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RESEARCH ARTICLE

Enhancing tamarind quality and shelf-life through improved storage techniques

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Abstract

Tamarind (*Tamarindus indica* L.) is a versatile spice crop with economic significance, known for its diverse applications in pulp, seed and timber. Thriving in challenging conditions like poor soils and drought, it has become crucial in various uses, particularly in wastelands. In this post-harvest study, tamarind pods underwent deshelling, deseeding and defibering before applying treatments to extend the shelf life of the pulp. Five additives and four packaging materials, under 2 storage conditions, were tested in a factorial design. Results of over 6 months revealed that treating tamarind pulp with 0.2 % sulphur fumes, packed in aluminium foil, and stored refrigerated minimized browning and moisture content. This treatment also showed lower total carbohydrate, reducing sugar, protein, amino acid and total phenol content. Conversely, pulp treated with 2.0 % ascorbic acid, packed in palmyrah leaf bags and stored refrigerated exhibited higher acidity. Pulp treated with 0.2 % sulphur fumes, packed in palmyrah leaf bags and stored under ambience showed consistently higher total soluble solids. The findings suggest that treating pulp with 0.2 % sulphur fumes, using aluminium foil for packing and refrigerated storage can significantly reduce browning, making it an ideal choice for extended stability and potential export markets. Furthermore, adopting aluminium foil as a packing material in Indian conditions proves economically feasible, ensuring better pulp quality during prolonged storage, particularly for small-scale tamarind growers.

Keywords

tamarind pulp; post-harvest storage; packaging materials; food additives; storage temperature; browning; shelf-life

Introduction

India is endowed with diverse agro-climatic conditions across its regions, providing extensive opportunities for cultivating various spice crops. Spices have played an integral role in culinary practices, offering indispensable flavouring to foods since ancient times. Many spices boast valuable attributes, serving as colorants, odorants, preservatives and nutraceuticals. Beyond their role as flavour enhancers, spices find widespread application in health, personal care and hygiene sectors, thereby playing a crucial and substantial role in the country's economy. Tamarind undeniably possesses considerable utility, being one of the species preserved when a segment of the Savanna undergoes clearance for agricultural purposes (1). Originating from Africa, the fruits of this plant are frequently ingested and engaged in

commercial transactions within the continent (2). India stands as the world's largest producer and consumer of spices, earning the well-deserved moniker "Home of Spices". Tamarind, a fruit of *Tamarindus indica*, exemplifies this rich spice heritage. The versatile nature of tamarind, particularly its pulp, lends itself to various applications in food preparation. Renowned for its distinctive sweet and sour flavour, tamarind pulp is highly sought after for its culinary and flavouring qualities.

The quality of tamarind pulp after harvest is significantly affected by various pre-harvest factors. Key influences include the climate, soil quality, irrigation and harvesting methods. Extreme weather conditions during the flowering and fruit development stages can lead to subpar fruit quality at harvest (3). Soil characteristics, such as pH, nutrient levels and organic matter content, have a direct impact on the sweetness and overall quality of the tamarind pulp. Inadequate water supply during the growth period can adversely affect the fruit's shelf-life post-harvest. Additionally, careful handling during harvest is crucial to prevent fruit damage and spoilage. Ensuring optimal timing and intervals for harvesting is essential for maintaining fruit quality (3).

The tamarind fruit pulp, known for its pleasantly acidic taste and rich aroma, serves as a primary souring agent in curries, sauces and beverages. Its widespread use, both domestically and industrially, is attributed to its high acidity resulting from tartaric acid. The unripe pulp, initially green and relatively sweet, undergoes a colour transformation from green to yellowish-green, brown and ultimately black as it ripens. During ripening, the pulp exhibits polyphenol oxidase (PPO) activity and an increase in reducing sugars and amino acids, particularly lysine, leading to the Maillard reaction and subsequent non-enzymatic browning. Understanding the biochemical changes during storage is crucial to retard or delay the Maillard reaction and prevent browning. In various food and agricultural products, non-enzymatic browning, specifically through the Maillard reaction, arises from the interaction of reducing sugars with amino acids. In tamarind, this reaction is a significant concern, contributing to the deterioration of quality. Lysine, a key amino acid in tamarind pulp, plays a substantial role in the Maillard reaction due to its free E-amino group's ready interaction with reducing sugars. The Maillard reaction, known for causing substantial quality losses in food, may lead to undesirable changes and the formation of chemically stable yet nutritionally unavailable derivatives called melanoidins. Higher temperatures accelerate enzymatic reactions, particularly those of polyphenol oxidase (PPO), which leads to browning in tamarind pulp (4). In Indian households, tamarind is preserved by mixing it with salt. After harvest, the deshelled pods are layered and stored in earthen pots. Farmwomen traditionally add about 10 g of salt per kilogram of tamarind pulp between these layers. This method helps prevent pest infestations, such as beetles and the Indian meal moth (*Plodia cautella*). Additionally, the salt helps to loosen the tamarind flesh, making it easier to handle during cooking (5). Changes in moisture content, along with titrable acidity (TA) and reducing sugars (RS), increase the likelihood of tamarind pulp browning at room temperature (6). Polyethylene pouches retain moisture, promoting enzymatic activity and raising the temperature, which further increases browning. The presence and interaction of sugars, acids and phenolic compounds also enhance browning during storage (7).

A food additive is a chemical directly added to food to enhance its quality, safety, sensory characteristics and other properties. According to the Codex Alimentarius, food additives are defined as "any substance not typically consumed as food on its own and not commonly used as a characteristic ingredient of food, regardless of its nutritional value, that is intentionally added to food for a technological purpose during its manufacture, processing, preparation, treatment, packaging, transport or storage, resulting in it or its by-products becoming a component of such foods, either directly or indirectly". Some additives, like vinegar, salt and sulphur dioxide, have been used for preservation for centuries (8). The food additives used in this study include 4 % sodium chloride, 2 % ascorbic acid, 4 % citric acid, 4 % gingelly oil and 0.2 % sulphur.

In the current study, tamarind pods were harvested and subsequently the collected pods underwent deshelling, deveining and deseeding before exposure to various post-harvest treatments. The study investigated the effect of different food additives, packaging materials and storage temperatures on the physicochemical properties of tamarind pulp over a 6 months storage period. The findings and implications are discussed herein.

Materials and Methods

The study aimed to assess the post-harvest effects of additives, packaging materials and storage temperature on tamarind pulp (*Tamarindus indica* L.) cv. PKM1 conducted at Horticultural College and Research Institute, Periyakulam, with the methodologies outlined below. The tamarind pods were collected from the trees that received the pre-harvest treatment of potassium sulphate 1 % at 3 different development stages *viz.,* at the time of flowering, peak flowering and greed mature pod stage. The same treatment was justified with higher yields in tamarind by our previous results (unpublished data). The pods were harvested by shaking the branches of the tamarind tree and the fallen fruits were collected. The pulp from pods was manually extracted, devoid of shell, seed and fibre, by sun-drying the harvested pods. The specifics of the treatments are illustrated in Fig. 1 and Table 1.

The browning degree of pulp samples was determined following the method suggested (9). Weighed samples (2 g) were thoroughly extracted with 60 % hot alcohol, reaching a final volume of 100 mL after centrifugation. The absorbance of the supernatant, measured at 440 nm wavelength using 60 % alcohol as a blank, was expressed as optical density values. Total carbohydrate content was estimated via the recommended procedure (10) and expressed in percentage. Total soluble solids were measured using a hand refractometer (ERMA ERB-32). A 0.5 mg

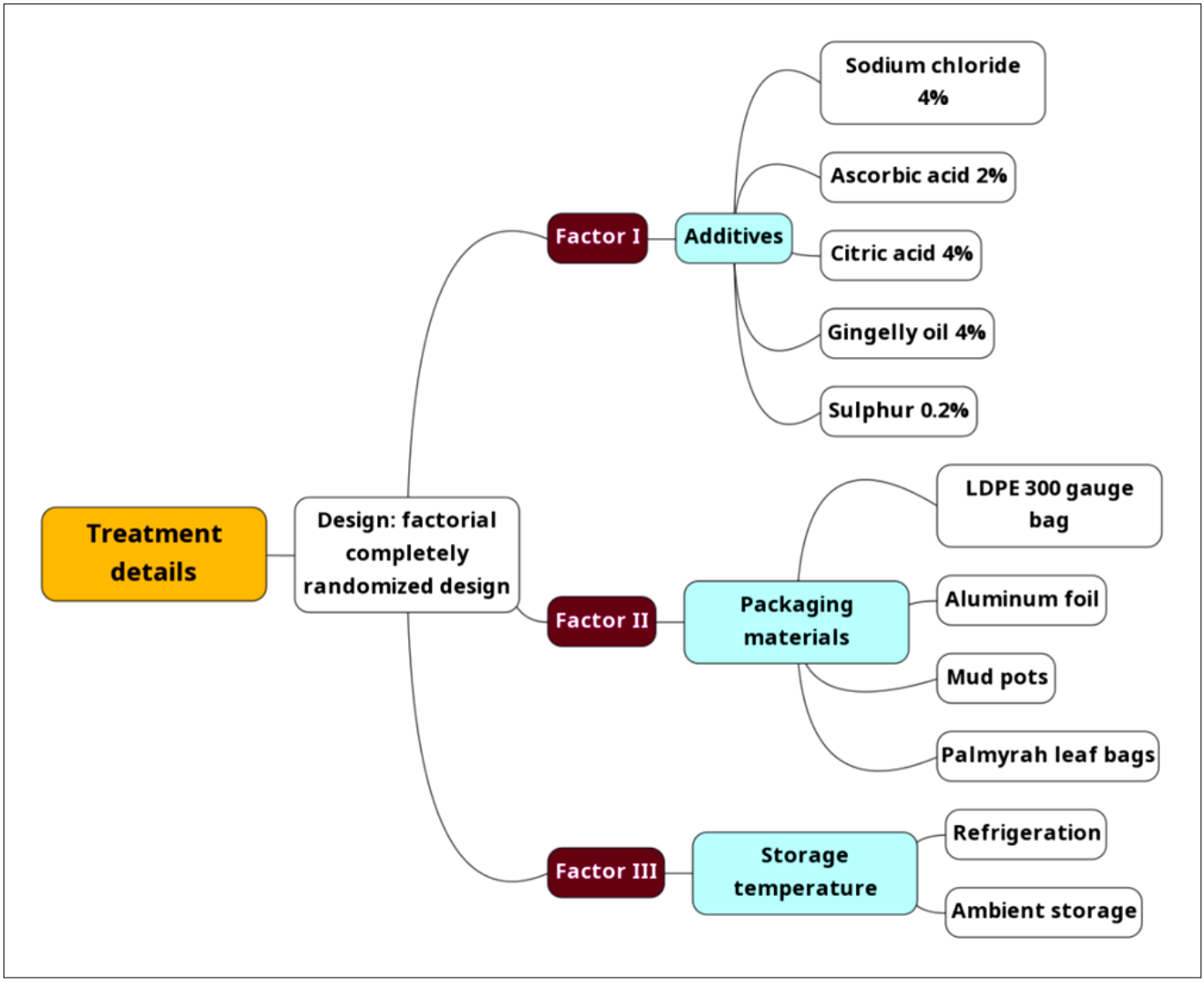

Fig. 1. Treatment details.

Table 1. Treatment details.

