Sustainable
Food Technology

ROYAL SOCIETY
OF CHEMISTRY

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/d5fb00866b

Ladakhi wild apricot kernel protein-based films: effect of protein and plasticizers on the mechanical, moisture interaction and optical properties

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Received 31st October 2025
Accepted 8th May 2026

DOI: 10.1039/d5fb00866b

rsc.li/susfoodtech

In the present study, an attempt was made to utilize the de-oiled wild apricot kernels from the Ladakh region of India to produce packaging films. Apricot kernel protein isolate (AKPI) films were developed using the solution casting method and characterized for their properties, which varied depending on the protein concentration and the type and level of plasticizer used. The amino acid profile of AKPI revealed the predominant presence of negatively charged amino acids, particularly glutamic and aspartic acids. A minimum of 8% protein was essential to produce wild apricot kernel protein-based films with good properties. Sorbitol-plasticized films exhibited significantly higher tensile and seal strength ($p < 0.05$) than glycerol-plasticized films. In contrast, glycerol-plasticized films demonstrated higher elongation at break. Sorbitol-plasticized films also showed significantly lower WVTR values than glycerol-plasticized films. Films with higher protein concentrations exhibited increased L^*, a^*, and b^* values, which signify greater light scattering and enhanced redness and yellowness. Sorbitol-plasticized films typically had lower L^* and a^* values and higher b^* values than glycerol-plasticized films. Principal component analysis (PCA) identified three principal components that collectively explained 94.24% of the data variance, indicating the significant influence of the tensile strength, seal strength, swelling ratio, and moisture content on the properties of AKPI films. Hierarchical cluster analysis (HCA) further grouped the films based on sorbitol or glycerol plasticization, revealing distinct clusters and patterns in the dataset. The study demonstrated the effective utilization of de-oiled apricot kernels for producing potentially biodegradable materials, which could be further explored for food and other packaging applications.

Sustainability spotlight

Valorization of stone fruit enables the transformation of agricultural byproducts into sustainable resources through their conversion into biodegradable packaging films. This research study explores the sustainable use of de-oiled wild apricot kernels from the Ladakh region of India to extract protein, which is then successfully converted into biodegradable packaging films. The effects of plasticizers, namely, glycerol and sorbitol, on the mechanical, moisture interaction, and optical properties of apricot kernel protein isolate (AKPI) are examined. Sorbitol-plasticized biodegradable films show better mechanical properties than glycerol-plasticized films. Converting AKPI into biodegradable films supports a circular economy and offers a green packaging solution.

1. Introduction

Plastics have become the dominant choice for packaging due to their unique properties, including their durability, excellent mechanical and barrier properties, lightweight nature, corrosion resistance, and favorable cost–benefit ratios.[1,2] The global plastic production was about 320 million tons in 2020 and is expected to rise significantly, reaching over 1.1 billion tons by 2050.[3,4] Plastic products, especially single-use plastics, contribute significantly to waste and toxic pollutants,[5] with only 9% of plastic products being recycled.[6,7] They take several centuries to completely degrade, and during the degradation

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process, they produce microplastics (mPLs) and nanoplastics (nPLs). In recent times, there has been a growing interest in understanding the detrimental effects of microplastics (mPLs) and nanoplastics (nPLs) on animals, humans, and aquatic and terrestrial ecosystems.[8–13] Evidence of the presence of mPLs or nPLs in milk,[14] food and beverages,[15–17] edible oils,[18] and other food products is increasing day-by-day. Further, Borrelle *et al.*[19] reported that the projected plastic waste exceeds the efforts to mitigate plastic pollution, necessitating extraordinary efforts. Hence, the quest for plastic-alternative materials has led to increasing interest and research in bio-based and biodegradable plastics,[20,21] with an emphasis on polymers based on carbohydrates and proteins[22–24] and agricultural and food waste,[25,26] which are also improperly disposed of.

Among biopolymers, proteins have an advantage over carbohydrates for the preparation of packaging films due to their thermoplastic behaviour, outstanding film-forming ability,[27–29] and relatively better mechanical and barrier properties.[30–32] In the past, a number of plant- and animal-origin proteins, such as cereal proteins,[33] pulse proteins,[34,35] tuber proteins,[36] casein,[37] whey proteins,[38] gelatin,[39,40] fish protein,[41] and others,[42,43] have been successfully utilized to develop thermoplastic materials for packaging applications.

The global production of apricots in 2023 was about 3.7 million metric tons (MT), with Turkiye being the largest producer (0.75 MT).[44] During the same period, the production of apricots in India was 15 155 MT. It is grown in the *trans*-Himalayan region, with Ladakh, a union territory of India, contributing to more than 62% of the production. Ladakhi apricots are locally known as *chuli*. Dried apricots are the most common form of value-added products, leaving behind stones consisting of kernels and shells as waste.[45] Apricots with bitter kernels are called "*khante*" (meaning "bitter"), while those with sweet kernels are called "*nyarmo*" (meaning "sweet").[46,47] Stone fruit kernels contain varying amounts of hydrogen cyanide (HCN). About 23 glycosides have been discovered in 2000 cyanogenic plants, with amygdalin being the most common. Sweet apricot kernels have lower HCN concentrations (below 50 mg/100 g) than bitter ones (200 mg/100 g). The amygdalin content increases bitterness.[48] Some debittering techniques include soaking in water, brine, blanching, enzyme treatment, microbial fermentation, and ultrasonication.[49] Apricot kernels, like other plant seeds, are rich in fat, protein, fiber, carbohydrates, and minerals (K, Fe, Mg, and P). Apricot oil contains oleic, linoleic, and vitamin E acids. Deoiled apricot kernels have 34.3–44.5% protein.[50] Apricot kernels are a good source of protein, so they are used in food, animal feed, and fertilizers.[45] With the growing interest in bio-based and biodegradable plastics, debittered wild apricot kernel press cakes could be exploited to make protein-based, potentially biodegradable packaging.

Biodegradable films primarily consist of biopolymers and low-molecular-weight substances called plasticizers. Plasticizers are nonvolatile polyols that enhance the mechanical and barrier properties of packaging materials when added as additives.[51] Plasticizers, which penetrate and intercalate between biopolymer chains, disrupt hydrogen bonding and increase interchain spacing, thereby enhancing the barrier and mechanical properties of the film.[52] The effectiveness of a plasticizer in a film matrix depends on its composition, structure, size, and shape.[53,54] Generally, hydrophilic plasticizers such as sorbitol, glycerol, and polyethylene glycol are incorporated into biodegradable films.[55,56] Glycerol and sorbitol are the most commonly used plasticizers for making biodegradable protein films because they lower the hydrogen bonding between polymer chains, increasing the films' flexibility.[57] Glycerol-plasticized films have higher elongation, water permeability, and lower tensile strength, while sorbitol produces biodegradable films with high tensile strength, lower elongation, and lower water permeability. In view of the limited or no studies on developing edible or potentially biodegradable films from the Ladakhi wild apricot kernel proteins, there is a need to understand the effect of protein concentration, type of plasticizers and their levels on their film-forming ability. The current investigation is aimed at studying the effect of the concentration of protein and different concentrations of glycerol and sorbitol as plasticising agents on the mechanical, moisture interaction, and optical properties of Ladakhi wild apricot kernel protein isolate (AKPI)-based films.

2 Materials and methods

2.1 Materials

The apricot stones were obtained from the areas in the Alchi, Leh, and Saspol regions of Ladakh, a union territory of India. Pooled apricot stones were used in the study. Glycerol and sorbitol (70%) were bought from M/s Merck Specialities Private Limited, Mumbai (India), and M/s Thomas Baker (Chemicals) Private Limited, Mumbai (India), respectively, and used as plasticizers. All other chemicals were procured from M/s Sigma-Aldrich, St. Louis, Missouri (USA).

2.2 Extraction of apricot kernel protein isolate (AKPI) and amino acid profiling

Apricot kernels were subjected to mechanical expression for oil extraction for maximum oil recovery, followed by solvent (petroleum ether) extraction to remove the residual oil content. Prior to protein isolation, the de-oiled apricot kernel cake was subjected to hydrothermal treatment (1 : 20; 100 °C for 1 h) to remove hydrocyanic acid, a toxic and bitter compound.[50] The solution was then cooled to room temperature, and the protein was isolated using the alkali solubilization (pH 8.0, using 0.1 N NaOH) and acid precipitation (pH 4.0, using 1% citric acid) technique described by Sharma *et al.*[50] with slight modifications. The solution was finally centrifuged (4500 rpm for 15 min) to isolate the protein in a pellet form. The obtained pellets were washed twice with distilled water to reduce residual impurities and vacuum-dried (60 °C for 12 h). The dried protein powder was analyzed for the proximate composition,[58] amino acid profile, and residual hydrocyanic acid content and stored for subsequent use. For the amino acid content determination, both apricot kernel and the apricot kernel protein isolate samples were hydrolysed using 6 N HCl for 16 h at 110 °C and progressively derivatised utilising *o*-phthalaldehyde (OPA) and 9-fluorenylmethyl chloroformate (FMOC-Cl). The amino acid separation was done by the HPLC method on a Zorbax Eclipse C18 column with a photodiode array (PDA) detector using a gradient elution, and quantification was performed by calibrating it with an amino acid standard mixture (M/s Agilent Technologies International Pvt Ltd, Manesar, Haryana, India; Agilent application note: 5980–3088 EN).

