 h) on the production of bioplastics. These parameters are important in the production of bioplastics. Higher temperatures or drying times foster the production of a tighter and more homogenous bioplastic. On the other hand, lower temperature or drying times lead to the production of bioplastics with unfinished structural formation. Results showed that the optimum values were attained with increasing drying temperatures but decreasing drying times. Decreasing values in tensile strengths and elongation at break with increasing drying temperatures and times were attributed to the evaporation of chitosan and glycerol respectively [18]. investigated the effect of increasing chitosan on the characteristics of bioplastic from starch talas (Colocasia esculenta) using plasticizer sorbitol. Results from the mechanical properties showed increasing tensile strength with chitosan due to the formation of hydrogen bonds with starch. On the other hand, increasing concentrations of sorbitol as a plasticizer reduced the tensile strength due to the interference in the hydrogen bonds between the polymer chains but increased the flexibility. Tests on the morphology showed the presence of rigid and fragile regions meaning incomplete dissolution of chitosan in the acid. In addition to these, it was observed that increasing concentrations increased the gelatinization temperature due to the addition of more hydrogen bonds, thereby reducing the space between the starch molecules [19]. evaluated the synthesis and characterization of starch-based bioplastics using varying plant-based ingredients (banana peels, rice, and corn), plasticizers and natural fillers. The moisture content was observed to increase upon addition of plasticizers while the control with no additive had the highest rate of water absorption due to the presence of the hydroxyl groups found in starch. To reduce the solubility of the bioplastics, fillers such as potato peel powder and wood dust were added. Biodegradation was observed to improve with increase in concentration of plasticizers due to the increased moisture content which facilitates soil action.

Marichelvam et al. [20] conducted an experimental investigation on corn and rich starch-based bioplastics as alternative packaging materials. The motivation for the research work was due to the absence of literature showing the use of hybrid starch (corn and rice) bioplastics for packaging materials. The bioplastics produced with the hybrid starch were found to compete favourably with commercial plastics. The samples had high tensile strengths, low water absorption and low solubility rates. The bioplastics decomposed within 15 days.

Obunwo et al. [21] evaluated the potential of producing bioplastics from rubber seed oil and cocoyam starch using additives such as glycerol and vinegar. The mechanical properties of the samples were enhanced with the use of glycerol. It was also reported that the produced bioplastics were biodegradable based on degradability time within the soil.

Marichelvam et al. [15] conducted a study on the extraction and development of eco-friendly and sustainable starch-based bioplastics from the *Prosopis juliflora* plant using varying concentrations of citric acid, gelatine and glycerol. It was reported that an increase in citric acid and glycerol further reduced the tensile strength, and increased the thickness, water solubility and rate of biodegradability of the sample. This was attributed to an increase in moisture content as water facilitates biodegradation. In addition to these, morphological investigations revealed a more homogeneous surface as the additives were increased. The plant's starch was seen to be a good alternative and suitable for use in the packaging industries. In Nigeria, the biodegradable plastic market is currently at infantry, despite the abundance of raw materials to promote the adoption of these biodegradable plastics. Hence, the rationale behind this study.

The choice of starch source for this research is wild cocoyam. Wild cocoyam (*Caladium bicolor*) is a non-edible plant commonly located along riverbanks, lakes, brooks and so on. Locally, in the Eastern part of Nigeria, this is known as "*Ede Umuagbara*" [22]. This untapped resource has found useful applications as a feedstock for broiler chicks and in the bioethanol industry.

Alobi et al. [11] investigated the properties of starch from non-edible root and tubers (wild cocoyam, false yam, wild sweet yam, and oyster mushroom) as raw materials to synthesize biodegradable plastics. These materials were found useful in producing bioplastics. Hence in this study, the potential and suitability of wild cocoyam as a raw material to produce bioplastics were studied. To improve the properties, additives such as gelatine, glycerine and vinegar were used. These additives were mixed in varying concentrations with the starch to produce various samples of bioplastic films. Moisture content, water absorption, water solubility, and soil biodegradability tests were carried out on the bioplastics. The morphology of the bioplastics was studied to understand the behaviour of the produced bioplastic films. Bioplastic is known to have poor resistance to moisture which tends to reduce its usage on a larger scale [19]. As such, additives with increased hydrophobic properties are useful in reducing its resistance to moisture. To achieve this, a comparative analysis on the impact of vegetable oil in biodegradable

plastics as an alternative to gelatine was study.

2. Experimental methods

2.1. Materials and methods

The fresh wild cocoyam (*Caladium bicolor)* corms were harvested from Ankpa, Kogi State, Nigeria (7°22′14″N 7°37′31″E). The gelatine powder was procured from a commercial store in Abuja, Nigeria. The glycerine, vinegar and distilled water were supplied by the Chemistry laboratory at Nile University of Nigeria, Abuja Nigeria. All extractions were carried out in the laboratory at Nile University of Nigeria, Abuja.

2.1.1. Extraction of wild cocoyam starch (WCS)

The method described by Arawande [23] was used for WCS extraction. About 585 g of the corms were peeled, washed, diced into small pieces, and blended using the LS-69 Fadar commercial blender. The cocoyam slurry was washed with distilled water and filtered using the muslin cloth. The filtrate was allowed to settle for 7 h. The starch was collected by decantation. The above process was repeated 3 to 4 times to produce purer starch. The wet starch was air-dried for two days and afterwards, ground to powder form. The extraction process is illustrated in Fig. 1. The starch yield from the extraction process was calculated using Equation (1).

$$\text{Starch yield } (\%) = \frac{\text{Weight of extracted starch (g)}}{\text{Weight of cocoyam}} \times 100 \quad (1)$$

2.2. Characterization of WCS

2.2.1. Determination of moisture content in samples of WCS

The moisture content was determined using the methodology proposed by Alobi et al. [11]. A weighed quantity of WCS was dried in an oven at 105 ° C for 24 h. The dried sample was weighed, and the percentage moisture content was calculated using Equation (2).

$$\text{Moisture content } (\%) = \frac{\text{Initial} - \text{Final weight}}{\text{Initial weight}} \times 100 \quad (2)$$

2.2.2. Determination of amylose content in samples of WCS

The amylose content of WCS was determined using the methodology proposed by Avaro et al. [24]. Dried WCS (1 g), ethanol (1 ml of 95 %) NaOH (9 ml of 1 M) were added to a conical flask. The mixture was placed in a boiling BHS-4 JOANLAB digital water bath for 10 min and allowed to cool for 10 min. After boiling, the volume was made up to 100 ml using distilled water Aliquot (5 ml) of the solution was transferred to a 100 ml volumetric flask, the pH was maintained at 6 using 1 ml of 1 N acetic acid. Iodine solution (2 ml of 0.2 %) was mixed with water and the absorbance was recorded at 620 nm using UV-6100A NJouka Spectrophotometer.

