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EFFECT OF PACKAGING MATERIALS, STORAGE TEMPERATURES, AND STORAGE DURATIONS ON PHYSICO-CHEMICAL QUALITIES OF RED-HOT PEPPER (*Capsicum annum* L.) POWDER

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ABSTRACT

Red hot pepper is the most widely grown vegetable in Ethiopia, valued for its nutritional, medicinal, and economic importance. This study aimed to determine how red pepper powder's physicochemical properties are affected by packaging materials, storage temperatures, and storage duration. Aluminum poaches (ALP), high-density polyethylene (HDPE), Low-density polyethylene (LDPE), and black-coloured low-density polyethylene bags (BLDPE) were the packaging materials used for storage. Samples were stored for ten months at ambient and refrigerated condition and moisture content (MC), water activity (a_w), Nonenzymatic browning index (NEBI) total carotenoids content (TCC), extractable color (ASTA value), pungency index (PI), oleoresin content (OC), and total antioxidant capacities (TAOC) of the samples were measured at two-month interval. Under refrigerated conditions, the MC increased from 10.24 -11.71%, 10.90-12.34%, 11.12-13.03%, and 11.15-12.59%, while at ambient temperature it increased from 10.19 -11.25%, 10.49-12.18%, 11.01-12.83%, and 10.88-12.88% at ambient conditions for ALP, HDPE, LDPE, and BLDPE bags, respectively. Similarly, a_w increased from 0.26-0.31, 0.26-0.35, 0.26-0.53, and 0.26-0.5 under refrigerated conditions, and from 0.26-0.35, 0.26-0.36, 0.26-0.5, and 0.26-0.44 at ambient temperature. NEBI also increased from 0.15-0.18, 0.15-0.19, 0.15-0.24, and 0.15-0.23 abs/g under refrigerated storage, and from 0.15-0.34, 0.15-0.35, 0.15-43, and 0.15-0.38 at ambient temperature. On the other hand, the PI reduced by 60.30%, 43.28%, 50.11%, and 40.11% in LDPE, HDPE BLDPE, and ALP, respectively under refrigerated storage, while at ambient temperature, it reduced by 65.2, 49.11, 55.01, and 45.24% in LDPE, HDPE BLDPE, and ALP in the same storage materials. Similarly, the extractable color lost at the end of the storage month was 3.33%, 18.29%, 25.56%, and 38.40% in ALP, HDPE, LDPE, and BLDPE packaging materials under refrigerated storage conditions, compared to 14.31%, 21.19%, 32.86%, and 50.15% at ambient temperature. Similarly, the percentage of TCC lost at the end of the storage period was also 8.41%, 14.19%, 21.23% and 30.68% in ALP, HDPE, LDPE and BLDPE under refrigerated storage condition, and 10.91%, 17.65%, 25.01% and 52.02%, respectively in the same packaging materials at ambient temperature. The percentage of TAOC lost was also 46.76%, 56.40%, 66.22%, and 61.52%, respectively, under refrigerated conditions, and 57.29%, 67.45%, 68.50 and 66.36%, at ambient temperature. Oleoresin content decreased over the storage durations in all packaging materials under both storage conditions. The loss in Oleoresin content at the end of the storage period was 44.34%, 37.82%, 37.25%, and 20.77% at ambient temperature and 32.27%, 27.25%, 28.16%, and 13.42% loss under refrigerated conditions in LDPE, HDPE, BLDPE, and ALP, respectively. In conclusion, samples stored in ALP maintained high functional qualities in both storage conditions at the end of the storage period.

Keywords: Physicochemical quality, Storage conditions, Red hot pepper powder

INTRODUCTION

Red hot pepper (*Capsicum annum* L.) used as a vegetable, spice, condiment, dried good, or processed product. In 2023, China is the world's largest producer with an annual output of over 16,721,691 million metric tonnes, followed by Turkey in second place with approximately 3,091,295 metric tonnes (**FrutPlaner, 2023**). It gives pungency, aroma, color to the food, and has economic, nutritional, and medicinal importance **(Sarafi *et al.*, 2017; Singh *et al.*, 2018)**. In terms of nutrition, they are rich in vitamins A and C, as well as minerals like potassium and magnesium, and medicinally, are also used to treat burns, postherpetic neuralgia, headaches, blood clots, asthma, and arthritis (**Madala & Nutakki, 2020**). When red pepper powder is applied to a variety of food products, the shelf life of the foods extend due to its antibacterial and functional properties **(Okur, 2022)**.
In Ethiopia, red hot pepper powder or "*berbere*," is a valuable commodity and everyday food due to its therapeutic properties, colour, pungency, and other valuable attributes (**Zekarias, 2012**). Ethiopia harvested 2,959,805.08 quintals of dry pepper and 6,433.73 quintals of green pepper from 168,345.57 hectares in 2021 (CSA, 2020/2021). According to the Central Statistical Agency (CSA), red pepper took a share of 73.13% of the area covered by vegetable production, followed by kale, which took 17.81% (**CSA, 2020**). However, diseases, lower access to fertilizers, improved varieties, pesticides, under mature harvesting, ineffective post-harvest practices, and marketing challenges such as uncertain markets, fluctuating prices, subpar product quality, inappropriate operational scale, low governmental support, and transportation problems are the main challenges in value chain of red hot pepper (**Hegena & Tigistu, 2022**). In Ethiopia, the primary causes of loss are inappropriate packaging materials and the high cost of hermetic packaging materials (**Satheesh *et al.*, 2023**). **Yeshiwas & Tadele (2021)** reported 27.56% of by total estimated postharvest loss from marketing, transportation, and storage of 10%, 10%, and 7.56%, respectively. Comparably, **Fufa (2022)** documented losses from loading and unloading, transportation, adulteration attributed to water addition, and incorrect drying of 1-2%, 1%, 5–10%, and 5%, respectively.
Addala *et al.* (2015) revealed that storage conditions influence the rate at which the color of paprika-based products deteriorates. Products stored at high temperatures and humidity levels showed a faster rate of colour degradation than those stored at room temperature. However, the primary cause of carotenoid degradation results from processing such as drying, seed removal, and grinding (**Pérez-Gálvez *et al.*, 1999; Loizzo *et al.*, 2013**). Additionally, storing samples with high water activity at higher temperatures activates the rate of carotenoid pigments breakdown and the development of browning compounds, causing pepper powder's red colour to turn brown or black (Rhim and Hong, 2011). Furthermore, **Khobragade & Borkar (2018)** suggested careful selection of packaging materials that have a barrier to light, moisture, and oxygen to reduce the rate of carotenoid degradation during storage.
Satheesh *et al.* (2023) reported that red hot pepper producers, wholesalers, retailers, and retailers do not know pest management, temperature and moisture management to maintain the quality of red pepper in storage. About 90% of farmers, retailers, and wholesalers store their pepper pods in the sack and 10% stored in a gotra, floor, or the sickled stalk with the stem (**Nagasa, 2022**). Additionally, berbere powder prepared once in a year and stored for up to one year in poor quality and damaged plastic and polypropylene packaging materials by 90% of consumers, however 70% of them reported spoilage with prolonged storage due to no usage of hermetic packaging materials and cold storage (**Satheesh *et al.*, 2023**). Besides, laying the stack one over the other, lack of storage sanitation,

