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Effects of plasticisers on the mechanical and physical properties of sodium alginate films

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ABSTRACT

Sodium alginate (SA) films show strong potential as biodegradable plastic alternatives because of their transparency, mechanical properties, and biodegradability. However, films composed solely of SA are limited in tensile strength and elongation properties. Incorporating biologically-sourced plasticisers can enhance these qualities, producing stronger or more stretchable films. In this study, selected plasticisers from distinct molecular classes (celluloses, polyols, carbohydrate sugars and oils) were combined with liquid SA, and the resulting formed films assessed for tensile strength, elongation, transparency at 600 nm, and thickness. Additionally, aliquots of SA-plasticiser solutions were dropped into calcium chloride to form insoluble beads, which were tested for water barrier properties. Overall, plasticisers improved SA film performance. Cellulose increased tensile strength, while polyols enhanced elongation but reduced tensile strength. Carbohydrates produced moderate improvements in both properties but to a lesser degree. Additions of plasticisers typically produced higher tensile strength or elongation properties compared to 2.5% (*w/v*) SA film alone (tensile strength 42.4 MPa; elongation to break 4.2%); for example, in SA films containing 10% (*w/v*) cellulose nanocrystals (tensile strength of 80.5 MPa); or in SA films containing 2% (*w/v*) fructose and 4% (w/v) xylitol (elongation to break 137.0%). All films were below the maximum thickness threshold for plastic classification (<0.25 mm), confirming uniformity and suitability for future applications. These findings highlight the potential of multi-plasticiser formulations to enhance the mechanical and barrier properties of SA films, supporting their development as sustainable, comparable alternatives to petroleum-derived plastics.

1. Introduction

Plastic films in the food industry consist mainly of fossil-fuel derived materials [1]. In 2022, 400.3 mt of plastic was produced globally [2]. Bioplastics currently make up 0.5% of global plastic production, equating to 2180 kt in 2023, with the production of bioplastics predicted to rise to 7430 kt by 2028 [3]. Bioplastics have been explored as alternatives to fossil fuel–derived plastics since the early 20th century, beginning with the development of cellulose-based materials such as celluloid and cellophane. [4,5]. Now, plastic packaging, including films, are moving to a bio-based material composition, made from plant-based materials including starch, cellulose, oils, lignin, proteins and polysaccharides. More natural bases for packaging will help reduce the effect plastic pollution is having on the environment [6]. For example, sodium alginate (SA) films would have advantages over fossil fuel-derived synthetic films if the synthetic film properties can be mimicked [7,8]; with a key advantage being the rapid biodegradability of the SA film [9–11].

Alginate is the main structural polysaccharide found in the cell wall and intracellular matrix of brown seaweeds (*Phaeophyceae*) [12] where it provides strength and flexibility to the alga. It is currently extensively used as an ingredient within the food, pharmaceutical and cosmetic industries, with further potential for use as a major contributor to biodegradable food packaging [13]. Synthetic films have dominated this market to date, but interest in sustainable and circular products is increasing [7], following consumers' demand for more eco-friendly packaging [14]. Alginic acid consists of 1,4-linked β-D-mannuronic acid (M) and α-L-guluronic acid (G), with the unbranched polymer containing homopolymorphic M or G blocks joined by heteropolymorphic MG blocks [15]. The structural conformation between M-M, M-G and G-G molecules include the 'egg box' structure seen in poly-G blocks as shown in Fig. 1. This structure enables chelation of poly-G

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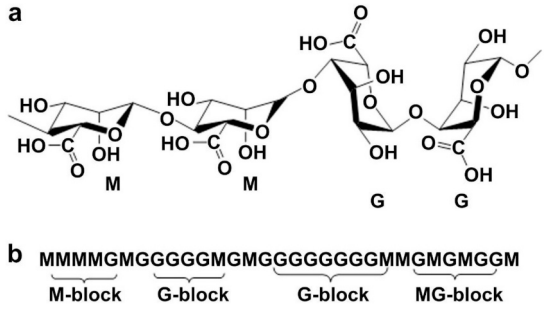

Fig. 1. Alginic acid molecular structure, showing (a) linear polymer formation and (b) block distribution. M = mannuronic acid, G = guluronic acid. Note the 'egg box' structure which would occur with multiple guluronic acids forming a 'G-block'. Reproduced from [18].

blocks with divalent metal cations, such as calcium (Ca) ions [16–18], to create tightly held junctions, forming a gel at scale. MG blocks can also create weak junctions, meaning that the higher the G proportion, the stronger the gel [18]. The addition of Ca^{2+} ions can either be through the addition of ions within the alginate solution, and a pH change to slowly release the cations [19]; or by diffusing Ca into the alginate solution from an external source e.g. by bathing the film in a solution of multivalent cations [20]. This insoluble Ca-alginate gel is typically produced from stable, soluble sodium (Na)-alginate [21], with the Na^{+} ion being exchanged for Ca^{2+} ions during these processes. However, though binding with Ca^{2+} has been repeatedly shown to improve water solubility [18,22] and tensile strength [23,24], other properties such as transparency, elongation at break and water vapour permeability are not typically reported, indicating a current gap in our knowledge of this resource [18].

A major challenge for SA films in the packaging industry is the limitations of their mechanical properties. SA films exhibit low tensile strength and poor elongation at break measurements [9,25,26]. A plasticiser is a material added to a base compound, typically making it softer or more pliable, especially in reference to plastics or elastomers [27]. If incorporated into a biodegradable film, it can alter the mechanical and/or biodegradable properties, and must be included in the definition when referring to developed films [28]. SA films can rapidly dissolve in water and will degrade in soil composting systems. This is an additional end-of-life scenario which provides circular disposal advantages in certain environments where recycling infrastructure is lacking or if the films are contaminated e.g. with food residues. Literature shows a range of plasticiser compounds that have been trialled with SA and other carbohydrate polymers, with the main mechanical property/ies enhanced by their inclusion summarised in Table 1. To improve a film's tensile strength, cellulose, proteins, sugars, alcohol sugars (polyols) and crosslinkable ions are commonly used. Elongation properties are less frequently enhanced, often achieved using polyols and the polysaccharide "cashew tree gum" [28,29]. Previous thin-film property assessments characterise and test on the basis of a single performance improvement, but this does not reflect the dynamic chemistry of plasticiser and polymer interactions. Table 1 therefore also shows a potential knowledge gap of overall performance improvements associated with plasticiser incorporation into the films.

This work aimed to determine and assess the properties and functionality of alginate-based films by systematically trialling combinations of plasticisers with SA, with the goal to identify more environmentally friendly alternatives to fossil fuel-derived films.

2. Materials and methods

2.1. Materials

Commercial grade sodium alginate (12,000–14,000 molecular weight, viscosity 5–40 cP; no M/G given) (Sigma, Gillingham, Dorset, UK) formed the main chemical component of the films produced. The additional plasticisers explored in this study were the following: i) celluloses: cellulose nanofibrils supermass colloider (CNF Smc), cellulose nanofibrils high-pressure homogeniser (CNF Hph), cellulose nanofibrils prepared using 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO), and cellulose nanocrystals (CNC) (all Cellulose lab, Fredericton, New Brunswick, Canada); ii) polyols: glycerol (Sigma), xylitol and thymol (Alfa Aesar, Heysham, Lancashire, UK); iii) carbohydrate sugars: fructose and mannose (both Sigma); and oils: sunflower oil, vegetable oil, extra virgin olive oil, and rapeseed oil (all WM Morrisons Supermarkets, Bradford, UK). All oils used in this study were commercially available food grade vegetable oils intended for human consumption. Detailed fatty acid compositions were not available due to normal batch-to-batch variability associated with retail food products. Combinations and proportions of each plasticiser blend mixed with alginate solutions are detailed in Table 2, which also summarises the films used in each of the reported studies below. All films consisted of a SA backbone at 2.5% (*w/v*), with plasticisers added; with the exceptions of SA-only films, which were also made containing 2% and 3% sodium alginate (*w/v*). The plasticiser additions were grouped into celluloses (at 2.5%, 5%, 10% w/v addition), polyols (1%, 2%, 4% w/v addition), carbohydrates (1%, 2%, 3%, 4% w/v addition) and oils (0.1%, 0.2%, 0.4% w/v addition). Combinations of two plasticisers together, crossing different plasticiser types (e.g. carbohydrate-polyol; polyol-oil) were also made, as were selected combinations of three plasticisers (e.g. carbohydrate-polyol-cellulose).

Table 1
Plasticiser assessments in biodegradable films, considering film mechanical properties.