2.3 Preparation and characterization of the apricot kernel protein film

An apricot kernel protein film was produced using the solution casting method, in which a protein isolate powder at different concentrations (6–10% w/v) was dissolved in 100 mL of distilled water and continuously stirred at 400 rpm for 30 min on a magnetic stirrer (Digital Spinot, M/s Tarsons Pvt. Ltd). Subsequently, the pH was adjusted to 8.0 using 0.1 N NaOH for complete solubilisation of the protein powder. Later, the plasticizers, namely, glycerol (30 and 50 g per 100 g protein) and sorbitol (60 and 70 g per 100 g protein), were added, based on preliminary trials, at selected concentrations in different batches at 60 °C, and the mixture was continuously stirred for 1 h at 400 rpm and finally cooled to 25 °C before casting on a plastic (PET) tray and allowed to dry at 40 °C for 24 h. Later, the films were peeled and characterized for their properties. Preliminary trials indicated that films prepared with plasticizer levels lower than 30% for glycerol and 60% for sorbitol were brittle and difficult to handle, indicating insufficient plasticization of the protein matrix. Therefore, 30% glycerol and 60% sorbitol were selected as the minimum levels to obtain flexible, continuous films suitable for the characterization of AKPI films. Higher concentrations (up to 50% glycerol and 70% sorbitol) were included to evaluate the effect of increasing the plasticizer content on the mechanical and moisture interaction properties of the films. The different combinations of film-forming solutions based on the protein concentration, type of plasticizer and level of plasticizer have been assigned a six-letter alpha-numeric code, wherein the first letter is a number representing the protein concentration, followed by the next two letters as “AP” (for apricot kernel protein). The fourth and fifth letters are numbers representing the percentage of plasticizer used, and the sixth letter indicates the type of plasticizer (“S” for sorbitol, “G” for glycerol). For example, the formulation with code “6AP30G” indicates a solution containing 6% protein (6AP) with 30% glycerol (30 G). Details of different combinations are further given as SI data.

2.3.1 Mechanical properties. The mean thickness of the developed film was determined by measuring the thickness at 20 random points across the film using a digital micrometer (M/s Engineering Corporation, Saharanpur, Uttar Pradesh) having a sensitivity of 0.01 mm. The tensile strength and elongation at break were determined as per the ASTM method[59] using a universal testing machine (TA.XT.plus, M/s Stable Micro System, UK) equipped with a 50 kg load cell and having an inbuilt software (Exponent Connect Lite ver. 7.0.6.0) for operating the instrument and for the visualization of the data. Samples with dimensions (2.54 cm × 10 cm) were cut and conditioned at 30 °C ± 2 °C and 50% ± 2% relative humidity for 48 h before analysis. The crosshead speed and initial grip separation for tensile strength were set at 2 mm s^{-1} and 50 mm, respectively. The seal strength of the samples was determined by cutting the film into 2.54 cm × 10 cm strips and sealing the two strips at the shortest side (2.54 cm) using an impulse sealer (make: Sepack; power: 260 W) at 150 °C ± 2 °C for 1–2 s (dwell time).[60] Because a manual impulse sealer was employed in the study, an equivalent sealing pressure was applied to all the films. Sealed film strips were clamped through their unsealed ends between the jaws of the universal testing machine with a 5 cm spacing between the jaws and a 2 mm s^{-1} crosshead speed.

2.3.2 Moisture interaction properties. The moisture content of the developed films was determined using the gravimetric method.[61] The initial dry weight of the casted film (2.54 cm × 10 cm) was estimated by drying it at 105 °C for 24 h and immersing it in 50 mL of distilled water and continuously stirring (250 rpm) for 24 h. Later, the samples were removed and filtered through Whatman filter paper no. 1. Subsequently, the residue left on the filter paper was dried again at 100 °C for 24 h to estimate the final weight. The difference in the weight was considered and expressed as percentage water solubility.[62] The water vapor transmission rate (WVTR) of the film was determined at 38 °C ± 1 °C and 90% ± 1% relative humidity following the method described by ASTM[63] and reported in g m^{-2} h^{-1}. The swelling ratio of the protein films was determined using the procedure given by Huq *et al.*[64]

2.3.3 Color, transparency and FT-IR analyses of the film. The color parameters of the films were determined by digitizing the images (4000 × 3000 pixels) of the films and saving them in the JPG format for later use. Later, using ImageJ software (version 1.53 g), at four random places on the films (200 × 200 pixels), the color values were recorded in terms of lightness (L^*), greenness-redness (a^*), and blueness to yellowness (b^*). Subsequently, for transparency measurement, films were cut into strips of 10 mm × 30 mm and placed directly in a cuvette of a spectrophotometer; the absorbance was measured at 600 nm, and the transparency (opacity) was reported as the ratio of the absorbance at 600 nm to the thickness of the film.[65,66] To understand the molecular interactions between the protein and plasticizers and the functional groups involved, the FT-IR transmission spectra of the films were obtained using a FT-IR spectrometer (IR Affinity-01, Shimadzu, Japan) at room temperature over the wavenumber range of 4000–400 cm^{-1} with a resolution of 4 cm^{-1}, averaged across 30 scans.

2.4 Statistical analysis

A completely randomised three-factor factorial design was adopted in the study to determine the effect of the Ladakhi wild apricot kernel protein concentration, plasticizer type and plasticizer concentration. The response variables studied involved the mechanical, moisture interaction, and optical properties of the wild apricot kernel protein films. All the experiments were conducted in quadruplicate, and statistical multivariate analysis was carried out using IBM SPSS Statistics (version 26). Significant differences among the mean values were determined by applying Tukey's test. Principal component analysis and the hierarchical constellation plots of different properties were prepared using the mean values with the help of JMP Pro (version 14) software. Further, for some of the data visualizations, Tableau Public Desktop Edition software was used.

3 Results and discussion

3.1 Proximate composition and amino acid profile of apricot kernels and their protein isolate

The proximate composition of apricot kernels and apricot kernel protein isolate (AKPI) is presented in Fig. 1(a). The protein contents of apricot kernels and AKPI were found to be 26.16% and 92.72% on a dry matter basis, respectively. The fat content was observed to decrease significantly from 49.97% in apricot kernels to 0.84% in the AKPI ($p < 0.05$) due to the defatting of the apricot kernel sample before protein extraction. The ash content of AKPI significantly increased to 4.32% from 2.21% in apricot kernels ($p < 0.05$), while the carbohydrate content decreased from 21.91% in apricot kernels to 2.12% in AKPI, possibly due to the concentration of the protein and the removal of carbohydrates during the extraction process. Similarly, the crude fibre content of apricot kernels was also found to reduce from 4.32% to 2.21%. Sharma *et al.*[50] reported that the wild apricot kernels from the Himachal Pradesh region of India had a protein content in the range of 23.6–26.2%, which increased to 68.8%, corresponding to 75.69% on a dry matter basis, in the protein concentrate. The increased protein content in the present study could be attributed to varietal differences and slight modifications in the protein isolation technique adopted. Abd El-Aal *et al.*[67] reported that the protein contents of Egyptian apricot kernels and the protein isolate were 24.1% and 90.8%, respectively. The similar result of an apricot kernel protein isolate content of more than 90% protein was reported by Thakur *et al.*[68] Almost all stone fruits contain hydrocyanic acid (HCN), and if consumed, it can cause toxicity.[50,67] Joia *et al.*[47] reported that wild apricots contained about 1569 mg of HCN per kg. In the present study, the HCN content decreased to 0.367 mg/100 g in AKPI, compared to 21.5 mg/100 g in apricot kernels, indicating the effective detoxification and removal of cyanogenic compounds, such as amygdalin, during the tempering of the defatted apricot kernel cake.