$A_1P_1S_1$	Pulp treated with 4.0 % sodium chloride (common salt) and packed in a 300-gauge polyethylene bag and stored under refrigerated condition
$A_1P_2S_1$	Pulp treated with 4.0 % sodium chloride (common salt) and packed in aluminium foil and stored under refrigerated condition
$A_1P_3S_1$	Pulp treated with 4.0 % sodium chloride (common salt) and packed in a mud pot and stored under refrigerated condition
$A_1P_4S_1$	Pulp treated with 4.0 % sodium chloride (common salt) and packed in palmyrah leaf bag and stored under refrigerated condition
$A_2P_1S_1$	Pulp treated with 2.0 % ascorbic acid and packed in a 300-gauge polyethylene bag and stored under refrigerated condition
$A_2P_2S_1$	Pulp treated with 2.0 % ascorbic acid and packed in aluminium foil and stored under ambient condition
$A_2P_3S_1$	Pulp treated with ascorbic acid 2.0 % packed in mud pot and stored under refrigerated condition
$A_2P_4S_1$	Pulp treated with 2.0 % ascorbic acid and packed in palmyrah leaf bag and stored under refrigerated condition
$A_3P_1S_1$	Pulp treated with 4.0 % citric acid and packed in a 300-gauge polyethylene bag and stored under refrigerated condition
$A_3P_2S_1$	Pulp treated with 4.0 % citric acid and packed in aluminium foil and stored under refrigerated condition
$A_3P_3S_1$	Pulp treated with 4.0 % citric acid and packed in mud pot and stored under refrigerated condition
$A_3P_4S_1$	Pulp treated with 4.0 % citric acid and packed in palmyrah leaf bag and stored under refrigerated condition
$A_4P_1S_1$	Pulp treated with 4.0 % gingelly oil and packed in a 300-gauge polyethylene bag and stored under refrigerated condition
$A_4P_2S_1$	Pulp treated with 4.0 % gingelly oil and packed in aluminium foil and stored under refrigerated condition
$A_4P_3S_1$	Pulp treated with 4.0 % gingelly oil and packed in mud pot and stored under refrigerated condition
$A_4P_4S_1$	Pulp treated with 4.0 % gingelly oil and packed in palmyrah leaf bag and stored under refrigerated condition
$A_5P_1S_1$	Pulp treated with 0.2 % sulphur fumes and packed in a 300-gauge polyethylene bag and stored under refrigerated condition
$A_5P_2S_1$	Pulp treated with 0.2 % sulphur fumes and packed in aluminium foil and stored under refrigerated condition

$A_5P_3S_1$	Pulp treated with 0.2 % sulphur fumes and packed in mud pot and stored under refrigerated condition
$A_5P_4S_1$	Pulp treated with 0.2 % sulphur fumes and packed in palmyrah leaf bag and stored under refrigerated condition
$A_1P_1S_2$	Pulp treated with 4.0 % sodium chloride (common salt) and packed in a 300-gauge polyethylene bag and stored under ambient condition
$A_1P_2S_2$	Pulp treated with 4.0 % sodium chloride (common salt) packed in aluminium foil and stored under ambient condition
$A_1P_3S_2$	Pulp treated with 4.0 % sodium chloride (common salt) and packed in a mud pot and stored under ambient condition
$A_1P_4S_2$	Pulp treated with 4.0 % sodium chloride (common salt) and packed in palmyrah leaf bag and stored under ambient condition
$A_2P_1S_2$	Pulp treated with 2.0 % ascorbic acid and packed in a 300-gauge polyethylene bag and stored under ambient condition
$A_2P_2S_2$	Pulp treated with 2.0 % ascorbic acid and packed in aluminium foil and stored under ambient condition
$A_2P_3S_2$	Pulp treated with 2.0 % ascorbic acid packed in mud pot and stored under ambient condition
$A_2P_4S_2$	Pulp treated with 2.0 % ascorbic acid and packed in palmyrah leaf bag and stored under ambient condition
$A_3P_1S_2$	Pulp treated with 4.0 % citric acid and packed in a 300-gauge polyethylene bag and stored under ambient condition
$A_3P_2S_2$	Pulp treated with 4.0 % citric acid and packed in aluminium foil and stored under ambient condition
$A_3P_3S_2$	Pulp treated with 4.0 % citric acid and packed in mud pot and stored under ambient condition
$A_3P_4S_2$	Pulp treated with 4.0 % citric acid and packed in palmyrah leaf bag and stored under ambient condition
$A_4P_1S_2$	Pulp treated with 4.0 % gingelly oil and packed in a 300-gauge polyethylene bag and stored under ambient condition
$A_4P_2S_1$	Pulp treated with 4.0 % gingelly oil and packed in aluminium foil and stored under ambient condition
$A_4P_3S_2$	Pulp treated with 4.0 % gingelly oil and packed in a mud pot and stored under ambient condition
$A_4P_4S_2$	Pulp treated with 4.0 % gingelly oil and packed in palmyrah leaf bag and stored under ambient condition
$A_5P_1S_2$	Pulp treated with 0.2 % sulphur fumes and packed in a 300-gauge polyethylene bag and stored under ambient condition
$A_5P_2S_2$	Pulp treated with 0.2 % sulphur fumes and packed in aluminium foil and stored under ambient condition
$A_5P_3S_2$	Pulp treated with 0.2 % sulphur fumes and packed in mud pot and stored under ambient condition
$A_5P_4S_2$	Pulp treated with 0.2 % sulphur fumes and packed in palmyrah leaf bag and stored under ambient condition

sample was homogenized in hot 80 % ethanol and the residue was washed until the anthrone reagent failed to develop colour. The residue was then extracted with 5.0 mL of water and 6.5 mL of 52 % perchloric acid at 0 °C for 20 min and repeated twice. The pooled supernatant was brought to 100 mL and 0.1 mL of this solution was diluted to 1 mL with distilled water. After adding 4.0 mL of anthrone reagent, the mixture was heated for 8 min and then cooled, and the intensity of the green colour was measured at 630 nm in a spectrophotometer (Thermo Scientific SPECTRONIC 200). A standard curve using glucose was prepared and the glucose content was read and multiplied by 0.9 to obtain the total carbohydrate content (10). The total sugar and reducing sugar contents were determined. A 100 mg sample of the pulp was placed in a tube and hydrolysed in a boiling water bath for 3 h with 5 mL of 2.5 N HCl and then cooled to room temperature. The solution was neutralized with sodium carbonate, made up to 100 mL and centrifuged. Aliquots of 0.5 and 1 mL were taken for analysis. For the standard solution, 0.0 to 1.0 mL of working standards (with 0.0 mL as the blank) were prepared and brought to 1 mL with distilled water. Each tube, including the samples, received 4.0 mL of anthrone reagent and was heated for 8 min in a boiling water bath. After cooling, the green colour intensity was measured at 630 nm. A standard curve was plotted with concentration on the X-axis and absorbance on the Y-axis. The concentration of the sample was determined from this graph and expressed in percentage (10). For reducing sugar content estimation, a 100 g sample of tamarind pulp was extracted twice with 5 mL of hot 80 % ethanol. The supernatant was evaporated to dryness in a water bath and then dissolved in 10 mL of distilled water. A 0.1 mL aliquot was diluted to 2 mL and 1 mL of copper tartrate reagent was added. The mixture was heated in a boiling water bath for 10 min, cooled and then treated with arsenomolybdic acid. The volume was adjusted to 10 mL with distilled water. The blue colour's absorbance was measured at 620 nm after 10 min. A standard curve was prepared using a solution of 100 mg of glucose in 100 mL of water. The reducing sugar content in the pulp sample was calculated from the standard curve and expressed in percentage (10). Non-reducing sugar content was computed by deducting the reducing sugar content from the total sugar content and expressed in percentage. The TSS/acid ratio was calculated by dividing the total soluble solids values by the acidity value of each specific sample. The sugar/acid ratio was computed by dividing the total sugar values by the acidity value of each specific sample.

For protein estimation, a 500 mg sample of tamarind pulp was ground with 5–10 mL of buffer solution, centrifuged and the supernatant was used for protein estimation. A working standard was prepared by dissolving 50 mg of bovine serum albumin in distilled water and making it up to 50 mL. This stock was diluted to 50 mL and pipetted 0.2, 0.4, 0.6, 0.8 and 1.0 mL into test tubes. For the sample, 0.1 mL and 0.2 mL of supernatant were used, with 1 mL of water as the blank. Reagent 'C' was prepared by mixing 50 mL of 2 % sodium carbonate in 0.1 N NaOH (reagent 'A') with 1 mL of 0.5 % copper sulphate in 1 % potassium sodium tartrate (reagent 'B'). Reagent 'D' was prepared by

refluxing a mixture of sodium tungstate, sodium molybdate, water, phosphoric acid and HCl, then adding lithium sulphate, water and bromine water, boiling, cooling, diluting and filtering. Reagent 'C' (5 mL) was added to each tube, followed by reagent 'D'. The mixture was incubated in the dark at room temperature. The blue colour developed was read at 660 nm. Protein content was calculated from a standard graph and expressed in mg/g of sample (11). For total amino acid content estimation, a 500 mg sample of tamarind pulp was finely ground with acid-washed sand and homogenized with 5–10 mL of 80 % ethanol. The mixture was centrifuged and the residue was centrifuged again after removing the supernatant. The pooled supernatants were evaporated to reduce volume and the final extract was used for amino acid estimation. For the assay, 0.1 mL of the extract was mixed with 1 mL of Ninhydrin reagent and diluted to 2 mL with distilled water. This mixture was boiled for 20 min and then 5 mL of a diluent (equal parts water and n-propanol) was added. The colour intensity was measured at 570 nm using a reagent blank prepared with 0.1 mL of 80 % ethanol. A standard curve was prepared by dissolving 50 mg leucine in 50 mL of distilled water; diluting 10 mL of this stock to 100 mL. Aliquots ranging from 0.1 to 1 mL were used to create a concentration range of 10 to 100 µg. The absorbance at 570 nm was measured and the standard curve was used to estimate the total free amino acids in the sample expressed in percentage equivalent of leucine (11).

Anthocyanin content was spectrophotometrically measured. 10 g of the pulp sample was blended with 10 mL of ethanolic HCl (prepared by mixing 95 % ethanol and 1.5 N HCl in an 85:15 ratio) and transferred to a 100 mL volumetric flask. The volume was then adjusted to 100 mL. The sample was stored overnight at 4 °C in a refrigerator, filtered through Whatman No. 1 filter paper and the optical density (O.D) was measured at 535 nm (12). Polyphenol oxidase activity was assayed followed by grinding 1 g of tamarind pulp with 10 mL of 0.1 M phosphate buffer (pH 7), filtered and centrifuged at 2500 rpm for 15 min at 6 ° C. The supernatant was used for the enzyme assay. Optical density (OD) values were measured at the start and after 5 min at 663 nm using a spectrophotometer (13).

For determining total phenol content, 1 g sample was ground with 10 times its volume of 80 % ethanol and centrifuged at 1000 rpm for 20 min. The supernatant was retained and the residue was centrifuged again with 5 times the volume of 80 % ethanol. The supernatants were combined and evaporated to dryness. The residue was dissolved in 5 mL of distilled water and a 0.2 mL aliquot was diluted to 3 mL with distilled water. Then, 0.5 mL of Folin-Ciocalteau reagent was added, followed by 2 mL of 20 % sodium carbonate (Na_2CO_3) after 3 min. The mixture was placed in a boiling water bath for 1 min. The developed colour was measured at 650 nm against a reagent blank. A standard curve was created using various concentrations of catechol and the sample concentration was determined and expressed in mg per 100 g of the sample (14).

For moisture determination, a 10 g sample of the pulp was placed in a pre-weighed moisture box and dried in an oven at 100 °C. At 60 min intervals, the sample was removed, cooled and weighed. This process was repeated until a constant weight was achieved. The moisture percentage was calculated by using the formula below:

$$\text{Moisture \%} = \frac{\text{Weight of the oven-dried sample} \times 100}{\text{Fresh weight of the sample}} \quad \text{.....(Eqn. 1)}$$

The optimal post-harvest treatments were employed to create the subsequent products at the post-harvest laboratory of the Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam, Tamil Nadu, India. Subsequently, an organoleptic assessment was conducted for the following items: tamarind paste, tamarind jelly, tamarind juice, tamarind toffee and tamarind pickle. Tamarind toffee is prepared by first removing the fibers from the fruit pulp and then mixing the pulp with sugar. Tamarind juice is made by diluting the pulp extract with water and straining it. For pickle preparation, fresh mature tamarind pulp is soaked in water for 12 h before separating the pulp. For each kg of tamarind pulp, an equal amount of sugar is added and the mixture is boiled. Spices, salt and oil are then incorporated into the mixture, which is subsequently cooled and stored. Jelly is produced by boiling tamarind extract with pectin and then cooling the mixture. Tamarind pulp is prepared by removing the seeds and fibers and adding water (15). The consumer acceptability of tamarind products derived from the pulp was assessed by a panel consisting of 10 untrained judges. The evaluation encompassed parameters such as colour and appearance, flavour, texture, taste and overall consumer acceptability, employing a 9-point Hedonic scale (16).

