



Comparative effect of physical and chemical treatments on the mechanical and barrier properties of Bambara groundnut-based protein-lipid films

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Abstract

Aim: Increased awareness of environmentally friendly and biodegradable packaging materials and the need to reduce negative and harmful interactions of food with packaging materials have driven research efforts towards edible packaging using combinations of food-based polymeric substances. Such edible packaging materials, including protein-based, carbohydrate-based, lipid-based compounds and their combinations, have revolutionised packaging perception. In this study, protein-lipid films produced from the extract obtained via hydrothermal treatment of Bambara groundnut flour were essentially modified.

Methods: The effects of chemical modification (using formaldehyde as a cross-linking agent) and exposure to ultraviolet (UV) light on the film-forming solutions were investigated. Films from the modified and pure solutions were analysed for their barrier and mechanical properties, including water vapour permeability and elongation at break, among others. Also colour parameters of the protein-lipid films were examined.

Results: The findings revealed that the values for mechanical and barrier properties of the formed films were comparable to those of other composite films, and also presented an improvement over polysaccharide, protein, or lipid-only films. The film formation rate ranged from 2.92 ± 0.03 to 4.43 ± 0.03 g/10 min, while the film yield ranged from 5.46 ± 0.07 to 8.92 ± 0.02 g/100 mL. Water vapour permeability of the Bambara groundnut films ranged from 0.49–0.63 $\text{gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$. The films had high opacity values. Elongation at break values for the UV-modified film (44.37) were higher than those of the unmodified film (43.07).

Conclusions: The Bambara groundnut films had better mechanical strength compared to the reference soybean film. This indicates a possible use in the coating of brittle and light-sensitive foods.

Keywords

Bambara groundnut, edible packaging, protein-lipid films, barrier properties, mechanical properties



Introduction

Packaging materials serve multiple purposes [1], but the most important function deals with preserving the quality and safety of packed foods. These attributes (quality and safety) must be maintained throughout the food product's life cycle, from production and transportation to consumption. Synthetic plastic packaging (especially, high-density polyethylene and low-density polyethylene) is commonly used owing to their excellent mechanical properties and well-known effectiveness as barriers to oxygen and water [2]. However, these synthetic films pose significant ecological concerns because they are not biodegradable [3, 4]. According to Sabzevari et al. [5], the pervasive and often inappropriate application of high molecular weight petroleum-based polymers has, to a large extent, damaged the environment. Biopolymers that are derived from strictly biological sources are generally safe, abundant and eco-friendly, as well as being economical substitutes for synthetic polymers [6], but with abundant hydrophilic groups, possessing weak mechanical properties, markedly low resistance to heat, and poor barrier properties. However, consumers are known to associate eco-friendly packaging with perception of healthiness, powered by the heuristic relationships to its original-ecology sensory cues, sustainable connotations, cultural and morality signals and environmental consciousness [7].

Recently, there exists growing interest in edible films that are made from renewable and natural polymers such as proteins, polysaccharides, and lipids [8]. Edible packaging materials that are applied in the form of coatings and films widely used in the food industry are in greater demand in food packaging because of their eco-friendly nature, maintenance of quality and enhancements in the shelf life of foods and food products [4, 9]. Protein-based edible films have superior mechanical properties compared to those from polysaccharides and lipids, thanks to the unique structure of proteins, which consists of 20 different monomers. This structure allows for high potential intermolecular binding and a wide range of functional properties [10]. However, protein films are highly susceptible to water vapor, limiting their use in food packaging applications. Lipid films, on the other hand, are excellent barriers to moisture but normally require solvents and high temperatures for their formation, and have poor mechanical properties [11]. Composite protein-lipid films are usually developed through the endothermic polymerization of heat-denatured proteins or lipoprotein monomers at the liquid surface, a process aided by surface dehydration [12]. The films are formed via the integration of lipids into the protein network structure in the form of oil bodies [13, 14]. During heating, proteins in vegetable 'milk' undergo thermal denaturation and form intermolecular disulfide bonds via oxidation, and this leads to the development of a three-dimensional network structure. At the same time, dispersed components migrate to the air-water interface, where amphiphilic proteins reorient with hydrophobic domains facing the air, and hydrophilic regions toward the aqueous phase. Oil bodies are then entrapped within the evolving complex matrix, and continuous moisture evaporation further densifies the structure, ultimately yielding the hierarchical porous architecture characteristic of such films [15]. By combining proteins and lipids, these films benefit from the mechanical durability of protein films and the effective moisture barrier capabilities of lipid films.

