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ENHANCING DRYING EFFICIENCY FOR IMPROVING THE QUALITY OF *TERMINALIA CHEBULA* RETZ.: IMPACT OF PRE-TREATMENTS

Preeti Chaudhary[1], Priyanka Thakur[1], Vivek Sharma[2], Richa Salwan[3]*

Address(es): Titul(s) Firstname Surname of the corresponding author
[1] Department of Food Science and Technology, College of Horticulture and Forestry, (Dr. YS Parmar University of Horticulture and Forestry), Neri, Hamirpur (HP)-177001 (India).
[2] University Centre of Research and Development, Chandigarh University, Gharuan, Mohali (PB.) India 140413.
[3] Department of Basic Sciences, College of Horticulture and Forestry, (Dr. YS Parmar University of Horticulture and Forestry), Neri, Hamirpur (HP)-177001 (India).

*Corresponding author: richaihbt332@gmail.com

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ABSTRACT

Terminalia chebula Retz. (Harar) is an important medicinal fruit, known for its antioxidant and phenolic constituents. But due to the high moisture content and hygroscopic nature of the fruits, drying techniques are required for retention of bioactives, superior quality and microbial safety and prolonged storage.
The fruits were taken as whole and sliced and were treated with salt roasting, hot water blanching, sulphur fumigation, and dipping in sodium hydroxide and ethyl oleate. After pre-treatments, whole and sliced fruits were tray and solar dried and were utilized for evaluating physicochemical, antioxidant, and sensory properties.
Among drying methods, whole and slice fruits got dehydrated in 22-44 hours under controlled thermal exposure i.e., in tray drying compared to 38-76 hours over solar drying. Whole fruits (T_{10}) dipped in ethyl oleate dried rapidly due to increased microscopic pores in cuticle, allowing rapid diffusion of moisture and retained 445.26 mg/100 g phenolics, 17.03 mg/100 g ascorbic acid and 93.96% antioxidants. For evaluating the storage stability, fruits packed in aluminium pouches recorded 65% equilibrium relative humidity (ERH), indicating aluminium as a barrier to oxygen, light and moisture.
Ethyl oleate (EO) breaks the waxy cuticle and help moisture to remove rapidly in mechanical tray drying. Hermetic packaging also keeps the product safe from microbial and insect attack as well as prevents degradation of pigments, making the product suitable for prolonged storage. Further, studies are required to provide mechanistic validation for the industrial production of high-quality medicinal fruits for food and pharmaceutical sectors.

Keywords: Processing method, Shelf-life, Blanching, Drying, Harar, Ethyl-oleate, Hermatic, Pre-treatment

INTRODUCTION

Terminalia chebula, commonly known as harar, is a popular medicinal plant with a rich history in various traditional healthcare systems. Harar fruits have long been known for medicinal importance in Ayurvedic, Siddha Tibb, and Unani (Choi et al., 2015; Thanigaivel et al., 2017). The presence of various phytochemicals has originally contributed to its pharmacological importance (Nigam et al. 2020). Various types of phytochemicals including flavonoids, esters, organic acids, and tannins like corrilagin, chebulagic acid, chebulic acid, and gallic acid are found in harar fruits (Bulbul et al., 2022). The fruits possess a thick and fibrous waxy cuticle which serves as a blockade for diffusion of water vapours and makes the fruits vulnerable to microbial spoilage. Moreover, appearance of dark brown colour in fruits is caused by the non-enzymatic browning and degradation of bioactives leading to lower grade harar fruits.
Traditionally, harar fruits were dried in sun which often resulted into poor quality products in terms of nutrients and color retention and lower consumer acceptance (Pangavhane and Sawhney, 2002). This may be due to the uneven heat exposure, slow moisture removal and enzymatic browning. Thereafter, other approaches like freeze drying, tray drying, and oven drying are also used in terms of preserving the characteristics like color, flavor, and nutrients (Adiletta et al., 2016; Hussein et al., 2021). To preserve the quality of harar fruits, pre-treatments play important role in yielding high quality products. Pre-treatments involve salt roasting, sulfur fumigation and dipping in ethyl oleate which leads to high diffusion rate of moisture, inactivate enzymes and speed up the drying process. Drying is also important in view of preserving the nutritional value of fruits which are season specific. Similar studies involving pre-treatments of fruits in hot and cold blanching (Arroqui et al., 2001), salt roasting (Prajapati et al., 2011), dipping in NaOH (Shi et al., 2008), peeling and sulphuring (Abano and Sam-Amoah, 2011) are available.
Accordingly, the present study was undertaken to assess the comparative impact of pre-treatments on drying period by analysing physic-chemical, nutritional, and sensory properties of harar fruits for technological advancements. The hypothesis of the study involves the potential of this technological advancement in maintaining the structural integrity, retaining bioactives for flavour and aroma profile during post-harvest processing and prolonged storage of harar fruits.