The amino acid contents of apricot kernels and AKPI are presented in Fig. 1(b). The amino acid contents of apricot kernels and AKPI revealed that negatively charged (acidic) amino acids, namely, glutamic and aspartic acids, made the highest contribution to the total amino acid content. The glutamic acid content was observed to increase from 5.31% in apricot kernels to 22.32% in AKPI. By contrast, the aspartic acid content increased from 2.48% to 9.82%. Among the positively charged (basic) amino acids, arginine and histidine were found to be in higher quantities than lysine. The total contents of non-polar amino acids, comprising leucine, phenylalanine, alanine, valine, isoleucine, proline, cysteine and methionine, in apricot kernels and AKPI were 5.69% and 21.91%, respectively. In the AKPI, the contents of sulphur-containing amino acids cysteine and methionine were found to be 2.14% and 0.03%, respectively. By contrast, the polar amino acid (threonine, serine, tyrosine, and glycine) contents were limited to 2.52% and 9.77% in apricot kernels and AKPI, respectively. In contrast to the

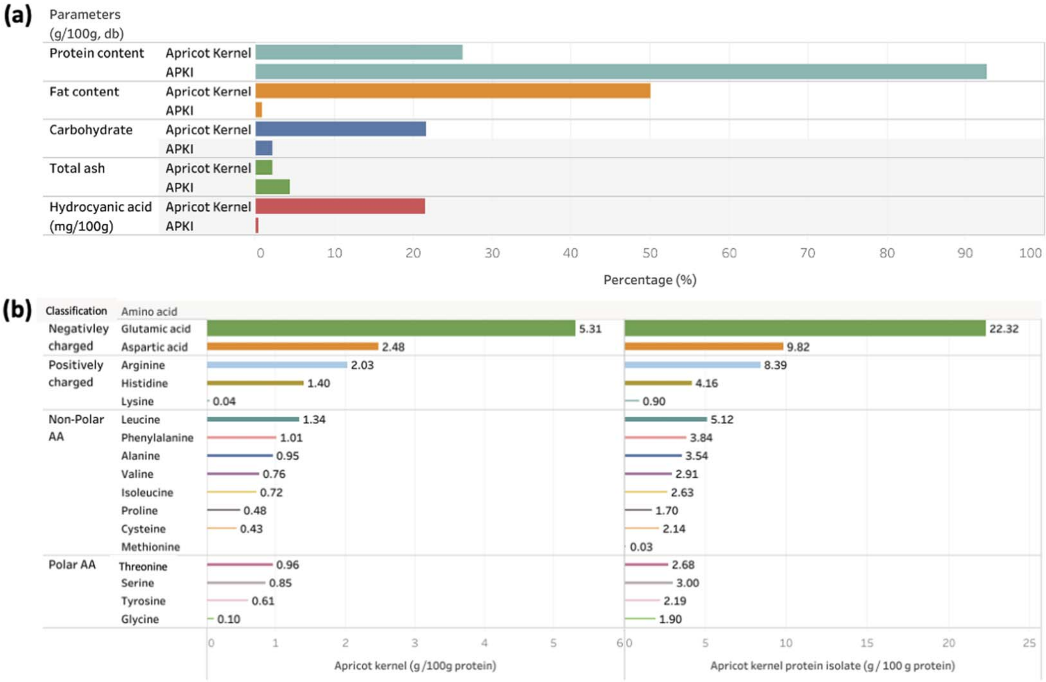


Fig. 1 The proximate composition (a) and amino acids content (b) of apricot kernels and apricot kernel protein isolate (AKPI).

presented findings, the kernels of apricots grown in Serbia had higher levels of arginine and leucine,[69] while those grown in China had elevated glutamic acid contents.[70] In similar studies on the wild Himalayan apricot kernels, it was reported that they contained higher levels of glutamic acid (26.5%), followed by arginine (10.1%), cysteine (1.19%), and aspartic acid (11.3%), with valine (4.34%), lysine (2.95%), leucine (6.84%), and threonine (2.71%) present in lesser amounts.[47,71] The Serbian apricot kernels (*Prunus sibirica* L.) obtained from Mongolia contained elevated glutamic acid levels, followed by aspartic acid and arginine.[71] The type of amino acids present in a protein source plays a critical role in the properties and performance of edible or biodegradable films. Their influence extends to the film-forming ability, mechanical strength, water resistance, barrier properties, and biodegradability. In one of the earliest studies on plant protein-based films, Shih[72] reported that disulfide, hydrophobic, and hydrogen bonding interactions are involved in the film-forming mechanism, which contribute to the development of film characteristics. In the present investigation, the high levels of glutamic acid and aspartic acid might have promoted hydrogen bonding and hydrophilic interactions, enhancing the APKI's film-forming ability[73] and film strength.[74] Higher levels of negatively charged amino acids, such as aspartic and glutamic acids, along with other polar residues such as histidine and arginine, may have contributed to the increased water solubility, swelling ratio, and WVTR due to their hydrophilic nature.[73] The abundance of hydrophilic sites facilitates the diffusion of water molecules through the polymer matrix, which directly affects the WVTR of the AKPI films. Garrido *et al.*[75] reported that the presence of methionine and cysteine (sulfur-containing amino acids) improved the mechanical strength of the film by promoting disulfide linkages within the protein matrix. However, in the present study, the amounts of cysteine and methionine were significantly low and hence might have played a limited role. Reports indicated that a high percentage of water-soluble amino acids was beneficial for film formation as water acts as a solvent for protein solubilization.[76,77] The details of the amino acids in the AKPI of the present study will be useful in understanding the film-forming ability in the presence of glycerol and sorbitol as plasticizers.

3.2 Mechanical properties of the protein films

The mechanical properties of AKPI-based films, namely, thickness, tensile strength, elongation at break, and seal strength, are presented in Fig. 2(a). The thickness of the films was observed to be within the range of 0.14–0.31 mm and found to increase with increasing protein content in the formulation ($p < 0.05$). However, at a constant protein concentration the same plasticizer concentration, the thickness of the films was found to be similar ($p > 0.05$). This indicated that higher protein and plasticizer concentrations synergistically increased the film's thickness. Previous studies on protein-based films reported that with an increase in the protein concentration, the composition of the casting solution and the volume of the film-forming solution would affect the thickness of the films.[78–82] Tensile strength is the maximum stress that a film can withstand before breaking. Films made with formulations containing less than 30% plasticiser (glycerol) or less than 60% plasticiser (sorbitol) were brittle and difficult to handle, so plasticisers at higher concentrations were selected. The tensile strength of the AKPI-based films made with 10% protein and plasticized with sorbitol (60% on protein basis) (10AP60S) recorded the highest tensile strength value, while the films made with 6% protein and plasticized with glycerol (30% on protein basis) (6AP30G) recorded the lowest tensile strength. The tensile strength analysis of the AKPI-based films revealed that at a constant protein concentration, the tensile strength of sorbitol-containing films was significantly higher than that of the glycerol-plasticized films ($p < 0.05$) (Fig. 2(a)). The sorbitol-plasticised AKPI films recorded tensile strength values in the range from 2.52 to 3.43 MPa, while the glycerol-plasticised films recorded strength values in the range from 0.83 to 1.45 MPa. It was also observed that at all protein concentrations, with an increase in either glycerol or sorbitol levels, the tensile strength insignificantly decreased ($p > 0.05$). In a study on squid protein-based films, Murrieta-Matinez *et al.*[82] reported that the glycerol-plasticized films were more elastic with lower tensile strength compared to the sorbitol-plasticized films, which had higher tensile strength. Faust *et al.*[83] reported that the tensile strength of the protein films decreased with increasing concentration of glycerol. The higher tensile strength of sorbitol-plasticised films could be attributed to the higher molecular weight and reduced plasticising effect compared to glycerol.[84] Bourtoom *et al.*[76] noted that sorbitol-plasticised films had superior tensile strength to glycerol-plasticised films. Shih[72] reported that the tensile strengths of soy protein and wheat protein were 1–4 MPa and 0.4–4.5 MPa, respectively. Sothornvit and Krochta[85] studied the tensile strength of β-lactoglobulin films with different plasticizers and reported that the tensile strength of glycerol-plasticized films was in the range from 4.98 to 16.01 MPa, while that of the sorbitol-plasticized films was in the range from 2.71 to 10 MPa, contrary to the findings of the present study. Further, it was reported that using polyethylene glycol as a plasticizer resulted in the lowest tensile strength values.

In the present study, the increased tensile strength of the films could be due to increased protein–protein interactions that led to the formation of a continuous and cohesive film matrix. Further, due to its highly hydrophilic characteristics, the hydroxyl group of glycerol forms hydrogen bonds with the amide groups of the protein and reduces internal hydrogen bonds within the protein. This decreases the internal forces and increases the intermolecular spacing.[91] The decreased tensile strength of glycerol-plasticized AKPI films could be ascribed to the reduced internal forces and increased intermolecular spacing of the apricot kernel protein. Due to the difficulty in directly comparing the tensile strength of AKPI films with that of other protein-based films from the available literature, an attempt has been made to present the data in Table 1.