Plasticiser (Biodegradable film base)	Film Backbone Material	Mechanical Property Enhanced	References
Calcium chloride crosslinking	Sodium alginate	Tensile strength	[23,24]
Cashew tree gum	Sodium alginate	Elongation	[29]
Cations and anions as crosslinking agents: $FeCl_2$, $FeCl_3$, $FeSO_4$	Sodium alginate	Tensile strength	[23]
Cellulose	Sodium alginate	Tensile strength	[9,48]
Cellulose nanofibrils and nanocrystals	Sodium alginate	Tensile strength	[49]
Fructose	Pullulan	Tensile strength	[28]
Glycerol	Sodium alginate, Pullulan	Tensile strength and Elongation	[28,35,50]
Hemicellulose	Sodium alginate	Tensile strength	[25]
Nanocrystalline cellulose	Sodium alginate	Tensile strength	[26]
Silver nano particles	Agar	Tensile strength	[51]
Sorbitol	Pullulan	Elongation	[28]
Soy protein isolate	Dialdehyde Starch	Tensile strength	[32]
Xylitol	Pullulan	Elongation	[28]

$FeCl_2$ = Iron (II) chloride, $FeCl_3$ = Ferric chloride, $FeSO_4$ = Iron (II)sulphate.

2.2. Preparation of silicone moulds

Replicate silicone moulds were produced pouring liquid silicone rubber combined with a tin catalyst (ProMold, Epideco LTD, Plymouth, UK) into 90 mm^2 petri dishes. An area measuring 60 mm × 50 mm was removed from the centre of each mould to be used for casting and drying the films. The silicone moulds were then placed onto plate glass sheets measuring 400 mm^2 to create a glass casting surface. Following casting the glass plates and silicone moulds were rinsed and cleaned using hot tap water and a microfibre cloth to remove any film residue that remained before air drying and recasting.

Table 2
Plasticiser additions to film solutions.

Sodium alginate (*w/v*)	Added plasticiser (w/v)	Plasticiser grouping title	Film inclusion within study:				
			Film Screening	Film Transparency	Film Thickness	Mechanical Testing	Water Barrier Properties
2%	–	- (low sodium alginate)	Yes	Yes	Yes	Yes	
2.5%	–	- (sodium alginate control)	Yes	Yes	Yes	Yes	Yes
3%	–	- (high sodium alginate)	Yes	Yes	Yes	Yes	
2.5%	CNF Smc 2.5%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNF Smc 5%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNF Smc 10%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNF Hph 2.5%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNF Hph 5%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNF Hph 10%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNF TEMPO 2.5%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNF TEMPO 5%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNF TEMPO 10%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNC 2.5%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	CNC 5%	Cellulose	Yes	Yes	Yes	Yes	Yes
2.5%	CNC 10%	Cellulose	Yes	Yes	Yes	Yes	
2.5%	Fructose 1%	Carbohydrate	Yes	Yes	Yes		
2.5%	Fructose 2%	Carbohydrate	Yes	Yes	Yes	Yes	Yes
2.5%	Fructose 4%	Carbohydrate	Yes	Yes	Yes		
2.5%	Sucrose 1%	Carbohydrate	Yes	Yes	Yes		
2.5%	Sucrose 2%	Carbohydrate	Yes	Yes	Yes		
2.5%	Sucrose 3%	Carbohydrate	Yes	Yes	Yes		
2.5%	Mannose 0.5%	Carbohydrate		Yes	Yes	Yes	Yes
2.5%	Mannose 1%	Carbohydrate	Yes	Yes	Yes		
2.5%	Mannose 2%	Carbohydrate	Yes	Yes	Yes		
2.5%	Mannose 4%	Carbohydrate	Yes	Yes	Yes		
2.5%	Sunflower oil 0.1%	Oil	Yes	Yes	Yes		
2.5%	Sunflower oil 0.2%	Oil	Yes	Yes	Yes		
2.5%	Sunflower oil 0.4%	Oil	Yes	Yes	Yes		
2.5%	Vegetable oil 0.1%	Oil	Yes	Yes	Yes		
2.5%	Vegetable oil 0.2%	Oil	Yes	Yes	Yes		
2.5%	Vegetable oil 0.4%	Oil	Yes	Yes	Yes		
2.5%	Extra virgin olive oil 0.1%	Oil	Yes	Yes	Yes		
2.5%	Extra virgin olive oil 0.2%	Oil	Yes	Yes	Yes		
2.5%	Extra virgin olive oil 0.4%	Oil	Yes	Yes	Yes		
2.5%	Rapeseed oil 0.1%	Oil	Yes	Yes	Yes		
2.5%	Rapeseed oil 0.2%	Oil	Yes	Yes	Yes		
2.5%	Rapeseed oil 0.4%	Oil	Yes	Yes	Yes		
2.5%	Thymol 1%	Polyol			Yes		
2.5%	Mannitol 1%	Polyol	Yes		Yes		
2.5%	Mannitol 2%	Polyol	Yes		Yes		
2.5%	Mannitol 4%	Polyol	Yes		Yes		
2.5%	Glycerol 1%	Polyol	Yes	Yes	Yes	Yes	Yes
2.5%	Glycerol 2%	Polyol	Yes		Yes		
2.5%	Glycerol 4%	Polyol	Yes		Yes		
2.5%	Xylitol 1%	Polyol	Yes		Yes		
2.5%	Xylitol 2%	Polyol	Yes		Yes		
2.5%	Xylitol 4%	Polyol	Yes	Yes	Yes	Yes	Yes
2.5%	Fructose 0.5%, Xylitol 1%	Two plasticiser combinations			Yes		
2.5%	Fructose 1%, Xylitol 2%	Two plasticiser combinations			Yes		
2.5%	Fructose 0.5%, Mannose 0.125%	Two plasticiser combinations			Yes		
2.5%	Fructose 1%, Mannose 0.25%	Two plasticiser combinations			Yes		
2.5%	Fructose 2%, Mannose 0.5%	Two plasticiser combinations			Yes		
2.5%	Fructose 0.5%, Vegetable oil 0.0025%	Two plasticiser combinations			Yes		
2.5%	Fructose 1%, Vegetable oil 0.05%	Two plasticiser combinations			Yes		
2.5%	Fructose 2%, Vegetable oil 0.1%	Two plasticiser combinations			Yes		
2.5%	Mannose 0.125%, Xylitol 1%	Two plasticiser combinations			Yes		
2.5%	Mannose 0.25%, Xylitol 2%	Two plasticiser combinations			Yes		
2.5%	Mannose 0.5%, Xylitol 4%	Two plasticiser combinations			Yes		
2.5%	Mannose 0.125%, Vegetable oil 0.025%	Two plasticiser combinations			Yes		

(*continued on next page*)

Table 2 (*continued*)

Sodium alginate (*w/v*)	Added plasticiser (w/v)	Plasticiser grouping title	Film inclusion within study:				
			Film Screening	Film Transparency	Film Thickness	Mechanical Testing	Water Barrier Properties
2.5%	Mannose 0.25%, Vegetable oil 0.05%	Two plasticiser combinations			Yes		
2.5%	Mannose 0.5%, Vegetable oil 0.1%	Two plasticiser combinations			Yes		
2.5%	Xylitol 1%, Vegetable oil 0.025%	Two plasticiser combinations			Yes		
2.5%	Xylitol 2%, Vegetable oil 0.05%	Two plasticiser combinations			Yes		
2.5%	Xylitol 4%, Vegetable oil 0.1%	Two plasticiser combinations			Yes		
2.5%	Fructose 2%, Glycerol 1%	Two plasticiser combinations		Yes	Yes	Yes	Yes
2.5%	Fructose 2%, Xylitol 4%	Two plasticiser combinations		Yes	Yes	Yes	Yes
2.5%	Fructose 2%, CNC 5%	Two plasticiser combinations		Yes	Yes	Yes	Yes
2.5%	Mannose 0.5%, Glycerol 1%	Two plasticiser combinations		Yes	Yes	Yes	Yes
2.5%	Mannose 0.5%, Xylitol 4%	Two plasticiser combinations		Yes	Yes		Yes
2.5%	Mannose 0.5%, CNC 5%	Two plasticiser combinations		Yes	Yes	Yes	Yes
2.5%	Glycerol 1%, CNC 5%	Two plasticiser combinations		Yes	Yes	Yes	Yes
2.5%	Xylitol 4%, CNC 5%	Two plasticiser combinations		Yes	Yes		Yes
2.5%	Fructose 2%, Glycerol 1%, CNC 5%	Three plasticiser combinations		Yes	Yes	Yes	Yes
2.5%	Fructose 2%, Xylitol 4%, CNC 5%	Three plasticiser combinations		Yes	Yes		Yes
2.5%	Mannose 0.5%, Glycerol 1%, CNC 5%	Three plasticiser combinations		Yes	Yes	Yes	Yes
2.5%	Mannose 0.5%, Xylitol 4%, CNC 5%	Three plasticiser combinations		Yes	Yes		Yes

CNF smc - Cellulose nanofibrils supermass colloider, CNF Hph - Cellulose nanofibrils high-pressure homogeniser, CNF TEMPO - Cellulose nanofibrils prepared using 2,2,6,6-tetramethylpiperidine-1-oxyl, CNC - Cellulose nanocrystals.