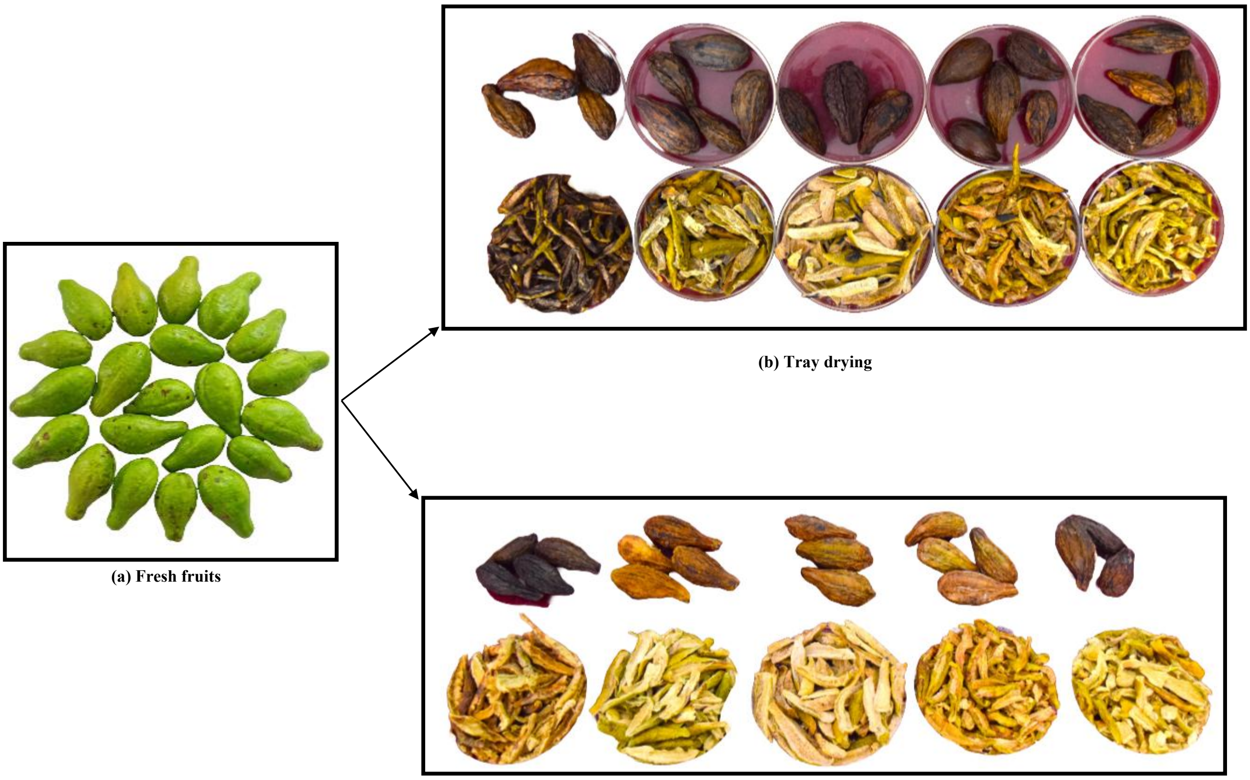
MATERIAL AND METHODS

Procurement of chemicals

Chemicals and reagents such as hydrogen peroxide, 2,2-diphenyl-1-picrylhydrazyl (DPPH) (HiMedia,), ethyl oleate (Thermofischer Scientific), Sodium hydroxoide (NaOH) (Sisco Research laboratories) sulphur (Qualigens) and Folin-ciocalteu's (FC) phenol reagent (Sigma) were used for experimental studies.

Collection of fruits

The fresh ripened fruits of harar (*Terminalia chebula*) strain Kallar were harvested from the experimental farm at Khagal, Neri II; Department of Agroforestry and Silviculture, CoHF, Neri, Hamirpur.



(b) Tray drying

(a) Fresh fruits

(c) Solar drying

Figure 1 Morphological characteristics of *Terminalia chebula* Retz.: visual comparison of Kallar strain at different stages, **(a)** fresh harvested fruits, **(b)** fruits after tray drying at 55 °C; and **(c)** fruits after solar drying.

Fruit slicing

The fresh and matured fruits were cleaned and dried before being manually sectioned into slices with a sharp knife (Fig. 1).

Table 1 Treatment of harar fruits, both whole and sliced, using solar and tray drying methods

Fruit type	Method	Treatment	Condition
Whole	Solar drying	T_1	Whole fruit
		T_2	*blanched
		T_3	*salt roasted
		T_4	*NaOH
		T_5	*Ethyl oleate
	Tray drying	T_6	Whole fruit
		T_7	blanched
		T_8	salt roasted
		T_9	NaOH
		T_{10}	Ethyl oleate
Sliced	Solar drying	T_{11}	Sliced fruit
		T_{12}	blanched
		T_{13}	Salt roasted
		T_{14}	NaOH
		T_{15}	Ethyl oleate
	Tray drying	T_{16}	Sliced fruit
		T_{17}	blanched
		T_{18}	salt roasted
		T_{19}	NaOH
		T_{20}	Ethyl oleate

*Blanching was done at 85°C for 3 min; salt roasting at 160°C for 6 min; boiling in 0.5% NaOH and 0.1% ethyl oleate for 5 min

Pre-treatment of whole and sliced harar fruits

The fruits were blanched, salt roasted, boiled in 0.5% of NaOH (Vinodh 2022) and 0.1% ethyl oleate (Suo et al., 2025) were considered as pre-treatment samples, while samples without any pre-treatment were considered as control (T_1, T_6, T_{11}, T_{16}). Sulphuring of the fruits was done using 200 ppm of SO_2 for 3 h (Wedzicha, 1987; Araújo et al., 2016). The fruits were blanched in hot water at 85 °C for 3 min (Pedreschi and Moyano, 2005; Garba et al., 2015). The fruits were subjected to a chemical dip by boiling in 0.5% NaOH and in 0.1% ethyl oleate without boiling, for 5 minutes, followed by salt roasting at 160°C for 6 minutes (Table 1).

Drying of whole and sliced harar fruits

The treated and non-treated fruit samples were uniformly placed in stainless steel. Traditional method i. e., solar drying and mechanical method i.e., tray drying were employed (Table 1). In tray drying, samples were dried by heating at 55°C for 3 days and monitored after every 4 h. The samples were dried until constant moisture level (10%) was achieved. The samples were analysed for physico-chemical and sensory evaluation. The dried samples were stored at room temperature in polythene bags. The dried fruits are also used for estimating equilibrium relative humidity (ERH) and moisture adsorption to obtain optimal/safe moisture content to avoid hostile environment for microbial attack.

Physicochemical characteristics of dehydrated fruits

Fruit parameters like average weight, size, shape, colour, dehydration and rehydration ratio, percent edible portion, fruit shrinkage and yield were measured by randomly selecting 10 fruits (Ranganna, 2017). Total soluble solids (TSS), sugars, pH, moisture, titratable acidity (citric acid), ascorbic acid, non-enzymic browning (NEB), equilibrium relative humidity and the rate of dehydration per unit time was estimated to plot drying curves of dehydrated fruits (Ranganna, 2017). The total phenols, free radical scavenging inhibition and tannins were estimated by FC method, DPPH (Kedare and Singh, 2011) and AOAC methods (Latimer et al., 2023), respectively. All the observations were recorded on dry weight basis.

Sensory evaluation of dehydrated harar fruits

The panel of 10 semi-trained judges evaluated the samples, focusing on specific sensory attributes including color, texture, and taste that determine consumer acceptance, on a 9-point Hedonic scale. During sensory evaluation, the judges were also provided with plain water for rinsing their mouths between sample evaluations or to act as a palate cleanser. The proforma approved by the Department of Food Science for sensory evaluation is given as supplementary material.

Storage stability of whole and sliced fruits

For evaluating the storage stability, dehydrated whole and sliced fruits were stored in various packaging materials (cotton bags, gunny bags, and aluminum pouches) under ambient (26-32°C) and refrigerated conditions. The physico-chemical and sensory evaluation was periodically done after 3- and 6-months storage period.