2.2.3. Determination of gelatinization temperature, pH, and ash content in samples of WCS

1 g of WCS was placed in a beaker filled with 10 ml of distilled water and subjected to heat treatments using a hot plate. The gelatinization temperature was recorded with a thermometer. The pH of the starch was recorded using a calibrated FP20 Mettler Toledo pH meter. The ash content was determined using the methodology proposed by Alobi et al. [11]. Dried WCS was weighed and placed in a muffle furnace at 500 ° C for 8 h. After 8 h, the ash was placed in a desiccator and allowed to cool. The cooled ash was weighed and calculated using Equation (3).

$$\text{Ash content } (\%) = \frac{\text{Weight of ash}}{\text{Weight of dry starch}} \times 100 \quad (3)$$

2.3. Preparation of WCS bioplastics films

The materials used in preparing the bioplastic films are gelatine, glycerine, vegetable oil and vinegar. These are additives which improve the machinability of the bioplastics. The composition of the materials is varied and seven different samples are produced using slightly modified methods of Marichelvam et al. [15] and Ginting et al. [18]. The weight of WCS (10 g) and the volume of water (100 ml) were kept as constant for all the samples. The concentration of the additives was increased. Wild cocoyam starch, gelatine, glycerine, vinegar, and distilled water were mixed thoroughly by stirring at a constant speed of 180 rpm for 10 min at 100 ° C. Different compositions for the mixtures are highlighted in Table 1. The resulting gel substance is removed from the beaker and spread uniformly on a glass plate. The gel is air-dried for 3–4 days and then, the bioplastic film is separated from the glass plate. The films produced are shown in Fig. 2. A comparative analysis is made between glycerine and vegetable oil (olive oil) as suitable plasticizers.

2.4. Characterization of WCS bioplastic films

2.4.1. Determination of the mechanical properties of WCS bioplastic films

The mechanical properties of the bioplastic film were determined using the methodology proposed by Hasan et al. [16]. A tensile velocity of 100 mm/min with a maximum load of 500 N was used. The samples

Fig. 1. Procedures for the extraction of starch.

Table 1
Composition of materials for the formulation of starch-based bioplastic films.

Sample Number	Starch (g)	Gelatine (g)	Vinegar (ml)	Glycerine (ml)	Distilled Water (ml)	Vegetable Oil (ml)
S1	10	2	1	3	100	–
S2	10	2	2	3	100	–
S3	10	3	2	3	100	–
S4	10	3	2	4	100	–
S5	10	3	3	4	100	–
S6	10	3	3	5	100	–
S7	10	3	3	-	100	5

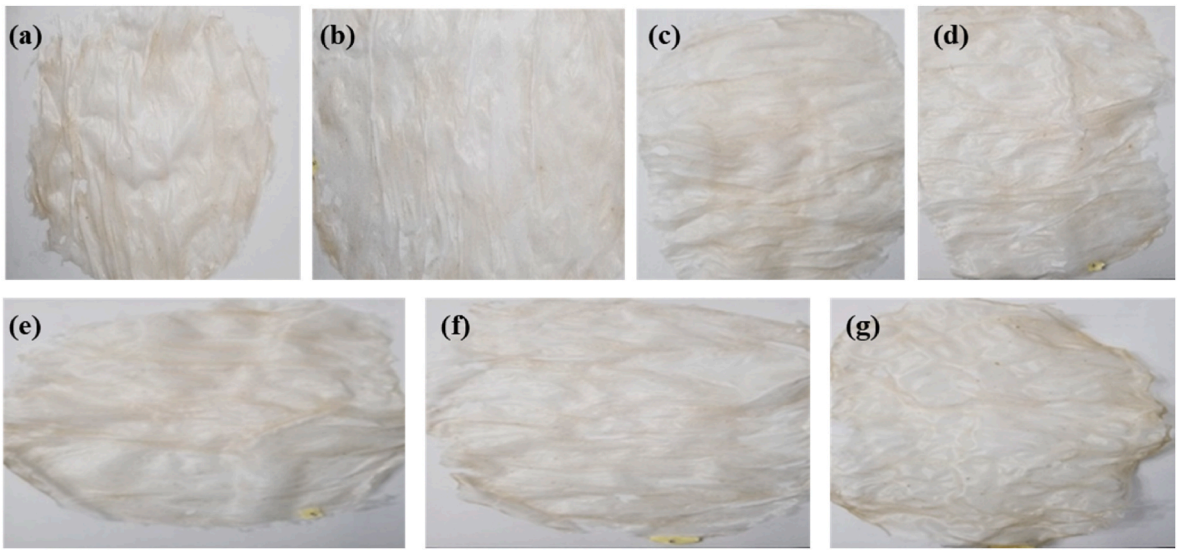

Fig. 2. Produced bioplastics (a) S1 (b) S2 (c) S3 (d) S4 (d) S5 (f) S6 (g) S7.

were clamped on the TSL-1002 universal testing machine and run according to the set conditions. The mathematical expressions used to determine the tensile strength, Young's modulus and elongation at break are shown in Equations (4-6), respectively [16].

$$\text{Tensile strength, } \sigma\ (\text{MPa}) = \frac{\text{Force}}{\text{Area}} \tag{4}$$

$$\text{Elongation at break, } \varepsilon(\%) = \frac{\text{Extension} \times 100}{\text{Initial length of bioplastic}} \tag{5}$$

$$\text{Young's modulus } (\text{MPa}) = \frac{\text{Tensile strength}}{\text{Elongation at break}} \tag{6}$$

2.4.2. Determination of the thickness and moisture content of WCS bioplastic films

The thickness of the bioplastic was observed using the micrometre screw gauge. Each sample was recorded at five different points. The mean value was recorded as the thickness of the bioplastic.