2.3. Film preparation

A film-forming solution was made from 2.5% (*w/v*) sodium alginate (SA) based on Rhim [24]. Replicates of each plasticiser at the concentrations shown in Table 2 were incorporated into the SA solutions using magnetic stirring at 400 rpm for 30 min at room temperature. Aliquots of 9 mL of each film-forming solution were then cast into silicone moulds placed on glass plates (detailed in 2.2). The films were dried at 40 °C for 24 h in a Genlab Prime fan oven (Genlab Ltd., Widnes, Cheshire, UK) positioned within a dry laboratory environment but without humidity controls. Once dried, the films were removed from the glass plate and stored in individual polyethylene zip lock bags, each containing a silica gel sachet to avoid rehydration prior to removal for analysis; with zip lock bags stored in a dark, dry, ambient environment matching that of the experimental laboratory. For each formulation, three independently-cast films were prepared. Each film was cut into three tensile strips (15 mm × 60 mm), resulting in $n = 9$ samples per formulation.

Films were excluded from further analysis if they exhibited: (i) visible phase separation or oil vesicle formation under ×40 microscopy, or (ii) consistent microcrack formation across replicate films, indicating loss of functional integrity.

2.4. Visual and structural imaging

One sample of each plasticiser and concentration variation (60 mm × 50 mm) was observed and photographed using a Canon EOS 90D (32MP) camera coupled with electro-focus short-back focus 18–55 mm f/ 3.5–5.6 image stabiliser stepping motor lenses; within a photo box with consistent lighting. Each film was photographed using a £1 coin as a control, behind or half behind the film, to assess visual film clarity (examples shown in Supplementary Fig. S1). One sample of each plasticiser and concentration variation (60 mm × 50 mm) was observed under a systems microscope (Olympus BX 40, Japan) at x 40 magnification and diameter of 100 μm to identify variations in the films such as microcracks or plasticiser immiscibility. Any film samples showing variations were further examined with at least two other replicate film samples to confirm consistency within that plasticiser combination.

2.5. Film transparency at 600 nm

The absorbance of films was measured using a Jenway 6715 UV/visible scanning spectrophotometer (Cole-Parmer, Cambridgeshire, UK) at 600 nm wavelength [30]. Films were cut into 1 cm width strips and inserted into cuvettes. An empty cuvette was used as the blank control.

2.6. Film thickness

Film thickness was measured using a digital micrometre with a resolution of 0.001 mm (Quanta mike, Mitutoyo Co., Japan) following methodology in ASTMD6988–21 [31]. Five thickness measurements were taken per film at set positions over the film surface, as detailed in Rhim [32]. All films were 50 mm × 60 mm, with the first thickness measurement taken at the centre (30 mm from the top x 25 mm from each side). The remaining four points were taken at 15 mm from the top or bottom edge x 12.5 mm from each side edge. Triplicate films were analysed for each plasticiser combination.

2.7. Tensile properties

When drying, the cast film adhered to the mould, meaning that a

raised edge occurred around each film produced. To standardise the films, this was removed using sharp scissors prior to further analysis. Each plasticiser combination film for analysis was cut into a further three pieces each 15 mm × 60 mm as required for ASTM D882–18 [33]. Tensile measurements were conducted using an Instron Universal Testing Machine (Instron Engineering Corporation, Canton, MA). The initial grip separation used was 35 mm at 25 mm min^{-1} crosshead speed with a 500 N load cell. Each film was assessed to failure and the elongation at break and tensile stress at maximum force were recorded.

2.8. Water loss assessment

The film-forming SA solution plus each plasticiser and plasticiser blends were trialled in their initial aqueous form to conduct a water loss test. Individual droplets (20 μL) of each film solution, excluding the oil-containing films, were immersed into an excess of 1% (*w/v*) calcium chloride solution. The calcified droplets formed near-spherical beads, which were removed, patted dry to eliminate excess calcium chloride solution on the outer surface, and weighed. For each formulation, five beads ($n = 5$) were prepared and weighed at each time point. The beads were stored at ambient temperature and reweighed after 24, 48 and 72 h. This assay provides an indirect, comparative assessment of water retention in crosslinked alginate systems without directly measuring water vapour permeability.

2.9. Statistical analysis

Analysis of variance (ANOVA) and Multivariate analysis of variance (MANOVA) were conducted using SPSS 25 software (IBM, Armonk, NY, USA) after initial data collation and review using Excel (Microsoft 365, Redmond, WA, USA). ANOVAs were used to compare tensile properties (tensile stress at maximum force and elongation at break); and the film thicknesses as the response variables. Factors considered the variation of plasticiser type (Table 2) as a category and within this the plasticiser type's concentration (Table 2). A MANOVA was used to compare the weight loss of the water loss assessment over time. Factors considered were the number of plasticisers incorporated into the film (none, one, two and three) and the plasticiser type incorporated into the SA films. All assumptions for ANOVA, including normality, homogeneity of variances, and independence were tested and satisfied. For the water loss assessment, bead weights were the response variables. The significance of the mean values was separated ($P < 0.05$) with Tukey's Highest Significant Difference. For the MANOVA, the dependent variables were bead weight measured at 24, 48, and 72 h. Measurements were analysed as fixed time points rather than repeated measures; therefore, sphericity assumptions were not applicable.

3. Results

3.1. Visual and structural limitations

Films produced with SA and no plasticiser appeared as polypropylene-like films, being fully transparent. When cellulose or sugars were added to the solution, this also produced polypropylene-like films due to their transparency.

Films with plasticiser combinations which consistently generated non-homogeneous films were excluded from further studies. Examples of non-homogeneous film characteristics included: reduced transparency to the point where it could not be seen through with the naked eye; and inconsistent plasticiser formation within the film or on the film surface. Film visual examples are seen in Supplementary Fig. S1.

Film microcracks were also a prevalent problem, frequently observed in films containing glycerol as the plasticiser, with 4% (*w/v*) glycerol resulting in microcrack formation most frequently (see Fig. 2a). Microcracks were present in other polyol films including 4% (*w/v*) mannitol and 1% (w/v) thymol; film combinations with detected microcracks were removed from further study. Films containing oils as a plasticiser resulted in lower clarity, producing a film with oil vesicles clearly seen by microscopy (Fig. 2b) and a visually decreased quality (Supplementary Fig. S1) but were retained in the study for the thickness and transparency study following initial screening (3.2). Films containing 1% (w/v) glycerol did not form microcracks and were included in subsequent property trials. Films containing celluloses and carbohydrates did not exhibit any visual or structural impairments and were also included in later studies.

For assessing transparency, the variation of absorbance at 600 nm compared to a blank control was used as a measure of opacity. Here, plasticiser incorporation resulted in a range of absorbance changes, from 0.043 to 0.281. Fig. 3 shows the range of absorbances at 600 nm, colour-coded to differentiate between plasticiser types. The majority of the cellulose and carbohydrate-containing films grouped around the reference film (2.5% (*w/v*) SA) absorbance (0.069) were not significantly different in absorbance to the reference or each other. Polyols, cellulose, and films containing a combination of two plasticisers had absorbance values both above and below the reference value. Films containing three plasticisers had absorbances of 0.056–0.281, almost the full range, though three of the four tested were in the highest quartile, including the highest absorbance value (0.281, for the SA film containing 2% (*w/v*) fructose, 4% (w/v) xylose and 5% (w/v) CNC). Also giving high absorbance values, indicating greater opacity, were films containing rapeseed oil (0.194), vegetable oil (0.186) and the two plasticiser combination of 4% (*w/v*) xylitol and 5% (w/v) CNC, (0.135).

3.2. Film thickness

Film thicknesses varied between 0.022 mm and 0.149 mm (Fig. 4), again colour-coded by plasticiser type. The SA control (2.5% SA only) was among the thinnest of the films (0.028 mm) with only a 5% (w/v) CNC film (0.026 mm) and the 2% (w/v) SA film (0.022 mm) thinner (Fig. 4); which was also significantly lower ($P < 0.05$) than the 2.5% (w/v) SA film.