uncontrolled temperature and moisture during storage, and unsorted rotted and moulded pods are the major problems in farmers, retailers, and wholesalers' storage **(Nagasa, 2022; Satheesh *et al.*, 2023**).

Though many research was done on agronomic practices to improve yield and productivity (**Delelegn, 201**1), processing (**Kefale *et al.*, 2023**), assessment of aflatoxin contamination in red pepper powder **(Hunduma *et al.*, 2020; Aberedew & Ayelign, 2023; Alemu Degefe & Geleta, 2024**), marketing constraints reducing productivity of red hot pepper (**Goshme & Ayele, 2019**); the report on causes of postharvest losses (Nagasa, **2022; Satheesh *et al.*, 2023**), study on red hot pepper powder storage solutions and packaging materials that are appropriate for growers, dealers, and consumers in Ethiopia has not yet been studied. Therefore, the objective of our study was to investigate the effects of packaging materials, storage temperatures, and storage duration on the physicochemical qualities of red-hot pepper powder.

MATERIALS AND METHODS

Sample collection and preparation

The sample preparation, processing, and laboratory analysis were conducted at Ambo University's Biology and Chemistry laboratories. The commercially available hot pepper variety that has wide acceptance, namely Mareko Fana, was bought from farmers from Jimma Zone, Asendabo District. Then red-hot pepper pods were sorted to remove debris, dusts, malformed, and damaged pods. The stalks were removed, and the cleaned pods were dried under the open sun on canvas until a constant weight was achieved. The moisture content of dried samples was determined using the forced-air oven (Leicester, LE67 5FT, England) drying method (**AOAC, 2012**). The dried red-hot pepper pods were sorted to remove the stalk, debris, soil, malformed, bleached, and diseased pods. The samples were milled using (KARLBOLB D-6072, Dreich, West Germany) Miller, and sieved by a 0.5 mm mesh wire to obtain uniform particle size. The powder was packed in black polyethylene sheets, Aluminum foil laminate pouches, low-density polyethylene, and high-density polypropylene bags. The properties of the packaging materials are presented in Table 1. Samples were carefully thermally sealed using a pedal seaming machine for barrier functions against water vapor and oxygen migration and against loss of volatile aroma and stored for later analysis at ambient (25±2ºC) and refrigerated (4±2ºC) temperatures.

Packaging materials were chosen for their good sealability, low cost, and barrier capacities to moisture, oxygen, light, aroma, and greasy substances **(FOODTR, 2020**). LDPE was chosen because of its tough, flexible, and slightly translucent material, which provides a good barrier to water vapor but a poor barrier to gases. LDPE has a temperature range of -50°C to +80°C and is commonly used as bags, flexible lids, or bottles. Furthermore, HDPE is stiffer and harder than LDPE and has better oil and grease resistance. It can be used at temperatures ranging from -40°C to +120°C. The aluminum laminate pouch has absolute oxygen, moisture, and light barriers. Black low-density polyethylene (BLDPE) was selected for its light barriers because coloured materials absorb light radiation (**Birley *et al.*, 1982; Muhammad, 1993**). Packaging materials' permeability to water vapor pressure and oxygen are presented in Table 1.

Table 1 Packaging materials' permeability to water vapor pressure and oxygen.

№	Packaging materials	Thickness (μm)	WVPR ($g/m^2/day$)	OTR ($cm^3/m^2/day$)
1	Aluminum laminated pouch	60	3-7	<0.05
2	High-density polyethylene	80	5-12	1500-2000
3	Low-density polyethylene	30	15-25	7000-8000

WVTR=water vapor transmission rate in g/m2/day, OTR=oxygen transmission rate in $cm^3/m^2/day$. Source: **(Amberg-Schwab, 2005).**

Experimental design and treatment combinations

A three-factor factorial design with three replications was used. The three factors are 1) Packaging material (four levels: LDPE, HDPE, BLDPE, and ALP), 2) Storage duration (five levels: 2, 4, 6, 8, and 10 months), and 3) Storage temperatures (ambient and refrigerated conditions). The baseline data used to assess the trend of functional quality indicators was the initial values measured at time zero before the commencement of storage (Table 2).

Table 2 The initial data of the studied parameters

Parameters	Value before storage
Moisture Content (%)	10.6
Water activity (Aw)	0.26
None-Enzymatic Browning Index (NEBI) (abs/g)	0.15
Colour value (ASTA Units/ gram)	252.56
Total Carotenoid Content (μg/g)	4158.95
Pungency Index (PI) (abs/ g)	5.01
Oleoresin (%)	12.25
Total Antioxidant Capacity (TAOC) (AAE mg/100g)	752.96

Data collected

Determination of moisture content

The moisture contents of the samples were determined according to the official method of **AOAC (2012)**. A three-gram red hot pepper powder sample was weighed into a crucible and placed into a hot air oven at 105°C for 1 hour (Leicester, LE67 5FT, England). The crucible plus the sample was allowed to cool in desiccators and reweighed afterward. Then, the moisture content was calculated using Eq. 1.

$$\text{Moisture content } (\%) = \frac{Weight\ after\ oven}{Weight\ before\ oven} x100 \text{ ………………..…. Eq. 16}$$

Determination of water activity

The water activity (a_w) of the pod and powder was determined using a Pawkit water activity meter (Decagon Devices, Inc., Pullman, Washington, USA) at ambient temperature (25 ± 2ºC). The sample cup was half-filled with 5 g of powder to ensure the accuracy of the result and to avoid the powder covering the instrument sensor. The Pawkit water activity meter was positioned over the cup, and the water activity level was measured within 5 minutes.