The moisture content of WCS bioplastic film was determined using the methodology proposed by Ginting et al. [18]. The bioplastic film was cut into square pieces of 2 cm^2. The weight of the sample before and after being dried in an oven at 85 °C for 24 h was recorded. The moisture content expressed in percentage was calculated using Equation (7):

$$\text{Moisture content } (\%) = \frac{\text{Initial} - \text{Final weight}}{\text{Initial weight}} \times 100 \tag{7}$$

2.4.3. Determination of the water solubility and absorption of WCS bioplastic films

The water solubility and water absorption of WCS bioplastic film was determined using the methodology proposed by Ginting et al. [18]. The bioplastic film was cut into square sizes of 2 cm^2. The sample was dried in an oven at 85 °C for 24 h. The dried sample was immersed in 50 ml of distilled water for 24 h. After 24 h, the water was filtered, and the bioplastic film was dried in an oven at 85 °C for 24 h. Water solubility, expressed in percentage was calculated using Equation (8):

$$\text{Water solubility } (\%) = \frac{\text{Initial or dry weight} - \text{Final weight}}{\text{Initial weight}} \times 100 \tag{8}$$

To determine the rate of absorption, the bioplastic film was cut into square sizes of 2 cm^2 and dried in an oven at 85 °C for 24 h. The dry weight of the sample was recorded. The dried sample was immersed in 50 ml of distilled water for 24 h. After 24 h, the water was filtered, and the final weight of the bioplastic was recorded. The percentage of water absorption was calculated using Equation (9).

$$\text{Water absorption } (\%) = \frac{\text{Final} - \text{Dry or initial weight}}{\text{Initial weight}} \times 100 \tag{9}$$

2.4.4. Determination of the soil biodegradability of WCS bioplastic films

The soil biodegradability of WCS bioplastic film was determined using the methodology proposed by Shaqfat et al. [19]. This test was conducted to determine the rate of biodegradability of the bioplastic film. The sample was cut into square dimensions measuring 2 cm^2. The cut sample was concealed beneath a layer of moist soil obtained from the vicinity of plant roots, with a depth of 2 cm. The initial weight of the bioplastic was recorded. After 5 days, the sample was collected from the soil, washed with water, and dried in an oven at 85 °C for 24 h. The sample was monitored at various time intervals until complete biodegradation was observed. Equation (10) was used to obtain the percentage of biodegradation [10].

$$\text{Soil biodegradability } (\%) = \frac{\text{Initial} - \text{Final weight}}{\text{Initial weight}} \times 100 \tag{10}$$

2.4.5. FT-IR and morphological analyses of WCS bioplastic films

Analysis of the functional groups present in the bioplastic film was performed using the Nicholas iS5 ThermoFischer Fourier Infrared Spectroscopy equipment. Approximately 2 mg of bioplastic film and about 300 mg of dry potassium bromide (KBr) powder were weighed and placed into an agate mortar. The mixture was then pulverized and thoroughly mixed to ensure the samples were well dispersed. This mixture was subsequently pressed into a transparent disc using a tablet machine for 10 min. The resulting discs were analysed using FTIR, with the spectra recorded over a range of 4000-650 cm^{-1} at a resolution of 4 cm^{-1}.

Morphological investigations of the bioplastic films were performed using the EVO LS 10 ZEISS scanning electron microscopy at an accelerating voltage of 10 kV and a working distance of 7.4 mm. The films were gold-coated before conducting the SEM analysis [17]. These were conducted on four samples (the best, medium and least performing samples using gelatine) while sample produced using vegetable oil was also examined for comparative purpose.

2.4.6. Statistical analysis

The data obtained from the experiments were carried out in triplicates except FTIR and SEM analysis. The results were analysed and reported in terms of mean and standard deviation. Analysis was carried out using Microsoft Excel.

3. Results and discussions

3.1. Characterization of WCS

3.1.1. Starch yield and moisture content of WCS

The starch yield from wild cocoyam (Caladium bicolor) was found to be 92.85 g, representing 15.87 % of the total tuber weight. While this yield is lower compared to other starchy crops like edible cocoyam, which ranges from 11.47 % to 31.7 % [23], potato starch at 24.20 % [25], and Talas starch at 31.7 % [18], wild cocoyam offers distinct advantages despite its modest starch yield. Wild cocoyam is a sustainable, underutilized crop that grows in marginal lands without the need for intensive agricultural inputs. This positions it as an environmentally friendly alternative to crops like corn and potato, which require significant land, water, and fertilizers. Utilizing wild cocoyam for starch extraction promotes resource efficiency, especially in regions like Nigeria where it can be harvested with minimal environmental impact, supporting a circular bioeconomy. This contrasts with traditional starch crops, which are more resource-intensive to cultivate [22]. Although its starch yield is lower, wild cocoyam's sustainability and reduced competition with food crops make it an appealing choice for bioplastic production. The decision to use wild cocoyam can also be seen as a move towards diversifying starch sources, avoiding over-reliance on high-yield crops like corn and potato. Moreover, the suitability of starch for specific applications, such as bioplastics, depends more on its molecular structure and interaction with plasticizers than on the overall yield. The moisture content of wild cocoyam starch (WCS) was measured at 12.33 %, lower than that of edible cocoyam (15.05 %) [23] and palado seed starch (19.64 %) [26]. This lower moisture content is favorable for industrial applications, such as bioplastic production, where reduced moisture enhances the physical properties, shelf-life, and mechanical stability of the final product. The lower water activity decreases microbial degradation risks and improves the overall stability of the starch, making wild cocoyam a promising candidate for sustainable bioplastic production.

