International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; 9(7): 1385-1389
www.biochemjournal.com
Received: 08-06-2025
Accepted: 10-07-2025

Swati Shukla
Ph.D. Research Scholar, Department of Fruit Science, IGKV, Raipur, Chhattisgarh, India

Prabhakar Singh
Professor, Department of Fruit Science, IGKV, Raipur, Chhattisgarh, India

Gaurav Sharma
Professor & Head, Post Harvest Technology, RLBCAU, Jhansi, Uttar Pradesh, India

Hemant Kumar Panigrahi
Assistant Professor, Department of Fruit Science, IGKV, Raipur, Chhattisgarh, India

Gunja Thakur
Ph.D. Research Scholar, Department of Fruit Science, IGKV, Raipur, Chhattisgarh, India

Diksha Meher
Ph.D. Research Scholar, Department of Fruit Science, IGKV, Raipur, Chhattisgarh, India

K Hita
Ph.D. Research Scholar, Department of Fruit Science, IGKV, Raipur, Chhattisgarh, India

Corresponding Author:
Swati Shukla
Ph.D. Research Scholar, Department of Fruit Science, IGKV, Raipur, Chhattisgarh, India

Modeling of solar drying behavior and quality evaluation of sun-dried wood apple (*Limonia acidissima*) pulp

Swati Shukla, Prabhakar Singh, Gaurav Sharma, Hemant Kumar Panigrahi, Gunja Thakur, Diksha Meher and K Hita

DOI: https://www.doi.org/10.33545/26174693.2025.v9.i7q.4991

Abstract
Wood apple (*Limonia acidissima* L.), an underutilized indigenous fruit rich in bioactive compounds, was processed into a stable powder through solar drying under Bundelkhand's climatic conditions. The study aimed to evaluate the drying kinetics, physico-chemical composition, antioxidant properties, and functional quality of the sun-dried product. The pulp was dried in a solar dryer, and moisture loss was recorded at regular intervals. Thin-layer drying models were fitted to the experimental data, with the Page model showing superior fit (RMSE = 0.017) compared to the Newton model (RMSE = 0.030). The resulting powder exhibited high carbohydrate content (86.45%), moderate protein (4.13%), and low fat (1.34%), with moisture reduced to 6.77%, ensuring storage stability. Total phenolics (30.67 mg GAE/g) and ascorbic acid (10.42 mg/100 g) levels confirmed the product's antioxidant potential. FTIR analysis revealed characteristic peaks associated with hydroxyl, carboxyl, and aromatic functional groups, validating the presence of polyphenols, organic acids, and carbohydrates. Sensory evaluation indicated high consumer acceptability, with scores above 7.0 for all attributes. These findings demonstrate that solar drying is an effective, low-cost method for converting wood apple pulp into a value-added functional ingredient, suitable for use in nutraceuticals and health-oriented food products.

Keywords: Wood apple, solar drying, drying kinetics, page model, functional properties, FTIR etc.

Introduction

Wood apple (*Limonia acidissima* L.), commonly known as kaitha or elephant apple, is an indigenous fruit-bearing tree belonging to the Rutaceae family. It is well-adapted to arid and semi-arid regions of India and holds considerable promise for nutritional security, rural income generation, and agroforestry development. The fruit pulp is a rich source of carbohydrates, calcium, phosphorus, iron, dietary fiber, and bioactive compounds such as polyphenols and tannins, which impart antioxidant, antimicrobial, and hepatoprotective properties (Baliga *et al.*, 2011) [3]. Traditionally, the pulp is used in chutneys, beverages, jams, and Ayurvedic preparations (Goyary *et al.*, 2024) [7].

Despite its nutritional and medicinal value, wood apple remains underutilized due to limited public awareness, lack of organized cultivation, and poor postharvest management. According to the ICAR-NBPGR (2020) [20], wood apple predominantly exists in wild or semi-wild forms across various Indian states, including Chhattisgarh, Madhya Pradesh, Uttar Pradesh, and Tamil Nadu. Although national production statistics are not well-documented, localized assessments suggest increasing interest in its cultivation, particularly in tribal and dryland areas.

The Bundelkhand region, encompassing parts of southern Uttar Pradesh and northern Madhya Pradesh, provides ideal agro-climatic conditions for solar drying of horticultural produce. With 9-10 hours of daily sunshine, summer temperatures ranging from 35 °C to 45 °C, and relative humidity often below 30%, the region is naturally suited for efficient, low-cost solar drying (IMD, 2023) [9]. Yadav *et al.*, (2023) [16] highlighted Bundelkhand's high solar energy potential, underscoring the viability of solar drying as an eco-friendly preservation method.