While many studies have focused on edible films made with soy protein [13–15], there is limited information on the use of other legume proteins as raw materials for edible films [16]. However, with the world's population growing rapidly and faster than agricultural growth, it is essential to increase the production of staple crops and also pay attention to previously neglected and underutilized crops. One such crop is the Bambara groundnut [*Vigna subterranean* (L.) Verdc.], which has been widely cultivated in Africa even before the introduction of the peanut (*Arachis hypogaea*). According to Padhi et al. [17], Bambara groundnut possesses considerable potential to address protein energy malnutrition, enhance dietary diversity and multi-industry applications. Bambara groundnut is high in protein (20–26% crude protein), containing essential amino acids such as lysine, isoleucine, leucine, methionine, phenylalanine, valine, and threonine, with 63% carbohydrates, 18% oil, and fatty acids that are primarily linoleic, palmitic, and linolenic acids [18]. However, its application as an edible packaging material has not been fully explored. This study investigated the comparative effects of ultraviolet (UV) irradiation and formaldehyde treatments on the mechanical and barrier properties of Bambara groundnut-based protein-lipid films for product preservation.

Materials and methods

Sample preparation

The Bambara groundnut seeds obtained from a local market in Akure were sorted and washed. The seeds were then cooked (85°C) for 10 min prior to dehulling in order to separate the seed from its pericarp, which hardens once the seed is cool. The dehulled Bambara groundnut seeds were wet milled to obtain a viscous slurry, which was then sieved and the milk collected, as adapted from Ariwaodo and Obasi [19] and Babatuyi et al. [20]. Glycerol was added as a plasticizer at a concentration of 0.30 mL/g of slurry. Thereafter, the residue was discarded, while the milk was divided into 3 parts. To the first part was added 2% w/w formaldehyde. The second part was exposed to short wave UV light for 1 hour. The third part was left as is, without any additions or modifications (pure). Each of the three milk samples (pure and modified) was heated slowly on a mantle and the temperature changes were monitored with the aid of a thermometer. At around 82–85°C, there was formation of thin films on the surface of the milk solutions. These films were picked with the aid of a spatula and placed in separate containers. At over 85 °C, there was a breakdown of the film and the milk was then cooled for the process to be repeated. The films produced were air dried using vacuum oven and stored at 4°C prior to analyses.

Determination of film yield

A known volume of Bambara groundnut milk was heated (as described above) and the resultant film produced was weighed using a laboratory weighing balance. The film yield was determined as the weight (in grams) of protein-lipid film produced from 100 mL of the Bambara milk sample solution, and derived from the following relationship (adapted from Li et al. [14]):

$$Y = \frac{(M \times 100)}{G}$$

Where,

Y = film yield (g/100 mL);

M = total protein-lipid film output (g);

G = volume of milk for film formation (mL).

Determination of film formation rate

The film formation rate was determined as the weight (in grams) of protein-lipid film produced from the Bambara groundnut milk solution after every ten minutes. The determinations were carried out in triplicate and calculated using the following formula:

$$V = \frac{(M \times 10)}{T}$$

Where,

V = film formation rate (g/10 min);

M = total protein-lipid film output (g);

T = total time for film formation (min).