3.1.2. Amylose content of WCS

The amylose content of wild cocoyam starch (WCS) was found to be 11.7 % as shown in Table 2. This value aligns well with similar starch sources, such as wild cocoyam, which has an amylose content of 11.1 % [11]. The amylose content of wild cocoyam starch (WCS) is higher than that of palado seed starch [26] but lower than some traditional sources, such as corn (29.4 %) [20], talas starch (32.47 %) [18], and edible cocoyam (23.50 %) [23]. This unique amylose profile presents distinct advantages for bioplastic production, as it can influence the mechanical properties, biodegradability, and processing characteristics of the resulting bioplastics. Amylose plays a crucial role in enhancing the material properties of bioplastics. Its linear structure contributes to increased film strength, stiffness, and improved thermal stability—key factors for high-performance bioplastic materials [27,28]. The 11.7 % amylose content of WCS is ideal for producing bioplastics that strike a balance between flexibility and durability. This is particularly valuable in applications requiring materials that are strong enough to hold their shape while remaining flexible enough for practical use. Furthermore, the amylose content in WCS will provide bioplastics with excellent film-forming properties, which is critical for creating cohesive, uniform films [29]. These films are likely to exhibit good mechanical strength and resistance to deformation, making WCS-derived bioplastics suitable for a wide range of applications, from food packaging to agricultural films. The remaining starch composition is likely dominated by amylopectin, which further enhances the performance of bioplastics. Amylopectin's branched structure contributes to flexibility and smooth film formation, allowing for better moldability and adaptability in processing [30]. This makes WCS-derived bioplastics versatile in applications where flexibility and biodegradability are key, such as disposable packaging, single-use items, and biodegradable products. The combination of amylose and amylopectin in WCS ensures that bioplastics produced from this starch can meet the growing demand for sustainable materials while maintaining excellent functional properties.

Table 2
Characterization results of wild cocoyam starch.

Characteristics	Values
Moisture content (%)	12.33 ± 0.04
Amylose content (%)	11.7 ± 0.02
Gelatinization temperature (° C)	71 ± 4.00
pH	4.27 ±0.02
Ash content (%)	0.33 ±0.01

3.1.3. Gelatinization temperature of WCS

Amylose begins to solubilize at 60 °C, though this varies with different starch sources. The gelatinization temperatures are listed in Table 2. For wild cocoyam starch (WCS), the gelatinization temperature is 71 °C, slightly lower than the 81 °C reported by the Alobi group [11]. This difference is due to variations in amylose and amylopectin composition; a higher amylopectin content results in more thermally stable branched chains [31]. A lower gelatinization temperature speeds up gel formation, reducing production time. This suggests that the wild cocoyam used in this study is advantageous.

3.1.4. pH of WCS

The pH of WCS is 4.27 as shown in Table 2. Research indicates that the pH of starch typically ranges from 4 to 7 [32]. This variation is attributed to different starch sources and plant species. Starch has been reported to have a wide pH range from 4.0 to 7.5 [33], influenced by factors such as geographical differences, processing methods, plant variability, and storage conditions [11,34]. For example, a pH value of 6.7 was reported for agung banana peel starch, 7.2 for edible cocoyam starch (7.19) [23] and 7.8 for wild cocoyam [11].

3.1.5. Ash content of WCS

The ash content of the wild cocoyam starch used in this study was found to be 0.33 %. Ash content is a critical parameter in assessing the purity of starch, as it reflects the amount of inorganic material present. Lower ash content typically indicates fewer mineral impurities, which is

desirable for applications such as bioplastic production, where high purity enhances the performance of the material. In comparison with other starch sources used in bioplastics, the ash content of wild cocoyam starch is within an acceptable range. For instance, research by Alobi et al. [11] on bioplastics derived from wild cocoyam, wild sweet yam, and false yam reported ash content values are 0.6, 0.3 and 0.1 % respectively. Similarly, Marichelvam et al. [20] examined corn and rice starch for bioplastic applications and found the ash contents to be 0.32 and 0.29 % respectively. jackfruit seed starch used in bioplastic films has also shown comparable ash contents [35]. Variation in ash content of starch may be attributed to environmental factors, such as soil composition and harvesting conditions, as well as variations in extraction and purification processes. Despite this, the ash content of the starch in this study is not expected to significantly affect the processing or functional properties of the resulting bioplastic. Given that bioplastics made from starches with similar or higher ash contents have demonstrated success in previous studies, wild cocoyam starch can be confidently considered suitable for bioplastic synthesis.

3.2. Characterization of the WCS bioplastic films

3.2.1. Mechanical properties of WCS bioplastic films

The mechanical properties of the different samples are presented in Fig. 3. The tensile strength of the bioplastic film with 2 g of gelatine, 1 ml of vinegar and 3 ml of glycerine is 6.5 MPa (sample 1). This is higher than the tensile strength of other starch sources, such as *Prosopis juliflora* (5.81 MPa) [15], rice starch (4.48 MPa) [36] and Potato starch-based bioplastics (0.49–1 MPa) [37]. This higher tensile strength can be attributed to the added gelatine and the amylose content of WCS, which forms a denser and more cohesive polymer matrix. The ability of amylose to form strong hydrogen bonds within the starch network enhances the film's ability to withstand stress before breaking. The molecular structure of amylose promotes a tighter packing of the starch chains, contributing to the material's stiffness and resistance to deformation, making it suitable for applications requiring durable packaging materials.

Increasing the concentrations of vinegar and glycerine results in a reduction in tensile strength across the samples. This trend can be explained by glycerine's role as a plasticizer, which enhances flexibility but compromises the rigidity and strength of the bioplastic matrix. The interaction between glycerine and the starch components may lead to a more pliable but less mechanically robust structure, ultimately affecting overall performance. Glycerine disrupts the intermolecular forces between starch molecules, increasing the mobility of polymer chains and reducing stiffness, thereby lowering tensile strength. This is a typical outcome in bioplastics, as plasticizers like glycerine improve flexibility but compromise strength at higher concentrations [37,38]. The influence of vinegar (acetic acid) in moderating the gelation of starch also contributes to this reduction, as it further disrupts the starch matrix.