Percentage elongation or elongation at break indicates the film's extensibility and flexibility, in other words, its ability to resist shape changes without breaking. In this study, it was observed that the elongation at break of the films increased with increasing protein concentration (Fig. 2(a)). However,

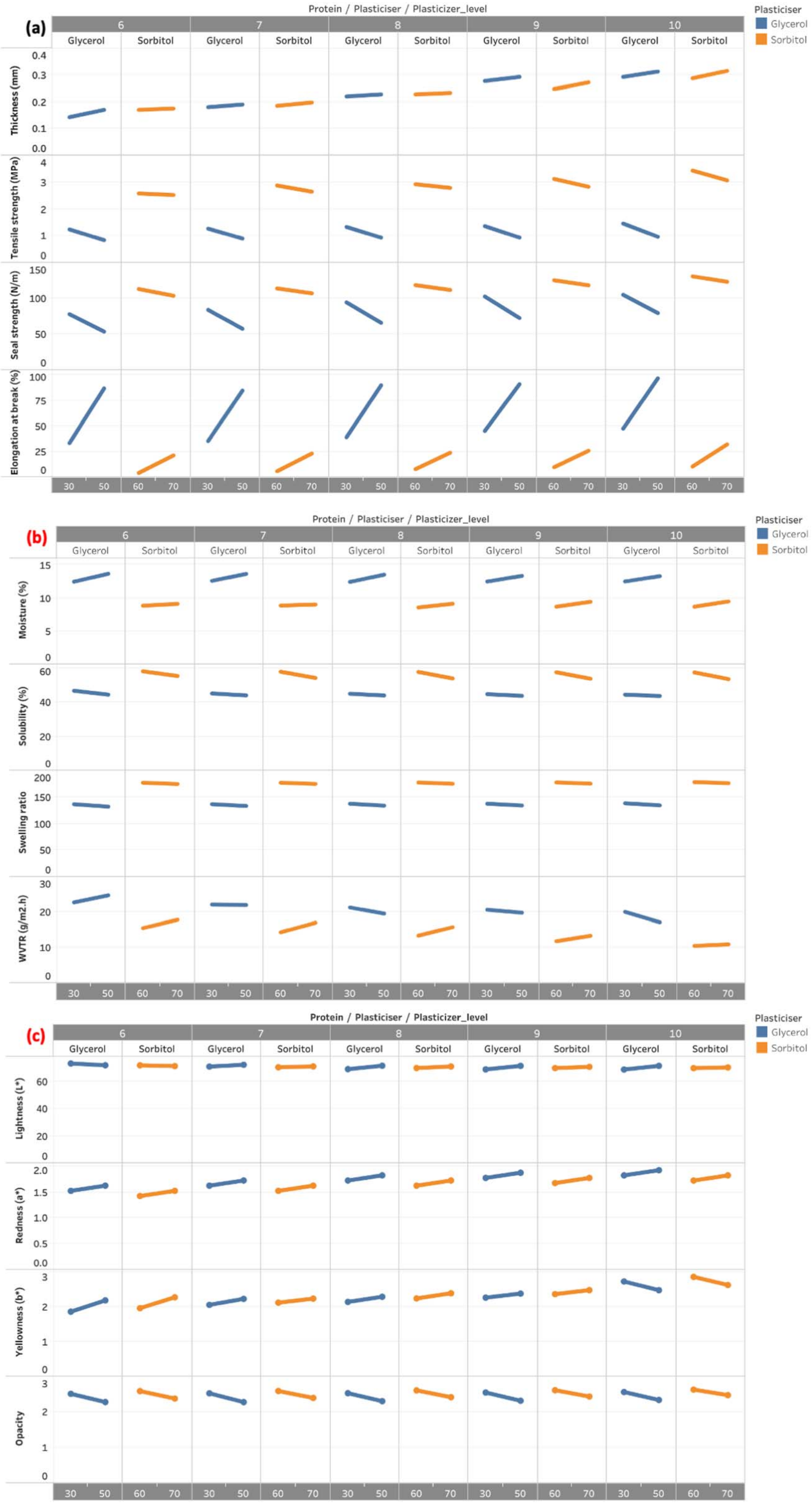


Fig. 2 (a) Effect of the protein concentration and plasticizer type and level on the mechanical properties of the AKPI-based films. (b) Effect of the protein concentration and plasticizer type and level on the moisture-interaction properties of the AKPI-based films. (c) Effect of the protein concentration and plasticizer type and level on the optical properties of the AKPI-based films.

significant differences were recorded only above 8% protein-containing films. It was also observed that across the protein concentrations, glycerol-plasticized films recorded significantly higher percentage elongation than sorbitol-plasticized films ($p < 0.05$). The highest percent elongation (96.76%) of the film was observed for the films prepared with 10% protein and glycerol

Table 1 Tensile strength and water barrier properties of various protein-based films

Film type	Plasticiser	Tensile strength (MPa)	Water vapour transmission rate	Water vapour permeability	Ref.
Apricot kernel protein isolate (AKPI)	Glycerol or sorbitol	0.83–3.43	252–594 g m^{-2} day (10.48–24.76 g m^{-2} h^{-1})	—	Present study
Soy protein isolate	Glycerol	1.6–3.5[a]	Not reported	Not reported	86
Canola protein	Glycerol	1.19–4.31[b]	Not reported	0.94–1.5[c] g mm m^{-2} h^{-1} kPa^{-1}	87
Pea protein-canola oil composite[d]	Glycerol	5.2	Not reported	2.0 g mm m^{-2} h^{-1} kPa^{-1}	34
Lentil protein-canola oil composite[d]	Glycerol	4.0	Not reported	2.4 g mm m^{-2} h^{-1} kPa^{-1}	34
Faba bean protein-canola oil composite[d]	Glycerol	4.2	Not reported	2.2 g mm m^{-2} h^{-1} kPa^{-1}	34
Potato protein isolate[e]	Glycerol	0.64–1.88	793–1341 g m^{-2} day^{-1}	Not reported	36
Honey bee brood protein composite film	Glycerol	5.16–7.95	Not reported	0.09–0.188 g mm m^{-2} h^{-1} kPa^{-1}	74

[a] The minimum and maximum tensile strength values were of the soy protein isolate films prepared with 6% and 10% protein, respectively. The film thicknesses ranged between 143 and 165 μm. [b] The minimum and maximum tensile strength values were of the 5% canola protein isolate-containing films prepared with 50 and 30 g glycerol per 100 g of protein, respectively. [c] The minimum and maximum WVP values were of the 7.5% canola protein isolate-containing films prepared with 30 and 50 g glycerol per 100 g protein, respectively. [d] The thickness of the composite films made from pea protein, lentil protein, and faba bean protein ranged between 0.25 and 0.28 mm. [e] The thickness of the potato protein isolate-based film with varying levels of glycerol (100–140% protein weight) ranged between 229 and 246 μm.

(50% on protein basis) (10AP50G), while the lowest (4.13%) was observed for films prepared with 6% protein and sorbitol (60% on protein basis) (6AP60S) (Fig. 2(a)). This may be due to the lower plasticising effect of sorbitol compared to that of glycerol. Glycerol has been reported to be more effective in plasticising owing to its smaller molecular size, which enables it to easily intercalate among polymer chains, thereby reducing the free volume of the biomolecules and increasing the flexibility and mobility of the protein chains.[2,92] Studies on different types of proteins have reported different elongation percentages owing to the internal and external plasticization effects. External plasticizers such as polyols solvate between and lubricate the protein chains and also increase the free volume.[91] The elongation at break of sorbitol-plasticised fish myofibrillar protein films varied from 13% to 64%, while that of β-lactoglobulin films ranged from 3% to 10%.[54,85] Seal strength refers to the capacity of packaging materials to maintain seal integrity under the influence of mechanical stress.[93] In this study, it was observed that sorbitol-plasticized films had significantly higher seal strength than glycerol-plasticized films ($p < 0.05$) (Fig. 2(a)). Further, it was observed that with an increase in either glycerol or sorbitol concentrations, the seal strength of the films decreased significantly ($p < 0.05$). The seal strength of glycerol-plasticised apricot protein-based films ranged from 53.58 to 105.01 N m^{-1}, whereas sorbitol-plasticised films' seal strength ranged from 103.71 to 130.86 N m^{-1}. It was observed that sorbitol–protein interaction was crucial for seal strength. The lower seal strength of glycerol-plasticized apricot kernel protein isolate (AKPI) films might be due to increased molecular mobility and reduced cohesion force in the seal area.[94] Previous researchers reported that the seal strengths of glycerol-sorbitol-plasticised protein isolate/lipid films and starch films were 302–322 N m^{-1} and 375 N m^{-1}, respectively.[95,96] Kim and Ustunol[96] reported that the seal strength of glycerol-plasticised whey protein isolate varied from 140 to 320 N m^{-1}, whereas that of sorbitol-plasticised films ranged from 105 to 300 N m^{-1}.