Microbial assessment

Total microbial count of the dehydrated harar was evaluated at 0, 3, and 6 months of storage. Total plate count was taken for bacterial and fungal growth based on serial dilution agar plating method on nutrient agar and potato dextrose agar, respectively. The count was taken by preparing 9 ml sterile water blanks, followed by spreading on specific media and results are expressed as colony-forming units per gram (CFU/g) of the sample.

Statistical analysis

The study represents biological replicates, as each treatment was applied to independent batches of fruit samples processed under identical conditions. The results were analysed by taking mean of three replicates in OPSTAT (online statistical tool). For analysing physico-chemical characteristics, complete randomised design (CRD) was applied. Three-way ANOVA was used at 5% significance level to study the effects and interactions of whole vs. sliced fruits, tray vs. solar drying methods, and pre-treatments. Significant differences were obtained based on *Tukey's post hoc* comparison across specific treatments.

RESULTS AND DISCUSSION

Fruit characteristics before drying

The fruit is typically elliptical (or oval/oblong) and has a light green color during its fresh, mature stage before fully ripening to a yellow or reddish-brown. Fruit dimensions include a size of 6.34 cm x 3.04 cm, high edible portion 89.3% and stone size 2.75 × 1.21 cm (Table 2). Due to this high edible content, the Kallar strain is highly regarded for dehydration processes and other nutritional application. The physicochemical characteristics revealed an average pH of 2.91, moisture content of 68.27%, total solids of 31.73%, TSS 15.75 °B, titratable acidity3.05%, reducing sugars of 5.31%, ascorbic acid 6.24 mg per 100 grams, phenols 200.83 mg per 100 grams, and antioxidants of 77.52% before drying (Table 2).

Table 2 Physico-chemical characteristics of harar fruits prior to drying

Parameter		
Fruit weight[a](g)		26.22± 1.5
Fruit size[a]	Length(cm)	6.34± 0.17
	Diameter(cm)	3.04± 0.10
Fruit density[a](g/cm^3)		1.03± 0.04
Fruit shape[a]		Elliptical
Fruit colour[a]		Light green colour
Edible portion[a] (%)		89.30± 1.40
Fruit stone weight[a](g)		2.80± 0.13
Fruit stone size[a]	Length(cm)	2.75± 0.09
	Diameter(cm)	1.21± 0.02
Moisture (%)		68.27± 0.24
Total solids (%)		31.73±0.15
[*]TSS (°B)		15.75±0.05
Titratable Acidity (%)		3.05±0.10
pH		2.91±0.04
Reducing sugars (%)		5.31±0.10
Non reducing sugars (%)		1.97±0.10
Total sugars (%)		7.38±0.16
Ascorbic acid (mg/100g)		6.24±0.26
Phenol (mg /100g)		200.83±0.18
Tannins (%)		11.54±0.36
Antioxidants activity (%)		77.52±0.85
Non enzymatic browning (OD)		1.93±0.02
Ash (%)		2.95±0.04

[*] Total soluble solids [a]n=10 (number of replication)

The physico-chemical properties aligned with the findings reported on dried fruits including dates, raisins, prunes, Goji berry, chokeberry, rose hip, sea buckthorn, berberis, physalis, haritaki, noni and juniper (Rybicka et al., 2021). However, some minor variations in acidity, ascorbic acid, sugar, water removal and moisture ratio were recorded with reference to previous studies on mango, guava and aonla (Kumar et al., 2014) and on ber slices (Singh et al., 2017). These differences may be due to differences in quality of traits, low sugar content, climatic as well as location specific conditions.

Sensory characteristics of fruits after drying among various treatments

Among all treatments, ethyl oleate treated dehydrated whole and sliced harar fruits exhibited superior sensory scores. Based on sensory, tray-dried fruits were more preferred over solar-dried counterparts due to superior color, flavor, texture, and taste (Fig. 2). Besides this, these fruits have retained more nutrients, lower browning index and rapid drying period. Moreover, tray dried fruits also offer good textural properties due to reduced water availability, more consistency as well as better taste, aroma and flavour profile with higher consumer acceptability over solar dried fruits.

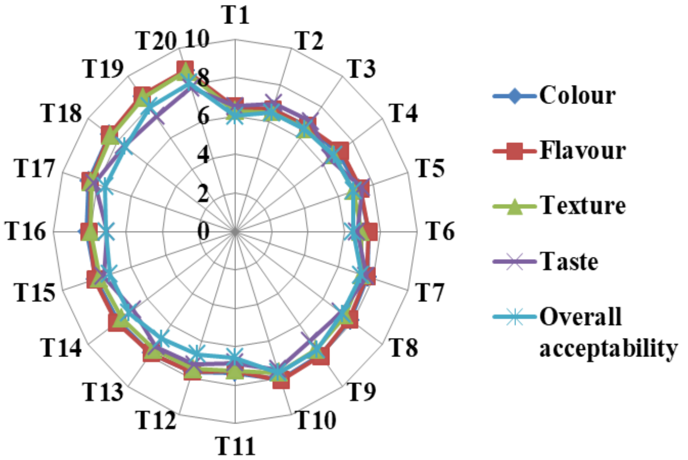


Figure 2 Sensory evaluation of dried harar fruits across different treatments. Attributes including colour, flavour, texture, taste and overall acceptability were rated by most of the panellists based on 9-point hidden scale. The numbers indicate values given.

Physical characteristics of dehydrated harar fruits

The results indicate fast drying of whole fruits in tray drying (T_6-T_{10}) over solar drying (T_1-T_5). Tray drying recorded 22-44 h while solar drying recorded 38-76 h (Table 3). Among pre-treatments, harar fruits dipped in ethyl oleate have taken less time for drying over other treatments. Further, both dehydration and rehydration were found more in ethyl-oleate treated (T_5, T_{10}, T_{15}, T_{20}) harar fruits over blanched (T_2, T_7, T_{12}, T_{17}), salt roasted (T_3, T_8, T_{13}, T_{18}), NaOH (T_4, T_9, T_{14}, T_{19}), and control (T_1, T_6, T_{11}, T_{16}) samples (Table 3). Fast drying in ethyl oleate and tray dried samples might be due to the constant heat transfer and uniform air velocity. Structurally ethyl oleate weakens the highly resistant lipophilic waxy cuticle and enlarges the epidermal pores of fruit to allow fast removal of moisture and hence fastening the process of drying. Similar studies have also reported enhanced porosity of fruit skin by involving chemical improvers to remove moisture content (Suo et al., 2025).