The elongation at break of WCS bioplastic films demonstrates the material's flexibility. Sample 1, with 77 % elongation, exhibited the highest flexibility among the formulations. This high elongation value is comparable to the agar/chitosan blend (78.26 %) [39] and is significantly higher than other starch sources such as chitosan/yellow pumpkin starch (13.45 %) and yam bean starch (2.44 %) [40]. The increased elongation is largely due to the role of glycerine as a plasticizer, which increases the mobility of polymer chains and improves flexibility. As glycerine content increases, the films become more ductile, allowing for

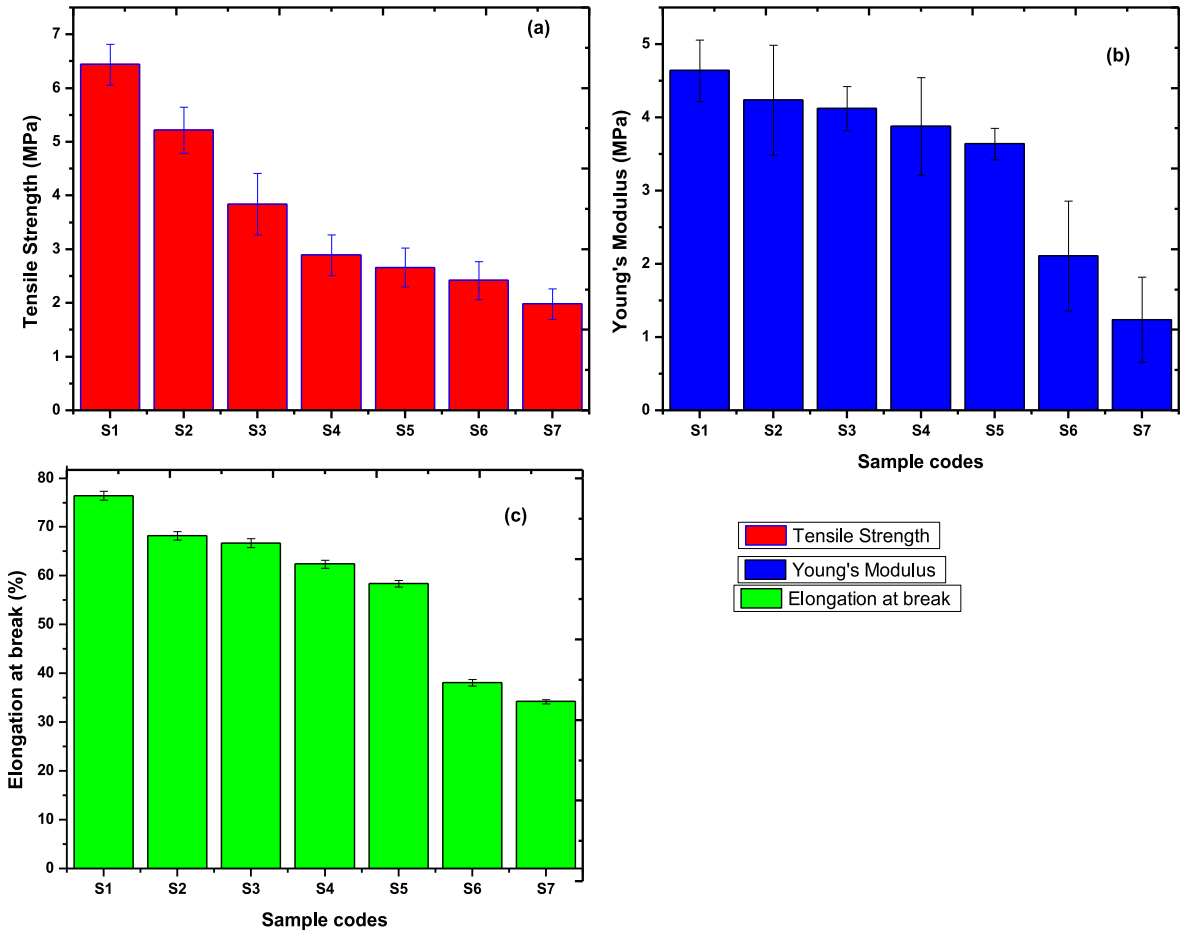

Fig. 3. Mechanical properties of WCS bioplastic films.

greater elongation at break.

The lower elongation at break in Sample 7 (31 %), which lacked glycerine but included vegetable oil, highlights the importance of glycerine in enhancing flexibility. The absence of glycerine reduces the plasticizing effect, leading to a stiffer, less extensible film. Although vegetable oil contributes some flexibility by acting as a hydrophobic agent, its impact on elongation is not as pronounced as glycerine's, indicating the critical role of the latter in achieving the desired flexibility in bioplastic formulations. Young's modulus, a measure of the stiffness of the bioplastic, was highest in Sample 1 (4.6 MPa) and decreased to 1 MPa in Sample 7 as the glycerine and vinegar concentrations increased. This trend is consistent with the influence of plasticizers, where higher glycerine concentrations reduce stiffness by allowing greater polymer chain mobility, leading to lower Young's modulus values. This result is comparable to that of banana peel starch, which has a Young's modulus of 1.88 MPa [41]. The ability to tune Young's modulus by adjusting plasticizer concentrations offers flexibility in tailoring the mechanical properties of the bioplastic for specific applications.

3.2.2. *Thickness of WCS bioplastic films*

The thickness of the bioplastic films is presented in Fig. 4. From Fig. 4, the thickness of the bioplastic films is greater than 270 μm. This is greater than the standard minimum requirement of 50 μm [20]. This suggests that the bioplastic films are suitable for use in packaging applications. This is compared to the thickness in corn and rice starch [20] and *Prosopis juliflora* plant starch [15]. The thickness of corn and rice starch is 250 μm. The thickness of WCS is 35.89 % better than rice and corn starch. The thickness of Prospis Juliflora plant starch is 390 μm. This suggests that the bioplastic films produced from the starch sources competes favourably with each other.

3.2.3. *Moisture content, water solubility, water absorption and soil biodegradability of WCS bioplastic films*

The moisture content, water solubility, water absorption, and biodegradability results of the WCS bioplastic films are detailed in Fig. 5. The moisture content shows an increasing trend as the concentration of additives, such as gelatin and glycerine, is raised. Sample 6 has the highest moisture content (8.47 %), which is lower than typical starch sources like corn, rice (11.7–13.9 %), and banana peel starch (7.3–14 %) [42], as well as biofilm from agar/chitosan blend which range from 12.24 to 23.54 % [43]. The chemical structure of gelatine and glycerine reveals the presence of the hydroxyl group which has great affinity for water molecules. This interaction allows for the formation of hydrogen bonds and the presence of water in their structure. Hence, the reason for the observed increasing trend. The lower moisture content in WCS bioplastics enhances their potential use in food packaging applications, where minimizing moisture is crucial to prevent microbial growth and maintain food quality [44].