Determination of nonenzymatic browning

The nonenzymatic browning was monitored with time using the method of **Hendel *et al.* (1955)**. Accordingly, 0.1 g of the powder was dissolved in 50 mL of distilled water. After two hours of sporadic stirring at 30ºC using a thermostatic water bath shaker, the supernatant was filtered using Whatman №. 2 filter paper. The optical density (O.D.) of the filtrate was obtained based on the dry solid weight of 0.1 g by compensating for the moisture content of the sample using the absorbance of the filtrate measured with a UV VIS Spectrophotometer (Optizen POP, Korea) at 420 nm against a blank using distilled water as a standard.

Determination of Total Carotenoids Content (TCC)

Total carotenoid content was extracted according to the scheme described by (**Carvalho *et al.*, 2015**), and the total carotenoid content was estimated according to (**de Carvalho *et al.*, 2012)** (Eq. 2). Accordingly, 0.5 g of powder sample was homogenized with 5 mL of acetone and filtered. The residue was re-homogenized twice in the same manner. The precipitate of each sample was soaked overnight in 20 ml of acetone and washed until it became colourless. The extract was collected and transferred to a separatory funnel containing 20 ml of petroleum ether 40-60ºC, followed by a few drops of distilled water and careful shaking. This step was repeated two times. The petroleum ether layer was separated and filtered over anhydrous sodium sulfate to remove water. The absorbance of the carotenoid was recorded at 450 nm. Eventually, the total carotenoid content of red-hot pepper powder was calculated as follows:

$$Total\ carotenoids\ (\mu g/g) = \frac{A * V(10000)}{A_{1cm}^{1\%} P(g)} \text{……………………………Eq. 2}$$

Where: A = Absorbance of the tube sample at 450 nm; V = Total volume of extract; $A\frac{1\%}{1cm}$ = 2592 (Extinction Coefficient of β-carotene in the solvent); P = weight of sample (g).

Measurement of hot pepper powder extractable colour

The extractable colour was determined following ASTA 20.1 (**ASTA, 1997**) using Equation 3 below. A 0.1 g was weighed and placed in an amber-coloured 100 ml volumetric flask, and the volume was made up to the mark with acetone. The samples were left in the dark at room temperature for 16h for colour extraction, and absorbance was measured using a spectrophotometer (Optizen POP, Korea) at 460 nm wavelength using acetone as a blank. Finally, results were reported in ASTA units as follows.

$ASTA\ Extractable\ Color = (Absorbanceat\ 460\ nm \text{ X } 16.4)/Sample\ weigh\ t$ (g)……… Eq. 3

Measurement of pungency

The pungency of samples was assessed using the technique outlined by **Hossain & Bala (2007).** A colourless acetone solution was produced by extracting 4 g of pepper samples with acetone. Acetone was used to fill the volume to 100 mL. The extract was kept at room temperature for three hours. Five milliliters of acetone was added to a beaker and heated in a water bath until completely dry. Then, 5 mL of 0.1 N Sodium hydroxide and 3 mL of a solution containing 3% phosphomolybdic acid were added and left at room temperature for an hour. Finally, the optical density of the samples was measured by a spectrophotometer (Optizen POP, Korea) at 650 nm. The samples' optical density value was used as their pungency index. Samples with higher optical densities were assumed to be hotter because they contained more capsaicin.

Oleoresin content

The oleoresin was extracted in a Soxhlet apparatus using acetone as a solvent (**Wesolowska *et al.*, 2011**). A 20g powder of the samples was taken into a thimble and placed in a Soxhlet apparatus. The apparatus was set up with 150 mL of acetone solvent, and extraction was performed for 6 hours. After extraction, the dark red extract was obtained, cooled, filtered, and concentrated. The dark red concentrated extract volume was recorded, and 5 ml was poured into a Petri dish. The excess acetone was allowed to evaporate from the Petri dish at room temperature to obtain a thick, sticky, dark brown mass. This crude dried mass was weighed, and the oleoresin content was calculated using the following formula (Eq. 4):

$$C\ (\%) = \frac{DxV}{5*20} x100 \qquad \text{Eq. 4}$$

Where: C = Oleoresin content (%), D = Weight of oleoresin obtained from 5ml of extract, and V= Total volume of extract obtained.

Determination of total antioxidant capacity

The total antioxidant capacity was determined according to the method of **Prieto *et al.* (1999)**. An aliquot of 0.5 mL of sample solution was combined with 4.5 mL reagent solution (0.6 M sulfuric acid, 28 mM sodium phosphate, and four mM ammonium molybdate). In the case of blank, 0.5 mL of 45% ethanol was used in place of the sample. The tubes were incubated in a water bath at 95°C for 90 min. After the samples were cooled to room temperature, the absorbance of each sample's aqueous solution was measured at 695 nm against a blank in a UV-2450 spectrophotometer (Optizen POP, Korea). Ascorbic acid was used as a standard. The total antioxidant activity was expressed as the absorbance of the sample at 695 nm.

Statistical analysis

The statistical analysis was conducted using Minitab version 21 software. For each response variable, the validity of model assumptions (normal distribution and constant variance assumptions on the error terms) was verified by examining the residuals as described in (Montgomery, 2020). The independence assumption was met through random selection of the samples and randomization of the order of the experiment. For significant ($p < 0.05$) and marginally significant ($0.05 < p < 0.001$) interaction effects, multiple means comparison of the 40 treatment combinations was made using Tukey's multiple range test at the 5% level of significance to generate letter grouping.

RESULTS AND DISCUSSION

Effects of packaging materials, storage temperature, and storage duration on the quality of red pepper powder

Moisture content (MC)

Moisture content of foods significantly influences their stability during storage. Over ten months of storage under both storage conditions, our study revealed a progressive increase in the moisture content of all samples and storage materials (Fig. 1). The interaction effect of packaging materials, storage temperatures, and storage durations was not significant ($p > 0.05$). However, for ALP, HDPE, LDPE, and BLDP bags, the moisture content increased under refrigerated conditions from 10.24 -11.71%, 10.90-12.34%, 11.12-13.03%, and 11.15-12.59%, and under ambient conditions from 10.19 -11.25%, 10.49-12.18%, 11.01-12.83%, and 10.88-12.88%, respectively, over two to ten months of storage.