3.3 Moisture interaction properties of the films

The effects of different levels of protein concentration and plasticizer type and concentration are presented in Fig. 2(b). It can be seen that with an increase in the protein concentration and at a constant level of either of the plasticizers, there were no significant changes in the moisture content of the films ($p > 0.05$). However, at a constant protein content, with an increase in the glycerol content, the moisture content of the films significantly increased ($p < 0.05$); on the contrary, non-significant differences were recorded in the moisture content of sorbitol-plasticized films ($p > 0.05$). It was also observed that, across all protein concentrations, glycerol-plasticized films had higher moisture contents than sorbitol-plasticized films. Shaw *et al.*[97] reported that glycerol-plasticised whey protein isolate films had higher moisture contents than sorbitol-plasticised films. Shroti and Saini[98] also observed that an increased plasticizer concentration led to a higher moisture content in brewers' spent grain protein-based films. The difference in the moisture content between sorbitol- and glycerol-plasticised films was mainly ascribed to the different molecular structures and intermolecular interactions of the plasticizers.[99] It can be seen from Fig. 2(b) that across all levels of protein, sorbitol-plasticised films exhibited significantly higher solubility than their glycerol counterparts ($p < 0.05$). However, with increasing sorbitol content from 60% to 70% (on protein basis), solubility decreased significantly ($p < 0.05$), while a non-significant difference was observed with increasing glycerol content from 30% to 50% (on protein basis) ($p > 0.05$). The sorbitol-containing films had solubility values in the range from 53.69% and 58.27%, while glycerol-containing films had solubility values in the range from 43.78% and 46.86%. The swelling ratio of the apricot kernel protein isolate-based films is shown in Fig. 2(b). It indicates the weight gain of the film is due to water absorption, which leads to changes in the spatial structure of the biopolymer.[100] This ratio is influenced by the nature and extent of intermolecular interactions between the plasticizer and biopolymer.[101] In the present study, across all the protein levels in the films, the swelling ratios of sorbitol-plasticized films were found to be significantly higher than those of glycerol-plasticized films ($p < 0.05$). The swelling ratio of sorbitol- and glycerol-plasticised films ranged from 174.73 to 178.37 and 132.10 to 138.40, respectively. Lopusiewicz *et al.*[61] reported that the swelling ratios for a glycerol-plasticised whey protein concentrate and a whey protein isolate film modified with melanin ranged from 324 to 469 and 75 to 147, respectively. Sirbu *et al.*[102] observed that sorbitol-plasticised starch exhibited a higher swelling ratio than glycerol-plasticised films. Chen *et al.*[103] similarly observed that an increase in the concentration of the plasticizer reduced the swelling ratio of curdlan edible films owing to an enhanced hydrogen bonding among the biopolymers. Hake protein isolate (extracted from hake fish) films plasticised with 25% glycerol exhibited 43.4% water solubility, attributed to the increased hydrophilicity of the protein.[104] Murrieta-Martinez *et al.*[82] also reported the higher water solubility of sorbitol-plasticised squid protein films (extracted from squid mantle) due to the blooming effect and larger molecular size compared to glycerol-plasticised films. The water solubility of glycerol-plasticised fish myofibrillar protein/gelatin hydrolysate films and mung bean protein films ranged from 79.5% to 82% and 19% to 50%, respectively; in contrast, sorbitol-plasticised fish myofibrillar protein films had a water solubility of 62.59%.[54,73,105] The type of plasticizer used in casting a bio-based film significantly influences the solubility and swelling behaviour. Glycerol is a small, tri-hydroxyl molecule, which is highly hygroscopic and flexible, while sorbitol is a sugar alcohol with six hydroxyl groups and a rigid structure. Glycerol interacts strongly with protein *via* hydrogen bonding, causing lower penetration of water and reduced swelling. By contrast, sorbitol interacts weakly due to its bulkier structure, but due to a higher number of hydroxyl groups, its water affinity is higher, which allows more water uptake and higher swelling and solubility.[54,106] In the present study, the higher solubility and higher swelling ratios of sorbitol-plasticized AKPI-based films could be attributed to the weaker interaction of sorbitol with AKPI, its greater hydrophilicity and its tendency to form a less compact matrix, allowing more water uptake and penetration.

The effect of the protein concentration and selected plasticizers (glycerol and sorbitol) at different levels on the water vapour transmission rate (WVTR) of AKPI is presented in Fig. 2(b). The WVTR of different films varied between 10.48 and 24.76 g m^{-2} h^{-1}. It can be seen that at all protein concentrations, sorbitol-containing films recorded significantly ($p < 0.05$) lower WVTR values compared to glycerol-containing films. Further, with increasing protein concentration, the WVTR decreased significantly ($p < 0.05$). The WVTR of AKPI films plasticised with sorbitol ranged between 10.48 and 17.86 g m^{-2} h^{-1}, while that of glycerol-plasticised films ranged between 17.16 and 24.76 g m^{-2} h^{-1}. Among all, the lowest WVTR (10.48 g m^{-2} h^{-1}) was observed in case of the film produced with 10% apricot protein and plasticized with sorbitol incorporated at 60% of the protein level (code: 10AP60S), whereas the highest value (24.76 g m^{-2} h^{-1}) was obtained for the film produced with 6% apricot protein and plasticized with glycerol incorporated at 50% of the protein level (code: 6AP50G). Murrieta-Martinez *et al.*[82] reported a higher WVTR for the glycerol-plasticised squid protein film than for the sorbitol-plasticised film, as glycerol's structure facilitates water diffusion, while sorbitol's hinders it. Kumar *et al.*[60] reported that the WVTR of sodium caseinate films plasticised with glycerol was 15.02 g m^{-2} h^{-1}. Glycerol, as a small and highly hydrophilic molecule, disrupts the polymer matrix and increases the free volume between protein chains, causing easy diffusion of water, increased water holding and, hence, increased permeability. By contrast, sorbitol has a larger molecular size and less hygroscopicity than glycerol, forming more stable and tighter hydrogen bonds with protein chains. This leads to less disruption of the matrix, resulting in lower water transmission and permeability.[107–109] Protein films exhibit higher WVTRs due to a greater number of hydrophilic sites in protein chains and plasticizer (polyols) molecules.[110] In the present study, apart from the role of plasticizers, the presence of hydrophilic (polar) amino acids, namely, arginine and histidine (Fig. 1(b)), which have affinity for water, might also have contributed to the WVTR of the films. Due to the difficulty in directly comparing the water vapor transmission rate of AKPI films with that of other protein-based films from the available literature, representative information is presented in Table 1 for illustrative purposes.