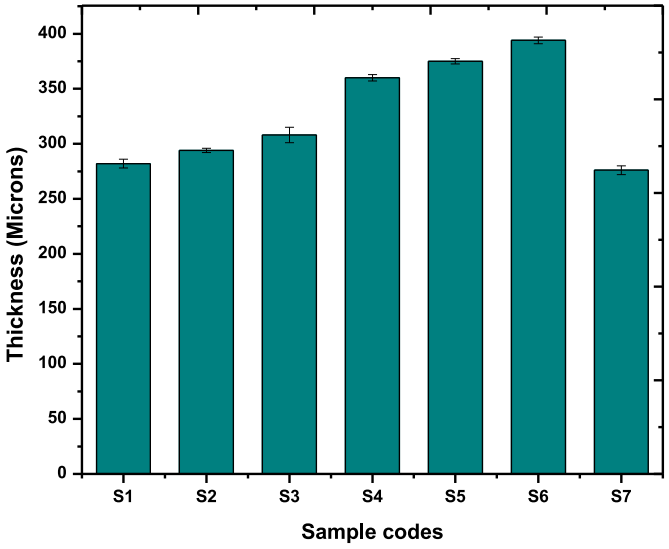

Fig. 4. Thickness of the bioplastics with increasing concentration of additives.

Water solubility varies across the samples, with Sample 6 showing the highest solubility at 63.44 %. The increase in solubility is proportional to film thickness, as reported by Ulyarti et al. [45]. However, the addition of vegetable oil in Sample 7 reduced solubility to 46.72 %, due to the hydrophobic nature of oil, which limits water interaction. Shafqat and co-workers [19] reported similar trend is observed in the decreased rate of solubility in the presence of clove oil. Bioplastics with this level of water solubility are particularly useful in applications such as single-use packaging, agricultural films, detergent pods, and cosmetic or medical applications, where controlled solubility is essential. The water solubility of WCS bioplastic is compared to *Prosopis juliflora* plant starch [15] and yam starch [45]. The rate of water solubility in *P. juliflora* is 23.73 % higher than WCS.

Water absorption increases with the addition of gelatin and glycerine, peaking at 60.41 % in Sample 6. In contrast, Sample 7, which includes vegetable oil, exhibits the lowest absorption rate at 10.49 %. This reduction is due to the hydrophobic nature of the oil, which acts as a barrier to water penetration—a valuable characteristic for applications that require water resistance. When compared to potato peel waste (83.57 %), wild taro starch (60.13%–76.46 %) [46], and banana peel starch (85.66%–218.39 %) [19], WCS bioplastic's lower water absorption rates make it a competitive option for commercial packaging applications.

Biodegradability results indicate that Sample 6 had the highest rate of biodegradation (70 %) and the shortest time to complete degradation (7 days). Increased moisture content in the bioplastics accelerates microbial activity, thereby speeding up biodegradation. Compared to wild taro starch (64.5 %) [46]and corn/rice starch (48.73 %, 15 days) [20], WCS bioplastics degrade faster, positioning them as an environmentally friendly option for reducing plastic waste in packaging and other applications. This rapid biodegradability is a significant advantage for WCS bioplastics, addressing concerns over plastic pollution.

3.2.4. *FT-IR analysis of WCS bioplastic films*

The FTIR spectra of different samples are presented in Fig. 6. In comparison to yam bean starch [40], the characteristic peaks of starch are observed with the wavenumbers 3700–3200, 3000–2840 and 1205–1050 cm^{-1}. These confirm the presence of O-H stretching (also influenced by the presence of glycerine), C-H stretching of CH_2 and C-O stretching in starch. Peaks between 1420 and 1330 cm^{-1} show O-H bending due to the presence of water present in the starch and additives. The C-O-C ring vibrations in the glucose unit of starch are confirmed by the peaks within the range of 900-700 cm^{-1}. The observed peaks reveal the interactions that occur during the film-forming process, evidenced by the increase or decrease in properties (e.g. moisture content, flexibility, etc.). Sample 7 shows an additional peak at 1714 cm^{-1} which indicates the presence of carboxylic acid. This accounts for the hydrophobic nature of the sample and explains minimal interactions with water (moisture content, water absorption, water solubility and rate of biodegradability) observed in sample 7.

3.2.5. *Morphological analysis of WCS bioplastic films*

Fig. 7(a–g) presents the SEM images of the bioplastic samples. The smooth and uniform surface observed in Samples S1 and S2 indicates strong polymer interaction and effective blending of the components. Sample S1 stands out with superior structural integrity, exhibiting fewer pores and smaller un-gelatinized granules compared to the other samples, which enhances its mechanical properties. In contrast, Sample S6 demonstrates poor structural integrity and arrangement, characterized by a higher number of larger pores, coarse granules, and greater