Determination of water vapour permeability (WVP)

WVP was determined using the slightly modified method of Taqi et al. [21]. Films made from the three samples (both pure and modified) were first sealed in a glass permeation cup before placement in a desiccator cabinet containing silica gel [0% relative humidity (RH); the silica gel was subjected to heat at 180 °C for 3 hours or more, then cooled prior to use]. The weight of the edible film was intermittently monitored until a constant weight was achieved. The WVP ($\text{gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$) of the film was then calculated as follows:

$$\text{WVP} = \frac{\text{Weight of film (g)} \times \text{thickness of film (mm)}}{\text{Area of film (m}^2\text{)} \times \text{time (h)} \times (\text{P}_2 - \text{P}_1)(\text{kPa})}$$

$\text{P}_2 - \text{P}_1$ = vapour pressure difference across the films

Determination of oxygen permeability (OP)

OP was determined by employing the method described by Taqi et al. [21]. At 23 °C and $50 \pm 1\%$ RH, films were placed in a stainless-steel mask with an open testing area of 5 cm². The masked films were placed in the test cell and exposed to a flow of 88% N₂ and 12% H₂ on one side and pure oxygen on the other. OP was calculated by multiplying the oxygen gas transmission rate (OGTR) by the average film thickness and dividing by the partial pressure difference of oxygen over the film surface.

Determination of opacity

The film samples were cut into rectangular shapes and placed on the internal side of a spectrophotometer cell, following a modified standard procedure of the British Standards Institute [22]. Film opacity was calculated by measuring the area under the absorbance curve with respect to wavelength (400 to 600 nm) and expressing it as absorbance units (AU) $\times$ absorbance/unit thickness (μm).

Determination of mechanical properties

Films produced from each sample were moulded into identical shapes with uniform area and thickness according to the ASTM D882-10 standard method [23]. Mechanical properties, including stress and strain at break, load at break and elongation at break, as well as modulus of elasticity, were determined using a Universal Testing Machine (Haida model HD-B615-S) at the Engineering Materials Development Institute (EMDI), Akure.

Determination of film colour

Colour of the films was measured following the method of Zhang et al. [24], using a HunterLab ColourFlex EZ 45 colourimeter (HunterLab Associates Laboratory, Colourflex, USA). The instrument was calibrated using a white standard plate. Lightness (L) and chromaticity parameters a^* (red-green) and b^* (yellow-blue) were all measured via placing the film samples over the standard white plate. Five readings from randomly selected sites of each film were recorded. The total colour difference (ΔE), whiteness index (WI), and yellowness index (YI) were calculated using the following formulas:

$$\Delta E = \sqrt{(L^* - L)^2 + (a^* - a)^2 + (b^* - b)^2}$$

$$\text{WI} = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2}$$

$$\text{YI} = \frac{142.86 \times (b^*)}{(L^*)}$$

where L , a , and b are the colour parameter values of the white standard ($L = 91.83$, $a = -0.73$, $b = 1.52$), and L^* , a^* , and b^* are the colour parameter values of the films.

Statistical analysis

The experimental procedures were carried out in triplicate determinations, and data obtained were subjected to one-way analysis of variance (ANOVA) to determine the significant differences at 5% level ($p < 0.05$). The values were expressed as mean $\pm$ s.d. and separated using New Duncan's Multiple Range Test.

Results

Film formation properties

Table 1 presents the film formation properties of Bambara groundnut milk. The film formation rate among all the samples ranged from 2.92 ± 0.03 to 4.43 ± 0.03 g/10 min, while the film yield ranged from 5.46 ± 0.07 to 8.92 ± 0.02 g/100 mL. Formaldehyde treatment gave higher values for both the film formation rate and the film yield than the UV-treated sample and untreated film. However, the protein-lipid film from

soybean (yuba) had higher film formation rate and film yield compared to all the Bambara groundnut protein-lipid films (both treated and untreated). UV radiation treatment negatively affected the film formation parameters, taking significantly ($p < 0.05$) longer to form the film, with lower yields.

Table 1. Film formation parameters of protein-lipid films from Bambara groundnut.