3.4 Optical properties of the films

The effect of the protein concentration and selected plasticizers (glycerol and sorbitol) at different levels on the optical properties of AKPI, namely, lightness (L^*), redness (a^*), yellowness (b^*) and opacity, is presented in Fig. 2(c). With an increase in both protein and plasticizer concentrations, significant variations ($p < 0.05$) were observed in the optical properties of AKPI films. The L^* values of the films varied between 69.11 and 73.55, with the lowest L^* value observed for the films prepared using 9% and 10% protein with glycerol as a plasticizer at 30% of the protein level (codes: 10AP30G and 9AP30G), while the highest was observed for the film prepared with 6% protein and glycerol as a plasticizer at 30% of the protein level (code: 6AP30G). Shroti and Saini[98] reported that the L^* values of brewer's spent grain protein-based films decreased as the protein content increased. The increased L^* value of the films with increasing protein concentration could be attributed to molecular aggregation and interactions in the dense protein matrix of the film, resulting in greater scattering of light.[54] The optical properties of protein films are also affected by the types and characteristics of plasticizers.[111] The L^* values of sorbitol-plasticised films were relatively lower than those of glycerol-plasticised films at a constant protein concentration and across all concentrations, which could be attributed to the crystalline nature of the sorbitol powder compared to glycerol, which might have led to more scattering of light.[112,113] Similar observations were made by Murrieta-Martinez *et al.* for squid protein films.[82] The redness (a^*) values of the films were found to increase significantly ($p < 0.05$) with increasing protein concentration and with increasing plasticizer concentration at a constant protein level. Overall, the a^* values ranged between 1.42 and 1.92, with the highest value (1.92) recorded for the film prepared with 10% protein containing glycerol at 50% of the protein level (code: 10AP50G), while the lowest (1.42) was recorded for the film prepared with 6% protein containing sorbitol at 60% of the protein level (code: 6AP60S). Among the different films, glycerol-plasticised films exhibited higher a^* values than sorbitol-plasticised films. The increased a^* values indicate enhanced redness in the film, which could be due to the protein–plasticizer interactions and Maillard browning during the heating of the film-forming solution between relatively more reactive amino acids such as lysine, glycine, and tyrosine, and the residual carbohydrates present in the APKI. Similar observations were made by Rosmawati *et al.*[114] in Snakehead gelatin and *K*-carrageenan-based composite edible films. The yellowness (b^*) values of the films were also observed to increase significantly ($p < 0.05$) with increasing protein concentrations. The b^* values ranged between 1.86 and 2.86. The lowest b^* value (1.86) was also recorded for films made with 6% protein (code: 6AP30G), while the highest (2.86) was also observed for films prepared with 10% protein (code: 10AP60S). Among all the films, the films containing higher concentrations of protein and 70% sorbitol were found to have increased b^* values, potentially due to plasticizer–protein interactions. In this study, it was observed that the most transparent films were produced at a 6–7% apricot kernel protein concentration and a 30% glycerol concentration (6AP30G/7AP30G).

It can be seen from Fig. 2(c) that the opacity of the AKPI films decreased significantly ($p < 0.05$) with an increase in the plasticizer concentration at all protein levels. Glycerol-plasticised films exhibited lower opacity, ranging between 2.27 and 2.56, compared to sorbitol-plasticised films, which ranged between 2.37 and 2.63. Studies have reported contrary results on the transparency of protein-based films plasticised with glycerol and sorbitol, with canola protein isolate-based films plasticised with glycerol being more transparent than sorbitol- and polyethylene glycol-plasticised films,[84] while fish myofibrillar protein films were more transparent when plasticised with sorbitol.[54] The relatively higher opacity of AKPI films provides an extra functional benefit in terms of limited light transmission, as it may prevent the photo-oxidation of the fat-rich products and may also reduce oxidative rancidity during storage.[73] In the present study, the biodegradability of AKPI films is not reported. However, the AKPI films contain natural biopolymers (proteins) and food-grade plasticizers (glycerol and sorbitol), which are prone to microbial and enzymatic degradation. Previous research on protein-based films such as whey, soy, and gelatin has demonstrated that these films are biodegradable in the natural environment.[23,27,29,90] Therefore, AKPI films are expected to have potentially biodegradable properties, although additional studies like soil burial tests are needed to confirm this biodegradability.

3.5 FTIR spectroscopic analysis of apricot kernel protein plasticised films

In the present study, FTIR spectroscopy was used to understand the effects of the protein concentration, the plasticizer type (glycerol and sorbitol) and its levels on the chemical structure, molecular interactions, and functional groups present in the apricot kernel protein isolate-based films (Fig. 3). FTIR spectra revealed molecular interactions between apricot kernel protein isolate (AKPI) and glycerol, including hydrogen bonding and changes in protein matrix compactness with varying protein

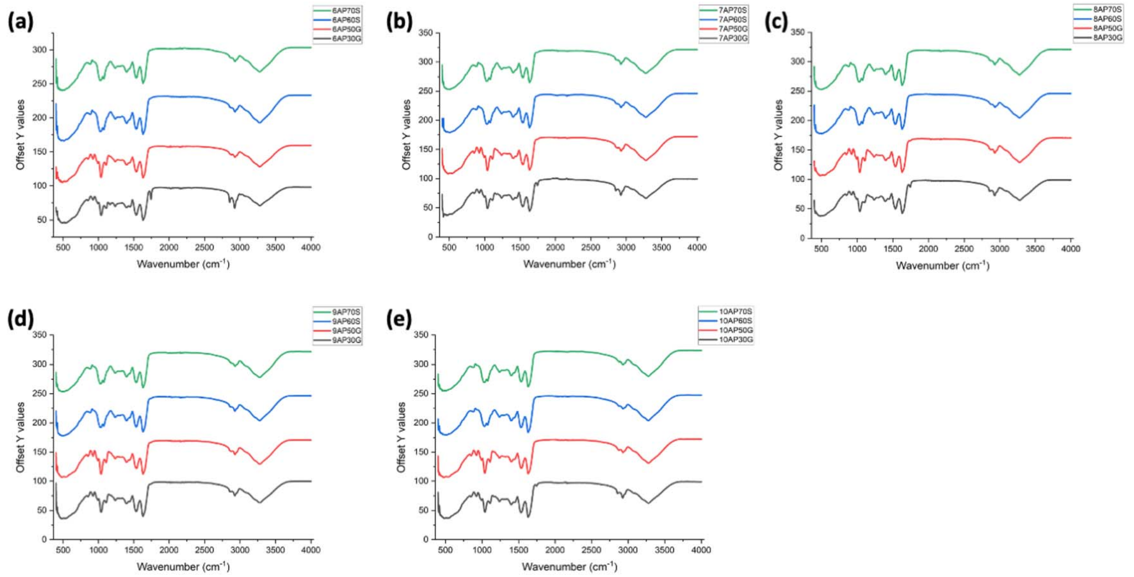


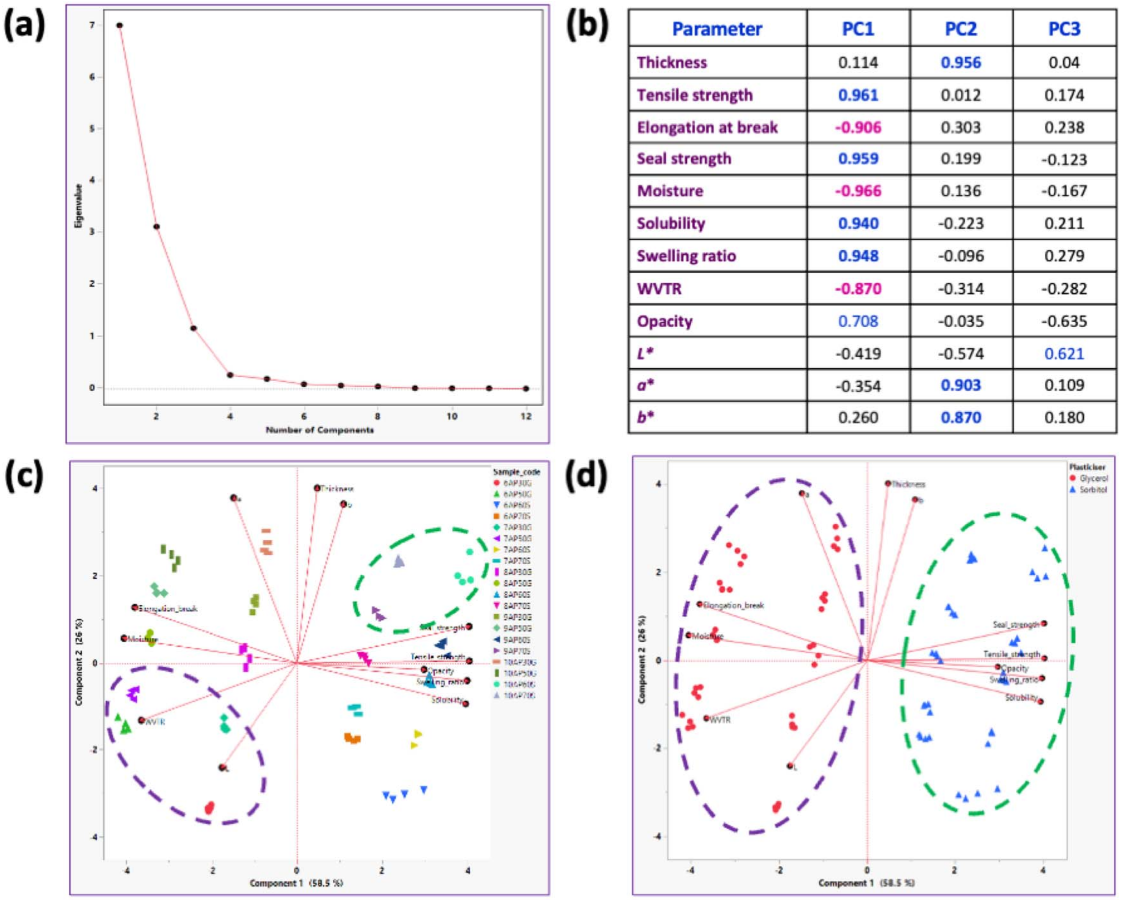
Fig. 3 FTIR spectra showing the effect of the protein concentration and plasticizer type and levels on the AKPI films: (a) 6% protein film, (b) 7% protein film, (c) 8% protein film, (d) 9% protein film, and (e) 10% protein film.