Further, sliced fruits dried more rapidly in comparion to whole fruits. This refers to surface area to volume (SA/V) ratio and the fruit's integrity. In comparison to control samples, sliced fruits have taken 22 (T_{16}-T_{20}) and 38 h (T_{11}-T_{15}) in tray and solar drying, respectively (Table 3). It is reported that small surface area of sliced fruits contributes to less drying time but more exposure to oxygen leads to degradation of ascorbic acid compared to whole fruits which took more time due to more surface area (Li et al., 2019). Therefore, more antioxidants (93.96%) were retained in whole fruits due to limited supply of oxygen to the pulp and protecting it from oxidative stress.

Similarly, moisture content was recorded more in control samples compared to sliced fruits. Less moisture content in sliced fruits is due to higher surface area and more escape of water vapours from the surface makes them thoroughly dried (Table 3). Similar findings have been reported for nutmeg mace (Alfiya et al., 2025), dried carrot (Kumar, 2018) and aonla slices (Al-Amin et al., 2015; Choudhary et al., 2021). The depletion in moisture content in ethyl oleate treated whole harar fruits were observed within first two hours, indicating reduced moisture level which later becomes constant (Fig. 3). Previous studies have shown that dipping of grapes (Pangavhane and Sawhney, 2002), apricot (Doymaz 2004), ginger (Deshmukh et al., 2013), red pepper (Doymaz and Pala, 2002) and tomato (Doymaz, 2007) in ethyl oleate solution significantly accelerated the drying rate.

Table 3 Effect of various treatments on physical characteristics of dehydrated harar fruits

Treatment	Drying time (h)	Yield (%)	Dehydration ratio	Rehydration ratio	Shrinkage percentage	Moisture (%)
T_{1}	80	44.74±0.99^{b}	2.72±0.76^{c}	1.44±0.55 ^{e}	65.46±0.45^{f}	10.31±0.25^{a}
T_{2}	76	41.56±0.80^{d}	2.86±0.57^{c}	1.69± 0.57^{e}	63.9±0.37^{g}	9.05±0.28^{bc}
T_{3}	76	39.38±0.90^{ef}	2.91±0.67^{c}	1.59±0.51 ^{e}	61.59±0.41^{h}	8.42±0.55^{c}
T_{4}	76	40.66±1.04^{de}	2.99±0.81^{c}	1.64±0.67^{e}	58.64±0.25^{k}	8.38±0.46^{c}
T_{5}	76	46.28±0.82^{a}	3.14±0.59^{c}	1.74±0.38^{e}	60.81±0.59^{i}	8.17±0.48^{c}
T_{6}	48	40.32±1.19^{de}	2.89±0.96^{c}	1.77±0.44^{e}	59.9±0.42^{j}	9.52±0.58^{ab}
T_{7}	44	39.64±0.95^{ef}	2.98±0.72^{c}	1.91±0.37^{cde}	57.70±0.35^{l}	8.86±0.72^{bc}
T_{8}	44	27.44±0.59^{j}	3.24±0.36^{c}	1.87±0.57^{de}	57.14±0.38^{l}	8.26±0.62^{c}
T_{9}	44	39.80±0.91^{ef}	3.54±0.68^{bc}	1.89±0.43^{cde}	54.16±0.44^{n}	8.12±0.39^{c}
T_{10}	44	43.16±1.18^{c}	3.59±0.95^{bc}	1.95±0.38^{cde}	56.26±0.54^{m}	8.07±0.52^{c}
T_{11}	40	38.21±0.87^{f}	4.53±0.64^{ab}	1.87±0.28^{de}	85.46±0.61^{a}	6.59±0.64^{d}
T_{12}	38	30.52±0.62^{i}	4.75±0.39^{ab}	2.85±0.54^{abc}	83.57±0.27^{b}	6.10±0.81^{de}
T_{13}	38	30.87±0.90^{i}	4.94±0.67^{a}	1.93±0.61^{cde}	82.90±0.15^{b}	6.02±0.57^{de}
T_{14}	38	26.78±0.67^{j}	5.08±0.44^{a}	2.34±0.54^{bcde}	80.79±0.48^{d}	5.45±0.74^{e}
T_{15}	38	35.88±0.80^{g}	5.21±0.57^{a}	3.04±0.41^{ab}	81.26±0.59^{cd}	5.32±0.61^{e}
T_{16}	24	35.64±0.50^{g}	4.73±0.27^{ab}	2.02±0.49^{cde}	83.1±0.38^{b}	6.06±0.49^{de}
T_{17}	22	27.78±0.79^{j}	4.91±0.56^{a}	2.27±0.59^{bcde}	81.59±0.24^{c}	5.71±0.71^{de}
T_{18}	22	28.00±1.05^{j}	5.18±0.82^{a}	2.78±0.66^{abcd}	80.88±0.37^{cd}	5.46±0.84^{e}
T_{19}	22	23.72±1.14^{k}	5.41±0.91^{a}	3.33±0.51^{a}	79.01±0.39^{e}	5.26±0.42^{e}
T_{20}	22	32.44±0.87^{h}	5.59±0.64^{a}	3.54±0.26^{a}	79.6±0.53^{e}	5.15±0.37^{e}

Values are presented as mean ± SD; Values within rows sharing the same letters are not significantly different according to Duncan's LSD *post-hoc* analysis at $p \leq 0.05$.

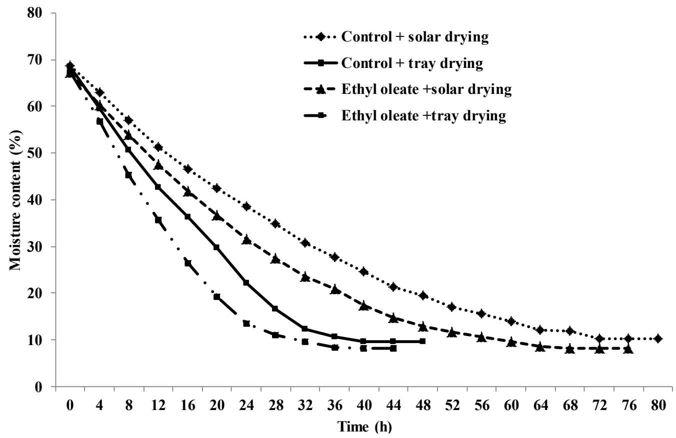


Figure 3 Drying curves illustrating the moisture retention (%) over time (h) for ethyl oleate treated (0.1%) whole harar fruits subjected to tray (55 °C) and solar drying methods.