Solar drying, one of the oldest and most accessible food preservation techniques, is often associated with variability in product quality due to fluctuating environmental conditions and the absence of standardization. Mathematical modelling of drying kinetics is essential to optimize drying processes, predict moisture loss behaviour and ensure product consistency. Thin-layer drying models—such as Newton and Page—have been widely applied to characterize the drying behaviour of fruits and vegetables.

Currently, wood apple lacks commercially available value-added products. Promoting solar drying during the off-season could create new income opportunities for farmers in dryland regions. This study aims to model the drying kinetics of wood apple pulp under Bundelkhand's solar conditions and to evaluate the functional quality of the resultant dried powder.

Materials and Methods

Raw Material Collection and Preparation

Mature wood apple (*Limonia acidissima* L.) fruits were collected from farmers' fields in the Jhansi region of Uttar Pradesh, India. The fruits were manually sorted for uniform size and maturity, washed thoroughly under running tap water to remove surface impurities, and subsequently air-dried at ambient conditions. The hard outer shells were manually cracked using sanitized stainless-steel tools and the pulp was carefully extracted to avoid contamination. The extracted pulp was immediately subjected to solar drying.

Solar Drying Procedure

Drying was carried out using a passive solar dryer with a capacity of 500 kg. The pulp was spread evenly in a thin layer over perforated stainless-steel trays to ensure uniform exposure to sunlight. Drying was conducted under ambient conditions typical of Bundelkhand's summer climate, with regular monitoring of temperature and humidity. To study the drying kinetics, the weight of the pulp was recorded at one-hour intervals using a digital balance. The weight loss data were used to calculate the moisture content at each time point. Moisture content (wet basis) was determined using the following equation:

$$\text{Moisture Content (\%)} = \{(W_t - W_d)/W_t\} \times 100$$

Where

- W_t = weight of the sample at time *t*
- W_d = dry weight of the sample

The drying process continued until a constant weight was achieved, indicating equilibrium moisture content. A schematic representation of the solar drying process is shown in Figure 1.

Selection of wood apple fruits
↓
Washing and deshelling of fruits
↓
Pulp extraction with seed
↓
Drying of pulp in sun drying cabinet
↓
Cooling of dried pulp at room temperature
↓
Grinding dried pulp
↓
Wood apple pulp powder
↓
Packaging and Storage

Fig 1: Flow chart for preparation of sun-dried wood apple pulp powder

Physico-Chemical Analysis

The proximate composition of dried wood apple pulp powder was analyzed using standard methods. Moisture content (%), ash content (%), and crude fat content (%) were determined following AOAC procedures (AOAC, 2000) [1]. Crude protein content was estimated using the Kjeldahl method, and total protein was calculated using a nitrogen-to-protein conversion factor of 6.25.

Quantitative Analysis of Antioxidant Compounds

Total Phenolics Content

The total phenolic content (TPC) was determined using the Folin-Ciocalteu colorimetric method as described by Bray and Thorpe (1954) [4], with catechol used as the standard. One gram of dried and ground sample was homogenized and centrifuged at 5000 rpm. The supernatant was filtered and evaporated to dryness in a hot air oven. The dried residue was reconstituted in 5 mL of distilled water.

Aliquots ranging from 0.2 to 2.0 mL were transferred into test tubes and diluted to a total volume of 3 mL with distilled water. To each tube, 0.5 mL of Folin-Ciocalteu reagent was added. After 3 minutes, 2 mL of 20% sodium carbonate (Na_2CO_3) solution was added and mixed thoroughly. The reaction mixtures were placed in a boiling water bath for 1 minute, then cooled to room temperature. Absorbance was measured at 650 nm using a Spectronic-20 spectrophotometer. The total phenolic content was calculated from a standard calibration curve.

Ascorbic Acid Content

Ascorbic acid content was determined according to the method described by Ranganna (2000) [10]. Five grams of sample were homogenized with 80 mL of cold 3% metaphosphoric acid solution using a blender. The mixture was filtered, and a 5 mL aliquot of the filtrate was titrated with a standard 2,6-dichlorophenol-indophenol dye solution until a persistent pink endpoint was observed. The results were expressed as mg ascorbic acid per 100 g of sample.

Statistical Analysis

All analytical measurements were performed in triplicate to ensure reproducibility. Results were expressed as mean values±standard deviations. Analysis of variance (ANOVA) was conducted to determine significant differences among treatments, with a significance level of $p<0.05$.