The statistical significance at 0.05 % level among the different treatments was carried out by standard procedures (17). Multivariate analysis involves the observation and examination of multiple statistical outcome variables simultaneously. In both design and analysis, this methodology is applied to conduct thorough investigations across various dimensions, considering the impact of all variables on the responses of interest. In this research, distinct analyses, namely principal component analysis, hierarchical clustering analysis and Pearson correlation analysis have been conducted. The principal component analysis was carried out in RStudio with the packages 'Factoextra' and 'FactoMiner'. The cluster analysis and the Pearson correlation analysis were executed with the base functions of R Studio (18).

Results and Discussion

Effect of different treatments on biochemical parameters of tamarind pulp

Effect of different additive substances

Various additives, including sodium chloride (4.0 %), ascorbic acid (2.0 %), citric acid (4.0 %), gingelly oil (4.0 %)

and sulphur fumes (0.2 %), were incorporated into tamarind pulp before storage. During the 6 months storage, sulphur fumes (0.2 %) treatment exhibited the lowest moisture content, followed by ascorbic acid and citric acid. Conversely, gingelly oil and sodium chloride had relatively higher moisture content. The higher moisture content in tamarind pulp accelerates respiratory activities, leading to increased deterioration, possibly due to the oxidation of soluble carbohydrates, organic acids, lipids and proteins for energy production. Sulphur fumes and citric acid, functioning as reducing agents, inhibited respiratory metabolism, thereby preventing substrate oxidation. Despite the initial low moisture content, tamarind pulp moisture content showed an increasing trend over the storage period, possibly due to the slow degradation of reducing agents (19, 20).

Sulphur fumes at 0.2 %, followed by ascorbic acid and citric acid treatments, resulted in the lowest OD values, indicating their effectiveness in maintaining superior storage stability for tamarind pulp compared to other additives (21) (Table 2). These findings align with earlier outcomes (22, 23), demonstrating the browning retardation effects of ascorbic acid and sulphur compounds. Sulphites inhibit non-enzymatic browning by reacting with carbonyl intermediates, preventing the formation of brown pigments. Sodium chloride at 4 %, however, exhibited higher OD values, potentially due to increased pH, promoting browning by altering redox equilibrium (19).

Tamarind pulp acidity increased during storage, with the highest values observed for 2.0 % ascorbic acid addition (Fig. 2). The enzymes in the browning reaction are irreversibly inactivated at pH values of 3 or lower, achievable by acidulents like ascorbic acid. Ascorbic acid addition raised the pulp's acidity, attributed to the combined effects of tamarind pulp's tartaric acid and the added ascorbic acid (24). Ascorbic acid's oxygen scavenging activity

Table 2. Effect of food additives, packaging materials and storage temperature on browning (optical density) of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	0.2553		0.2561		0.2566		0.2584		0.2594		0.2625	
P2	0.2534		0.2539		0.2546		0.2558		0.2561		0.2577	**S**
P3	0.2573		0.2596		0.2609		0.2632		0.2632		0.2656	
P4	0.2591		0.2603		0.2623		0.2645		0.2659		0.2689	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.0009	0.0018	0.0009	0.0018	0.0009	0.0019	0.0009	0.0019	0.0009	0.0019	0.0009	0.0019
P	0.0008	0.0016	0.0008	0.0016	0.0008	0.0017	0.0008	0.0017	0.0008	0.0017	0.0008	0.0017
S	0.0005	0.0012	0.0006	0.0012	0.0006	0.0012	0.0006	0.0012	0.0006	0.0012	0.0006	0.0012
AP	0.0018	NS	0.0018	NS	0.0018	NS	0.0019	NS	0.0019	0.0038	0.0019	0.0038
PS	0.0011	0.0023	0.0011	0.0023	0.0012	0.0024	0.0012	0.0024	0.0012	0.0024	0.0012	0.0024
AS	0.0013	0.0026	0.0013	0.0026	0.0013	0.0026	0.0013	0.0027	0.0013	0.0027	0.0013	0.0027
APS	0.0025	NS	0.0026	0.0052	0.0026	0.0052	0.0026	0.0053	0.0026	0.0053	0.0026	0.0053

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

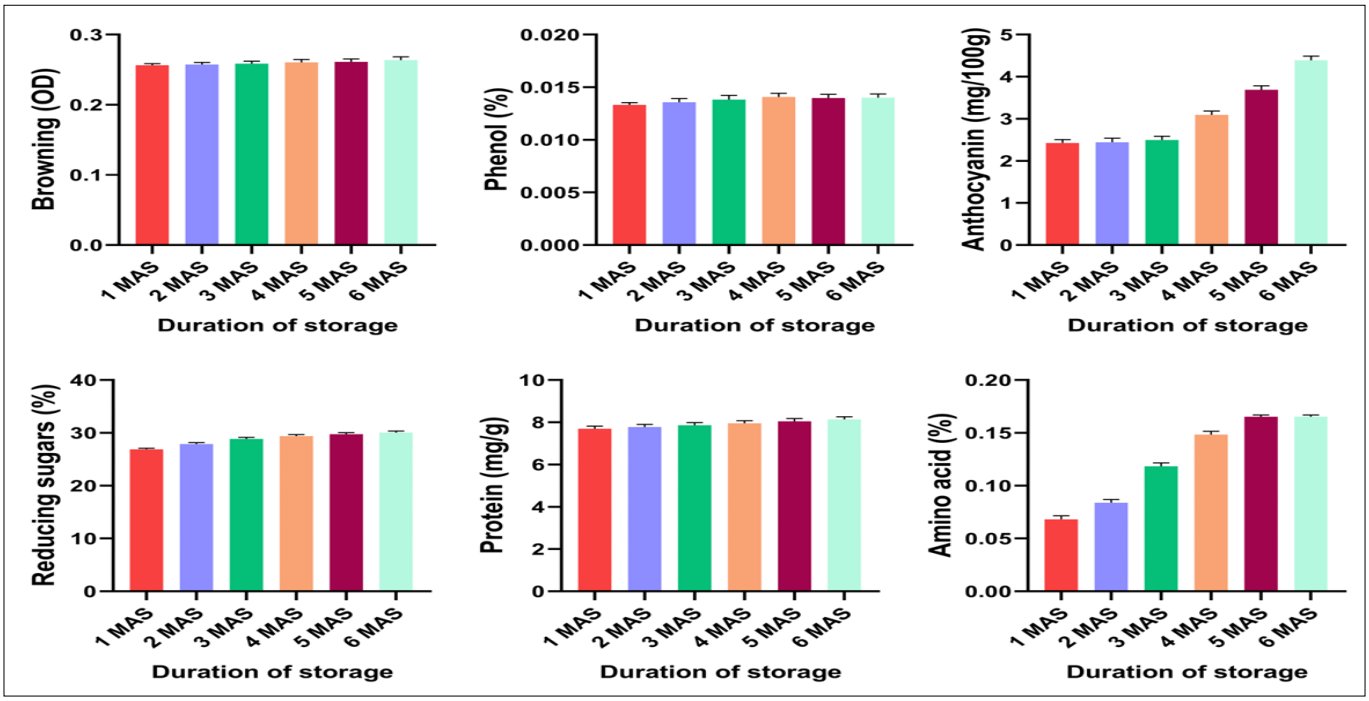

Fig. 2. Means of the browning (OD) and its major driver.

supports its role in preventing browning (25, 26). Acid dips, like those with ascorbic acid or sulphite are used to lower pH, delaying browning. Tamarind pulp, naturally highly acidic, inhibits phenolase enzyme activity below pH 7.0. It recommended acid baths with ascorbic acid or sulphite for preventing browning reactions as ascorbic acid interacts with quinones, preventing browning and oxygenating closed storage containers (27).

Sulphur fumes and citric acid treatments resulted in the highest TSS content, while gingelly oil treatment recorded the lowest compared to other storage methods (Table 3). The lower TSS in gingelly oil-treated pulp may be attributed to increased carbohydrate consumption during respiration (20). Sulphur dioxide (SO_2) acts as a reducing agent, retarding respiration and preventing starch consumption, leading to higher TSS. Ascorbic acid and citric acid, being natural antioxidants, elevate respiratory rates and prevent carbohydrate oxidation, contributing to higher TSS content. Citric acid inhibits cytosolic pyruvate kinase action, increasing phosphoenol pyruvate concentration and reducing glycolysis (19, 28).

Tamarind pulp treated with 2 % ascorbic acid exhibited higher acidity during the 6 months storage, likely due to the added ascorbic acid. The addition of ascorbic acid decreased browning rates in grapes, apples and cranberry juice (29). Tamarind pulp's high pH played a crucial role in non-enzymatic browning, consistent with the findings of sulphur fumes, which also recorded elevated acidity values. It was proposed irreversible inactivation of browning reactions at pH values of 3 or less, achievable with acidulants like ascorbic acid and citric acid, aligning with the present study's results (24).

During fruit ripening, the conversion of starch, hemicelluloses and organic acids into sugars leads to an increase in sugar content from harvest to ripening, followed by a decline during the peak of the senescence. This investigation observed that tamarind pulp treated with 0.2 % sulphur fumes exhibited the highest total sugar content, followed by 2 % ascorbic acid, while a 4.0 % sodium chloride treatment resulted in the lowest total sugar content (Table 4). Ascorbic acid demonstrated efficacy in preventing sugar breakdown and oxidation, maintaining higher

Table 3. Effect of food additives, packaging materials and storage temperature on total soluble solids of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	16.74		16.84		16.99		17.08		17.16		17.29	
P2	16.72		16.76		16.90		16.98		17.05		17.17	**S**
P3	17.02		17.11		17.27		17.35		17.43		17.58	
P4	17.16		17.24		17.40		17.50		17.58		17.70	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.061	0.123	0.061	0.124	0.062	0.126	0.063	0.126	0.063	0.127	0.064	0.129
P	0.054	0.110	0.055	0.111	0.056	0.113	0.056	0.113	0.056	0.113	0.057	0.115
S	0.039	0.077	0.0389	0.079	0.039	0.079	0.039	0.079	0.039	0.080	0.040	0.082
AP	0.122	0.246	0.123	0.248	0.125	0.252	0.125	0.253	0.125	0.254	0.128	0.258
PS	0.077	NS	0.0778	NS	0.0789	NS	0.079	NS	0.079	NS	0.081	NS
AS	0.086	0.174	0.087	0.175	0.088	0.178	0.088	0.179	0.089	0.179	0.090	0.183
APS	0.172	0.348	0.174	0.351	0.176	0.356	0.177	0.357	0.177	0.358	0.180	0.365

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

Table 4. Effect of food additives, packaging materials and storage temperature on total sugars of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	37.84		36.34		35.54		34.87		34.58		33.31	
P2	37.93		36.43		35.63		35.04		34.75		33.48	**S**
P3	37.76		36.26		35.46		34.74		34.42		33.16	
P4	37.56		36.06		35.24		34.65		34.32		33.05	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.136	0.275	0.130	0.264	0.128	0.258	0.125	NS	0.124	NS	0.120	NS
P	0.121	0.246	0.117	0.236	0.114	0.231	0.112	0.227	0.111	0.225	0.107	0.217
S	0.086	0.173	0.082	0.167	0.081	0.163	0.079	0.160	0.078	0.159	0.076	0.153
AP	0.272	NS	0.261	NS	0.256	NS	0.251	0.508	0.249	0.504	0.240	0.486
PS	0.172	NS	0.165	NS	0.162	NS	0.159	0.321	0.157	0.319	0.152	0.307
AS	0.192	0.388	0.185	0.374	0.181	0.366	0.177	NS	0.176	NS	0.170	NS
APS	0.384	NS	0.370	NS	0.362	NS	0.355	0.718	0.353	0.713	0.340	0.687

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

levels. Treatments involving sulphur fumes, ascorbic acid and citric acid exhibited relatively low reducing sugar content, potentially due to diminished invertase enzyme activity (Table 5). In contrast, gingelly oil and sodium chloride treatments recorded higher reducing sugar levels, suggesting their possible role as catalysts in polysaccharide conversion. These findings are consistent with earlier research (30).