The Equilibrium Relative Humidity (ERH) curves revealed hygroscopic nature of the fruits. The sigmoidal shape of the ERH curves indicated a typical Type II isotherm behaviour, characteristic of fibrous medicinal fruits containing complex carbohydrates. Analysis revealed 62 and 56% ERH along with 13.31 and 13.14% of equilibrium moisture content (EMC) for ethyl oleate treated and control fruits, respectively (Fig. 4). Exposure of fruits to high ERH revealed substantial changes in its color and texture. Hence, irrespective of pre-treatment, the critical point (where the harar become soggy and soft) and danger point (5% lower relative humidity than that of critical point) were recorded at 70 and 65% of relative humidity for fruits, respectively (Fig. 4). At 60 to 70% relative humidity, the fruits turned dark brown while beyond 70% humidity, the product turned into soft texture with mouldy growth. It indicates a critical threshold where high humidity causes dry products to absorb moisture, leading to free water availability, mold growth, and active enzyme degradation (Yewle et al., 2021).

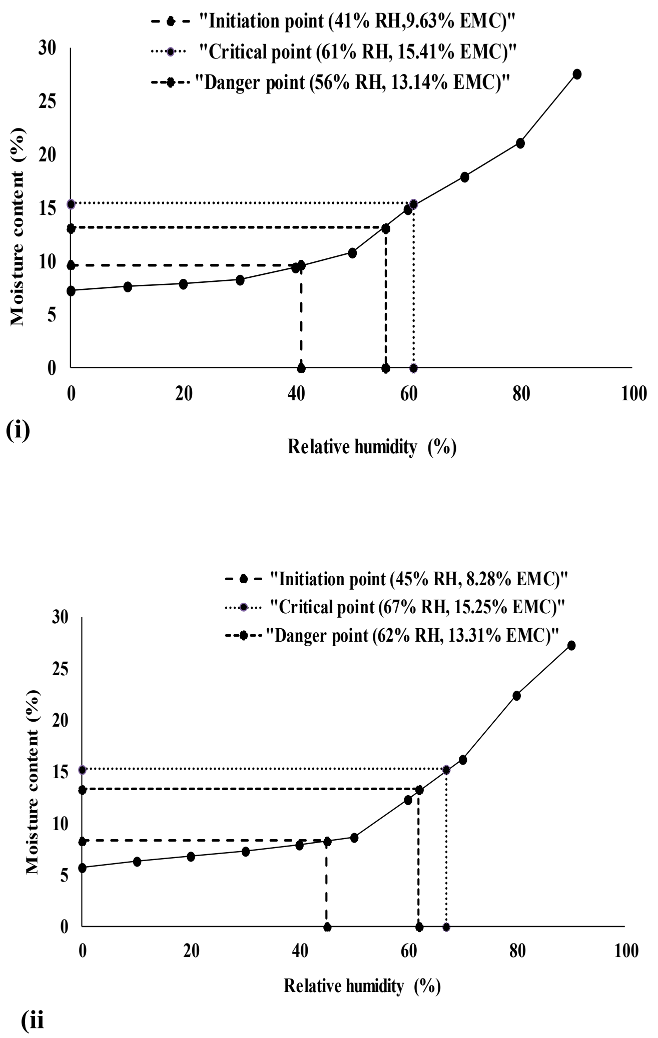


Figure 4 Equilibrium Relative Humidity (ERH) curves comparing control harar fruits (i) and ethyl oleate treated dehydrated whole harar fruits (ii) to determine hygroscopic stability and storage safety points.

Chemical characteristics of dehydrated fruits

Chemical characteristics of dried harar fruits revealed 7.49 to 10.96% titratable acidity, 21.70 to 32.15 °Brix TSS, 3.36-4.22 pH range, 12.06-21.90% reducing sugars, and 17.99-30.81 total sugars among all treatments and were reported higher in sliced fruits over whole fruits (Table 4). These findings depend upon the drying rate, moisture level and non-enzymatic browning. Thermal exposure of fruits causes loss of antioxidants, flavonoids and phenolics compounds. For instance, drying can enhance the antioxidant activity of certain fruits due to the concentration of bioactive compounds following moisture removal, or through the formation of new compounds via chemical reactions. While many bioactive compounds are sensitive to heat, specific drying methods can increase antioxidant levels. Accordingly, in the present study, higher percentage of antioxidants (93.96%) were retained in tray dried whole fruits (T_{10}) compared to sliced fruits. Similarly, ethyl oleate treated whole fruits exhibited higher contents of ascorbic acid 17.03 mg per 100 gram (Table 4) similar to that report in dried red chillies (Gupta et al., 2002). Further, total phenolics 445.26 mg per 100 grams were recorded higher in tray dried harar fruits. It is concluded that mechanical drying performed under controlled conditions is responsible for retention of bioactives and other nutrients and preserved the fruits by removing moisture and preventing oxidative damage. Moreover, the superior retention of color is possibly due to the weakening of waxy cuticle expediting towards lower water activity, and preventing the activity of antioxidant related enzymes (Alfiya et al., 2025).

Table 4 Effect of various treatments on chemical characteristics of dehydrated harar fruits