Sample	Film formation rate (g/10 min)	Film yield (g/100 mL)
SN	4.43 ± 0.03^d	8.92 ± 0.02^d
BN	3.52 ± 0.04^b	6.64 ± 0.03^b
BF	3.87 ± 0.06^c	6.73 ± 0.02^c
BUV	2.92 ± 0.03^a	5.46 ± 0.07^a

Values are expressed as mean $\pm$ standard deviation. Values with the same superscript along the same column indicate no significant difference at $p < 0.05$. BF: Bambara groundnut formaldehyde treated film; BN: Bambara groundnut untreated film; BUV: Bambara groundnut ultraviolet treated film; SN: soybean film (yuba).

Barrier properties of the films

The results of barrier properties of both raw and modified Bambara groundnut protein-lipid films, alongside the control (soybean yuba) are presented in Table 2. Film thickness increased from 0.06 mm to 0.11 mm, and opacity increased from 1.12 to 1.28, while solubility in water increased from 20.36% to 25.21%. On the other hand, OP decreased from initial $1.51 \text{ gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$ down to $1.46 \text{ gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$, whereas WVP increased from $0.49 \text{ gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$ to $0.63 \text{ gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$.

Table 2. Barrier properties of protein-lipid films from Bambara groundnut.

Sample	Film thickness (mm)	Solubility in water (%)	Opacity	Oxygen permeability ($\text{gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$)	Water vapour permeability ($\text{gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$)
SN	0.08 ± 0.01^{bc}	35.20 ± 0.12^d	0.76 ± 0.12^a	2.13 ± 0.08^c	0.80 ± 0.03^c
BN	0.06 ± 0.01^a	20.36 ± 0.03^a	1.12 ± 0.01^b	1.51 ± 0.11^b	0.49 ± 0.05^a
BF	0.09 ± 0.01^c	25.21 ± 0.08^c	1.16 ± 0.02^b	1.48 ± 0.03^{ab}	0.51 ± 0.02^a
BUV	0.11 ± 0.01^d	24.36 ± 0.10^b	1.28 ± 0.02^c	1.46 ± 0.02^a	0.63 ± 0.01^b

Values are expressed as mean $\pm$ standard deviation. Values with the same superscript along the same column indicate no significant difference at $p < 0.05$. BF: Bambara groundnut formaldehyde treated film; BN: Bambara groundnut untreated film; BUV: Bambara groundnut ultraviolet treated film; SN: soybean film (yuba).

Apart from film thickness and opacity, the other evaluated parameters gave higher values in the control soybean yuba than in both the untreated and modified Bambara groundnut protein-lipid films. This variability was most noticeable in the solubility of the films in water. Modification with formaldehyde gave higher oxygen permeability than the UV light treated film. The untreated Bambara groundnut film had higher OP and lower WVP than the films modified using physical and chemical treatments, which means that it was more porous to oxygen as a barrier packaging material, but could withstand water vapour than the treated films.

Colour parameters of the produced films

The colour parameters that were determined, including L^* , a^* , b^* , ΔE , WI, and YI of pure and modified protein-lipid films from Bambara groundnut, using the CIE Lab coordinates, are presented in Table 3. Significant differences ($p < 0.05$) were observed in the b^* values of all the films produced.

Other colour parameters/functions such as ΔE , WI, and YI can be used to interpret the effect of modification on the colour of the films. The ΔE values, which indicate the degree of ΔE from the standard plate, decreased with modification in the Bambara groundnut films, with higher L^* values corresponding to lower ΔE values. Conversely, WI values increased in the films, while YI values were significantly different ($p < 0.05$) across all the films produced (both pure and modified). The Bambara groundnut films had negative YI values due to their negative b^* values, which tended towards blue rather than yellow colouration.

Table 3. Colour parameters of films from Bambara groundnut.