Of the films assessed, almost all were thicker than the control film made with just 2.5% (w/v) SA. This difference was statistically significant for the thirteen thickest films ($P < 0.001$, F-stat = 14.13, df = 102, $n = 3$). Five of these films contained a polyol, another five contained the highest concentration of cellulose plasticiser (10%) and the remaining three contained oils.

Sugar carbohydrate plasticiser thicknesses varied between 0.030 and 0.096 mm, with an average of 0.057 mm. Oils acting as plasticisers exhibited less variation (0.029–0.071 mm) and were thinner on average (mean thickness 0.049 mm).

The addition of polyols as plasticisers resulted in thicker films on average being created (0.073 mm) than the SA control and other single plasticiser-containing films. Relatedly, by including polyols as part of a plasticiser combination, thicker films were also produced than if the polyol were not included.

The incorporation of three plasticisers into a single SA film, as detailed in Table 2, resulted in significantly thicker films than in the SA control, with thicknesses ranging between 0.067 and 0.122 mm. However, crucially, all mean film thicknesses remained well below the standard for classification as a thin plastic film, 0.25 mm [31].

3.3. Tensile and elongation to break property assessments

SA films containing different forms or concentrations of plasticiser resulted in a change in the mechanical properties of the film. Tensile strength was quantified as tensile stress at maximum force (MPa), while film elasticity was assessed by elongation to break (%). A combination of different plasticisers has also shown to impact the resultant film's mechanical properties, as summarised in Fig. 5 with the mechanical property change predominantly either to an increased tensile strength or to greater elongation capacity compared to SA alone, with only the 0.5%

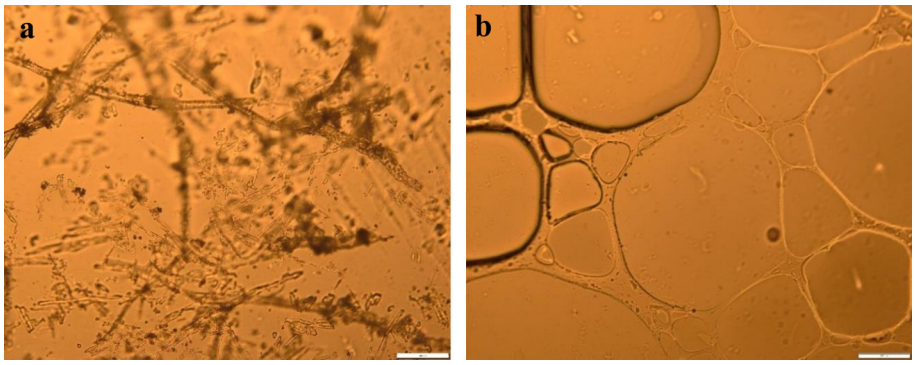

Fig. 2. Microscope images of sodium alginate films containing non-suitable plasticisers at x40 magnification. a = sodium alginate film containing 4% (w/v) glycerol, containing microcracks within it. b = sodium alginate film containing 0.4% (w/v) vegetable oil, showing oil vesicles affecting film consistency.

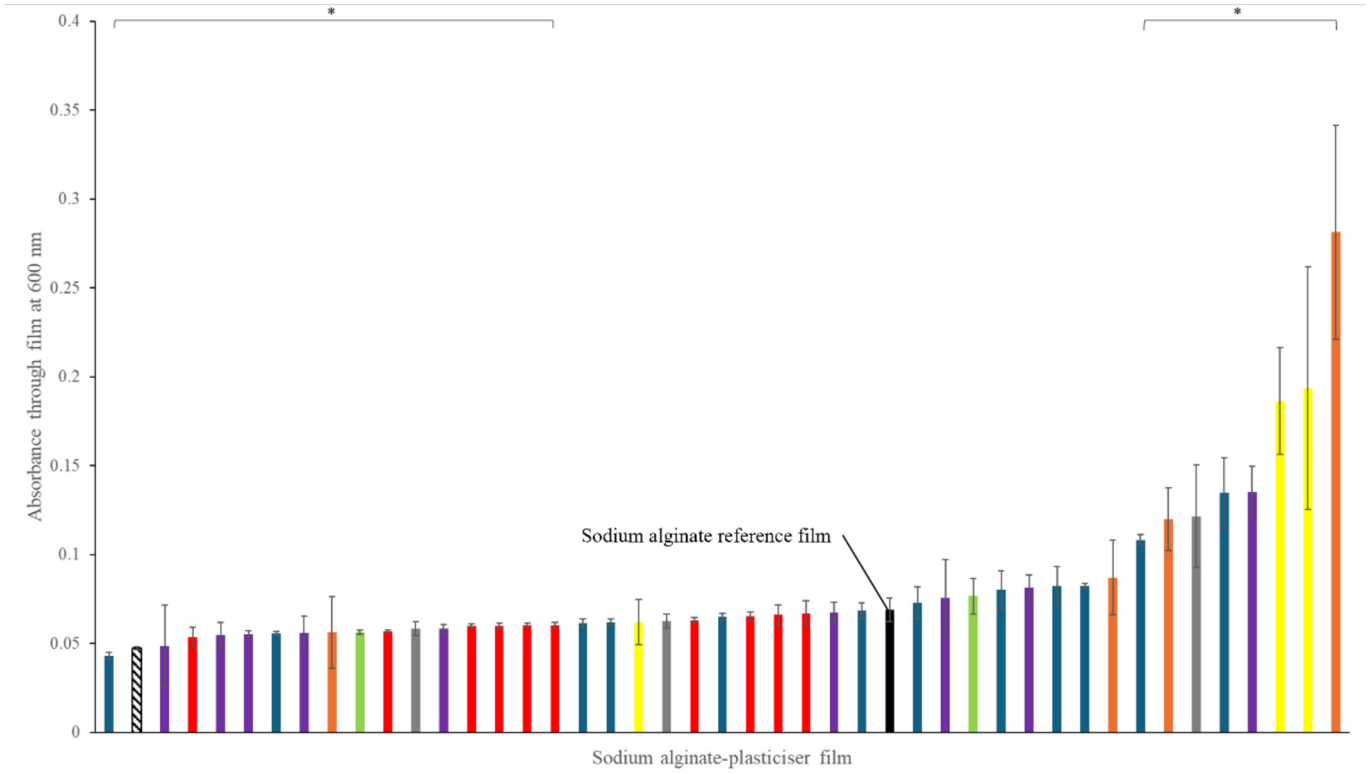

Fig. 3. Sodium alginate-based films containing plasticisers ranked by absorbance at 600 nm indicating transparency. Sodium alginate at 2.5% (w/v), the reference = black; sodium alginate with calcium chloride = black/white striped; Sodium alginate 'others' (2% and 3% w/v) = grey. Remainder = sodium alginate and plasticiser, where carbohydrates = red; oils = yellow; polyols = green; celluloses = blue; 2 plasticisers = violet; 3 plasticisers = orange. * Significantly different from sodium alginate reference absorbance ($P < 0.05$). n = 3, error bars = SEM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(*w/v*) mannose, 5% (*w/v*) CNC SA film having both a comparatively reduced tensile strength and reduced elongation. Three-plasticiser films containing xylitol were not measured for these parameters due to the properties of the films themselves. With high adhesion properties, they would not sit equally on the grips and manipulation to try to get them to led to the films being stretched or torn before analysis could be conducted, losing their integrity.

Celluloses, when used as a plasticiser, produced films with high strength, up to 80 MPa and consistently between 50 and 75 MPa. Films containing cellulose and a second plasticiser typically increased tensile strength more than films containing only that second plasticiser (e.g. SA films containing 2% (*w/v*) fructose or 1% (w/v) glycerol increased in tensile strength when 5% (w/v) CNC was also included). There were no notable differences in elongation when celluloses alone were incorporated compared to the control film. However, for some two plasticiser combinations of plasticiser films, a change in both mechanical properties was seen compared to the single plasticiser SA alternatives. For example, the 1% (*w/v*) glycerol, 5% (w/v) CNC SA film with a tensile strength of 25.2 MPa and an elongation to break of 31.4% had a distinct changes in strength and elongation properties compared to both SA single-plasticiser alternatives (1% (*w/v*) glycerol SA film had the mechanical properties of 11.1 MPa and 37.1% elongation to break; 5% (w/v) CNC SA film had 55.8 MPa and 5.8% elongation respectively).