In summary, sulphur fumes (0.2 %) treatment demonstrated promising results in minimizing moisture content, optical density values and browning, indicating its potential for enhancing the storage stability of tamarind pulp. Ascorbic acid (2.0 %) and citric acid (4.0 %) treatments also exhibited favourable outcomes. However, gingelly oil (4.0 %) and sodium chloride (4.0 %) treatments resulted in a darker appearance and higher OD values throughout the storage period.

observed in the polyethylene bag align with the earlier report (22). The lower OD values in polyethylene bag storage may be attributed to the modified environment inside the bag, characterized by high transparency and gas impermeability, leading to reduced respiration and biochemical degradation rates. These results are consistent with older reports on okra (34). Aluminium foil packaging exhibited lower OD values, likely reducing non-enzymatic browning due to lowered respiration in the modified atmospheric storage conditions. The foil also prevented light exposure, slowing colour intensification. This aligns with previous findings (35). Mud pot and palmyrah leaf bag recorded higher OD values, possibly due to O_2 availability and energy from natural light accelerating the browning reaction, consistent with earlier observations of light-induced browning in fruits (36).

Table 5. Effect of food additives, packaging materials and storage temperature on reducing sugars of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	26.79		27.77		28.68		29.26		29.65		29.82	
P2	26.61		27.59		28.57		29.03		29.43		29.72	**S**
P3	26.99		28.03		29.03		29.48		29.86		30.18	
P4	27.10		28.15		29.15		29.74		30.12		30.42	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.097	0.196	0.100	0.203	0.104	0.211	0.106	0.214	0.107	0.217	0.108	0.219
P	0.086	0.175	0.089	0.181	0.093	0.188	0.094	0.191	0.096	0.194	0.096	0.196
S	0.061	0.124	0.063	0.128	0.066	0.133	0.067	0.135	0.068	0.137	0.068	0.138
AP	0.194	NS	0.200	NS	0.208	0.422	0.212	0.428	0.215	NS	0.216	0.438
PS	0.122	NS	0.127	NS	0.132	NS	0.134	NS	0.136	NS	0.137	NS
AS	0.137	0.277	0.142	0.287	0.147	0.298	0.149	0.303	0.152	0.307	0.153	0.309
APS	0.274	NS	0.284	0.574	0.295	0.597	0.299	0.606	0.304	NS	0.306	0.619

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

Effect of different packaging materials

The utilization of polybags and aluminium foil is a widely acknowledged method for preserving perishable items, aiming to prolong their shelf life (31, 32). Tamarind pulp is conventionally stored in mud pots and palmyrah leaf bags at the household level. For this experiment, these 2 packaging materials are considered as the control conditions to investigate the effect of other advanced packaging materials. However, it is crucial to establish a standardized packaging material with minimal quality degradation. The objective of food packaging is to economically contain food, meet industry requirements and consumer preferences, ensure food safety and minimize environmental impact (33). In light of this, the current study investigated various packaging materials, including 300-gauge polyethylene bag (P1), aluminum foil (P2), mud pot (P3) and palmyrah leaf bag (P4), for storing tamarind pulp, evaluating biochemical compositions and colour changes over a 6 months period.

The outcomes demonstrated that aluminium foil packaging resulted in the lowest OD values, followed by 300-gauge polyethylene bag. The diminished OD values

Tamarind pulp stored in aluminium foil and polyethylene bag exhibited lower moisture content compared to pulp stored in mud pot and palmyrah leaf bag (Table 6). The high permeability of mud pot and palmyrah leaf bag facilitated the absorption of atmospheric moisture, resulting in increased moisture content. Similar findings were previously reported (37). In contrast, pulp stored in aluminium foil and polyethylene bag showed significantly lower moisture absorption rates, attributed to the impermeable nature of aluminium foil and polyethylene bag. It was also noted that aluminium foil demonstrated higher water vapour resistance, followed by the polyethylene bag (38).

Tamarind pulp stored in palmyrah leaf bag and mud pot exhibited higher acidity values, attributed to increased respiration due to the porous nature of these containers (Table 7). These results align with earlier findings (30). In contrast, tamarind pulp stored in aluminium foil and polyethylene bag showed lower acidity, possibly due to the modified atmosphere within the packaging (Table 7). Reduced respiratory conditions led to decreased carbohydrate decomposition, resulting in lower acidity. These

Table 6. Effect of food additives, packaging materials and storage temperature on moisture content of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	20.59		20.60		20.61		20.62		20.62		20.63	
P2	20.54		20.55		20.56		20.57		20.58		20.59	**S**
P3	21.05		21.07		21.08		21.09		21.09		21.10	
P4	21.21		21.23		21.23		21.25		21.26		21.27	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.074	0.151	0.075	0.151	0.075	0.151	0.075	0.151	0.075	0.151	0.075	0.151
P	0.067	0.135	0.067	0.135	0.067	0.135	0.067	0.135	0.067	0.135	0.067	0.135
S	0.047	0.095	0.047	0.095	0.047	0.095	0.047	0.095	0.047	0.095	0.047	0.095
AP	0.149	0.302	0.150	0.303	0.150	0.303	0.150	0.303	0.150	0.303	0.150	0.303
PS	0.094	0.191	0.094	0.191	0.094	0.191	0.094	0.191	0.094	0.191	0.094	0.191
AS	0.150	0.214	0.106	0.214	0.106	0.214	0.106	0.214	0.106	0.214	0.106	0.214
APS	0.211	0.428	0.212	0.428	0.212	0.428	0.212	0.428	0.212	0.428	0.212	0.428

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

Table 7. Effect of food additives, packaging materials and storage temperature on acidity of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	15.96		15.98		16.01		16.06		16.09		16.11	
P2	15.86		15.87		15.89		15.93		15.95		15.96	**S**
P3	16.15		16.18		16.21		16.26		16.28		16.31	
P4	16.26		16.28		16.32		16.37		16.40		16.43	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.059	0.120	0.059	0.120	0.059	0.120	0.059	0.120	0.059	0.120	0.059	0.121
P	0.053	0.107	0.053	0.107	0.053	0.107	0.053	0.107	0.053	0.107	0.053	0.107
S	0.037	0.076	0.037	0.076	0.037	0.076	0.037	0.076	0.037	0.076	0.037	0.076
AP	0.119	0.240	0.119	0.240	0.119	0.240	0.119	0.240	0.119	0.240	0.119	0.241
PS	0.075	0.152	0.075	0.152	0.075	0.152	0.075	0.152	0.075	0.152	0.075	0.152
AS	0.084	0.170	0.084	0.170	0.084	0.170	0.084	0.170	0.084	0.170	0.084	0.170
APS	0.168	0.340	0.168	0.340	0.168	0.340	0.168	0.340	0.168	0.340	0.168	0.340

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

findings are consistent with prior studies (39, 40). Tamarind pulp stored in palmyrah leaf bag and mud pot exhibited higher total soluble solid content, likely due to enhanced respiration, facilitating the breakdown of complex substances into simple sugars. This contrasts with tamarind pulp stored in aluminium foil and polyethylene bag, where lower total soluble solids were observed, possibly influenced by the barrier properties of these packaging materials (30).

Throughout the storage period, the total sugar content of tamarind pulp decreased with palmyrah leaf bag and mud pot packaging exhibiting higher total and reducing sugar content. This increase is likely attributed to the breakdown of carbohydrates/starch into simple sugars. The variability in total and reducing sugars in permeable materials may be due to the availability of oxygen radicals from atmospheric humidity during storage. It was previously reported that polyethylene bags have lower permeability compared to other materials (38). In contrast, tamarind pulp stored in aluminium foil and polyethylene bags showed higher non-reducing sugar content, possibly due to the barrier properties of these materials preventing the conversion of starch into simple sugars, as supported by the lower total and reducing sugar content observed in this packaging treatment (Table 8).

Palmyrah leaf bag and mud pot packaging resulted in higher amino acid content in tamarind pulp, likely due to increased respiration under the prevailing high moisture conditions. In contrast, tamarind pulp packed in aluminium foil and polyethylene bags showed lower amino acid content, possibly due to the creation of modified atmospheric conditions that slowed down the degradation rate of biochemical substances in the pulp (Table 9). Over the 6 months storage period, a gradual increase in protein content was observed in tamarind pulp (Fig. 2). Among the packaging materials, palmyrah leaf bag and mud pot packaging exhibited higher protein content (Table 10). Notably,

Table 8. Effect of food additives, packaging materials and storage temperature on non-reducing sugars of tamarind pulp at different stages of storage.

Factor 1					**A**							
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	11.05		8.57		6.86		5.61		4.93		3.49	
P2	11.32		8.83		7.06		6.01		5.31		3.76	**S**
P3	10.77		8.23		6.43		5.27		4.56		2.98	
P4	10.46		7.90		6.10		4.91		4.20		2.63	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.097	0.196	0.100	0.203	0.104	0.211	0.106	0.214	0.107	0.217	0.108	0.219
P	0.086	0.175	0.089	0.181	0.093	0.188	0.094	0.191	0.096	0.194	0.096	0.196
S	0.061	0.124	0.063	0.128	0.066	0.133	0.067	0.135	0.068	0.137	0.068	0.138
AP	0.194	NS	0.200	NS	0.208	0.422	0.212	0.428	0.215	NS	0.216	0.438
PS	0.122	NS	0.127	NS	0.132	NS	0.134	NS	0.136	NS	0.137	NS
AS	0.137	0.277	0.142	0.287	0.147	0.298	0.149	0.303	0.152	0.307	0.153	0.309
APS	0.274	NS	0.284	0.574	0.295	0.597	0.299	0.606	0.304	NS	0.306	0.619

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

Table 9. Effect of food additives, packaging materials and storage temperature on amino acid content of tamarind pulp at different stages of storage.

Factor 1					**A**							
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	0.066		0.082		0.117		0.147		0.165		0.165	
P2	0.065		0.081		0.115		0.145		0.163		0.163	**S**
P3	0.070		0.086		0.120		0.150		0.166		0.166	
P4	0.072		0.087		0.122		0.152		0.167		0.167	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.0002	0.0004	0.0003	0.0006	0.0004	0.0009	0.0006	0.0012	0.0006	0.0012	0.0084	0.0171
P	0.0002	0.0004	0.0003	0.0006	0.0004	0.0008	0.0005	0.0011	0.0005	0.0011	0.0076	0.0153
S	0.0001	0.0003	0.0002	0.0004	0.0003	0.0005	0.0004	0.0007	0.0004	0.0007	0.0053	0.0108
AP	0.0004	0.0008	0.0006	0.0012	0.0009	0.0017	0.0012	0.0024	0.0012	0.0024	0.0169	0.0341
PS	0.0003	0.0005	0.0004	0.0008	0.0005	0.0011	0.0007	0.0015	0.0007	0.0015	0.0106	0.0216
AS	0.0003	0.0006	0.0004	0.0009	0.0006	0.0012	0.0008	0.0017	0.0008	0.0017	0.0119	0.0241
APS	0.0006	0.0012	0.0009	0.0018	0.0012	0.0024	0.0016	0.0033	0.0016	0.0033	0.0239	0.0483

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

Table 10. Effect of food additives, packaging materials and storage temperature on protein of tamarind pulp at different stages of storage.