Treatment	TSS (°Brix)	Titratable acidity (%)	pH	Reducing sugars (%)	Total sugars (%)	Ascorbic acid (mg/100g)	Phenolics (mg/100g)	Tannins (%)	Antioxidants activity (%)	NEB
T_1	21.70 ± 0.33^{l}	9.34 ± 0.25^{de}	3.36 ± 0.60^{a}	12.06 ± 0.49^{n}	17.99 ± 0.37^{n}	9.48 ± 0.39^{i}	430.20 ± 0.49^{i}	39.60±0.35h	88.35 ± 0.47^{hi}	1.38 ± 0.21^{a}
T_2	24.45 ± 0.35^{k}	9.56 ± 0.37^{cde}	3.56 ± 0.62^{a}	12.89 ± 0.51^{n}	19.55 ± 0.49^{m}	9.91 ± 0.41^{hi}	432.52 ± 0.51^{h}	42.60 ± 0.37^{g}	89.75 ± 0.49^{efg}	1.21 ± 0.51^{a}
T_3	25.10 ± 0.37^{jk}	9.76 ± 0.11^{bcde}	3.55 ± 0.56^{a}	13.84 ± 0.53^{m}	21.53 ± 0.23^{l}	11.99 ± 0.43^{f}	434.69 ± 0.53^{g}	44.54 ± 0.39^{f}	89.96 ± 0.51^{ef}	1.26 ± 0.71^{a}
T_4	26.23 ± 0.40^{i}	9.93 ± 0.25^{bcd}	4.18 ± 0.72^{a}	14.39 ± 0.56^{lm}	22.56 ± 0.37^{jk}	12.88 ± 0.46^{de}	437.63 ± 0.56^{e}	45.63 ± 0.42^{e}	90.16 ± 0.54^{de}	1.30 ± 0.66^{a}
T_5	27.29 ± 0.43^{h}	10.36 ± 0.49^{ab}	3.50 ± 0.83^{a}	15.27 ± 0.59^{kl}	23.71 ± 0.61^{i}	13.52 ± 0.49^{cde}	438.96 ± 0.59^{d}	48.56 ± 0.45^{b}	90.95 ± 0.57^{cd}	1.19 ± 0.32^{a}
T_6	22.16 ± 0.46^{l}	9.74 ± 0.12^{bcde}	3.35 ± 0.79^{a}	14.23 ± 0.62^{m}	20.27 ± 0.24^{m}	12.66 ± 0.52^{ef}	436.50 ± 0.62^{f}	42.57 ± 0.48^{g}	91.34 ± 0.60^{c}	1.33 ± 0.79^{a}
T_7	25.43 ± 0.48^{ik}	9.98 ± 0.55^{bcd}	3.51 ± 0.42^{a}	15.77 ± 0.64^{jk}	22.26 ± 0.67^{kl}	13.78 ± 0.54^{cd}	438.82 ± 0.64^{d}	45.71 ± 0.50^{e}	92.75 ± 0.62^{b}	1.10 ± 0.36^{a}
T_8	26.08 ± 0.52^{i}	10.22 ± 0.28^{bc}	3.48 ± 0.92^{a}	16.38 ± 0.68^{ij}	23.34 ± 0.40^{ij}	14.20 ± 0.58^{c}	440.89 ± 0.68^{c}	46.51 ± 0.54^{d}	92.95 ± 0.66^{b}	1.23 ± 0.44^{a}
T_9	27.21 ± 0.55^{h}	10.38 ± 0.34^{ab}	4.14 ± 0.78^{a}	16.81 ± 0.71^{hi}	24.71 ± 0.46^{h}	16.13 ± 0.38^{b}	443.85 ± 0.71^{b}	47.61 ± 0.57^{c}	93.13 ± 0.69^{ab}	1.27 ± 0.82^{a}
T_{10}	28.27 ± 0.58^{fg}	10.96 ± 0.24^{a}	3.44 ± 0.67^{a}	17.61 ± 0.74^{gh}	25.62 ± 0.36^{g}	17.03 ± 0.46^{a}	445.26 ± 0.44^{a}	50.66 ± 0.60^{a}	93.96 ± 0.42^{a}	1.04 ± 0.54^{a}
T_{11}	27.70 ± 0.70^{gh}	7.49 ± 0.31^{i}	3.71 ± 0.83^{a}	17.39 ± 0.46^{h}	25.38 ± 0.43^{gh}	6.72 ± 0.29^{k}	397.15 ± 0.56^{o}	29.88 ± 0.72^{o}	85.27 ± 0.54^{l}	1.87 ± 0.28^{a}
T_{12}	28.92 ± 0.62^{ef}	7.71 ± 0.47^{hi}	3.90 ± 0.61^{a}	18.48 ± 0.48^{fg}	26.74 ± 0.59^{f}	7.64 ± 0.41^{k}	402.85 ± 0.38^{n}	32.92 ± 0.64^{m}	86.69 ± 0.36^{k}	1.31 ± 0.94^{a}
T_{13}	29.54 ± 0.66^{de}	7.91 ± 0.25^{ghi}	3.94 ± 0.66^{a}	18.94 ± 0.42^{f}	27.43 ± 0.37^{ef}	8.49 ± 0.74^{j}	403.53 ± 0.52^{n}	33.66 ± 0.38^{m}	86.93 ± 0.50^{k}	1.56 ± 0.73^{a}
T_{14}	30.16 ± 0.69^{cd}	8.08 ± 0.38^{ghi}	4.22 ± 0.59^{a}	19.43 ± 0.55^{def}	27.98 ± 0.50^{de}	10.47 ± 0.75^{gh}	406.28 ± 0.65^{m}	35.04 ± 0.51^{l}	87.15 ± 0.63^{jk}	1.61 ± 0.19^{a}
T_{15}	31.14 ± 0.47^{b}	8.51 ± 0.59^{fg}	3.82 ± 0.86^{a}	20.05 ± 0.63^{cde}	28.76 ± 0.71^{cd}	10.80 ± 0.84^{gh}	409.23 ± 0.53^{l}	36.76 ± 0.39^{j}	87.98 ± 0.51^{ij}	1.25 ± 0.29^{a}
T_{16}	28.75 ± 0.35^{ef}	7.89 ± 0.38^{ghi}	3.60 ± 0.54^{a}	19.08 ± 0.51^{ef}	27.44 ± 0.50^{ef}	9.43 ± 0.33^{i}	403.65 ± 0.41^{n}	31.74 ± 0.27^{n}	87.90 ± 0.39^{ij}	1.65 ± 0.84^{a}
T_{17}	29.93 ± 0.25^{cd}	8.13 ± 0.14^{ghi}	3.87 ± 0.76^{a}	20.23 ± 0.41^{cd}	28.75 ± 0.26^{cd}	10.93 ± 0.44^{g}	409.15 ± 0.61^{l}	35.82 ± 0.47^{kl}	88.68 ± 0.59^{hi}	1.20 ± 0.72^{a}
T_{18}	30.55 ± 0.50^{bc}	8.37 ± 0.47^{gh}	3.92 ± 0.64^{a}	20.87 ± 0.66^{bc}	29.47 ± 0.59^{bc}	10.10 ± 0.34^{ghi}	409.83 ± 0.46^{l}	36.61 ± 0.32^{jk}	88.85 ± 0.44^{ghi}	1.18 ± 0.78^{a}
T_{19}	31.17 ± 0.33^{b}	8.53 ± 0.29^{fg}	4.17 ± 0.71^{a}	21.26 ± 0.49^{ab}	29.99 ± 0.41^{b}	13.02 ± 0.42^{de}	412.58 ± 0.69^{k}	38.08 ± 0.55^{i}	89.16 ± 0.67^{fgh}	1.45 ± 0.69^{a}
T_{20}	32.15 ± 0.46^{a}	9.11 ± 0.43^{ef}	3.78 ± 0.91^{a}	21.91 ± 0.62^{a}	30.81 ± 0.55^{a}	14.15 ± 0.46^{c}	415.53 ± 0.52^{j}	39.38 ± 0.38^{h}	89.95 ± 0.50^{ef}	1.14 ± 0.26^{a}

Values are presented as mean ± SD; Values within rows sharing the same letters are not significantly different according to Duncan's LSD *post-hoc* analysis at $p \leq 0.05$.