The product packed in ALP packages comparably showed a lower increase in moisture content ($p<0.05$). This is because aluminum-laminate pouches have a lower water vapor transmission rate than other packaging materials, with HDPE plastic bags coming in second. Similarly, Lal *et al.* (2023) found that green chili pepper powder in aluminum foil maintained good moisture content stability compared to unpacked products and clear glass jars after three months. After four months of storage, it was also noted that samples of red and yellow peppers packed in aluminum foil had less moisture content than samples packed in polypropylene and HDPE bags (**Sachidananda *et al.*, 2013**). Similarly, after six months, mango tablets kept in aluminum laminate packaging materials retained moisture content than those kept in polyethylene bags at varying temperatures (4, 25, and 35ºC) and relative humidity (32% and 75%) (**Pranil *et al.*, 2021**). The investigation also showed that, regardless of the storage temperature, the moisture content of the chili powder in vacuum-packed bags remains constant, which is also explained by its barrier qualities (**Nath *et al.*, 2019**). The highest humidity in refrigerated conditions caused the rise in moisture content for samples stored under refrigerated conditions **(Razak *et al.*, 2018**).

Additionally, in this study, samples kept in a refrigerator had a higher moisture content ($p<0.05$) than samples kept in an ambient environment. The increasing trend of moisture content was similar in room temperature and refrigerated storage, despite the differences in rate. However, in contrast to the samples stored in LDPE and BLDP bags ($p<0.05$), the moisture content recorded in ALP and HDPE did not differ significantly between the two storage methods ($p>0.05$).

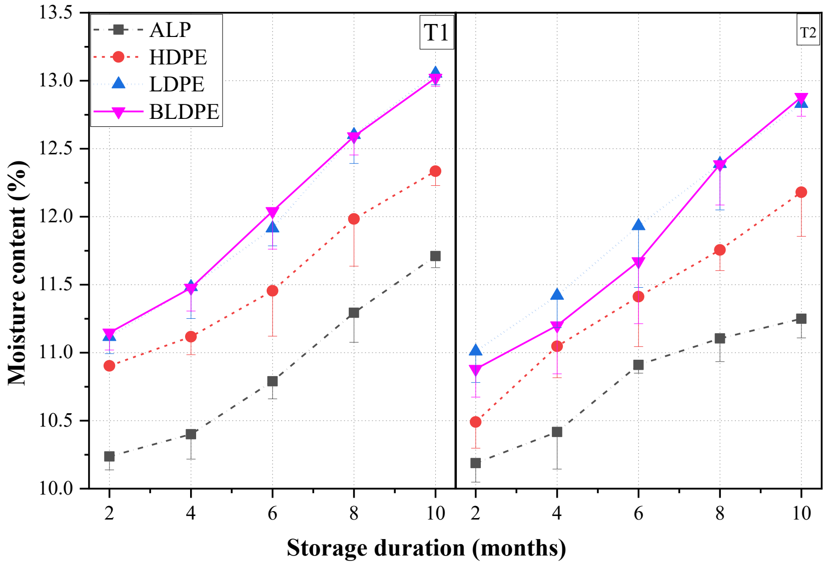

Figure 1 Effect of packaging materials, storage temperature, and storage duration on moisture content (%) of paper powder. T1 represents refrigerated storage, and T2 represents room temperature storage.

Water activity (a_w)

Water activity measures the effectiveness of the water in the chemical or physical reaction of food products, which ranges from 0.1 to 1. In this study, the a_w value ranged from 0.26-0.31, 0.26-0.35, 0.26-0.53, and 0.26-0.5 under refrigerated storage and, 0.26-0.35, 0.26-0.36, 0.26-0.5, and 0.26-0.44 in ALP, HDPE, LDPE, and BLDPE under ambient storage. In all cases, the a_w increased with storage duration under both refrigerated and room-temperature storage conditions (Fig. 2). The increase in a_w also has a linear relationship with the moisture content of the samples (**Chirife *et al.*, 2006**). The ANOVA result also indicated a significant three-way interaction effect of packaging materials, storage method, and storage durations on water activity ($p<0.05$). However, the impact of temperature was relatively lower compared to packaging materials and storage time, which agrees with the work of **Maltini *et al.* (2003**), who reported the influence of a_w on the quality of dried plant foods performed at reasonably high temperatures.

Relatively higher a_w values were recorded in samples stored under refrigerated storage as the storage period is extended. This is also because of the high humidity level in the refrigerator. **Jaworska *et al.* (2014**) reported a double increase in water activity under refrigerated conditions for mushrooms during the 24-month storage duration. The highest a_w was recorded in samples stored in BLDPE and LDPE, which could be associated with the migration of condensed moisture on the surface of the packaging materials at lower storage temperature. However, due to the more moisture-proof nature of HDPE and ALP, the change in a_w level was low regardless of storage temperature ($p<0.05$) (Fig.2). An increased a_w in the of the samples stored at ambient condition can be explained by the water vapor produced due to exposure to light **(Gao *et al.*, 2019; WU *et al.*, 2019**). The observed minor change might be the effect of a limited Millard reaction since water has been released from the reaction as a reaction product.

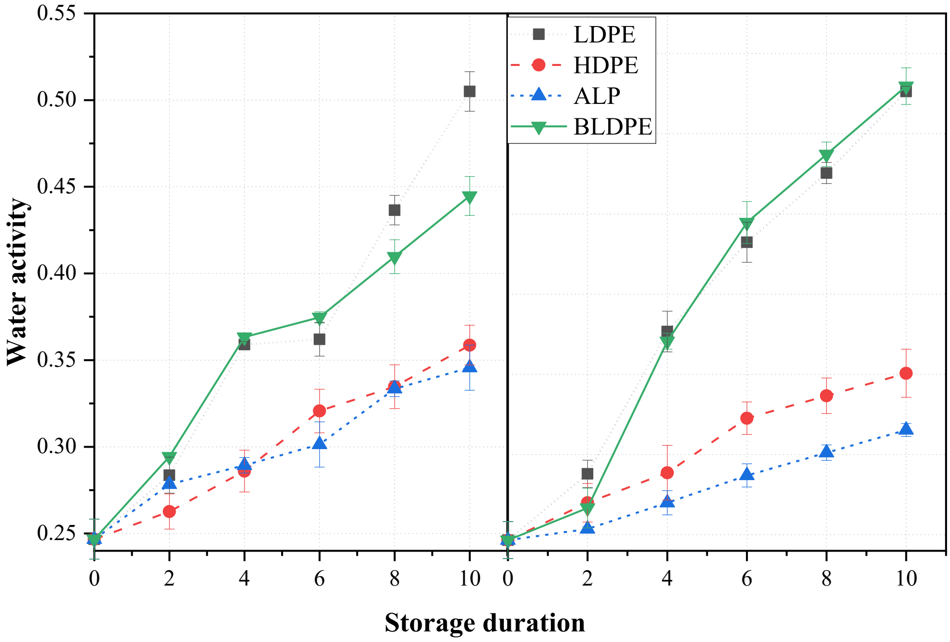

Figure 2 Effect of packaging materials, storage temperature and storage duration on water activity of paper powder. T1 represents refrigerated storage, and T2 represents room temperature storage.