Factor 1					**A**							
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	7.64		7.72		7.81		7.90		7.99		8.09	
P2	7.55		7.64		7.73		7.81		7.90		8.00	**S**
P3	7.73		7.80		7.90		7.99		8.08		8.17	
P4	7.85		7.94		8.02		8.11		8.21		8.29	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.027	0.055	0.027	0.055	0.028	0.057	0.028	0.057	0.029	0.058	0.029	0.059
P	0.245	0.049	0.024	0.050	0.025	0.051	0.025	0.051	0.026	0.052	0.026	0.052
S	0.017	0.035	0.017	0.035	0.017	0.036	0.018	0.036	0.018	0.037	0.018	0.037
AP	0.054	0.111	0.055	0.111	0.056	0.114	0.056	0.115	0.058	0.117	0.058	0.118
PS	0.034	0.070	0.035	0.070	0.035	0.072	0.036	0.072	0.036	0.074	0.037	0.074
AS	0.038	0.078	0.039	0.079	0.040	0.081	0.040	0.081	0.041	0.083	0.041	0.083
APS	0.077	0.157	0.078	0.158	0.080	0.162	0.080	0.162	0.082	0.166	0.082	0.167

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

treatments with higher protein content also recorded higher moisture content during storage. The interaction between nitrogen in the peptide link and water molecules could contribute to these observations (29).

Effect of different storage temperature

The study aimed to enhance the shelf life of tamarind pulp in ambient and refrigerated conditions. Results revealed that refrigerated storage led to higher moisture, acidity, total sugar and non-reducing sugar content in tamarind pulp. The elevated moisture content in refrigerated pulp may be attributed to the low temperature and high relative humidity, similar to other observations (41). Variations in storage environment conditions, particularly temperature and humidity, influenced moisture content changes in the produce. The high relative humidity and low temperature in refrigerated storage contributed to increased moisture in tamarind pulp. Conversely, ambient storage conditions resulted in lower moisture and acidity, possibly due to a higher respiration rate and water loss, aligning with previous report findings in mango (42).

It was noted that acidity declined more rapidly at ambient temperatures than at cooler temperatures, possibly due to increased respiration rates, as acids serve as crucial respiratory substrates in fruit catabolism (43). Conversely, higher respiratory rates under cool temperatures led to carbohydrate degradation, resulting in elevated total sugar and non-reducing sugar content in refrigerated storage. Tamarind pulp stored under ambient conditions exhibited higher levels of total soluble solids, total sugar, amino acids, proteins and reducing sugar (Fig. 2). The accelerated increase in total soluble solids in ambient conditions may be attributed to higher temperature and lower relative humidity, facilitating faster carbohydrate and sugar utilization. Higher OD values in ambient storage indicated increased browning in tamarind pulp, potentially linked to the accumulation of higher reducing sugars, amino acids and proteins, aligning with previous findings (30).

Interaction effect of additives, packaging materials and storage conditions

The study investigated the impact of additives, packaging and storage on tamarind pulp quality. Browning, indicating quality decline, occurs linearly with storage time due to non-enzymatic reactions involving total sugar, reducing sugar and amino acids (Fig. 3). The goal is to prevent this browning using various additives, packaging and storage conditions. Sulphur dioxide and sulphites are effective in controlling post-harvest browning by bleaching the natural colour and reducing pH. Ascorbic acid and citric acid act as reducing agents, inhibiting respiratory metabolism and slowing browning. Tamarind pulp stored in aluminium foil and 300-gauge polyethylene bags creates a modified atmospheric condition, reducing respiration rates and degradation, resulting in lower OD values.

The study found that SO_2 and acids, such as ascorbic acid and citric acid, act as acidulants, slowing down pH increase. The limited pH rise in tamarind pulp stored in aluminium foil and polyethylene bags may be attributed to delayed ripening and senescence, creating an optimally modified atmosphere. The higher acidity observed in these treatments might be due to the added acids. Similar effects of a modified atmosphere package on retaining titrable acid contents through slowed respiration have also been observed in apples (44) and guavas (45). Furthermore, under refrigerated storage conditions, the slow rate of respiration prevents the degradation of biochemicals, resulting in higher acidity in these treatments.

Similarly, elevated total soluble solid content was observed with sulphur fumes and acids, possibly attributed to SO_2 acting as a reducing agent, retarding respiration and preventing starch consumption, resulting in higher total soluble solid content. Higher total sugar content was noted with sulphur fumes and ascorbic acid. The addition of sulphur fumes and ascorbic acid reduced the pH of tamarind pulp, delaying or inhibiting physiological activities under low pH conditions and preventing the decomposition of total sugars into simple sugars. Packaging materials, especially the modified atmosphere created by aluminium foil and a 300-gauge polyethylene bag, slowed down starch conversion, leading to higher total sugar content. Refrigerated storage conditions also inhibited respiratory rate, preventing total sugar decomposition. These findings align with the earlier report on kiwi fruits (46). Additionally, higher non-reducing content in tamarind pulp treated with ascorbic acid, packed in polyethylene bags, and stored under refrigeration may be due to the reducing effect of ascorbic acid, polyethylene bag barrier properties and the low-temperature environment, maintaining respiratory rate and preventing starch conversion.

The browning of tamarind pulp was lower in treatments with low moisture content. Tamarind pulp, being hygroscopic, absorbs moisture from the atmospheric air. The porous nature of mud pots and polyethylene bags allows free entry of air, resulting in high moisture content in the pulp. Additives such as sodium chloride and gingelly oil further enhance the moisture content. Pulp treated with gingelly oil/sodium chloride, packed in mud pot/palmyrah leaf bag, and stored under refrigerated conditions exhibited high moisture content, possibly due to the low humidity of refrigerated conditions and the porous nature of packaging materials. Conversely, the low moisture content in tamarind pulp was observed in treatments with sulphur fumes/ascorbic acid, packed in aluminium foil/polyethylene bag and stored under refrigerated conditions. The impermeable nature of these packaging materials prevents air movement and moisture absorption from the atmosphere.

A model system was investigated with avicel, sucrose and invertase, noting increased reaction velocity with higher enzyme activity (47). Higher carbohydrate content in tamarind pulp during storage was observed with the addition of sulphur/ascorbic acid, packed in aluminium foil/polyethylene bag, and stored under refrigerated conditions. The results suggest that sulphur fumes and ascorbic acid, by lowering the pH under acidic conditions, delay physiological processes (catabolic processes). The impervious nature of packaging materials prevents gaseous exchange and low-temperature storage inhibits respi-

Fig. 3. Tamarind pulp samples subjected to different packaging materials and storage temperature.

ration, retarding catabolic processes and breakdown of complex sugars. Similarly, TSS and total sugar content were higher in pulp treated with sulphur fumes/ascorbic acid, packed in aluminium foil/polyethylene bag and stored under refrigerated conditions. The reducing agents, sulphur and ascorbic acid, slow down respiration, preventing carbohydrate oxidation and resulting in elevated TSS and total sugar contents. The development of an effective modified atmosphere during storage also slows down respiration, inhibiting carbohydrate breakdown and leading to higher TSS and total sugar levels.

The darkening of tamarind pulp was effectively delayed by adding sulphur fumes and ascorbic acid, packing in aluminium foil/polyethylene bags and storing under refrigerated conditions. These treatments, acting as reducing agents, lowered the pH of the product. Ascorbic acid, combined with the tartaric acid in tamarind pulp, increased acidity, further reducing the pH. This low pH inhibited most physiological activities, preventing the breakdown of carbohydrates into sugars, proteins and amino acids, which are crucial for the Maillard reaction. The effective modified atmosphere created by aluminium foil and polyethylene bag packing reduced oxygen and increased carbon dioxide levels, inhibiting respiratory rates. Reduced respiration slowed down the catabolic process, delaying the conversion of starch into simple sugars and resulting in a slower browning rate. Similarly, low-temperature storage further delayed the browning reaction by inhibiting respiration rates (44).

The total carbohydrates, anthocyanin and total phenol contents are furnished in Tables 11–13. These treatments demonstrated higher amounts of carbohydrates,

Table 11. Effect of food additives, packaging materials and storage temperature on total carbohydrates of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	61.06		61.41		61.28		61.43		61.62		61.77	
P2	60.93		61.11		61.08		61.25		61.43		61.49	**S**
P3	61.35		61.65		61.51		61.62		61.80		61.95	
P4	61.75		62.04		62.00		62.18		62.11		62.19	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.221	0.446	0.221	0.447	0.221	0.447	0.222	0.447	0.222	0.449	0.222	0.449
P	0.197	0.399	0.198	0.400	0.198	0.399	0.198	0.401	0.198	0.401	0.199	0.402
S	0.139	0.282	0.140	0.283	0.140	0.282	0.140	0.283	0.140	0.284	0.140	0.284
AP	0.441	NS	0.443	NS	0.443	NS	0.443	0.896	0.444	0.897	0.445	NS
PS	0.279	NS	0.280	NS	0.279	NS	0.280	NS	0.281	NS	0.281	NS
AS	0.312	NS	0.313	NS	0.312	NS	0.313	NS	0.314	NS	0.315	NS
APS	0.624	NS	0.626	NS	0.625	NS	0.626	NS	0.628	NS	0.629	1.272

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

Table 12. Effect of food additives, packaging materials and storage temperature on anthocyanin content of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	2.39		2.42		2.46		3.06		3.66		4.36	
P2	2.33		2.33		2.40		2.98		3.57		4.27	**S**
P3	2.46		2.47		2.52		3.13		3.72		4.43	
P4	2.52		2.56		2.61		3.20		3.80		4.50	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.0084	0.0171	0.0084	0.0171	0.0087	0.0177	0.0103	0.0208	0.0128	0.0260	0.0155	0.0313
P	0.0076	0.0153	0.0075	0.0153	0.0078	0.0157	0.0092	0.0186	0.0115	0.0233	0.0139	0.0280
S	0.0053	0.0108	0.0053	0.0107	0.0055	0.0111	0.0065	0.0132	0.0081	0.0165	0.0098	0.0198
AP	0.0168	0.0341	0.0168	0.0341	0.0175	0.0353	0.0206	0.0417	0.0257	0.0520	0.0310	0.0627
PS	0.0106	0.0215	0.0106	0.0215	0.0111	0.0223	0.0130	0.0264	0.0163	0.0329	0.0196	0.0397
AS	0.0119	0.0241	0.0119	0.0241	0.0123	0.0249	0.0145	0.0294	0.0182	0.0368	0.0219	0.0443
APS	0.0238	0.0482	0.0238	0.0482	0.0247	0.0499	0.0291	0.0589	0.0364	0.0736	0.0439	0.0886

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

Table 13. Effect of food additives, packaging materials and storage temperature on total phenol content of tamarind pulp at different stages of storage.

Factor 1							**A**					
Factor 2	**1 MAS**		**2 MAS**		**3 MAS**		**4 MAS**		**5 MAS**		**6 MAS**	**Factor 3**
P1	0.0132		0.0134		0.0136		0.0139		0.0138		0.0138	
P2	0.0131		0.0132		0.0134		0.0137		0.0136		0.0136	**S**
P3	0.0134		0.0137		0.0140		0.0142		0.0141		0.0142	
P4	0.0136		0.0140		0.0143		0.0145		0.0144		0.0144	
	SEd	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**	**SEd**	**CD**
A	0.00005	0.00010	0.00005	0.00011	0.00005	0.00011	0.00006	0.00011	0.00006	0.00011	0.00006	0.00011
P	0.00005	0.00009	0.00005	0.00010	0.00005	0.00010	0.00005	0.00010	0.00005	0.00010	0.00005	0.00010
S	0.00003	0.00007	0.00003	0.00007	0.00003	0.00007	0.00004	0.00007	0.00004	0.00007	0.00004	0.00007
AP	0.00010	0.00021	0.00011	0.00022	0.00011	0.00022	0.00011	0.00023	0.00011	0.00023	0.00011	0.00023
PS	0.00007	0.00013	0.00007	0.00014	0.00007	0.00014	0.00007	0.00014	0.00007	0.00014	0.00007	0.00014
AS	0.00007	0.00015	0.00008	0.00015	0.00008	0.00016	0.00008	0.00016	0.00008	0.00016	0.00008	0.00016
APS	0.00015	0.00030	0.00015	0.00031	0.00015	0.00031	0.00016	0.00032	0.00016	0.00032	0.00016	0.00032

MAS-Months after storage; **NS**-Non-significant; **A**-Additives; **S**-Storage conditions; **P1**-LDPE 300-gauge bags; **P2**-Aluminium foil; **P3**-Mud pots; **P4**-Palmyrah leaf bag (**P3** and **P4**-Controls).

total soluble solids (TSS), total sugar content and acidity. In contrast, high respiratory rates at ambient storage temperatures, coupled with the porous nature of palmyrah leaf bags and mud pots, increased carbohydrate degradation, leading to the conversion into reducing sugars, proteins and amino acids, favouring a higher browning rate. Additionally, the addition of gingelly oil or sodium chloride acted as catalysts or synergists for polysaccharide conversion and increased the pH, resulting in a higher browning rate. Similar findings were previously reported in various crops during post-harvest and storage periods of different food commodities (30, 36, 42, 43).