Table 5 Effect of packaging material on physico chemical characteristics of dehydrated harar fruits during storage at ambient temperature

Parameters	Packaging material	Storage interval		
		0 month	3 months	6 months
Rehydration ratio	Cotton bags	1.95^{Aa}	1.65^{ABc}	1.39^{Bc}
	Gunny bags	1.95^{Aa}	1.77^{Ab}	1.59^{Ab}
	Aluminium pouches	1.95^{Aa}	1.87^{Aa}	1.79^{Aa}
Rehydration percentage	Cotton bags	72.15^{Aa}	71.72^{ABa}	71.4^{Ba}
	Gunny bags	72.15^{Aa}	71.89^{Aa}	71.63^{Aa}
	Aluminium pouches	72.15^{Aa}	71.98^{Aa}	71.85^{Aa}
Moisture (%)	Cotton bags	8.07^{Ba}	8.56^{ABa}	9.06^{Aa}
	Gunny bags	8.07^{a}	8.47^{ABa}	8.85^{a}
	Aluminium pouches	8.07^{Aa}	8.38^{Aa}	8.54^{Aa}
TSS (°B)	Cotton bags	28.27^{Aa}	27.79^{ABa}	27.30^{Ba}
	Gunny bags	28.27^{Aa}	27.92^{ABa}	27.54^{Ba}
	Aluminium pouches	28.27^{Aa}	28.01^{ABa}	27.72^{Ba}
Acidity (%)	Cotton bags	10.96^{Aa}	10.52^{ABa}	10.07^{Ba}
	Gunny bags	10.96^{Aa}	10.65^{ABa}	10.31^{Ba}
	Aluminium pouches	10.96^{Aa}	10.73^{Aa}	10.48^{Aa}
pH (%)	Cotton bags	3.44^{Ca}	3.65^{Ba}	3.83^{Aa}
	Gunny bags	3.44^{Ca}	3.61^{Ba}	3.81^{Aa}
	Aluminium pouches	3.44^{Ca}	3.57^{Ba}	3.77^{Aa}
Ascorbic acid (mg/100g)	Cotton bags	17.03^{Aa}	15.69^{Ba}	14.85^{Ca}
	Gunny bags	17.03^{Aa}	15.84^{Ba}	15.26^{Ca}
	Aluminium pouches	17.03^{Aa}	16.04^{Ba}	15.49^{Ba}
Total sugars (%)	Cotton bags	25.62^{Aa}	25.33^{ABa}	25.05^{Ba}
	Gunny bags	25.62^{Aa}	25.49^{Aa}	25.36^{Aa}
	Aluminium pouches	25.62^{Aa}	25.53^{Aa}	25.42^{Aa}
Reducing sugars (%)	Cotton bags	17.61^{Aa}	17.83^{ABa}	18.15^{Ba}
	Gunny bags	17.61^{Ba}	17.88^{ABa}	18.23^{Aa}
	Aluminium pouches	17.61^{Ba}	18.06^{ABa}	18.53^{Aa}
Non reducing sugars (%)	Cotton bags	7.60^{Aa}	7.23^{Aa}	6.77^{Ba}
	Gunny bags	7.60^{Aa}	7.13^{Ba}	6.55^{Ca}
	Aluminium pouches	7.60^{Aa}	7.07^{Ba}	6.47^{Ca}
Tannins (%)	Cotton bags	50.66^{Aa}	50.22^{Ba}	49.92^{Ba}
	Gunny bags	50.66^{Aa}	50.32^{ABa}	50.02^{Ba}
	Aluminium pouches	50.66^{Aa}	50.43^{ABa}	50.22^{Ba}
NEB	Cotton bags	1.04^{Ba}	1.10^{ABa}	1.19^{Aa}
	Gunny bags	1.04^{Aa}	1.07^{Aa}	1.14^{Aa}
	Aluminium pouches	1.04^{Aa}	1.05^{Aa}	1.10^{Aa}

Capital letters superscript denotes storage interval effect and small letters superscript denote packing material effect; Values within rows sharing the same letters are not significantly different according to Duncan's LSD *post-hoc* analysis at $p \leq 0.05$

Fruit characteristics and microbial load during storage stability

Among all treatments, ethyl oleate treated and tray dried whole fruits displayed superior physico-chemical, nutritional, and sensory properties. For evaluating storage stability, harar fruits packed in aluminium pouches revealed better protection against moisture ingress in comparison to cotton and gunny bags (Table 5). Higher moisture absorption was recorded in cotton (9.06%) and gunny (8.85%) bags due to high porosity whereas lower moisture content (8.54%) in aluminium pouches (Table 5). Higher the moisture content, higher is the hygroscopic nature of fruits and allowing the fruits to swollen in the form of sponge. This moisture ingress is driven by the differences in vapour pressure of surrounding environment and dried fruits. Hence, aluminium packs have been reported as impermeable, non-porous hermetic shield against, oxygen, water vapour and light which protects fruits from softening and pigment degradation.

During shelf-life study, neither bacterial nor fungal count was not detected in fruits packed in aluminium pouches while 10^3 and 10^2 CFU/g fungal count was recorded in fruits packed in cotton and gunny bags, after 3 months, respectively. The study signifies the superior performance of aluminium pouches in terms of retention of color, reduced microbial and moisture content over cotton and gunny bags in medicinal fruits (Perera, 2005; Rivera-Espinoza and Gallardo-Navarro, 2010). Further, due to reduced oxidation of phenolic compounds in fruits, tannins were also reported higher in fruits packed in aluminium pouches as compared to cotton and gunny bags (Table 5). The dried fruits exhibit reduced non enzymatic browning in aluminium pouches packed fruits possibly due to the pouches' opacity, which prevents photo-oxidation of pigments in medicinal fruits (Perera, 2005).

These findings are in conformity with established trends in dried horticultural produce, including carrot slices (Dhiman et al., 2020), dehydrated pumpkin cubes, (Singh et al., 2014, 2017), ber powder (Foshanji et al., 2018), raisins (Ankush et al., 2019), bael slices (Wani et al., 2017; 2019), apricots (Thakur et al., 2010), pomegranate arils (Pareek and Kaushik, 2012), and aonla powder (Kaur et al., 2020).