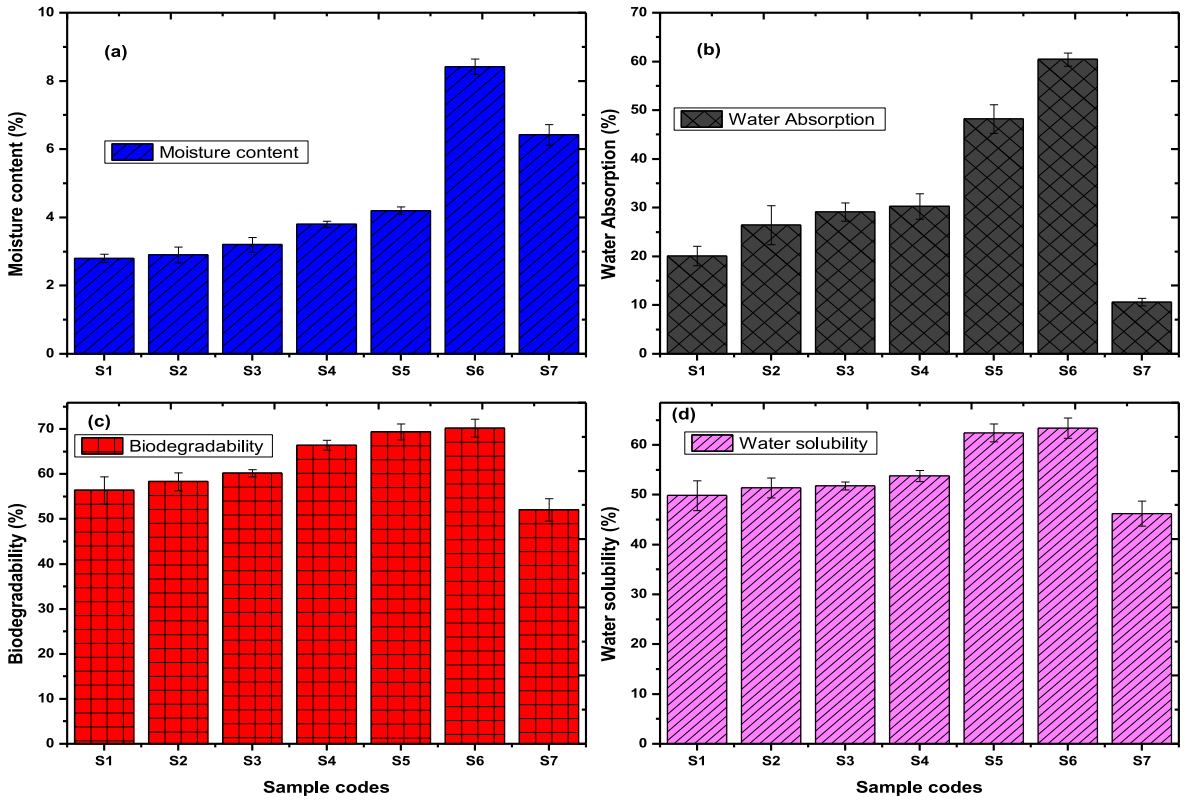

Fig. 5. Moisture content, water solubility, absorption, and soil biodegradability of WCS bioplastic films.

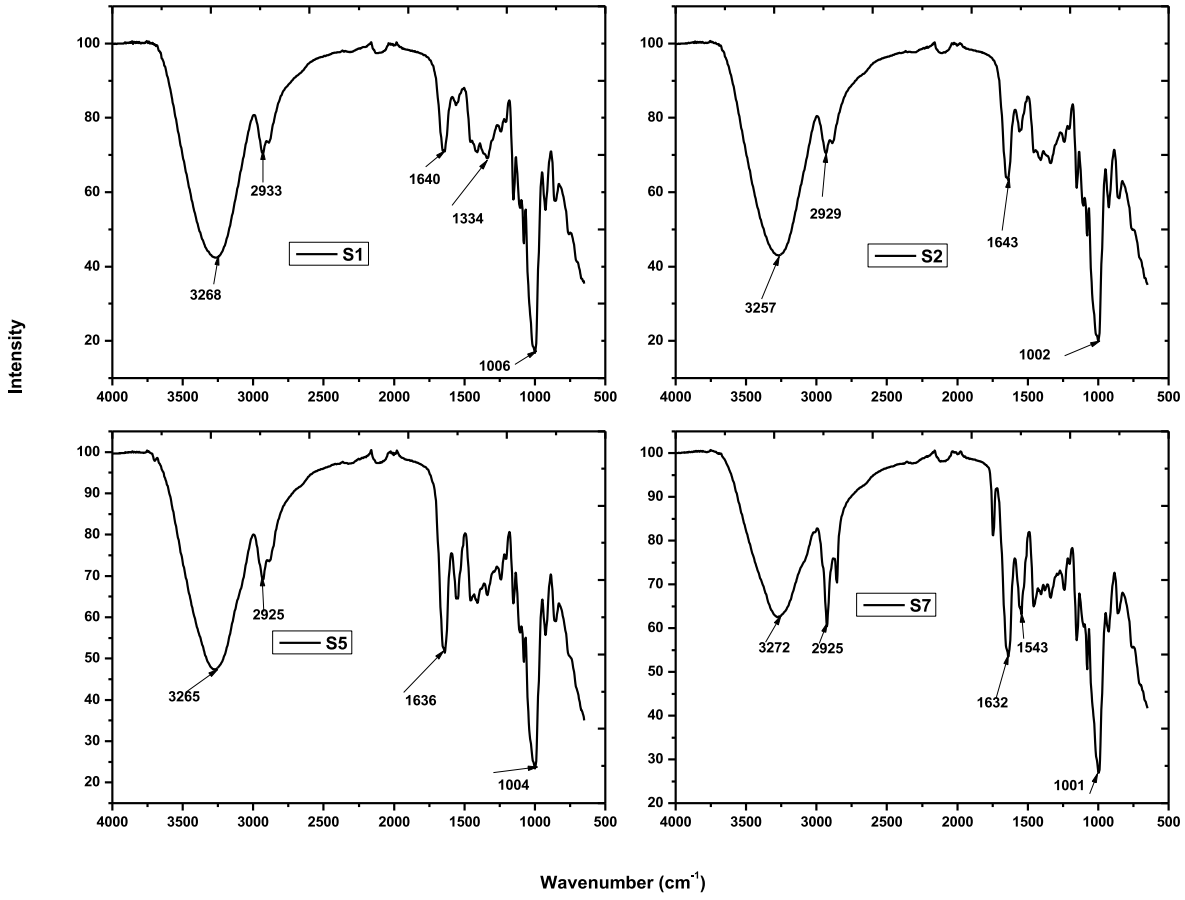

Fig. 6. Ftir of WCS Sample 1 (S1); Sample 2 (S2); Sample 6 (S6) and Sample 7 (S7).