Fig. 4, represented as a heatmap, provides a comprehensive visualization of the impact of various treatments on the studied biochemical traits. Once again, it underscores the efficacy of treatments A2P2S1 (tamarind pulp treated with 2.0 % ascorbic acid, packed in aluminium foil, and stored under ambient conditions), A5P1S1 (tamarind pulp treated with 0.2 % sulphur fumes and packed in a 300-gauge polyethylene bag, stored under refrigerated conditions) and A5P2S1 (tamarind pulp treated with 0.2 % sulphur fumes, packed in aluminium foil and stored under refrigerated conditions) in significantly extending shelf-life. This extension is attributed to the reduction in browning facilitated by the downregulation of its contributing factors. Thus, the application of aluminium foil or polyethylene bags under refrigerated conditions, combined with sulphur fumes under the same conditions, proves effective in ensuring prolonged storage life for tamarind pulp.

Sensorial evaluation

The pulp was made into various value-added products, namely tamarind pulp jelly (A), tamarind juice (B), tamarind toffee (C), tamarind paste (D) and tamarind pickle (E)

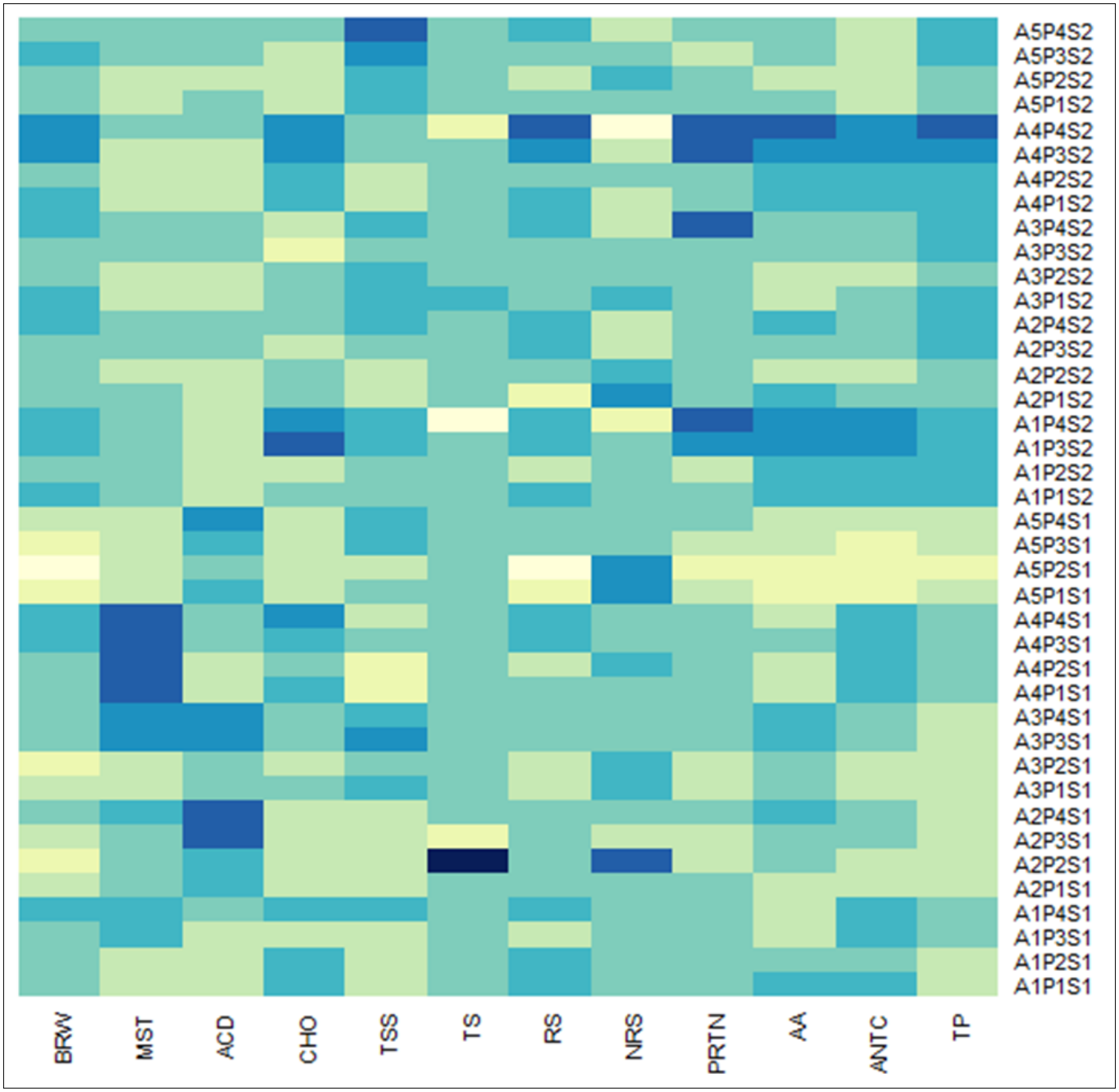

Fig. 4. Heatmap for the effect of different treatments for biochemical traits of tamarind pulp. **BRW**-Browning (OD), **MST**-Moisture content, **ACD**-Acidity, **CHO**-Total carbohydrates, **TSS**-Total soluble solids, **TS**-Total sugars, **RS**-Reducing sugar content, **NRS**-Non-reducing sugar content, **PRTN**-Protein content, **AA**-Amino acid content, **ANTC**-Anthocyanin content, **TP**-Total phenol content.

(Fig. 5). The consumer acceptability assessment utilized a 9-point hedonic scale with a panel of 10 untrained judges. Results, shown in Fig. 6, highlight the favourable reception of products derived from the optimal post-harvest treatment – tamarind pulp treated with 0.2 % sulphur fumes, packed in aluminium foil and stored under refrigeration. The products, including tamarind jelly (A), tamarind juice (B), tamarind toffee (C), tamarind paste (D) and tamarind pickle (E), received mean scores ranging from 6.6 to 7.9 for various attributes. Notably, tamarind toffee (C) achieved the highest overall mean score of 7.4 points, while tamarind jelly (A) recorded the lowest at 6.8 points.

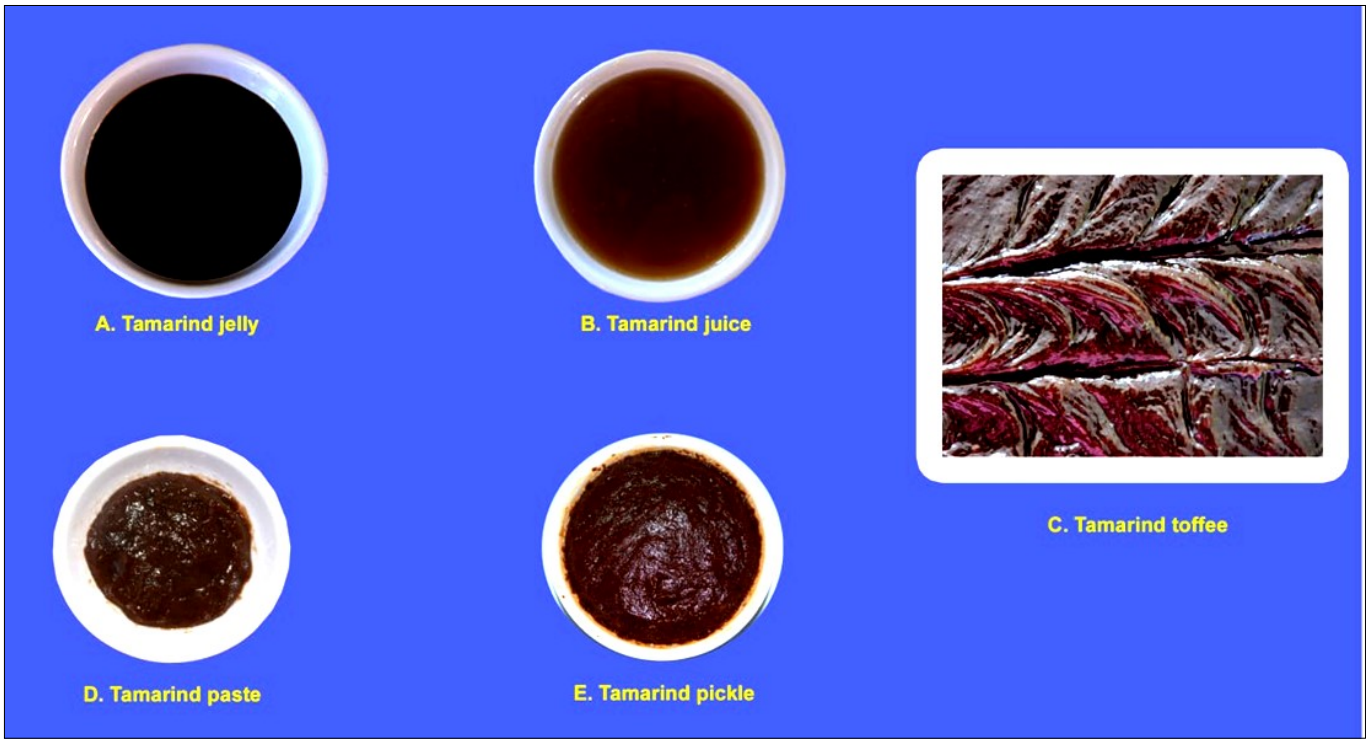

Fig. 5. Value-added products made from the stored tamarind pulp.