Sensory characteristics during prolonged period

The storage duration exerted a significant influence on the organoleptic profile of the dehydrated harar. On the 9-point hedonic scale, consumer acceptance decreased from a "like very much" towards "like moderately" rating across all attributes. The result highlights a decrease in overall flavor scores from 8.75 to 8.09, indicating a reduction in aromatic and volatile compounds in fruits. This transformation changes the balance from a complex taste profile to a more bitter astringent character, due to non-enzymatic browning and the degradation of organic acids.

During storage, harar fruits packed in aluminium pouches were significantly more effective in arresting sensory decay, reducing moisture absorption, and maintaining food quality compared to traditional packaging methods like gunny, and cotton bags (Fig. 5). The superior barrier properties in aluminium-packages prevent spoilage and maintain flavor and texture over extended storage period. By maintaining the critical moisture threshold, the pouch acts as moisture proof barrier, protecting the products texture against photo-oxidation, development of off-flavors, prevents microbial growth and maintains quality. The efficacy of hermetic packaging observed here is consistent with recent findings by Yewle et al. (2021), who emphasized that multi-layer barrier films are essential for preserving the sensory properties of medicinal fruits. Our results further align with established trends in other horticultural products, such as dried carrot slices (Sra et al., 2014) and pumpkin cubes (Dhiman et al., 2020), which demonstrate that permeable materials (cotton/gunny) fail to protect against the oxidative and hygroscopic flux responsible for organoleptic deterioration.

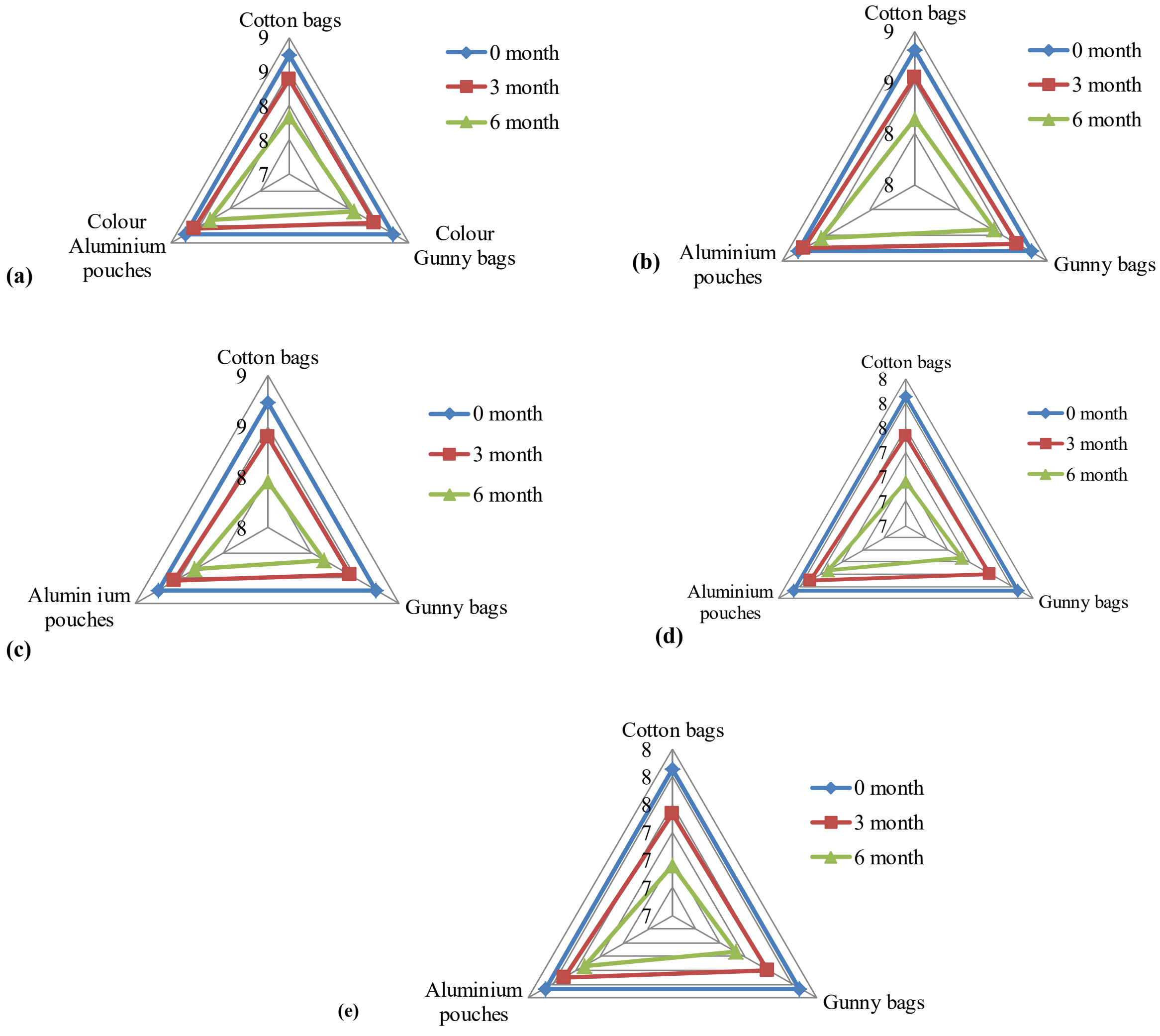


Figure 5 Storage stability and **s**ensory characteristics including colour, flavour, texture, taste and overall acceptability based on 9-point hidden scale of ethyl oleate treated dehydrated whole harar during 6 months storage period. The observations are based on a 9-point hedonic scale rated by a panellist.

CONCLUSION

The study highlights post-harvest processing of *Terminalia chebula* (Harar) for maintaining quality and consistency during drying from the pre-treatment phase till storage. The study reported treatment of harar fruits with 0.1% ethyl oleate as the most effective intervention due to the reduced enzymatic oxidation, retaining highest phenolics and ascorbic acids. Besides pre-treatments, tray drying ensures a higher quality, safer, and more consistent product, justifying its superiority over solar drying. The optimized drying conditions are promising by enhancing its nutraceutical and functional properties, ensuring microbial safety and consistent quality, suitable for commercialization. Future studies involving mechanistic investigations and large sample sizes would further strengthen and validate the biochemical mechanisms and ensuring high-quality processed fruits.

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Authors' contributions: PT performed experimental work, PC generated idea, VS and RS interpreted results, drafted and edited the original MS.

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