Nonenzymatic Browning Index (NEBI)

A series of chemical reactions that occur when food is prepared or stored leads to nonenzymatic browning (**Croguennec, 2016; Das *et al*., 2022**). In this study, NEBI value for both storage temperatures increased from the second to the tenth month of storage. It increased from 0.15-0.18, 0.15-0.19, 0.15-0.24, and 0.15-0.23 abs/g in ALP, HDPE, LDPE, and BLDPE under refrigerated storage. However, in ALP, HDPE, LDPE, and BLDPE, respectively, the index increased from 0.15-0.34, 0.15-0.35, 0.15-43, and 0.15-0.38 at room temperature storage. Table 2 shows that the NEBI values are significantly impacted ($p<0.05$) by the interaction of the storage conditions, packaging materials, and length of storage. The rate of change of NEBI followed the same trend of moisture content and water activity; both moisture content and a_w might affect the NEBI value. Similarly, **Chen *et al.* (2022)** reported a rise in the browning index with advanced storage durations at ambient, vacuum, and light-avoided packaging materials.

In contrast to the moisture content and a_w, the NEBI were found to be higher at ambient conditions, which is attributed to the formation of browning compounds at higher temperatures than in refrigerated storage conditions (Fig. 3). The residual moisture in the samples and oxygen in the packaging materials can also result in the rise of NEBI The studies also indicated that the light increased the browning index of tomato paste stored in the light compared to that of darkly stored samples (**Chen *et al*., 2022**). It also agrees with the report by **Haile *et al.* (2013)**, who reported that cooked ham wrapped in foil stored in the dark showed better resistance against discolouration than products packed in MAP and exposed to light.

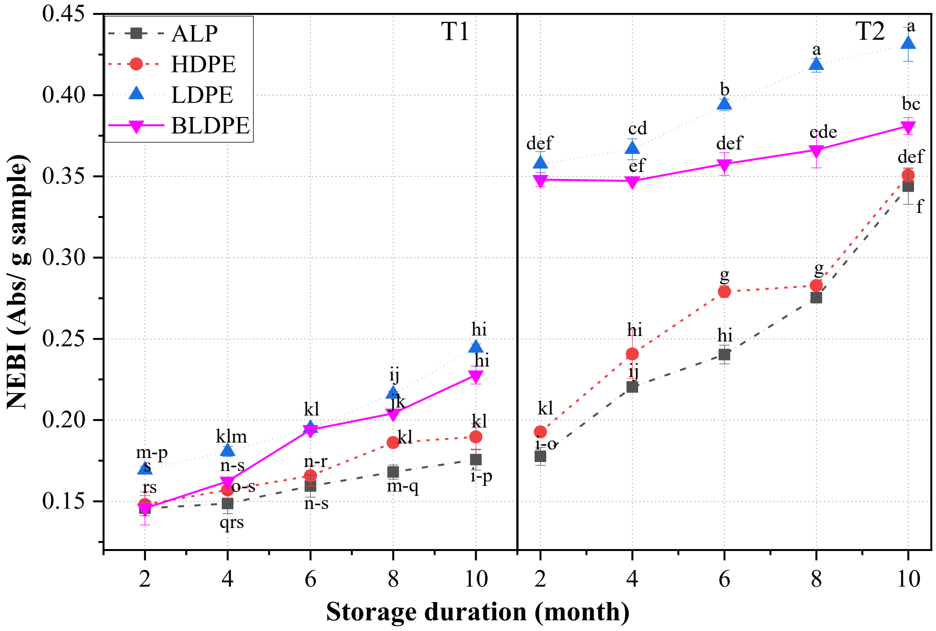

Figure 3 Effect of packaging materials, storage temperature, and storage duration on nonenzymatic browning index (Abs/g) of paper powder. Means sharing the same letter are not significantly different at α=0.05 level of significance. T1 represents refrigerated storage, and T2 represents room temperature storage.

Total Carotenoid content

The interaction effect of packaging materials, storage temperature, and storage duration significantly affected the total carotenoid content. The total carotenoid values ranged from 4158.95-3809.03, 4158.95-3568.67, and 4158.95-3275.9 and 4158.95-2882.78 under cold storage, and ranged from 4158.95-3705.34, 4158.95-3424.87, 4158.95-3118.83 and 4158.95-1995.56 under room temperature storage in AlP, HDPE, LDPE, and BLDPE, respectively. The highest value of total carotenoid content was recorded for the samples packed in AlP bags after ten months of storage duration under cold storage temperature, followed by HDPE bags. The minimum value of TCC was recorded for the samples packed in BLDPE bags (Fig. 4). Similarly, **Pranil *et al.* (2021)** found that low-density polyethylene recorded a maximum loss of beta-carotene at higher temperatures than storage laminated plastic bags. The highest TCC loss in LDPE might be attributed to its higher permeability to moisture and air compared to other packaging materials. Moreover, **Yao *et al.* (2020)** reported higher losses of β-carotene irrespective of packaging systems and storage temperatures after the six-month storage duration, attributed to the free radical activity that is more active at higher temperatures. **Atencio *et al.* (2022)** investigated that high temperature, light, and oxygen induce carotenoid losses during storage. Moreover, the severity of carotenoid loss depends on oxygen, while light is used as a catalyst to enhance oxidation (**Dutta *et al.*, 2005**). In this experiment, AlP and HDPE bags exhibited better retention of carotenoids with an extended storage time as compared to other packaging materials that are more prone to the diffusion of oxygen and moisture. It was also reported that packaging materials with higher oxygen and water vapour permeability rates have a much higher rate of carotenoid degradation during storage (**Júnior *et al.*, 2018; Chilungo *et al.*, 2019**).