Results and Discussion

Drying Behavior and Model Fitting of Wood Apple Pulp

The drying behavior of wood apple pulp during solar drying was assessed by analyzing the variation in moisture ratio over time. Two commonly used thin-layer drying models—Newton and Page—were applied to the experimental data to evaluate their suitability in describing the drying kinetics. Model fitting was performed by comparing the experimental moisture ratio values with those predicted by each model. The root mean square error (RMSE) was used as the statistical indicator to assess the goodness-of-fit. Lower RMSE values indicate better conformity between predicted and experimental data. The Page model demonstrated superior performance, with an RMSE of 0.017, compared to the Newton model, which yielded an RMSE of 0.030. This indicates that the Page model more accurately represents the moisture loss kinetics during the solar drying of wood apple pulp. Figure 2 illustrates the moisture ratio curves as a function of drying time, along with the model-predicted values from both Newton and Page equations. The Page model showed a closer fit to the experimental curve throughout the drying period.

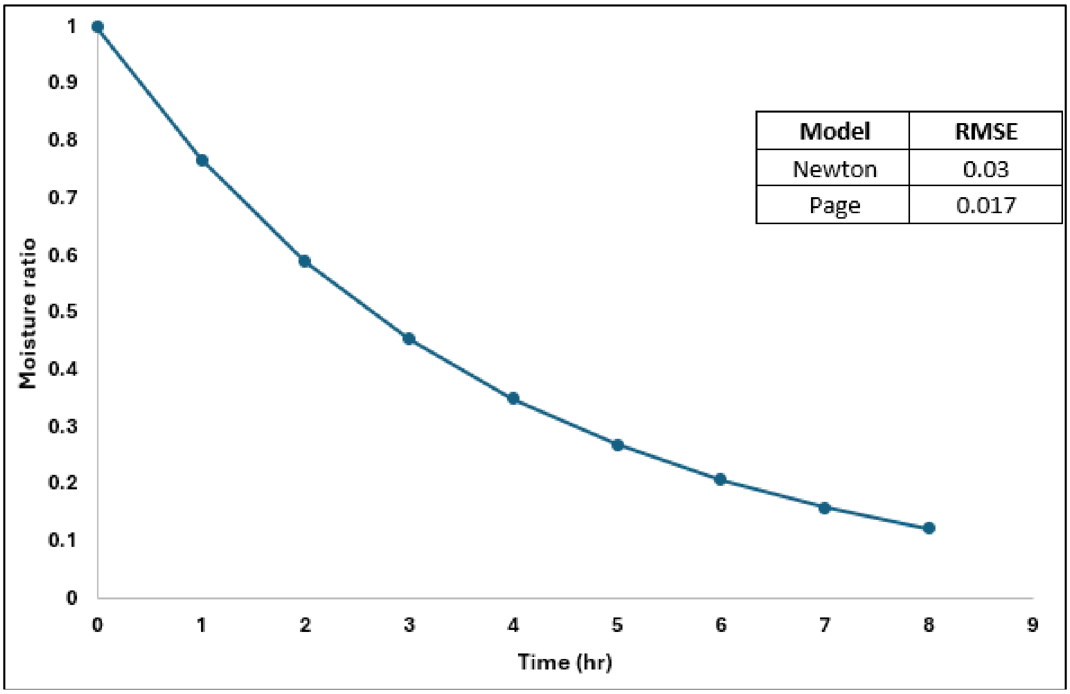

Fig 2: Variation of moisture ratio with drying time during sun drying of wood apple pulp along with model fitting (Newton and Page)

Proximate and Functional Properties

Table 1 presents the proximate composition and functional properties of sun-dried wood apple powder. The powder exhibited a high carbohydrate content (86.45±0.22%), indicating its potential as an energy-dense functional ingredient. These results are in agreement with Vijayakumar *et al.*, (2013) [14], who reported similar carbohydrate levels (84-88%) in dried wood apple pulp.

The crude protein content was found to be 4.13±0.05%, aligning with values reported by Sneha and Deb (2020) [12]. The low crude fat content (1.34±0.01%) is desirable for low-fat food formulations and is within acceptable ranges noted by Amardeep and Vijayakumar (2025) [2]. The moisture content of 6.77±0.02% confirms the effectiveness of sun drying in reducing water activity to safe storage levels. According to AOAC (2000) [1] and FAO (2013) [5], moisture levels below 10% in fruit powders inhibit microbial spoilage and prolong shelf life.