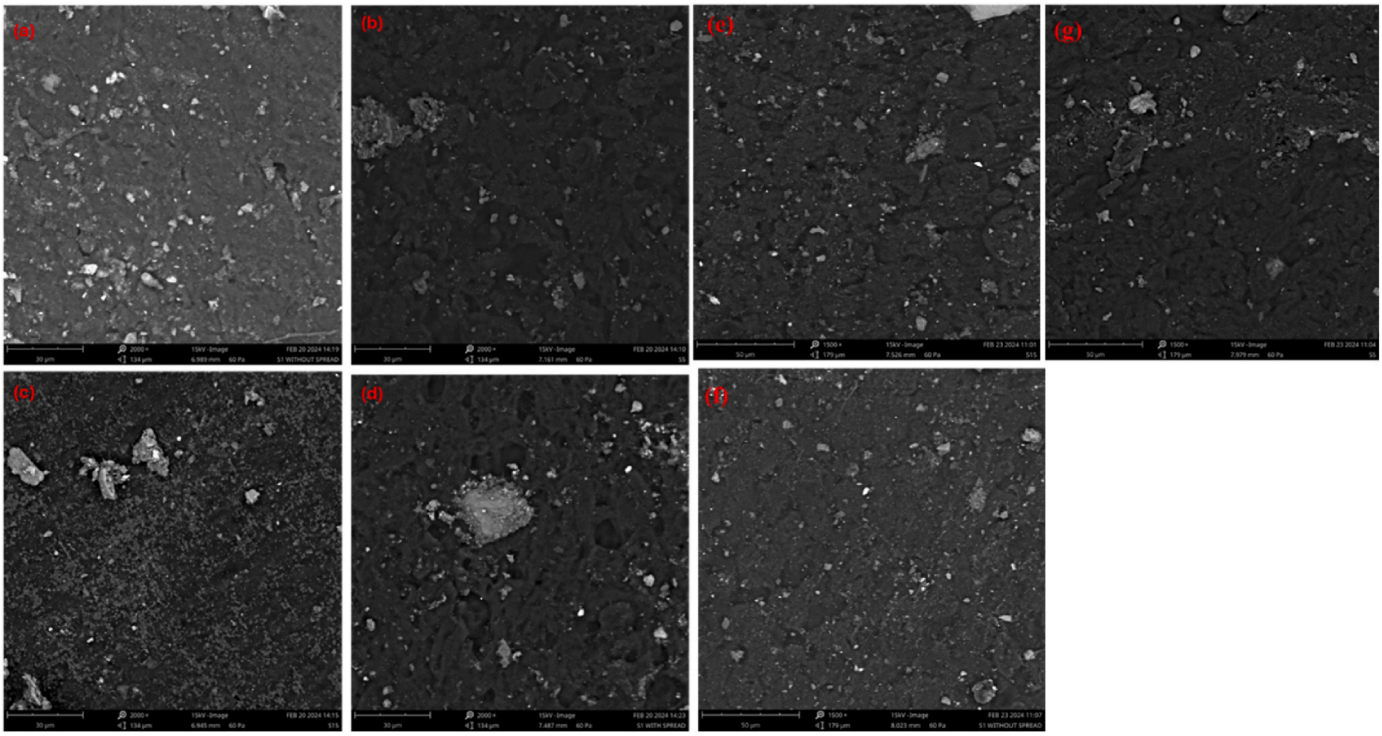

Fig. 7. Sem images (a) S1 (b) S4 (c) S5 (d) S6 (e) S2 (f) S3 (g)S7.

irregularities. This morphology correlates with its inferior mechanical properties, as shown in Fig. 3. Meanwhile, Samples S3, S4, and S5 present a more homogeneous arrangement than Samples S6 and S7, contributing to improved mechanical performance. These observations align with the findings of Oluwasina [47] and Amin et al. [48]. Additionally, the presence of glycerine in Samples S1 to S6 enhances the flexibility of the films, while the inclusion of olive oil in Sample S7 imparts more hydrophobic properties. In conclusion, the SEM analysis of the samples shows that Sample S1 and Sample S2 exhibit optimal mechanical properties due to their smooth and uniform surfaces, while Sample S6 shows compromised structural integrity with larger pores and irregularities, leading to inferior performance. The results highlight the critical role of formulation in enhancing flexibility and hydrophobicity across the different samples.

4. Conclusion

This study successfully demonstrated the potential of wild cocoyam starch in producing biodegradable bioplastic films with superior mechanical properties compared to conventional starch-based alternatives. By blending varying concentrations of gelatin, glycerine, vegetable oil, and vinegar, the resulting bioplastic films exhibited a tensile strength of 6.5 MPa and elongation at break of 77 %, surpassing many existing bioplastics in terms of flexibility and strength. The film thickness, exceeding 270 μm, aligns with commercial packaging standards, making it suitable for industrial applications. Additionally, the bioplastic's rapid biodegradation rate of 70 % within 7 days and its low moisture content and water solubility underscore its environmental compatibility. These properties suggest a broad range of applications, including single-use packaging, agricultural films, detergent pods, and even medical and cosmetic products, where biodegradability and water solubility are critical. However, despite these advantages, certain limitations, particularly regarding the material's moisture resistance and thermal stability remain. To increase the scope of its commercial viability, future research should focus on improving these aspects to ensure the material performs well under a wider range of environmental conditions. Overall, this study affirms wild cocoyam starch as a highly promising and sustainable alternative for eco-friendly bioplastic production. As industries and consumers continue to shift towards sustainable materials in response to global environmental challenges, the adoption of wild cocoyam starch bioplastics could significantly contribute to reducing plastic waste and promoting circular economy practices.

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CRediT authorship contribution statement

Chinaza Faithfulness Enwere: Funding acquisition, Formal analysis. **Ikechukwu Stanley Okafor:** Writing – original draft, Data curation, Conceptualization. **Adekunle A. Adeleke:** Writing – original draft, Methodology, Formal analysis. **Nzerem Petrus:** Resources, Methodology. **Khaleel Jakada:** Validation, Software. **Adebayo Isaac Olosho:** Writing – review & editing, Visualization, Funding acquisition. **Peter P. Ikubanni:** Visualization, Resources. **Prabhu Paramasivam:** Writing – review & editing, Visualization, Supervision. **Salihu Ayuba:** Supervision, Investigation, Data curation.

Declaration of competing interest

I, Prabhu Paramasivam, declare that:1. I have no financial interest or benefit that has arisen from the direct applications of my research or professional activities.2. I have not received any funding, grants, or other financial support from any organization or entity that could potentially influence the content or conclusions of my research or professional activities.3. I have no non-financial interests that may be affected by the publication of the research or the performance of my professional duties.4. I have complied with all ethical guidelines and regulations pertinent to my research and professional activities.

I understand that my declaration of interest will be publicly available and that I am responsible for updating this statement should any

relevant changes occur.

Data availability

Data will be made available on request.

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