When polyols were used as plasticisers, this increased the elastic traits to create a film of great elongation compared to the other films; up to 137% elongation, meaning that the initial 35 mm gauge was extended by a further 48 mm before breakage. This is compared to the 5.1% elongation before break seen with 2.5% (*w/v*) alginate only. This

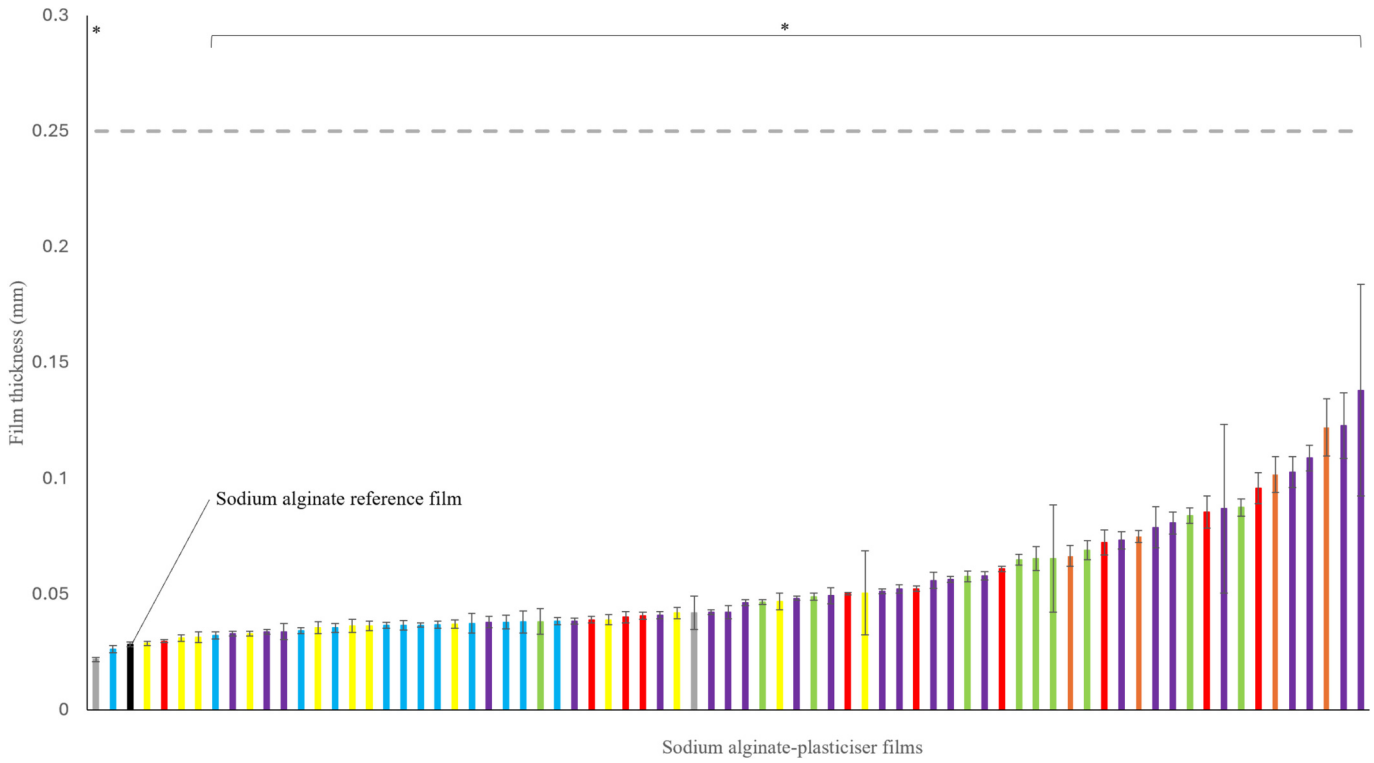

Fig. 4. Sodium alginate-based films containing plasticisers ranked by thickness. Sodium alginate at 2.5% (w/v), the reference = black; sodium alginate 'others' (2% and 3%) = grey. Remainder = sodium alginate and plasticiser, where carbohydrates = red; oils = yellow; polyols = green; celluloses = light blue; 2 plasticisers = violet; 3 plasticisers = orange. Dashed line = maximum thickness required to be classified as a plastic film. * Significantly different from sodium alginate reference ($P < 0.05$). n = 5 measurements × 3 replicates, error bars = SEM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increase in extension, however, was paired with a low degree of tensile strength (all polyols <12 MPa compared to 42 MPa for 2.5% (w/v) SA only).

Carbohydrates as plasticisers resulted in a balanced mixture of mechanical properties, with tensile stress and displacement scores around 30 MPa and 8% elongation, respectively. The elongation capacity is less than half of the polyols elongation to break, and just over half the tensile strength capabilities of the celluloses, generating a stronger, more elastic film.

Tensile stress at maximum force and displacement at maximum force showed significant differences between the groups assessed including a significant difference when compared to 2.5% (w/v) SA. This occurred with the displacement at maximum force ($P < 0.001$, F-stat = 45.64) and tensile stress at maximum force ($P < 0.001$, F-stat = 24.73, df = 27, $n = 6$) measurements. Elongation measurements showed film blends containing any number of plasticisers (1–3) added to the alginate preparation generated some films which were significantly more extendable prior to break than the control film. Tensile stress at maximum force showed films containing one, two and three plasticisers had eight, five and zero number of significantly stronger films respectively; and two, three, and two weaker films, respectively. Collectively this shows that the inclusion of plasticisers creates films which can be significantly more extendable and stronger, or weaker, than the SA films alone; depending on the plasticiser used.

3.4. Water loss assessment

A variety of single and combined plasticisers were produced in liquid SA solution, then dripped into 1% calcium chloride solution to form equal-sized beads which lost internal water (measured as weight loss) over time. Weight loss in this way indicates film barrier potential and showed overall that a more complex film structure increases water resistance. Water loss was greater in the first 24 h than in the following time periods for all film beads (Fig. 6), though all the beads lost water over between each time period assessed. Film beads containing one plasticiser had the lowest average weights through all the time points, indicating a lower ability to bind water initially; and films containing three plasticisers had the highest average weights through all the time points indicating more water was included and retained in the beads at each assessment compared to the control film beads. For weight loss at 24 h, no significant differences were seen in the number of plasticisers used. For 48 h there was a significant difference between single and two plasticisers ($p < 0.05$). At 72 h, films with single plasticisers showed a significantly lower rate of weight loss than those with two or three plasticisers ($p < 0.05$). No significant difference was observed between two- and three-plasticiser treatments.

4. Discussion

A key characteristic of alginate-based films is their high transparency [15,17]. In food packaging, transparency is vital for many films to see the contained food product. Variation in the absorbance values for the films generated in this study was due to the effect of specific plasticisers added to the SA solution before casting, as seen by the reduced absorbance values (Fig. 3) and visual quality decrease (Supplementary Fig. S1) for oil additions; with absorbance values increasing or decreasing based on the plasticiser concentration. Although films were dried at 40 °C for 24 h, a condition commonly used in alginate film preparation to allow controlled solvent evaporation while minimising film cracking and excessive crystallinity development [34]; microcracks did occur with high glycerol content films. Here, the drying process caused phase separation of the polyol from the water-based film, mimicking other studies with alginate-glycerol films [35]; these were removed from subsequent studies.