Sample	<i>L</i> *	<i>a</i> *	<i>b</i> *	ΔE	WI	YI
SN	76.02 ± 0.91 ^c	1.02 ± 0.01 ^a	25.34 ± 0.23 ^d	28.64 ± 0.24 ^a	65.10 ± 0.67 ^c	47.61 ± 0.86 ^d
BN	57.65 ± 0.65 ^a	1.35 ± 0.01 ^b	−8.31 ± 0.05 ^c	35.63 ± 0.89 ^c	56.82 ± 0.88 ^a	−20.60 ± 0.62 ^c
BF	60.87 ± 0.72 ^b	1.56 ± 0.01 ^c	−10.98 ± 0.11 ^b	33.47 ± 0.52 ^b	59.32 ± 0.76 ^b	−25.77 ± 0.53 ^b
BUV	61.64 ± 0.55 ^b	1.69 ± 0.02 ^d	−11.43 ± 0.13 ^a	32.94 ± 0.71 ^b	59.94 ± 0.59 ^b	−26.49 ± 0.57 ^a

Values are expressed as mean ± standard deviation. Values with the same superscript along the same column indicate no significant difference at $p < 0.05$. BF: Bambara groundnut formaldehyde treated film; BN: Bambara groundnut untreated film; BUV: Bambara groundnut ultraviolet treated film; SN: soybean film (yuba). ΔE : total colour difference; WI: whiteness index; YI: yellowness index.

Mechanical properties of the films

Mechanical properties of the films in this study are presented in Table 4. Elongation at break ranged from 24.92 mm in the control sample to 44.37 mm in the UV-treated film. Young's modulus ranged from 40 kPa in the control to 320 kPa in the untreated Bambara film. Strain at break ranged from 143% in the control to 414.64% in the UV-treated film. The untreated Bambara film gave highest values of all the parameters, except for elongation at break, in which it gave lower value than the UV-treated film. All the produced films exhibited longer elongations at break compared to the reference sample. The strain at break followed the same trend as elongation at break. Moreover, as all the films had uniform area and diameter prior to testing, the percentage deformation (strain) was directly proportional to elongation.

Table 4. Mechanical properties of protein-lipid films from Bambara groundnut.

Sample	Elongation at break (mm)	Strain at break (%)	Load at break (N)	Stress at break (kPa)	Energy at break (J)	Modulus (kPa)
SN	24.92 ^a	143.20 ^a	22.13 ^a	20.00 ^a	0.18 ^a	40.00 ^a
BN	43.07 ^c	402.51 ^c	141.28 ^d	190.00 ^c	0.63 ^d	320.00 ^d
BF	29.11 ^b	272.09 ^b	59.95 ^b	80.00 ^b	0.44 ^c	90.00 ^b
BUV	44.37 ^d	414.64 ^d	62.80 ^c	80.00 ^b	0.35 ^b	120.00 ^c

Values are expressed as means of three replications. Values with the same superscript along the same column indicate no significant difference at $p < 0.05$. BF: Bambara groundnut formaldehyde treated film; BN: Bambara groundnut untreated film; BUV: Bambara groundnut ultraviolet treated film; SN: soybean film (yuba).

Modification appeared to decrease the films' firmness, with lower loads at break observed for the modified films. The formaldehyde-modified film had the lowest load at break value. Stress at break, or force at break, is significantly affected by the load at break.

The modulus values confirm BN as the strongest of the produced films, while BF is the weakest, having the lowest stress-to-strain ratio. The reference sample was found to be weaker than all the produced films, exhibiting low values throughout.

Discussion

Bambara groundnut films exhibited good film formation rates (as shown in Table 1), which can be attributed to the protein-to-lipid ratio of Bambara groundnut. The film formation rate is the weight in grams of film produced per unit of time and is influenced by several factors, including the protein-lipid ratio of the film-forming solution, amino and fatty acid contents, the presence and type of plasticizer, pH, and temperature. The results obtained by Cai et al. [25] demonstrate that the structure and functional properties of protein particles significantly impact the film formation rate. According to Shen et al. [26], who studied the film formation rate of various soybean cultivars, a protein/lipid ratio of 3:0 is ideal for film formation. The composition of amino acids also plays a role in the film formation process, with more hydrophobic amino acids aiding film formation. The control/reference film demonstrated better formation rates compared to the experimental films (pure and modified).