The ash content (1.30±0.19%) indicates substantial mineral retention and is comparable to findings by Thirumaran *et al.* (2018) [13]. The energy content of the powder (383.87±0.83 kcal/100 g) places it in the category of calorific fruit-based powders, akin to tamarind and bael (Singhania & Ray, 2019) [11].

The reducing sugar and total sugar contents were recorded as 7.20±0.10% and 13.37±0.15%, respectively, consistent with prior studies (Sneha & Deb, 2020) [12]. The total soluble solids (TSS) content was 20.10±0.10 °Brix, further validating a high sugar-soluble solids profile and supporting its use in sweetened formulations (Vijayakumar *et al.*, 2013). The titratable acidity, expressed as citric acid, was found to be 5.60±0.10%, confirming the sour nature of wood apple pulp. This level of acidity enhances flavor and offers preservative properties, similar to the profiles reported by Gopalan *et al.*, (2004) [6].

The total phenolic content was 30.67±1.15 mg GAE/g, indicating strong antioxidant potential. The ascorbic acid content was 10.42±0.07 mg/100 g, which falls within the expected range for sun-dried tropical fruits. While slightly reduced compared to fresh pulp, the ascorbic acid content remains nutritionally relevant, as also observed by Amardeepa and Vijayakumar (2025) [2].

Table 1: Proximate and functional properties of sun-dried wood apple powder

Parameter	Mean±SD
Carbohydrate (%)	86.45±0.22
Crude Fat (%)	1.34±0.01
Crude Protein (%)	4.13±0.05
Moisture (%)	6.77±0.02
Ash (%)	1.30±0.19
Energy (kcal/100g)	383.87±0.83
Reducing Sugars (%)	7.20±0.10
Total Sugars (%)	13.37±0.15
TSS (°Brix)	20.10±0.10
Titratable Acidity (% CA)	5.60±0.10
Total Phenolics (mg GAE/g)	30.67±1.15
Ascorbic Acid (mg/100 g)	10.42±0.07

Sensory Evaluation

Sensory quality of the sun-dried wood apple powder was evaluated using a 9-point hedonic scale (Figure 3). The overall acceptability (OAA) score was 7.86±0.69, indicating a high degree of consumer acceptability. Among sensory attributes, colour received the highest score (8.00±0.82), reflecting minimal browning and retention of natural hue during drying.

Flavour (7.86±0.69) and taste (7.00±0.82) were positively evaluated, showing that the characteristic tangy-sweet profile of the pulp was well preserved. The texture score (7.00±0.82) suggests the powder was fine, lump-free, and had good flowability—important traits for reconstitution and blending in food products.