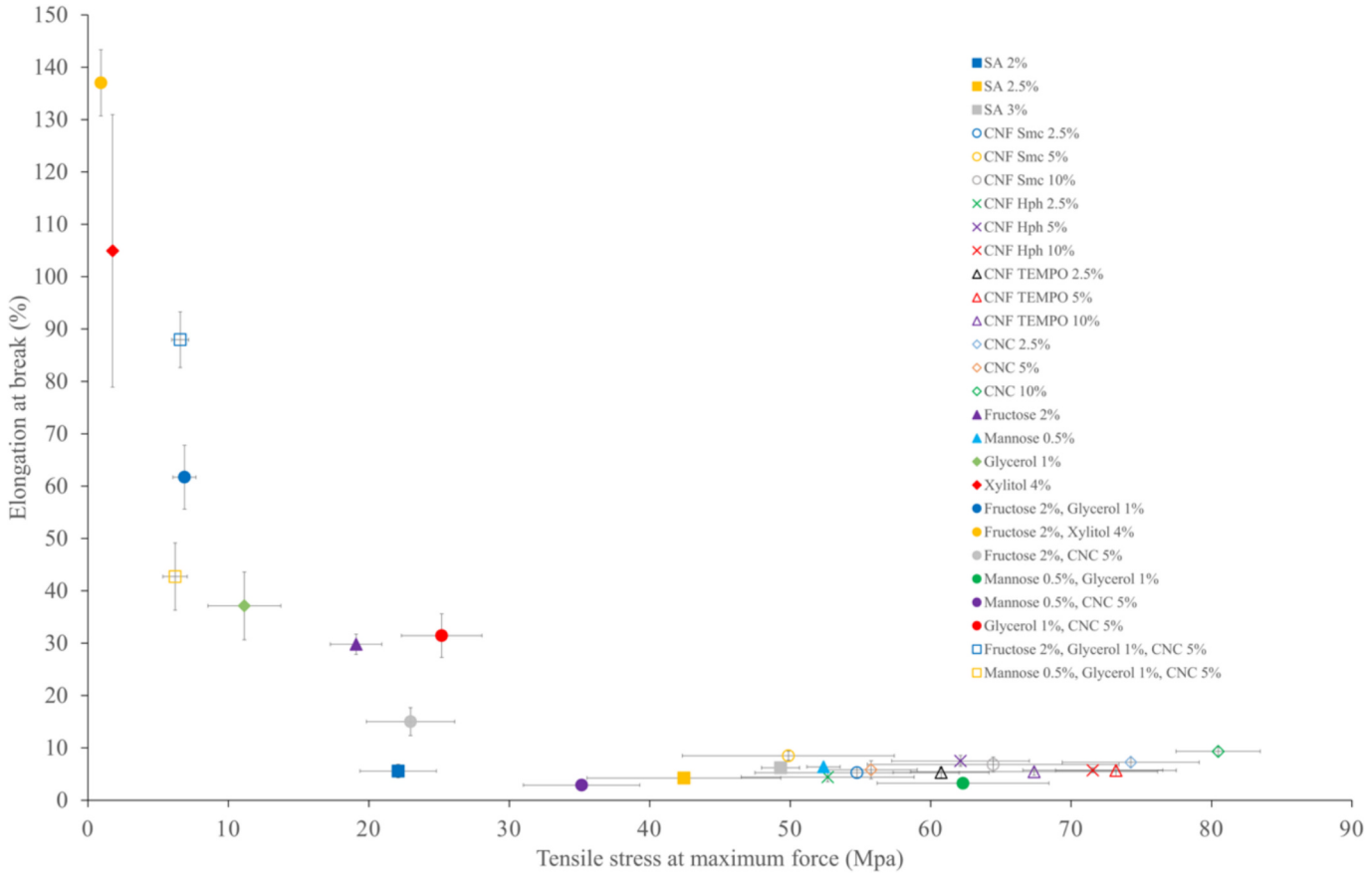

Fig. 5. Elongation to break (%) and Tensile stress at maximum force within different sodium alginate and plasticiser-based films. $n = 5$ per plasticiser type and concentration, error bars show standard error. SA = 2.5% (w/v) sodium alginate only, rest SA and plasticisers: CNF smc - Cellulose nanofibrils supermass colloider, CNF Hph - Cellulose nanofibrils high-pressure homogeniser, CNF TEMPO - Cellulose nanofibrils prepared using 2,2,6,6-tetramethylpiperidine-1-oxyl, CNC - Cellulose nanocrystals.

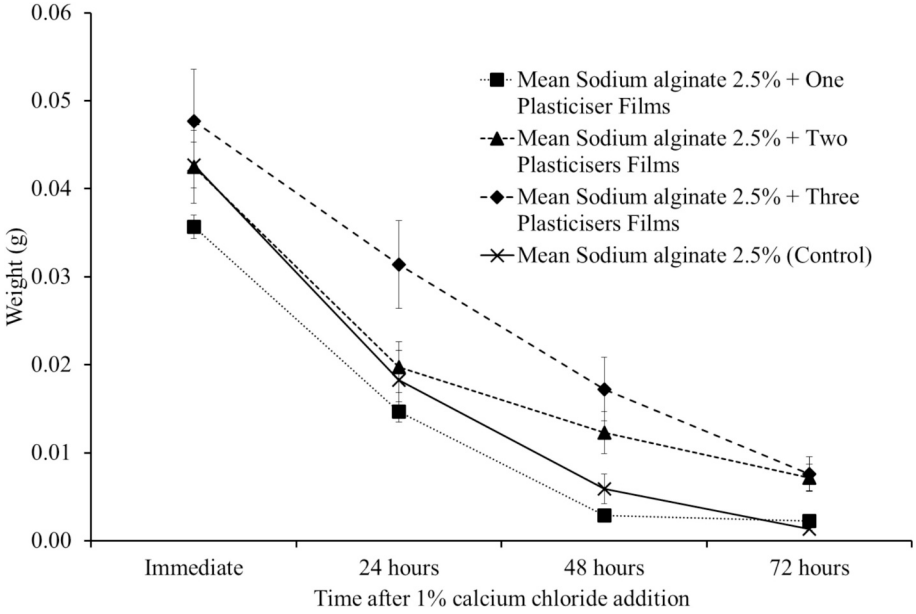

Fig. 6. Water loss assessment as comparison of average plasticiser film type (2.5% (w/v) sodium alginate beads containing one, two or three plasticisers) after crosslinking using a 1% (w/v) calcium chloride solution over time. $n = 5$, error bars show standard error.

The incorporation of plasticisers into a SA film solution also increases intermolecular bonding, offering opportunities for additional binding of water molecules [36] and viscosity [37]. This in turn results in more water being retained in the film [37], generating a thicker film as the

plasticiser concentration or quantity is increased. This is seen in Fig. 4, with only a lower-concentration SA film (2% (*w/v*)) and 5% (w/v) CNC being thinner than the SA-only film control; and films with multiple plasticisers dominating the range of thicker films. CNC has shown previous capabilities to reduce film thickness due to its strong interaction between CNC nanoparticles and polymer structures, showing a more efficient molecular arrangement [38] which created this decrease in film thickness. With the addition of the other, more polar plasticisers, increased hydrogen bonds are formed between these molecules and water molecules; and to the alginate polymer chain [35,39], both increasing the film thickness. However, all of the SA-based films were consistent with being thinner than the maximum required thickness for being classified as a plastic film (0.25 mm; Fig. 4) according to ASTM D883 [40]. This result means that all films in this study are suitable for consideration as a thin bioplastic film.

Both mechanical properties being assessed (tensile strength and elongation to break) were also affected through the addition of plasticisers to the film mix. For the majority of the plasticisers trialled (celluloses, polyols and plasticiser combinations) the mechanical property change was predominantly either to an increased tensile strength or to greater elongation. When cellulose was incorporated into an SA film, this resulted in a film able to resist higher tensile stress than as an SA film alone. Cellulose addition is known to increase tensile strength of SA films due to its fibrous contents [2], [14–16], but this has a secondary effect of brittleness, with elongation remaining as it was or decreasing slightly for these films.

The use of polyols in a SA film causes the film to become more extendable and elastic prior to break [28]. This occurs because the plasticiser tends to create hydrogen bonds through the hydroxyl groups present on neighbouring polymeric molecules [41]. The use of sucrose and mannose increased the tensile strength in SA-based films in a similar manner to fructose addition as described by Tong et al. [28]. Carbohydrates such as fructose and mannose contain multiple hydroxyl groups, which can act as intermolecular bridges by binding with carboxylate and hydroxyl groups on the alginate chain. Their small molecular size means that they can increase the free volume between the alginate chains, reducing the intermolecular forces between the chains directly; thus increasing the mobility of the polymers and improving its elongation capacity [42]. However, when three plasticisers were used for film preparation, no significantly stronger films were identified. With both three-plasticiser combinations measured, each containing a carbohydrate sugar, 1% (*w/v*) glycerol and 5% (w/v) CNC, these films had a decrease in tensile strength compared to their two-plasticiser alternatives (sugar x glycerol; sugar x CNC; glycerol x CNC). The causes of this decrease are considered to be a) the additional water contained within these thicker films, which acts as a plasticiser to the alginate itself, reducing alginate chain bond formation, as seen in [43]; and b) the increased proportion of plasticisers in the films which form hydrogen bonds to the alginate, diminishing the strength of the inter-polymer chain bonds, matching that in [44]. As a secondary property, by providing increased mobility between the polymer chains, the films frequently demonstrate greater elongation [42].

Separate comparison of plasticiser type is required to further breakdown the direct causation of tensile strength and elongation value increase; however, when a plasticiser typically improved elongation in SA on its own, this property was also observed when the same plasticiser was combined with a tensile strength improving plasticiser in SA. This tends to be at the detriment of tensile strength in the combined film e.g. glycerol and CNC individually improved elongation properties and tensile strength respectively but when combined only had an elongation enhancement and reduced tensile strength. One possible explanation for this behaviour is that glycerol disrupts the hydrogen-bonding network between cellulose nanocrystals and the alginate matrix, thereby reducing the reinforcing efficiency of CNC. At the same time, glycerol increases alginate chain mobility by acting as a low molecular weight plasticiser, promoting chain slippage and increased ductility at the expense of tensile strength. When glycerol increases the free volume between the CNC and the alginate network, this can reduce the effective stress transfer seen when only CNC is present [42].