Bambara groundnut milk produced good film yields, likely due to its high protein content and film formation rates. However, the film yields gave lower values than those reported by Shen et al. [26] for different soybean cultivars. Film yield refers to the weight in grams of film obtained from a known volume of the film-forming solution. It is usually influenced by the composition of the film-forming solution and the film formation rate. The reference sample had a higher film yield than all other samples (Table 1). Kumar et al. [27] found that the protein-lipid production method significantly affects yield, film formation rates, colour, and rehydration capacities of protein-lipid films when comparing ohmic heating to conventional or water bath heating. This suggests that temperature control and uniform heating of the solution are crucial factors for improving film yield.

Edible films possess physicochemical properties essential for maintaining integrity during food production, handling/transportation, and subsequent storage. These properties are influenced by the film type, component quality and microstructure, and production technology applied, as well as film formation conditions [28]. Film thickness is a crucial parameter for calculating mechanical and barrier properties. The thickness of the Bambara groundnut films ranged from 0.06 to 0.11 mm, comparable to those obtained by Rostamzad et al. [3] from films of silver carp.

Opacity is a measure of a film's transparency, with higher opacity values indicating lesser transparency. Film transparency directly impacts the appearance of the packaged product. In the present study, the films produced had opacity values ranging from 0.76 ± 0.12 to 1.28 ± 0.02 (Table 2). Modification increased the films' opacity, possibly due to protein denaturation. These results agree with those of Hamaguchi et al. [29], who reported that protein-based films have excellent UV light barrier properties, thanks to their high content of aromatic amino acids that absorb UV light. This makes them suitable for applications in foods susceptible to light deterioration.

Solubility is considered the maximum quantity of a particular substance that will be completely dissolved in a given concentration of solvent and is an important concept in research fields of chemistry, physics, food science, pharmaceuticals, and biological sciences. The solubility of a film represents the degree of water resistance and the integrity of such a film. In this study, the films exhibited high solubility values, likely because legume seed proteins are primarily albumins and globulins, which are water-soluble and account for about 40–90% of seed protein [30]. The Bambara groundnut films had lower solubility values than the reference film (35.20%) (Table 2). The solubility of the films was similar to those reported by Montalvo-Paquini et al. [31] for films from seven Mexican common beans, with solubility ranging from 25–35%.

Oxygen in food causes oxidation, affecting various parameters such as colour, flavour, odour, and sometimes nutrient content [32]. The ability of films to lower the rate of oxidation or degradation is a critical characteristic that affects the quality and shelf-life of the final product. The OP values of the films showed that Bambara groundnut films possessed reasonable oxygen impedance. Fat content is a major determinant of OP. This was shown by Tapia-Blácido et al. [33], who found that protein films from amaranth had lower OP than protein-lipid films also produced from amaranth. Ayranci and Tunc [34] observed that increasing the stearic acid content in methylcellulose films enhanced OP, attributing this to the formation of holes in the crystal structure of edible films as stearic acid content increased.

WVP of a film is a crucial indicator of the ability to lower rate of food spoilage and elongate shelf-life. WVP is influenced by composition, chemical structure and degree of cross-linking of the film, as well as the use of plasticizers. Some other factors affecting WVP include temperature and RH [35]. The Bambara groundnut films had low water permeability values, attributed to their high-fat content and high hydrophobic amino acid content. Properties such as permeability characteristics, colour retention, and mechanical properties are influenced by fatty acid types and concentrations. Yoshida and Antunes [36] suggested that WVP decreases with higher lipid content. Incorporating emulsion droplets in the film increases the distance travelled by water molecules, thereby decreasing WVP [37]. Kowalczyk et al. [38] proposed that adding lipid materials above 20% seemed to have less effect on reducing WVP, as the configuration of nonpolar components in the protein's structural matrix limits the effect of polar groups of

proteins and glycerol. The WVP values obtained in this study are lower than those reported by González et al. [39] for soy protein isolate films using glycerol as a plasticizer. Plasticizers usually aid in forming rigid structures within the film matrix.