contents. It was observed that films with lower protein contents (6%) exhibited higher transmittance due to a less-dense protein matrix and weaker molecular interactions. Denser peaks in the fingerprint region for higher-protein-content films indicated a denser protein matrix and stronger plasticizer–protein interactions. Sorbitol-plasticized films exhibited broader absorption bands and more hydrogen bonding than glycerol-plasticized films around a wavelength of 3270–3300 cm^{-1}, which may be attributed to the increased hydrogen bonding between the sorbitol molecule and protein chain due to a higher number of hydroxyl (O–H) groups present in the sorbitol molecule than in the glycerol molecule.[102] Broader peaks indicate a more extensive hydrogen bonding network. Sorbitol's higher hydroxyl groups strengthen the plasticizer–protein interaction, enhancing film rigidity and reducing brittleness. However, a higher glycerol content (50%) increases hydrogen bonding but typically results in increased flexibility and less dense packing. Strong hydrogen bonding improves intermolecular interactions, leading to stronger matrix compactness, but this depends on the plasticizer structure. Amide I and amide II bands confirmed the presence of a strong protein structure matrix in the films.[115] These bands were found to shift slightly, indicating modifications in the protein's secondary structure. Shifts in the amide I region indicated changes in hydrogen bonding within the protein backbone. Heating and pH changes likely caused partial denaturation and rearrangement into a more stable matrix, suggesting the formation of new intermolecular β-sheet structures and a stronger film. Shifts in the amide II region indicated plasticizers reorganizing protein folding. Further, they indicated that sorbitol stabilized β-sheet formation more than glycerol due to stronger H-bonding. Cheng *et al.* also observed amide I and amide II bands at 1631 cm^{-1} and 1533 cm^{-1}, respectively, in glycerol-plasticised pea isolate films. Gao *et al.*[116] also reported a similar shift in amide I and II bands with an increase in the glycerol concentration in kafirin protein films. The fingerprint region in the wavelength range of 800–1200 cm^{-1}, mainly associated with C–N and C–O in the case of sorbitol-plasticised films, was denser compared to that of glycerol films, indicating a stronger interaction between protein and sorbitol molecules.[54] Sorbitol films had denser peaks, leading to more-intense plasticizer–protein interactions, tighter hydrogen bonding networks, and likely higher tensile strength. This is because sorbitol integrates deeper into the protein matrix than glycerol. In the present study, due to this strong interaction, sorbitol-plasticized films positively correlated with the higher tensile strength of the AKPI film. The bands in the 1000–1200 cm^{-1} region might be attributed to the C–O bond stretching of plasticizer molecules.[117] Higher glycerol concentrations (50%) led to a broader absorption band (3270–3300 cm^{-1}) compared to 30% glycerol, indicating stronger N–H and O–H stretching vibrations and increased hydrogen bonding.[60] Higher protein concentrations resulted in more pronounced peaks around 2920–2850 cm^{-1}, associated with C–H stretching vibrations of the methyl group, suggesting the interaction of the OH groups of plasticizers with the $-CH_2$ group.[102,103] Thakur *et al.*[68] reported a broad band for apricot protein isolate at 2924.18 cm^{-1}, which was mainly due to the OH group stretching vibration of carboxylic acid present in the protein isolate. Increased C–H stretching suggests a denser protein network, increased interaction between the plasticizer's hydroxyl groups and the protein's $-CH_2$ groups, and the potential compaction of the protein matrix at higher protein contents. This results in a tighter, more cohesive film structure with higher protein concentrations.

3.6 Multivariate analysis of film properties

To understand the complex interrelationships among the physicochemical and functional properties of the AKPI-based films, multivariate statistical techniques, namely, principal component analysis (PCA) and hierarchical cluster analysis (HCA), were explored. PCA was utilized to reduce data dimensionality and to identify major trends and correlations among the measured variables. The resulting biplots of principal components representing both the sample distribution and the variable loadings are presented in Fig. 4.

In the present study, the similarities and differences among the mechanical, optical and moisture interaction properties, in terms of 12 attributes, were studied using PCA. As evidenced from Fig. 4(a), the PCA of the 12 attributes from different treatments resulted in three principal components (PC1, PC2, and PC3) whose eigenvalues were more than 1.0, a common statistical cutoff point.[118] The first three components collectively explained 94.24% of the relationship between the treatments and the attributes studied. Fig. 4(c) depicts the biplot of the first two components of the properties of AKPI-based films. PC1, which accounted for 58.5% of the data variance, was characterized by the tensile strength (0.961), seal strength (0.959), solubility (0.940), and swelling ratio (0.948) and opposed by the elongation at break (−0.906), moisture content (−0.966), and WVTR (−0.870) (Fig. 4(b)). By contrast, PC2 explained 26% of the variation defined by the thickness (0.956), a^* (0.903) and b^* (0.870) values and opposed by L^* (−0.574). PC3 accounted for only 9.74% of data variance. The correlation between a component and a variable, also called the loading matrix, estimates the information they share. The sum of the correlation between a variable and all the components is equal to 1.0. In the present study, loading with an absolute value greater than 0.800 (shown in bold type in Fig. 4(b)) represents a strong influence. The absolute loading of the tensile strength, seal strength, swelling ratio, solubility, moisture content, percentage elongation at break, and WVTR in PC1 with the thickness, redness and yellowness in PC2 was found to be more than 0.800, indicating a strong influence on the properties of AKPI-based films. It can be seen from Fig. 4(d) that among all the treatments, the relative positions of glycerol-plasticised films were associated with the negative axis of PC1, while the sorbitol-plasticised films were associated with the positive axis of PC1. Fig. 4(c) reveals that AKPI-based films prepared with 9% and 10% protein and plasticized with sorbitol (codes: 9AP70S, 10AP60S, and 10AP70S) were aligned in PC1, indicating the strong association of these film-forming combinations with the enhanced tensile strength, seal strength, and swelling ratio and reduced WVTR and percentage elongation at break.



Parameter	PC1	PC2	PC3
Thickness	0.114	0.956	0.04
Tensile strength	0.961	0.012	0.174
Elongation at break	-0.906	0.303	0.238
Seal strength	0.959	0.199	-0.123
Moisture	-0.966	0.136	-0.167
Solubility	0.940	-0.223	0.211
Swelling ratio	0.948	-0.096	0.279
WVTR	-0.870	-0.314	-0.282
Opacity	0.708	-0.035	-0.635
*L**	-0.419	-0.574	0.621
*a**	-0.354	0.903	0.109
*b**	0.260	0.870	0.180

Fig. 4 Principal component analysis of different attributes of the AKPI films as affected by their protein concentration, plasticizer type and level. (a) Scree plot highlighting the number of components having eigenvalues more than 1.0. (b) Principal components and loadings of the variables studied. (c) Biplot of loadings showing the relationship between the variables studied and the treatments. (d) Biplot of loadings showing the relationship between the variables studied and the plasticizers used.

Complementing PCA, the HCA grouped the AKPI films based on similarity across multiple attributes in the form of a constellation plot (Fig. 5). The constellation plot simplifies hierarchical clustering, displaying clusters as nodes connected by lines, wherein nodes represent clusters or data points, lines indicate relationships, and distances represent similarity. Fig. 5 reveals two distinct clusters comprising films plasticized with sorbitol (groups 1, 2 and 3; highlighted in orange ellipses) and films plasticized with glycerol (groups 4, 5, 6 and 7; highlighted in purple ellipses) formed at a selected distance threshold. This separation from the central node implies stronger dissimilarity in the characteristics of AKPI films plasticized by glycerol or sorbitol. Films containing 8%, 9% and 10% AKPI plasticized with 70% sorbitol (8AP70S, 9AP70S, 10AP70S) were clustered in group 1, while those plasticized with 60% sorbitol were clustered in group 2. Groups-1 and 2 film formulations had higher mechanical strength and lower WVTRs. Meanwhile, all films containing 6% and 7% protein either plasticized with 60% or 70% sorbitol were clustered in group 3. On the contrary, films plasticized with glycerol were clustered into four groups. Films containing 8–10% protein and plasticized with 30% glycerol (8AP30G, 9AP30G, and 10AP30G) were clustered in group 4, while the films prepared with both 6% and 7% protein and plasticized with 30% glycerol were clustered in group 5 (6AP30G, 7AP30G), and those plasticized with 50% glycerol were clustered in group 6. Glycerol-plasticized films prepared with 8–10% protein were clustered in group 7. Groups 4–7 (glycerol-plasticised films) represent formulations having higher flexibility than the other groups. The analysis showed that with 8% protein as the baseline, film formulations exhibited weaker mechanical and barrier properties below this level, regardless of the plasticiser used (groups 3 and 5). Together, these multivariate analyses (PCA and HCA) helped reveal the patterns and clusters in the dataset that are not apparent through univariate analysis alone. Based on the multivariate analysis, formulations containing 9–10% AKPI plasticized with 60–70% sorbitol were aligned along the positive side of PC1, which exhibited strong positive loadings for tensile strength (0.961) and seal strength (0.959) and a negative loading for the WVTR (−0.870). This suggests that these films offer higher mechanical strength and better moisture barrier properties than other formulations. However, the lower elongation at break (−0.906) indicates less flexibility, showing a trade-off between strength and extensibility. Therefore, sorbitol-plasticized films may be better suited