Cellulose nanocrystals particles are short and rod-shaped, whereas cellulose nanofiber particles are composed of longer fibres; so though both have the same chemical composition they differ in morphology, particle size and crystallinity; with further variation potentially arising depending on the method of synthesis [45]. The morphology provides all cellulose forms their increased strength characteristics when incorporated into films, with the inclusion of cellulose fibrils giving the resultant films greater tensile strength than those with the cellulose nanocrystals.

The water loss studies, giving indications regarding water vapour permeability (WVP), are commonly conducted on biopolymer films where WVP typically decreases when more plasticiser is added [46]. It is further reported that measurement temperature increases can cause the WVP to decrease [24]. As a higher weight was maintained through the initial time points in this study for beads produced from SA with three plasticiser combinations of carbohydrate (2% (*w/v*) fructose, 0.5% (w/v) mannose), polyol (1% (w/v) glycerol, 4% (w/v) xylitol) and 5% (w/v) CNC, it suggests that the more plasticiser content in the film, the more water loss is reduced [36]. This same result was not shown by the beads produced from SA with combinations of two plasticisers; or in beads produced from SA and a single plasticiser, where a lower initial weight of water in the beads resulted in a similar weight of water loss over the same time period. It has been suggested that plasticiser molecular weight can be an important factor in plasticiser embedding into the alginate network [36]. The best plasticiser combination for water retention, indicating water barrier potential in this study, was when using three plasticisers; however, not including any plasticisers resulted in a stronger interaction between SA and calcium chloride, enabling better crosslinking. This suggests that the increased resistance to water might be because of plasticiser quantity in the film over plasticiser type. This is reflected in the literature where the same result is seen for specific plasticisers like glycerol but not in others like sorbitol [36]. SA's consistent carboxyl group presence enables divalent ion binding [47]; however, these groups must be free and could be partially impeded by some of the plasticisers, resulting in a decrease in water retention over time [16]. This was shown at the 72 h sampling point where water loss was attributed to its evaporation through the film surface.

5. Conclusions

Sodium alginate films present a unique ability to create transparent, strong and extendable films consistent with the physical characteristics of oil-derived plastics. The addition of other chemicals, such as plasticisers, enhances film strength and elongation properties and can alter the film's transparency or thickness. For example, using 10% (*w/v*) cellulose nanocrystals with a 2.5% (w/v) SA will produce a film nearly twice as strong (80.5 MPa) as 2.5% (w/v) SA film alone (42.4 MPa). Conversely, a combination of 2% (w/v) fructose and 4% (w/v) xylitol in a 2.5% SA solution will produce a film over x30 more elastic (137.0% elongation before break) than a 2.5% (w/v) SA solution alone (4.2% elongation before break). The incorporation of bio-derived plasticisers such as cellulose and polyols significantly enhances the mechanical performance of SA films without compromising transparency or thickness. Future work should focus on quantitative biodegradation testing under standard industrial composting conditions to better align material performance with functional use and end-of-life requirements.

CRediT authorship contribution statement

Luke Ford-Barnett: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Natalia Falagán:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Jessica M.M. Adams:** Writing

– review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. A declaration of competing interests form has been attached to this submission.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.algal.2026.104658.

Data availability

The datasets generated during and/or analysed during the study have been deposited in Mendeley data, https://data.mendeley.com/datasets/n9mz7bhfwv/1