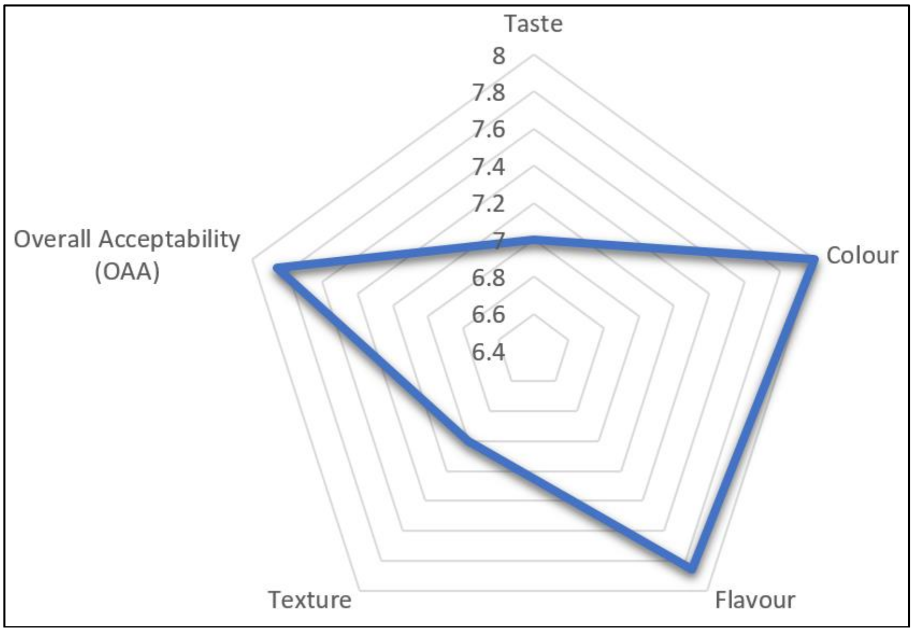

Fig 3: Spiderweb diagram of sensory scores of sun-dried wood apple powder

FTIR Analysis of Sun-Dried Wood Apple Powder

FTIR analysis of sun-dried wood apple powder was done to analyze the functional groups and authenticate the occurrence of the biochemical constituents. The FTIR spectrum (Figure 4) showed a number of typical absorption peaks in the range of 3500-1000 cm^{-1} that correspond to principal organic and bioactive molecules. The wide absorption band showing between 3626-3777 cm^{-1} and a strong peak at 3334 cm^{-1} are characteristic of intense O-H stretching vibrations, as caused by hydroxyl groups of phenolic molecules, carbohydrates, or water (Wang *et al.*, 2011). These peaks validate the existence of bioactive molecules such as polyphenols and flavonoids, which are accountable for antioxidant activity. The peaks at 2920.01 cm^{-1} and 2853.93 cm^{-1} are due to aliphatic C-H stretching, indicating the presence of lipid or fatty acid constituents. This is consistent with proximate analysis, which indicated the presence of trace but detectable fat content. A pointed peak at 1739.93 cm^{-1} shows C=O stretching, which is commonly seen in carboxylic acids, esters, or pectin constituents, confirming the presence of organic acids to be responsible for the titratable acidity in the sample. Absorption at 1597.73 cm^{-1} is attributed to aromatic C=C stretching or N-H bending, showing the presence of protein material or aromatic phenolics. Lastly, the intense absorbance at 1052.34 cm^{-1} is a result of C-O stretching, which supports the existence of carbohydrates or polysaccharides, aligning with the high content of carbohydrates (86.45%) from proximate analysis. All these observations substantiate that sun-dried wood apple powder is rich in the essential bioactive constituents and, therefore, can be used in nutraceuticals, functional foods, or value-added food formulations.