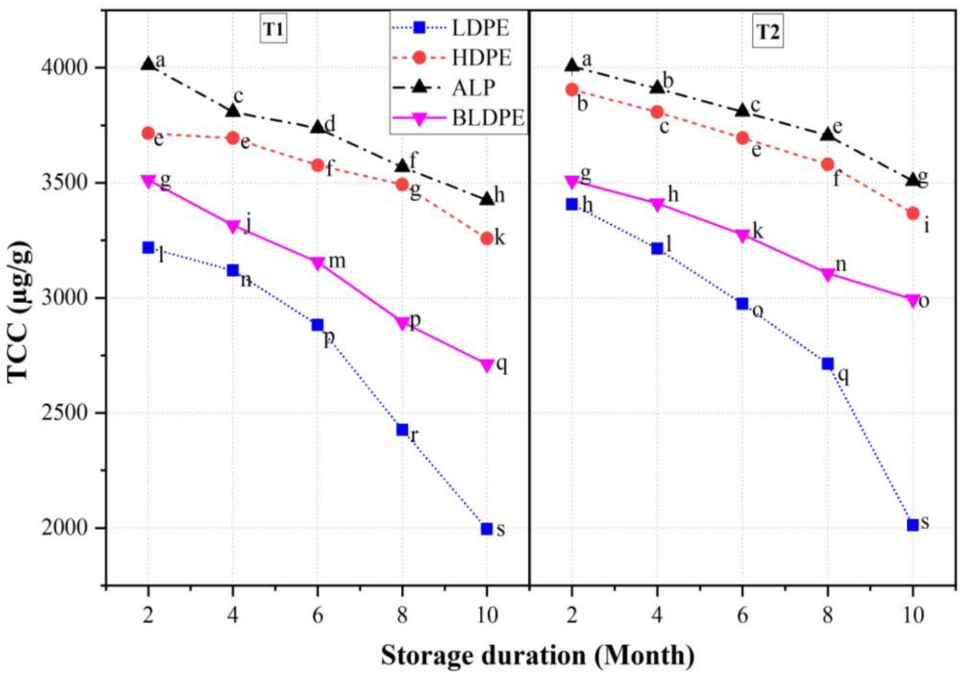

Figure 4 Effect of packing materials, storage temperature, and storage duration on total carotenoids content (μg/g) of paper powder. Means sharing the same letter are not significantly different at the α=0.05 level of significance. T1 represents refrigerated storage, and T2 represents room temperature storage.

Extractable colour

The extractable color values ranged from 252-244.1, 252-206.37, 252-188, and 252-155.58 under cold storage and ranged from 252-216.41, 252-199.04, 252-169.58, and 252-125.9 under room temperature storage in AlP, HDPE, LDPE, and BLDPE, respectively. The three-way interaction effects of packaging materials, storage methods, and storage duration did not significantly affect extractable colour. The loss of extractable color showed a similar trend in refrigerated and ambient storage in different packaging materials. However, the loss level was higher in ambient conditions than in cold storage. Though the rate of extractable colour degradation was slow up to two months of storage active rate of loss was observed a head to ten months. The highest degradation was observed in LDPE and BLDPE, whereas the highest colour retention capacity was recorded for AlP (Fig. 5). This result is in line with (**Topuz, 2008**), who reported that the colour degradation of paprika follows first-order kinetics with higher rates at higher temperatures and water activity during storage. This finding is in line with (**Lamberti & Escher, 2007**), who reported that aluminum foil laminate packages minimize reactions that negatively influence the stability of the packed food and prevent undesired quality loss of foods. **Kim *et al.* (2006**) found that the initial carotenoids, the antioxidant contents, the type of packaging material used, storage temperature, water activity value, light, nonenzymatic browning, and the period the product is stored caused colour degradation. Additionally, **Shishir *et al.*** (**2017**) reported better colour retention at a storage temperature of 5°C than at a storage temperature of 25°C for vacuum-packed pink guava powder packed in oriented polypropylene and Polyethylene Terephthalate, which showed less colour loss than the powder packed in LDPE due to the high moisture and oxygen barrier properties and non-transparent behavior to light.

Overall, the minimum variation in color during the storage period was observed for aluminum-packed samples throughout the storage duration. Similarly, **Sachidananda *et al.*** (**2013**) investigated the stability of color pepper slices, which was higher in aluminum laminates and medium in high-density polyethylene. **Rhim & Hong (2011)** indicated that elevated temperature and water activity promote the rate of colour fading, causing brown and tarnished black powder due to the development of browning compounds and carotenoid change. Additionally, a higher degradation of extractable colour value was reported at ambient storage of paprika-based products for six months (**Addala *et al.*, 2015**). Also, the more the packaging material is impermeable to oxygen and moisture and translucent to light, the more stable the colour is at the end of the storage period (**Nath *et al*., 2019**).

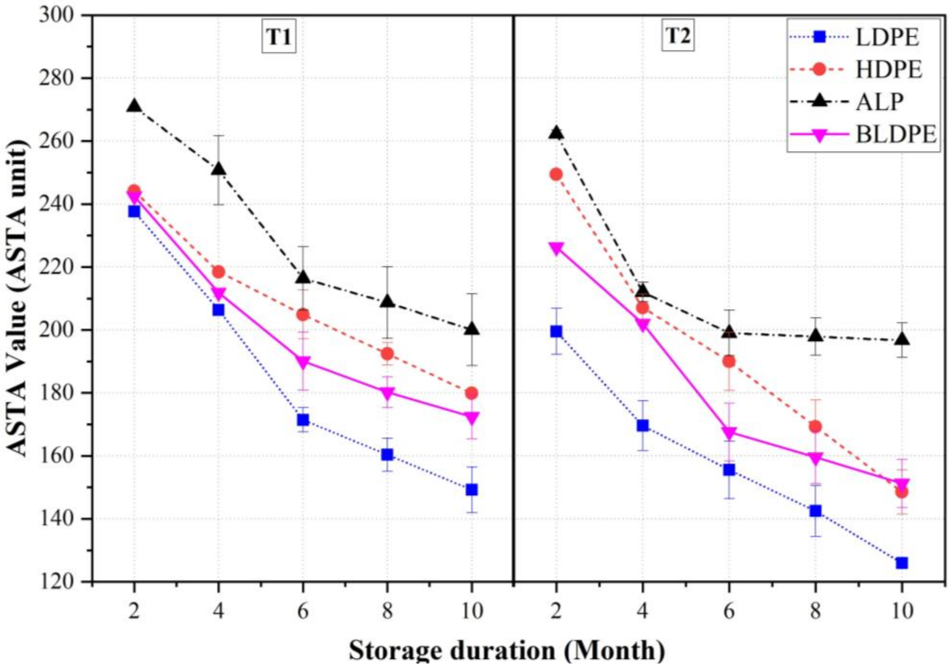

Figure 5 Effect of packing materials, storage temperature and storage duration on ASTA value (ASTA units) of paper powder. T1 represents refrigerated storage, and T2 represents room temperature storage.