References

[1] M. Padervand, E. Lichtfouse, D. Robert, C. Wang, Removal of microplastics from the environment. A review, Environ. Chem. Lett. 18 (3) (2020) 807–828, https://doi.org/10.1007/s10311-020-00983-1.
[2] PlasticsEurope, Plastics – The Fast Facts 2023, Accessed: Jul. 16, 2024. [Online]. Available: https://www.plasticseurope.org/en/resources/publications, 2023.
[3] S. Ishimwe, Bioplastics market development update, in: European Bioplastics e.V, 2023. Accessed: May 15, 2025. [Online]. Available: https://www.european-bioplastics.org/bioplastics-market-development-update-2023-2/.
[4] L. Serrano-Aguirre, M.A. Prieto, Can bioplastics always offer a truly sustainable alternative to fossil-based plastics? Microb. Biotechnol. 17 (4) (2024) e14458 https://doi.org/10.1111/1751-7915.14458.
[5] N.I. Ibrahim, F.S. Shahar, M.T.H. Sultan, A.U.M. Shah, S.N.A. Safri, M.H. Mat Yazik, Overview of bioplastic introduction and its applications in product packaging, Coatings 11 (11) (2021) 1423, https://doi.org/10.3390/coatings11111423.
[6] N. Jabeen, I. Majid, G.A. Nayik, Bioplastics and food packaging: a review, Cogent Food Agric. 1 (1) (2015) 1117749, https://doi.org/10.1080/23311932.2015.1117749.
[7] G.B. Bureau, 5 Types of Bioplastics: Starch, Cellulose, Protein, Organic, Aliphatic Polyesters, Green Business Bureau, 2022. Accessed: Jun. 23, 2022. [Online]. Available: https://greenbusinessbureau.com/green-practices/products/5-types-of-bioplastics-starch-cellulose-protein-organic-aliphatic-polyesters/.
[8] B. Immirzi, G. Santagata, G. Vox, E. Schettini, Preparation, characterisation and field-testing of a biodegradable sodium alginate-based spray mulch, Biosyst. Eng. 102 (4) (2009) 461–472, https://doi.org/10.1016/j.biosystemseng.2008.12.008.
[9] B. Deepa, E. Abraham, L. Pothan, N. Cordeiro, M. Faria, S. Thomas, Biodegradable nanocomposite films based on sodium alginate and cellulose Nanofibrils, Materials 9 (1) (2016) 50, https://doi.org/10.3390/ma9010050.
[10] T. Iwata, Biodegradable and bio-based polymers: future prospects of eco-friendly plastics, Angew. Chem. Int. Ed. 54 (11) (2015) 3210–3215, https://doi.org/10.1002/anie.201410770.
[11] X. Ren, Biodegradable plastics: a solution or a challenge? J. Clean. Prod. 11 (1) (2003) 27–40, https://doi.org/10.1016/S0959-6526(02)00020-3.
[12] M.A. Fawzy, M. Gomaa, A.F. Hifney, K.M. Abdel-Gawad, Optimization of alginate alkaline extraction technology from Sargassum latifolium and its potential antioxidant and emulsifying properties, Carbohydr. Polym. 157 (2017) 1903–1912, https://doi.org/10.1016/j.carbpol.2016.11.077.
[13] A.A.A. Alejandro Hurtado, V. Aljabali, M.M. Mishra, Tambuwala, Á. Serrano-Aroca, Alginate: enhancement strategies for advanced applications, Int. J. Mol. Sci. (2022), https://doi.org/10.3390/ijms23094486.
[14] A.D.A. Bin Abu Sofian, H.R. Lim, S. Manickam, W.L. Ang, P.L. Show, Towards a sustainable circular economy: algae-based bioplastics and the role of internet-of-things and machine learning, ChemBioEng. Rev. (2023) cben.202300028, https://doi.org/10.1002/cben.202300028.
[15] E.T. Kostas, J.M.M. Adams, H.A. Ruiz, G. Durán-Jiménez, G.J. Lye, Macroalgal biorefinery concepts for the circular bioeconomy: a review on biotechnological developments and future perspectives, Renew. Sust. Energ. Rev. 151 (2021) 111553, https://doi.org/10.1016/j.rser.2021.111553.
[16] G.T. Grant, et al., Biological interactions between polysaccharides and divalent cations: the egg-box model, FEBS Lett. 32 (1) (1973) 195–198, https://doi.org/10.1016/0014-5793(73)80770-7.
[17] Alan H. King, Brown seaweed extracts (alginates), in: Food hydrocolloids, CRC Press, Place of publication not identified, 2019.
[18] S.N. Pawar, K.J. Edgar, Alginate derivatization: a review of chemistry, properties and applications, Biomaterials 33 (11) (2012) 3279–3305, https://doi.org/10.1016/j.biomaterials.2012.01.007.
[19] K. Ingar Draget, K. Østgaard, O. Smidsrød, Homogeneous alginate gels: a technical approach, Carbohydr. Polym. 14 (2) (1990) 159–178, https://doi.org/10.1016/0144-8617(90)90028-Q.
[20] G. Kaletunc, A. Nussinovitch, M. Peleg, Alginate Texturization of highly acid fruit pulps and juices, J. Food Sci. 55 (6) (1990) 1759–1761, https://doi.org/10.1111/j.1365-2621.1990.tb03622.x.
[21] J.M.M. Adams, S.M. Morris, L. Steege, J. Robinson, C. Bavington, Food-grade biorefinery processing of macroalgae at scale: considerations, observations and recommendations, JMSE 9 (10) (2021) 1082, https://doi.org/10.3390/jmse9101082.
[22] A.E. Pavlath, A. Voisin, G.H. Robertson, Pectin-based biodegradable water insoluble films, Macromol. Symp. 140 (1) (1999) 107–113, https://doi.org/10.1002/masy.19991400112.
[23] Inyoung Choi, Youngwoo Lee, Ji Sou Lyu, Jung-Soo Lee, J. Han, Characterization of ionically crosslinked alginate films: effect of different anion-based metal cations on the improvement of water-resistant properties, Food Hydrocoll. (2022), https://doi.org/10.1016/j.foodhyd.2022.107785.
[24] J.-W. Rhim, Physical and mechanical properties of water resistant sodium alginate films, LWT Food Sci. Technol. 37 (3) (2004) 323–330, https://doi.org/10.1016/j.lwt.2003.09.008.
[25] M.M. Abe, M.C. Branciforti, M. Brienzo, Biodegradation of hemicellulose-cellulose-starch-based bioplastics and microbial polyesters, Recycling 6 (1) (2021) 22, https://doi.org/10.3390/recycling6010022.
[26] T. Huq, et al., Nanocrystalline cellulose (NCC) reinforced alginate based biodegradable nanocomposite film, Carbohydr. Polym. 90 (4) (2012) 1757–1763, https://doi.org/10.1016/j.carbpol.2012.07.065.
[27] A.D. Godwin, Plasticizers, in: Applied Plastics Engineering Handbook, Elsevier, 2011, pp. 487–501, https://doi.org/10.1016/B978-1-4377-3514-7.10028-5.
[28] Q. Tong, Q. Xiao, L.-T. Lim, Effects of glycerol, sorbitol, xylitol and fructose plasticisers on mechanical and moisture barrier properties of pullulan-alginate-carboxymethylcellulose blend films, Int. J. Food Sci. Technol. 48 (4) (2013) 870–878, https://doi.org/10.1111/ijfs.12039.
[29] H.M.C. Azeredo, U.S. Magalhães, S.A. Oliveira, H.L. Ribeiro, E.S. Brito, M.R. De Moura, Tensile and water vapour properties of calcium-crosslinked alginate-cashew tree gum films: alginate/cashew tree gum flims, Int. J. Food Sci. Technol. 47 (4) (2012) 710–715, https://doi.org/10.1111/j.1365-2621.2011.02897.x.
[30] J. Zhao, Y. Wang, C. Liu, Film transparency and opacity measurements, Food Anal. Methods (2022), https://doi.org/10.1007/s12161-022-02343-x.
[31] D20 Committee, Guide for Determination of Thickness of Plastic Film Test Specimens, ASTM International, 2021, https://doi.org/10.1520/D6988-21.
[32] J.-W. Rhim, A. Gennadios, C.L. Weller, Carole Cezeirat, M.A. Hanna, Soy protein isolate–dialdehyde starch films, Ind. Crop. Prod. 8 (3) (1998) 195–203, https://doi.org/10.1016/s0926-6690(98)00003-x.
[33] D20 Committee, Test Method for Tensile Properties of Thin Plastic Sheeting, ASTM International, 2018, https://doi.org/10.1520/D0882-18.
[34] F. Othman, S.N. Idris, N.A.H. Ahmad Nasir, M.A. Nawawi, Preparation and characterization of sodium alginate-based edible film with antibacterial additive using lemongrass oil, JSM 51 (2) (2022) 485–494, https://doi.org/10.17576/jsm-2022-5102-13.
[35] C. Gao, E. Pollet, L. Avérous, Properties of glycerol-plasticized alginate films obtained by thermo-mechanical mixing, Food Hydrocoll. 63 (2017) 414–420, https://doi.org/10.1016/j.foodhyd.2016.09.023.
[36] V. Jost, K. Kobsik, M. Schmid, K. Noller, Influence of plasticiser on the barrier, mechanical and grease resistance properties of alginate cast films, Carbohydr. Polym. 110 (2014) 309–319, https://doi.org/10.1016/j.carbpol.2014.03.096.
[37] G.M.D. Silva, et al., Fish gelatin edible films with prebiotics and structuring polysaccharides for probiotic delivery: physicochemical properties, viability, and in vitro gastrointestinal release, Polysaccharides 6 (3) (2025) 79, https://doi.org/10.3390/polysaccharides6030079.
[38] H. Etemadi, N. Ghasemian, H. Khezraqa, S. Tozihi, S.M. Sajjadi, O. Ahmadi, Evaluating the impact of cellulose nanocrystals on the performance of polycarbonate thin-film nanocomposite membranes for treating oily wastewater, Asia Pac. J. Chem. Eng. (2026) e70215, https://doi.org/10.1002/apj.70215.
[39] A. Syarifuddin, N. Haliza, N. Izzah, M.M. Tahir, A. Dirpan, Physical, mechanical, barrier, and optical properties of Sodium Alginate/Gum Arabic/Gluten edible films plasticized with glycerol and sorbitol, Foods 14 (7) (2025) 1219, https://doi.org/10.3390/foods14071219.
[40] D20 Committee, Terminology Relating to Plastics, ASTM International, 2023, https://doi.org/10.1520/D0883-22.
[41] J.M. Aguilar, C. Bengoechea, E. Pérez, A. Guerrero, Effect of different polyols as plasticizers in soy based bioplastics, Ind. Crop. Prod. 153 (2020) 112522, https://doi.org/10.1016/j.indcrop.2020.112522.
[42] Z. Eslami, S. Elkoun, M. Robert, K. Adjallé, A review of the effect of plasticizers on the physical and mechanical properties of alginate-based films, Molecules 28 (18) (2023) 6637, https://doi.org/10.3390/molecules28186637.
[43] S. Barbut, B.A. Harper, Dried ca-alginate films: effects of glycerol, relative humidity, soy fibers, and carrageenan, LWT 103 (2019) 260–265, https://doi.org/10.1016/j.lwt.2019.01.004.

[44] P. Kiattijiranon, R.A. Auras, A. Sane, Enhanced functional properties for packaging applications using sodium alginate/starch bilayer and multilayer films, ACS Appl. Polym. Mater. 6 (8) (2024) 4642–4650, https://doi.org/10.1021/acsapm.4c00224.
[45] T.W. Kurniawan, H. Sulistyarti, B. Rumhayati, A. Sabarudin, Cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs) as adsorbents of heavy metal ions, J. Chem. 2023 (2023) 1–36, https://doi.org/10.1155/2023/5037027.
[46] N. Gontard, S. Guilbert, J. Cuq, Water and glycerol as plasticizers affect mechanical and water vapor barrier properties of an edible wheat gluten film, J. Food Sci. 58 (1) (1993) 206–211, https://doi.org/10.1111/j.1365-2621.1993.tb03246.x.
[47] S.K. Papageorgiou, E.P. Kouvelos, E.P. Favvas, A.A. Sapalidis, G.E. Romanos, F. K. Katsaros, Metal–carboxylate interactions in metal–alginate complexes studied with FTIR spectroscopy, Carbohydr. Res. 345 (4) (2010) 469–473, https://doi.org/10.1016/j.carres.2009.12.010.
[48] N. Kanjanamosit, C. Muangnapoh, M. Phisalaphong, Biosynthesis and characterization of bacteria cellulose-alginate film, J. Appl. Polym. Sci. 115 (3) (2010) 1581–1588, https://doi.org/10.1002/app.31138.
[49] B. Deepa, et al., Nanofibrils vs nanocrystals bio-nanocomposites based on sodium alginate matrix: an improved-performance study, Heliyon 6 (2) (2020), https://doi.org/10.1016/j.heliyon.2020.e03266.
[50] F. Bagheri, M. Radi, S. Amiri, Drying conditions highly influence the characteristics of glycerol-plasticized alginate films, Food Hydrocoll. 90 (2019) 162–171, https://doi.org/10.1016/j.foodhyd.2018.12.001.
[51] J.W. Rhim, L.F. Wang, S.I. Hong, Preparation and characterization of agar/silver nanoparticles composite films with antimicrobial activity, Food Hydrocoll. 33 (2) (2013) 327–335, https://doi.org/10.1016/j.foodhyd.2013.04.002.

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