The consumer acceptability of any given product is generally influenced by the film colour. Typically, in edible film packaging and coating, high transparency and L^* are desirable characteristics [40]. The L^* values (57.65–76.02) observed in all the films in the present study are directly linked to their transparency. L^* values were significantly influenced by modification from the pure film, with a general decrease in L value after modification (Table 3). The reference sample (yuba) had the highest L^* value among all the films produced. Taqi et al. [21] observed that L^* values were affected by oil content, with increased thickness and reduced transparency in films containing higher oil contents. The a^* values of the produced films increased with modification in the Bambara films, resulting in higher a^* values compared to the reference sample, with significant differences ($p < 0.05$) observed among all the films produced. The b^* values decreased with modification in the Bambara groundnut films, with the reference sample showing very high b^* values and a visible yellowish colouration. These observed results agree with those of Siracusa et al. [41], who found that composite films made by combining citral essential oil, alginate and pectin with higher ΔE values were not too transparent.

Colour is critically important for biopolymer films and is significantly influenced by substrate type, manufacturing parameters, and storage conditions [24]. The optical properties of the films in the current investigation were mainly affected by substrate type and concentration. Modification disrupted the ordered structure of the film matrix (Table 3). Additionally, as the protein structure breaks down, the interaction between protein molecules and corresponding water molecules might alter the refractive index of the components, consequently changing the transparency of the resulting films.

The mechanical properties that characterize edible films and coatings are generally elaborated by the film constituents, their relative proportions, and the conditions of preparation [42]. Specific interactions observed among the film constituents, such as crosslinks, the different structural arrangements, or formation of heterogeneous biphasic structures, are also considered. Elongation at break measures the differential flexibility of a film and indicates its tendency to deform before collapsing. The high lipid concentration in the protein-lipid films may have caused segregation of the lipid phase, leading to early rupture during elongation [33]. Formaldehyde modification had adverse effects on the Bambara groundnut films, resulting in decreased elongation at break (Table 4). In contrast, UV modification slightly increased elongation at break.

The load at break is a measure of the maximum load a film could withstand prior to deformation, indicating its structural integrity under stress. The Bambara groundnut films were fragile and unable to handle high loads. The unmodified Bambara groundnut film (BN) had the highest stress at break among all samples, including the reference, due to its ability to withstand higher loads, while the formaldehyde and UV-modified samples (BF and BUV) had the lowest. Energy at break indicates the amount of energy (in joules) needed to deform the film and is linearly proportional to load at break, with BN having the highest value. The modulus of elasticity is a widely known indicator of mechanical strength and measures the stiffness of a solid material. It provides an overview of the ability of a material to withstand stress and not be deformed. Tapia-Blácido et al. [33] reported that high lipid concentrations in protein-lipid films hinder protein-protein interactions, leading to a decrease in modulus.

In conclusion, composite edible films offer many advantages over films made solely of protein, carbohydrate, or lipid. Protein-lipid films with excellent barrier and mechanical properties were produced from Bambara groundnut. Formaldehyde and UV light modifications caused the films to lose some firmness but improved their OP indices. These produced films could be suitable for use in the fruit and vegetable industry.

Abbreviations

ΔE : total colour difference

OP: oxygen permeability

RH: relative humidity

UV: ultraviolet

WI: whiteness index

WVP: water vapour permeability

YI: yellowness index

Declarations

Author contributions

AMO: Methodology, Formal analysis, Investigation, Writing—original draft. DOO: Formal analyses, Software, Writing—review & editing. AOA: Resources, Writing—review & editing. VNE: Conceptualization, Supervision, Writing—original draft, Writing—review & editing. All authors read and approved the submitted version.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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Consent to participate

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Not applicable.

Availability of data and materials

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