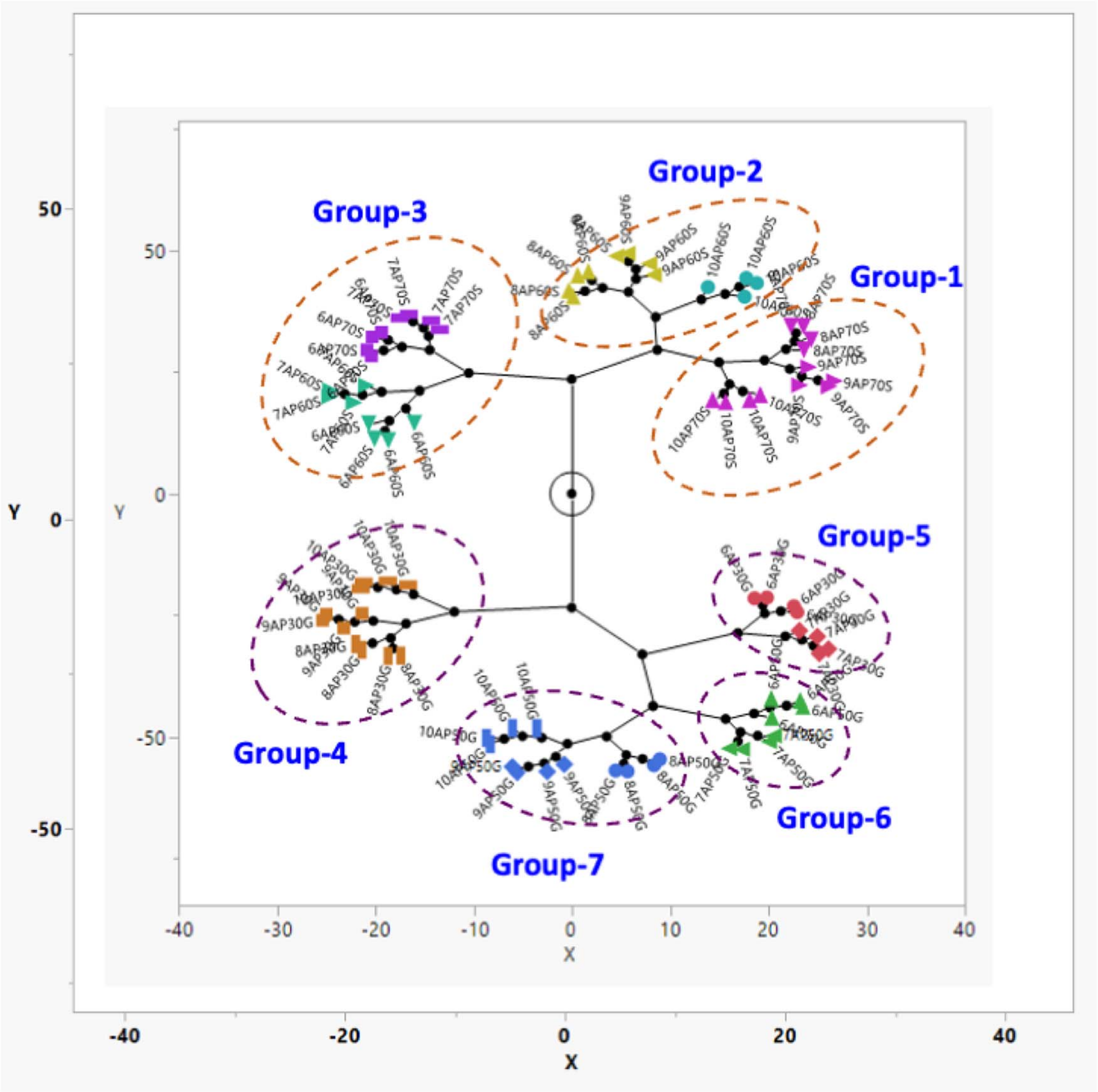


Fig. 5 Hierarchical constellation plot of the different combinations of the AKPI films as affected by their protein concentration and plasticizer type and level.

for applications requiring structural integrity and moisture resistance, while glycerol-plasticized films may be more appropriate where greater flexibility is needed.[88,89]

4 Conclusion

In the present investigation, the Ladakhi wild apricot kernel protein isolate (AKPI) had a protein content of 92.72% and a significantly reduced hydrocyanic acid content compared to apricot kernels. The HCN content was determined in the AKPI powder after detoxification and protein isolation. However, it was not measured in the final cast films. The amino acid profile of AKPI revealed a dominance of negatively charged amino acids, particularly glutamic and aspartic acids. The study investigated the effects of the protein concentration and plasticizer type (glycerol and sorbitol) on the properties of AKPI-based films. It was observed that a minimum of 8% protein was essential for producing a wild apricot kernel protein-based film with good properties. Films exhibited varying mechanical properties, with sorbitol-plasticized films demonstrating higher tensile strength than glycerol-plasticized films. By contrast, the glycerol-plasticized films exhibited higher elongation at break and lower seal strength than sorbitol-plasticized films. Sorbitol-plasticized films showed a higher moisture content, solubility, and swelling ratio but a lower WVTR compared to glycerol-plasticized films. The sorbitol-plasticised film displayed greater opacity and lower L^* and a^* values, while the glycerol-plasticised film had higher b^* values. FTIR spectra revealed shifts in the absorption bands with increasing glycerol concentration around the wavenumbers of 3270–3300 cm^{-1} and with increasing protein concentration around the wavenumbers of 2920–2850 cm^{-1}, as well as shifts in amide-I and amide-II absorption bands upon the addition of the plasticizer. They also revealed molecular interactions between AKPI and plasticizers, with sorbitol-plasticized films showing broader absorption bands and increased hydrogen bonding. PCA identified three principal components that collectively explained 94.24% of the data variance, highlighting the influence of the tensile strength, seal strength, swelling ratio, and moisture content on the films' properties. HCA grouped the films based on sorbitol or glycerol plasticization, revealing distinct clusters and patterns in the dataset. It can be concluded that Ladakhi wild apricot protein-based films could be prepared with a minimum of 8% protein and plasticized by sorbitol incorporated at either 60% or 70% levels. Among the formulations studied, films containing 9–10% protein plasticised with 60–70% sorbitol provided a favourable balance of tensile strength, seal strength and moisture barrier properties, while glycerol-plasticised films may be preferred in applications where higher flexibility is required. Based on the measured mechanical and moisture-interaction properties, these films may be further explored for the packaging of semi-solid and low-moisture dairy and food products. Any application involving direct food contact requires additional verification, including residual HCN in the final film and potential migration into recommended food simulants, depending on the intended application.

Author contributions

DK: writing – original draft; writing – review and editing; formal analysis; methodology; software; visualization; NRP: conceptualization; writing – review and editing; formal analysis; methodology; software; visualization; funding acquisition; SG: writing – review and editing; AKS: writing – review; supervision; AS: funding acquisition; resources; and CL: resources.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: the experimental values of the film properties. See DOI: https://doi.org/10.1039/d5fb00866b.

Acknowledgements

The Director, ICAR-NDRI, Karnal, is acknowledged for providing financial assistance in the form of Senior Research Fellowship to the first author. The financial support received from DST, Govt. of India, for the project # DST/CCP/NMSHE/MRDP/208/2021(G) is gratefully acknowledged. Authors acknowledge the Indian Council of Agricultural Research (ICAR), New Delhi for providing the necessary facilities. During the preparation of this work the authors used the “built-in writing tools of Microsoft Word (in Apple M3 Pro (iOS version Sequoia 15.5))” in order to “improve the English language”. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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