Pungency index (PI)

The present study also showed a gradual and steady decrease of the pungency index during storage for ten months ($p < 0.001$) under both storage conditions (Fig. 6). Unlike other parameters, the interaction effects of packaging materials, storage time, and storage conditions did not significantly affect the pungency index ($p > 0.05$). Moreover, the PI decreased by 60.30, 43.28, 50.11%, and 40.11% in LDPE, HDPE, BLDPE, and ALP under refrigerated storage, whereas it decreased by 65.2, 49.11, 55.01, and 45.24% in LDPE, HDPE, BLDPE, and ALP at ambient temperature. The samples stored at ambient temperature showed a higher decrease in PI than at refrigerated temperatures. The degradation rate did not significantly vary in the first four storage months, but a fast decrease was observed after four months of storage in refrigeration. Similarly, **Chetti *et al.* (2014)** reported the stability of capsaicin content for up to 3 months of storage with no significant effects regardless of packaging materials and storage conditions. In addition, there was no loss in capsaicin for six months in all the vacuum-packed samples in all storage conditions (light, dark, or cold storage and the moisture content of the samples before packaging); however, there was a 12.5% loss from the 9–12-month storage duration without significant difference. They suggested that the deterioration of capsaicin under ambient storage was attributed to oxidation and moisture absorption from the atmosphere due to the higher permeability of jute bags to oxygen and water vapor (**Fikiru *et al.*, 2024**). In contrast, a quick loss in pungency compounds up to three months storage durations, with minimum loss at room temperature (**Wang *et al*., 2009**). Additionally, **Giuffrida *et al.* (2014)** reported 25% of total capsaicinoids degradation under ambient storage, while no loss of capsaicinoids was recorded under cold storage during one year of storage.

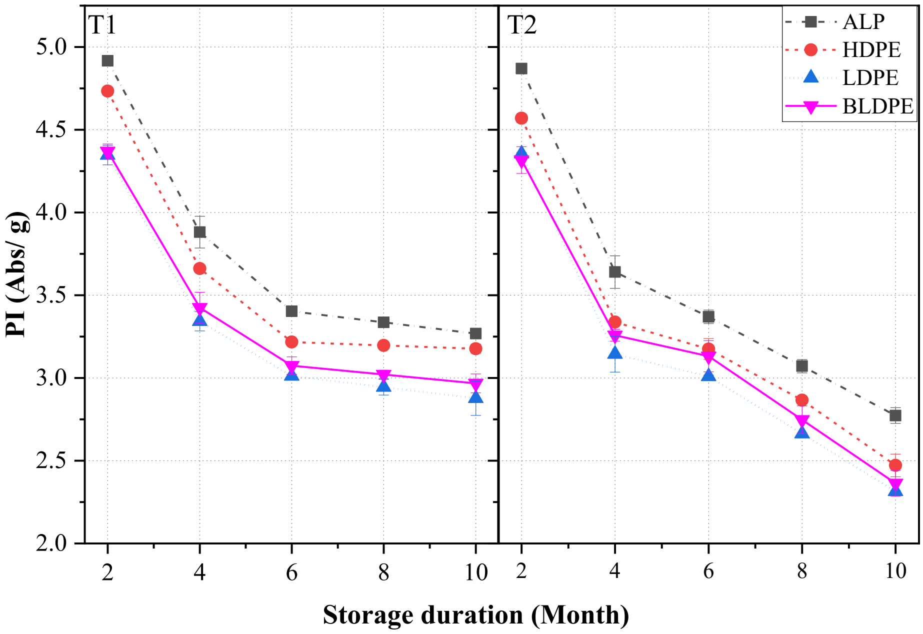

Figure 6 Effect of packing materials, storage temperature, and storage duration on pungency index (Abs/g) of paper powder. T1 represents refrigerated storage, and T2 represents room temperature storage.

Oleoresin

The result showed a significant interaction effect of storage durations, packaging materials, and storage conditions on the oleoresin contents of the red-hot pepper powder ($p<0.05$) (Fig. 7). Under both storage methods, oleoresin content was decreased across the storage durations in all packaging materials. For instance, oleoresin content loss was 44.34, 37.82, 37.25, and 20.77% at ambient temperature and 32.27, 27.25, 28.16, and 13.42% loss at refrigerated temperature in LDPE, HDPE, BLDPE, and ALP, respectively. The finding showed that ambient temperature storage caused a maximum loss of oleoresin contents compared to refrigeration temperature storage. A trend of loss of oleoresin content was similar during the first six months for both storage methods. However, after six months, the samples stored at room temperature showed faster degradation than those at refrigerated storage. Similarly, **Federzoni *et al.* (2019)** reported the reduction of oleoresin in paprika at higher temperatures due to the degradation of color. Additionally, **Anjaneyulu & Sharangi (2022)** reported a slow rate of loss of oleoresin endorsed by the oxidative deterioration of the active ingredients in chilli peppers at higher temperatures.

On the other hand, the maximum oleoresin content was preserved in aluminum pouch packaging materials, followed by HDPE bags. The minimum oleoresin content was retained in black low-density polyethylene bags, followed by LDPE bags, under both storage conditions. Similarly, **Apriyati *et al.* (2022)** reported that the degradation of oleoresin in polyethylene terephthalate (PET) bottles, polypropylene (PP) plastic bags, and aluminum foil bags from 15.66% to 5.78%, 5.66%, and 6.16% after nine months of storage of ginger. Accordingly, a higher degradation rate of oleoresin in plastic materials was due to its permeability to gas, aroma, and water. In the present study, oleoresin can be stored in all packaging materials for up to ten months under refrigerated storage, though aluminum pouches were the best. Additionally, aluminum pouches recorded the best preservation for up to ten months at room temperature.