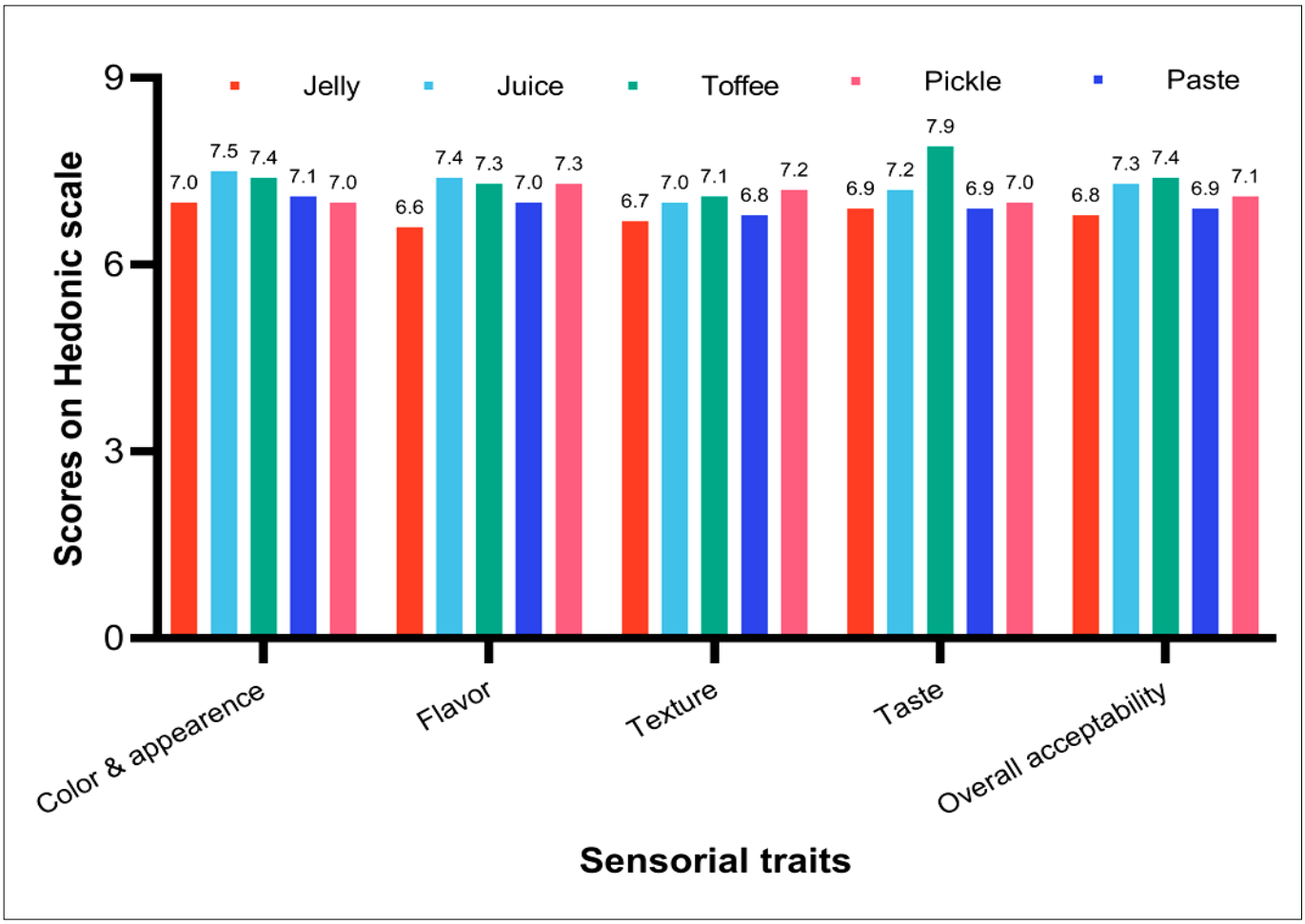

Fig. 6. Scores of sensorial traits on 9-point hedonic scale.

These findings provide valuable insights into the sensory preferences of consumers, informing potential strategies for product refinement and market positioning. Such sensorial evaluations on tamarind processed products were previously reported (48–50).

Assessment of effects through the multivariate approaches

Principal component analysis (PCA)

Principal Component Analysis (PCA), a technique for dimensionality reduction, was employed to assess the influence of treatments on a set of 12 biochemical parameters associated with tamarind pulp. Spectral decomposition was undertaken to scrutinize the interrelationships among these variables. The PCA results elucidated three principal components (PCs) governing the 12 parameters. Notably, PC1 manifested the highest eigenvalue (11.766), contributing significantly to 98.049 % of the total variance, as presented in Fig. 7a. This pre-eminence is visually depicted in Fig. 7a through the scree plot. The analysis unveiled that all biochemical parameters exhibited a heightened positive correlation with PC1, except for total sugars and non-reducing sugars, which demonstrated a pronounced negative correlation with the same component (Fig.7b).

Figs. 7c and 7d show the factor loading and contribution (%) of the different variables to the PCs. The higher positive loadings were scored by acidity (0.291), anthocyanin content (0.290), total phenol content (0.290), total soluble sugars (0.289), browning (0.289) and total carbohydrates content (0.289). In PC1, the highest contributing variables were acidity (8.487), non-reducing sugars (8.453), total phenol content (8.435) and very narrow scores were recorded by anthocyanin (8.423), browning (8.349), total carbohydrates content (8.359) and protein content (8.342). In PC2, the moisture content (32.381), amino acid content (19.231) and reducing sugar content (12.199) showed higher contributions. In PC3, the protein content (47.037), reducing sugar content (10.463), amino acid content (9.877) and total soluble sugars (9.569) showed higher contributions.

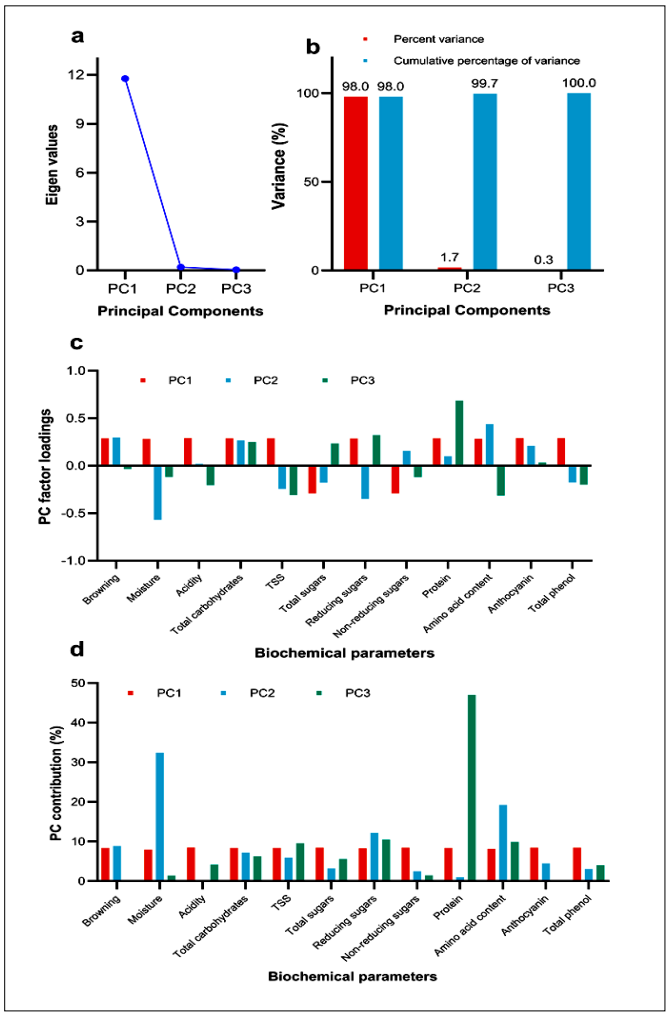

Fig. 7. **a**) Screeplot showing eigen values; **b**) Percent variance of principal components; **c**) Factor loadings of principal components; **d**) Contribution of biochemical parameters to principal components.

The PCA biplot effectively segregated the variables into distinct quadrants on the plot (Fig. 8). Notably, total sugars and non-reducing sugars were positioned in disparate quadrants, denoting a pronounced disparity between them. Conversely, moisture content, reducing sugar content, total soluble sugars, total phenol content and acidity were co-located within the same quadrant, signifying their analogous trends. Meanwhile, protein content, anthocyanin content, total carbohydrates content, browning and amino acid content formed a cohesive group, implying their pivotal roles as major determinants in the browning phenomenon. This collective grouping suggests that these traits substantially contribute to the observed browning phenomenon. Consequently, the PCA provides valuable insights into the factors influencing browning, thereby impacting the shelf-life of tamarind pulp and its acceptability among consumers. The analysis intricately dissects the effects of various treatments on stored tamarind pulp. Previous studies employing principal component analysis to study the factor influencing browning in other horticultural produce showed greater association with high total phenol and PPO contents (51–53).

Hierarchical clustering analysis

Hierarchical clustering analysis was employed to assess the impact of various treatments on the post-harvest biochemistry of tamarind pulp. The outcomes are elucidated in the form of a dendrogram (Fig. 9), revealing the formation of 4 distinct clusters. Cluster 1 encompasses treatments such as A4P4S2 (tamarind pulp treated with 4.0 % gingelly oil, packed in a palmyrah leaf bag and stored under ambient conditions), A1P4S2 (tamarind pulp treated with 4.0 % sodium chloride (common salt), packed in a palmyrah leaf bag and stored under ambient conditions), A1P3S2 (tamarind pulp treated with 4.0 % sodium chloride (common salt), packed in a mud pot and stored under ambient conditions) and A4P3S2 (tamarind pulp treated with 4.0 % gingelly oil, packed in a mud pot and stored under ambient conditions). These specific treatments exhibited suboptimal performance, resulting in heightened browning, shortened shelf-life and diminished appeal. Consequently, we posit that the storage of tamarind pulp in conventional storage materials, namely palmyrah leaf bags and mud pots, under ambient conditions is unfavourable for long-term storage.

Cluster 2 comprised 34 treatment classes, excluding

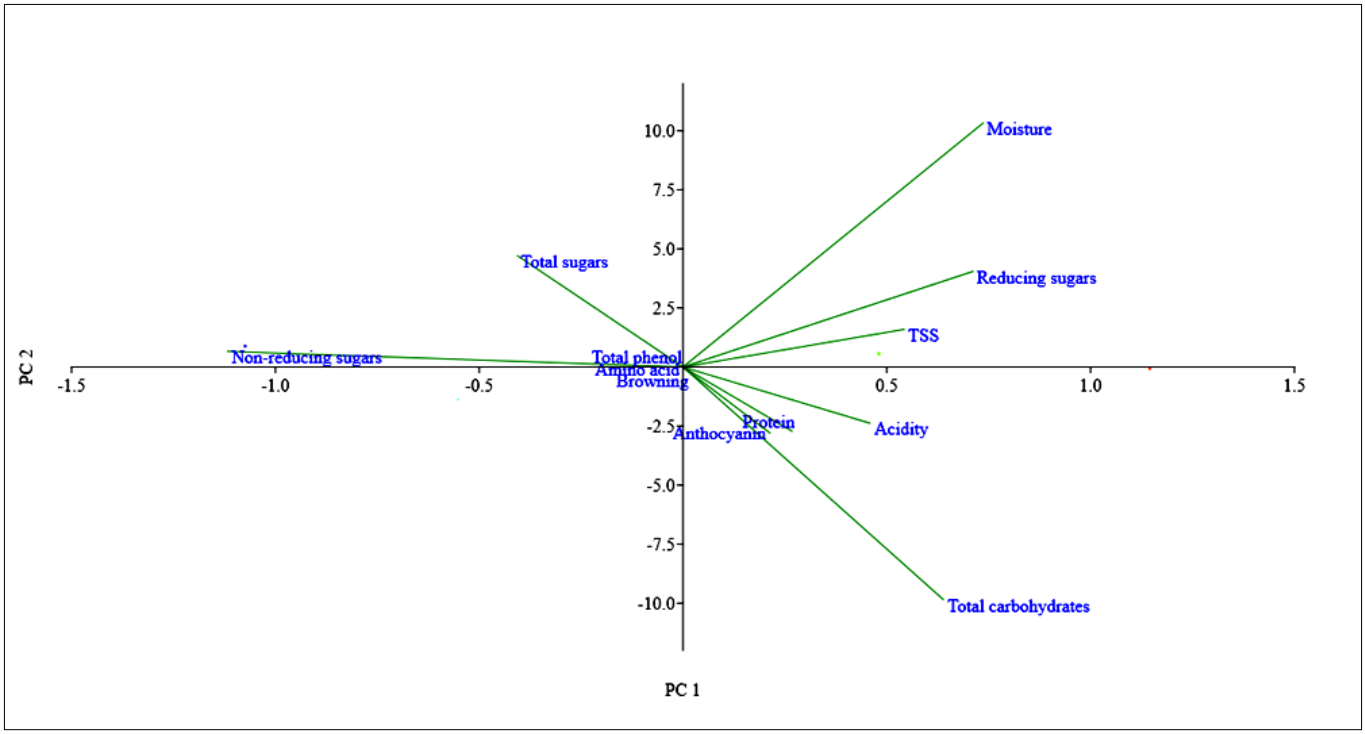

Fig. 8. PCA biplot for the first two principal components.