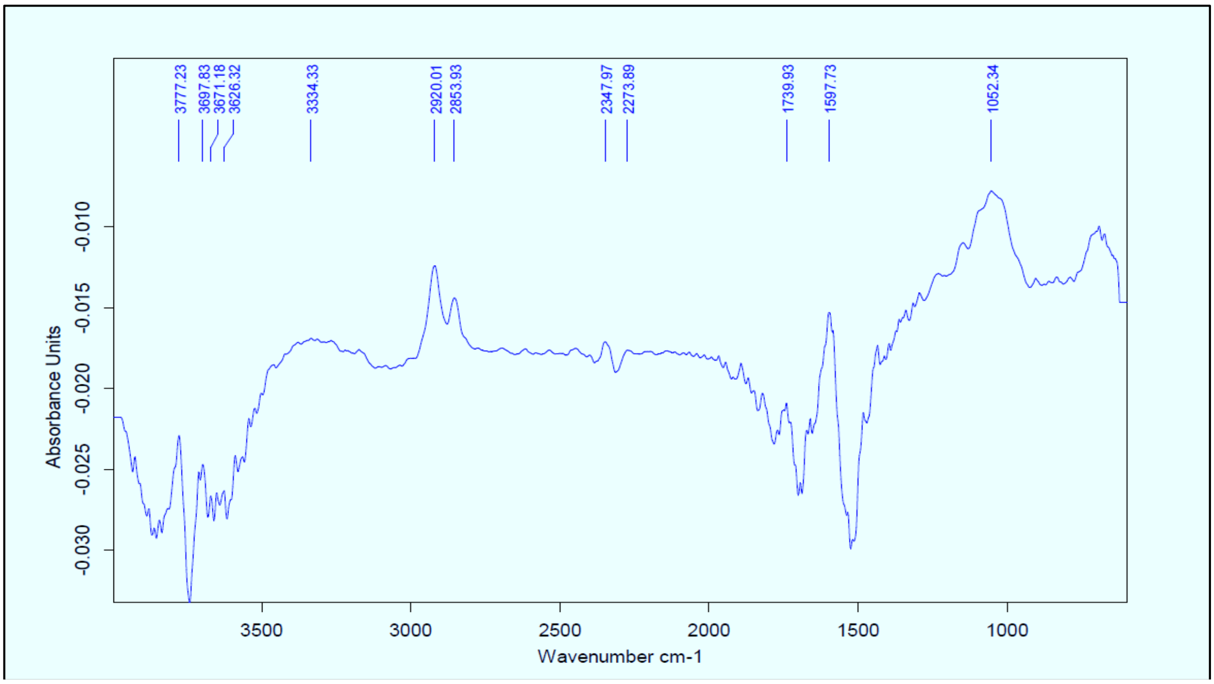

Fig 4: FTIR spectra of sun dried wood apple powder

Conclusion

This study demonstrated the successful solar drying of wood apple (*Limonia acidissima* L.) pulp under the agro-climatic conditions of Bundelkhand, resulting in a stable, energy-rich, and functionally valuable fruit powder. Among the drying models applied, the Page model best described the drying kinetics, with a lower RMSE (0.017) compared to the Newton model (0.030), indicating its suitability for modelling moisture loss behaviour in wood apple pulp under solar drying. The sun-dried product retained desirable physico-chemical properties, including high carbohydrate content (86.45%), appreciable protein and antioxidant levels, and safe moisture content (6.77%) suitable for extended storage. FTIR analysis confirmed the presence of key bioactive compounds such as phenolics, flavonoids, organic acids, and polysaccharides, reinforcing the functional and nutritional potential of the powder.

The sensory evaluation further affirmed consumer acceptability, with high scores for colour, flavour, and overall acceptability. The findings collectively support the use of solar drying as a cost-effective, eco-friendly method for processing underutilized fruits like wood apple into shelf-stable powders. This approach offers new opportunities for value addition, rural entrepreneurship, and the development of nutraceutical and functional food products in arid and semi-arid regions.

References

1. Association of Official Analytical Chemists. Official Methods of Analysis. 17th ed. Washington (DC): Association of Official Analytical Chemists; 2000.
2. Amardeepa, Vijayakumar P. Unveiling quantitative and qualitative traits of solar-dried Indian *Limonia acidissima* powder and its therapeutic findings. Pharmacognosy Research. 2025;17(1):232-243.
3. Baliga MS, Shivashankara AR, Haniadka R. Phytochemistry, nutritional and therapeutic potential of *Limonia acidissima*. Journal of Ethnopharmacology. 2011;135(2):539-554.
4. Bray HG, Thorpe WV. Analysis of phenolic compounds of interest in metabolism. Methods in Biochemical Analysis. 1954;1:27-52.
5. Food and Agriculture Organization of the United Nations. Manual on Post-Harvest Management of Fruits and Vegetables. Rome: Food and Agriculture Organization of the United Nations; 2013.
6. Gopalan C, Sastri BVR, Balasubramanian SC. Nutritive Value of Indian Foods. Hyderabad: National Institute of Nutrition; 2004.
7. Goyary J, Khobragade CB, Chudasama M, Kalse SB. A systematic review on processing and health benefits of wood apple. Food Science and Applied Biotechnology. 2024;7(2):368-379.
8. Indian Council of Agricultural Research-National Bureau of Plant Genetic Resources. Database on Underutilized Fruit Crops. New Delhi: Indian Council of Agricultural Research; 2020.
9. India Meteorological Department. Monthly Weather Summary Reports [Internet]. New Delhi: IMD; 2023 [cited 2025 Jul 30]. Available from: http://www.imd.gov.in/
10. Ranganna S. Handbook of Analysis and Quality Control for Fruit and Vegetable Products. 2nd ed. New Delhi: Tata McGraw-Hill; 2000.
11. Singhania N, Ray A. Effect of drying techniques on physicochemical properties of wood apple (*Limonia acidissima*). Journal of Agricultural Engineering and Food Technology. 2019;6(1):9-12.
12. Sneha, Deb P. Effect of drying methods and pre-drying treatments on physical quality of wood apple pulp powder. Journal of Pharmacognosy and Phytochemistry. 2020;9(2):105-108.
13. Thirumaran AS, Rajarajan R, Kandasamy P. Physicochemical characterization of wood apple pulp and its dried powder. Asian Journal of Dairy and Food Research. 2018;37(2):153-158.
14. Vijayakumar P, Punitha K, Banupriya L. Drying characteristics and quality evaluation of wood apple (*Limonia acidissima* L.) fruit pulp powder. International Journal of Current Trends in Research. 2013;2(1):147-150.
15. Wang L, Weller CL. Recent advances in extraction of nutraceuticals from plants. Trends in Food Science and Technology. 2006;17(6):300-312. doi:10.1016/j.tifs.2005.12.004
16. Yadav A, Garg S, Arunachalam A. Scoping wood apple cultivation for semi-arid Bundelkhand. AgriCos e-Newsletter. 2023;4(2):Article 01.