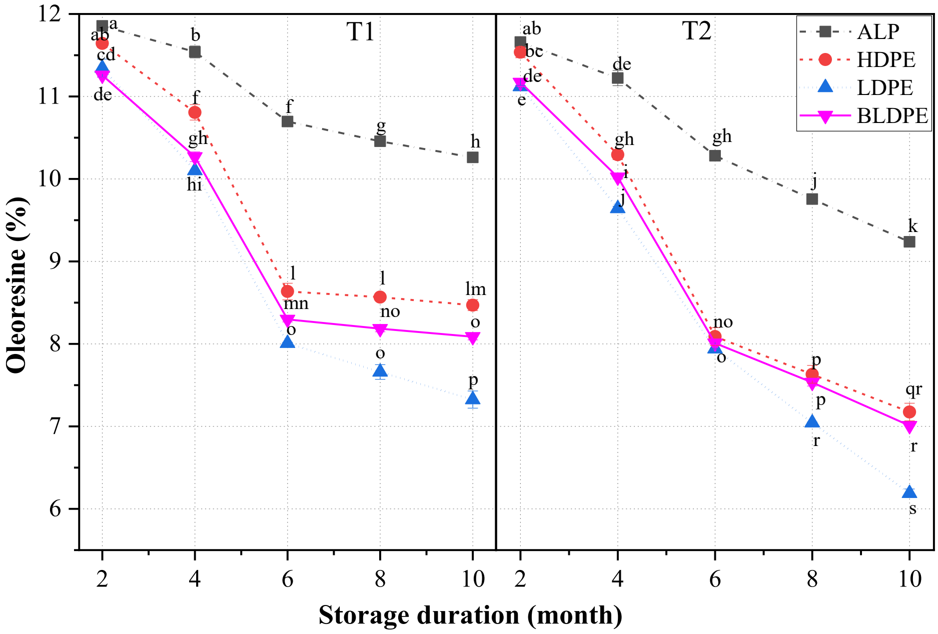

Figure 7 Effect of packing materials, storage temperature, and storage duration on oleoresin (percent) water activity of paper powder. Means sharing the same letter are not significantly different at the α=0.05 level of significance. T1 represents refrigerated storage, and T2 represents room temperature storage.

Total antioxidant capacity (TAC)

The ANOVA result showed a significant interaction effect of storage duration, packaging materials, and storage condition on the TAC ($p<0.05$) (Table 2). Overall, the result showed a decrease in TAC in packing materials at both storage conditions with advanced storage duration (Fig. 8). The total antioxidant activity values decreased from 752.96-400.85, 752.96-328.26, and 752.26-254.37 and 752.96-289.74 under cold storage, and decreased from 752.96-321.59, 752-245.11, 752.9-237.15 and 752.26-253.26 under room temperature storage in ALP, HDPE, LDPE, and BLDPE, respectively. The total antioxidant capacity loss was higher for red hot pepper powder packed in LDPE, BLDPE, and HDPE than AlP (Fig. 8) at room temperature and refrigerated storage methods. The decrease in TAC in all packaging materials under both storage conditions is caused by the degradation of phenolic compounds and carotenoids during extended storage time. It was also reported that antioxidant capacity is associated with red pepper phenolic compounds, capsaicinoids, and carotenoids (**Campos *et al.*, 2013; Tvrzník *et al.*, 2019**). In contrast, **Chong *et al.* (2013)** and **Udomkun *et al.* (2016)** reported that the antioxidant activities in dried papaya samples during storage were directly affected by phenolic compounds, while other constituents such as reducing carbohydrates, tocopherols, carotenoids, terpenes, and pigments contributed less to the total antioxidant capacity. **Udomkun *et al.* (2016)** also suggested that decreased antioxidant activity retention during storage could result from activating oxidative enzymes such as polyphenol oxidase or the chemical oxidation of phenolic compounds. Furthermore, the reduction of total antioxidant capacity could result from elevated moisture content, pH, and exposure to oxygen and light. Moreover, the result of the present study also indicated a higher antioxidant capacity degradation rate under ambient conditions than in refrigerated storage, which is attributed to the oxidation of certain fatty acids present in the cell structures at higher temperatures. **Le *et al.* (2024)** explained that in response to various temperatures and storage, H_2O_2 concentration and malondialdehyde rise, causing a reduction in total phenolic compounds and their antioxidant activity.

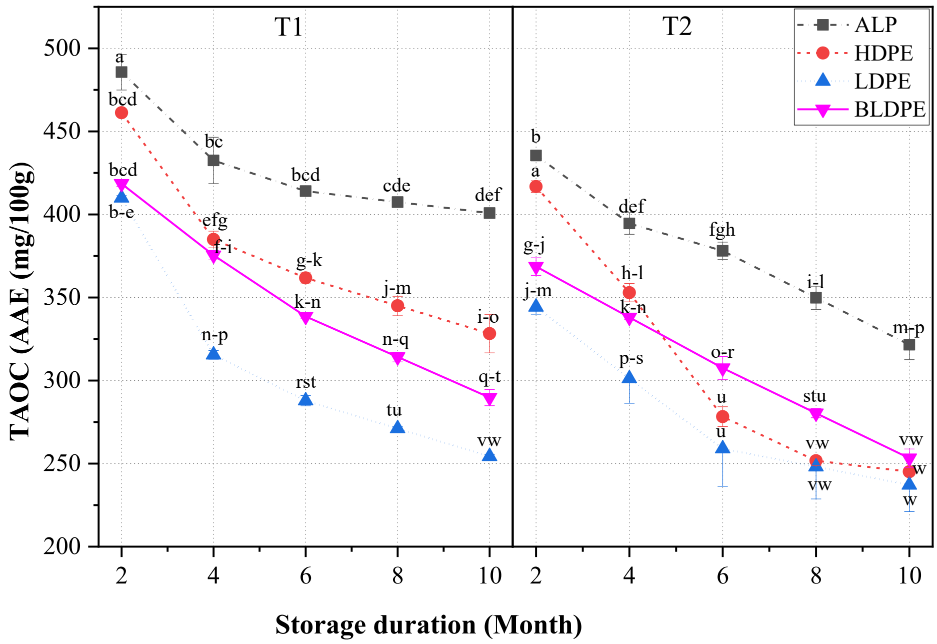

Figure 8 Effect of packing materials, storage temperature, and storage duration on total antioxidant capacity (AAE mg/g) of paper powder. Means sharing the same letter are not significantly different at the α=0.05 level of significance. T1 represents refrigerated storage, and T2 represents room temperature storage.

CONCLUSION

In this study, storage temperature, length, and packing materials all have a substantial impact on red pepper powder quality. Low-density polyethylene (LDPE) and black low-density polyethylene (BLDPE) bags had the most quality loss, whilst aluminum-laminated pouches (ALP) were the most successful at maintaining quality, followed by high-density polyethylene (HDPE) bags. Though the packaging material played a crucial role, quality was often kept better in refrigerated storage than in ambient circumstances. ALP provided the best barrier properties, maintaining the powder's qualities over time.

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Declaration of competing interest: The authors declare that they have no conflict of interest.

Data availability statement: The data that support this study are available on request from the corresponding author.

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