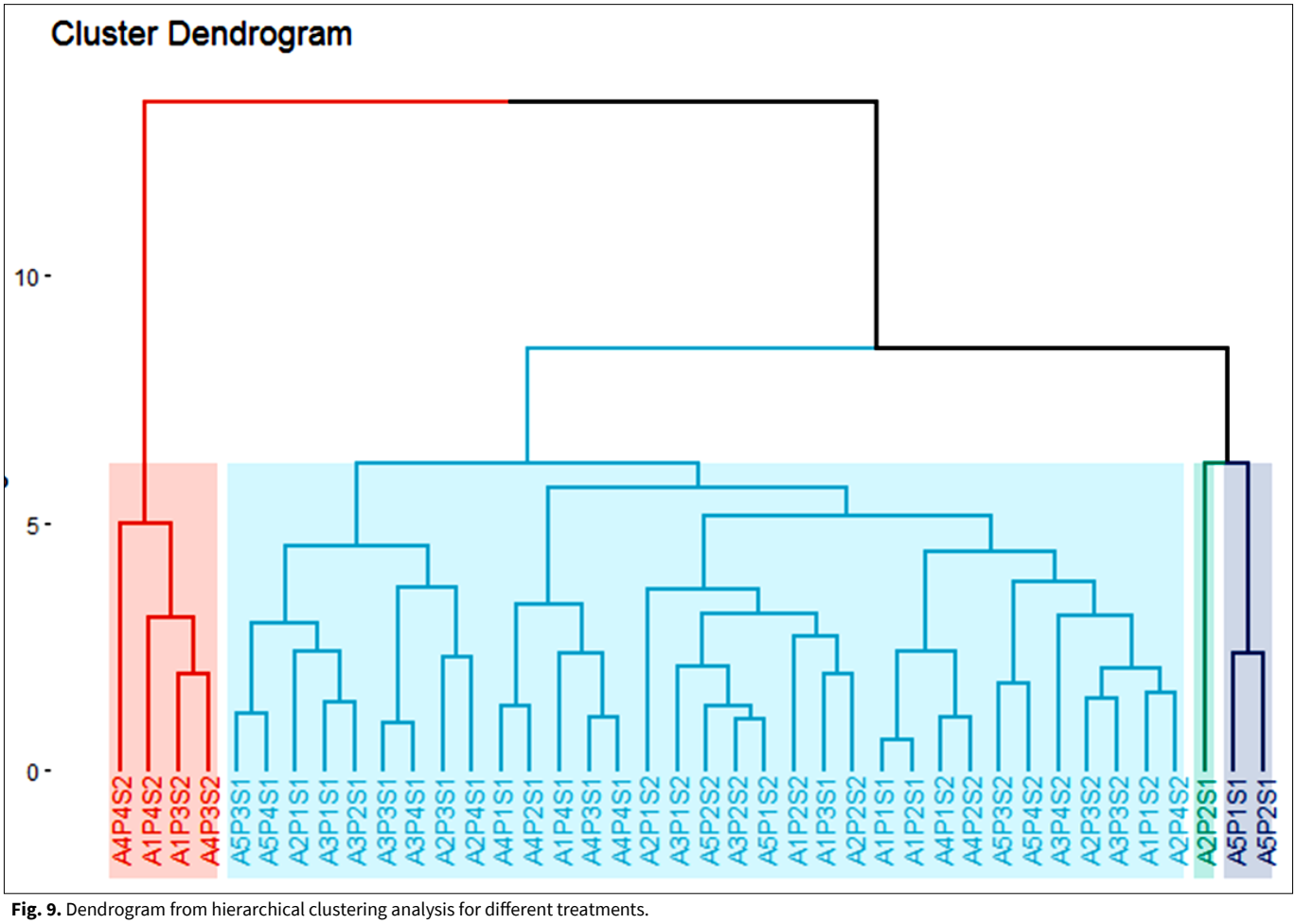

Fig. 9. Dendrogram from hierarchical clustering analysis for different treatments.

A2P2S1 (tamarind pulp treated with 2.0 % ascorbic acid, packed in aluminium foil and stored under ambient conditions); A5P1S1 (tamarind pulp treated with 0.2 % sulphur fumes and packed in a 300-gauge polyethylene bag, stored under refrigerated conditions) and A5P2S1 (tamarind pulp treated with 0.2 % sulphur fumes, packed in aluminium foil and stored under refrigerated conditions), which are assigned to cluster 3 and cluster 4 respectively. These treatments exhibit a notable extension of shelf-life, attributed to the reduction in browning through the down-regulation of its contributing factors. Consequently, the utilization of aluminium foil or polyethylene bags under refrigerated conditions, in conjunction with sulphur fumes under refrigerated conditions, proves to be effective in

ensuring a prolonged storage life for tamarind pulp. Similar studies employing hierarchical clustering analysis for identifying the best treatments for shelf-life enhancement prove this statistical tool to be efficient (53–57).

Pearson correlation analysis

The investigation involved conducting Pearson correlation analysis on all biochemical parameters under consideration. The resulting correlogram illustrating correlation coefficients and relationships among various traits is depicted in Fig. 10. The browning rate assumes paramount importance in determining both the storage life and acceptability of tamarind pulp. Notably, positive influences on browning were observed from total phenol content (0.86), anthocyanin content (0.80), reducing sugars (0.72), amino acid content (0.66) and total carbohydrates (0.64), establishing these parameters as primary contributors to the browning phenomenon. The mitigation of browning and improvement of storage life can be achieved by suppressing these influential parameters. Conversely, non-reducing sugars, total sugars and acidity displayed negative correlations with browning. Meanwhile, moisture content and total soluble sugars exhibited minimal correlation with browning, suggesting a negligible impact on shelf-life enhancement, although both factors play a substantial role in shaping the overall quality of tamarind pulp.

The total phenol content exhibited positive correlations with protein (0.75), amino acid (0.66), anthocyanin content (0.73) and total carbohydrates (0.59), indicating a pattern indicative of Maillard's reaction, a process contributing to browning. This observed trend suggests that an elevation in the aforementioned traits results in increased total phenol content, subsequently leading to heightened browning and a consequent reduction in shelf-life and consumer acceptability. Conversely, total phenol content demonstrated negative correlations with non-reducing sugars, acidity, and total sugars. A parallel trend was observed in the anthocyanin content. Therefore, strategic treatments aimed at downregulating browning and its principal drivers, namely total phenol and anthocyanin contents, could effectively extend the storage shelf-life. Such a strategy would be advantageous if it also upregu-

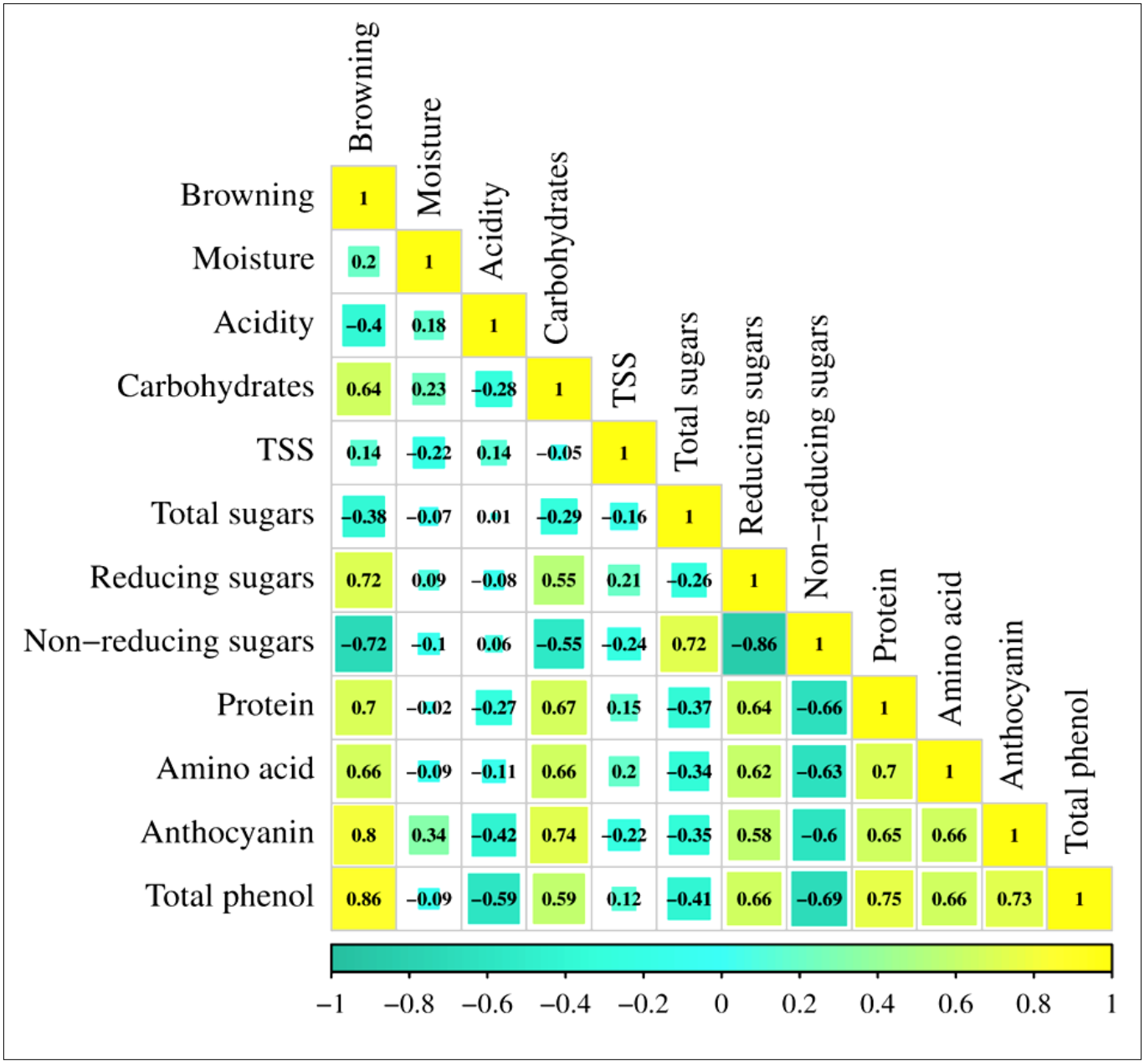

Fig. 10. Pearson correlation coefficients and correlogram presenting the correlation among the variables.

lates the negative regulators of browning while adhering to acceptable limits. The packaging materials, namely the aluminium foil and polyethylene bags are proven to provide such conditions, ensuring the retardation of browning. Earlier reports used Pearson correlation analysis to establish the relationship of PPO and total phenol contents on browning of various horticultural produce (51, 58–61).

Conclusion

In conclusion, our study involved deshelling, deseeding and defibering of tamarind pods, followed by treatments to enhance pulp shelf-life. Employing a factorial design, we tested 5 additives and 4 packaging materials under 2 storage conditions over a period of 6 months. The results highlighted that treating tamarind pulp with 0.2 % sulphur fumes, packed in aluminium foil and stored refrigerated effectively minimized browning, moisture content and various biochemical factors. Conversely, pulp treated with 2.0 % ascorbic acid, packed in palmyrah leaf bags and stored refrigerated exhibited higher acidity. Additionally, pulp treated with 0.2 % sulphur fumes, packed in palmyrah leaf bags and stored under ambience consistently displayed higher total soluble solids. These findings propose that the application of 0.2 % sulphur fumes, aluminium foil packaging and refrigerated storage can significantly mitigate browning, providing extended stability and potential for export markets. Furthermore, adopting aluminium foil as a packing material under Indian conditions proves economically viable, ensuring superior pulp quality during prolonged storage, particularly beneficial for small-scale tamarind growers.

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Authors' contributions

VP conceptualized the experiment, devised the methodologies, supervised and validated the experiment and reviewed the original manuscript. SS provided technical assistance, resource and validated the experiment and reviewed the original manuscript. MSM conducted the research methodologies, formal analysis and biochemical analysis and drafted the original manuscript. JJ carried out the formal analysis, data visualization and drafted the final manuscript. All the authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

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