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Research article

Drying kinetic models, thermodynamics, physicochemical qualities, and bioactive compounds of avocado (*Persea americana* Mill. Hass variety) seeds dried using various drying methods

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A B S T R A C T

Avocados are among the most well-known nutrient-rich fruits worldwide. However, there is a high production of by-product waste, mainly avocado seeds. Avocado seeds can be used in many functional food and non-food applications, due to their nutritional and health-promoting properties. However, preservation technologies such as drying are essential to increase shelf life and preserve bioactive compounds. It has been anticipated that pre-drying techniques could improve the quality of dried products. This study investigates the drying kinetics of avocado seed slices that have been subjected to different pre-treatments (ascorbic acid, blanching, roasting) and drying methods (fluidized bed dryer, hot air dryer, and solar dryer) using freeze-dried samples as a control. In addition, the interaction effect of pretreatment and drying methods on the thermodynamic properties, physicochemical quality, and bioactive compounds of dried avocado seeds were also evaluated. Results indicate that the logarithmic model provides the best fit for the experimental data on drying kinetics. Thermal profile coefficients for avocado seeds activation energy and effective moisture diffusivity were predicted to range from 80.91 to 97.02 $kJmol^{-1}$, and 4.8 to 5.8 $\times 10^{-10}$ m^2s^{-1}, respectively. Moreover, the study showed that the sample treated with roasting and dried using hot air drying (HAD) achieved the maximum desirability value of 0.9256 for thermal profile coefficients. In terms of nutritional and bioactive compound retention, samples treated with ascorbic acid and dried using a fluidized bed dryer (FBD) exhibited maximum values of phenols (106.6 mg GAE/100 g) and vitamin C (77 %), along with a total colour difference recovery of 86 %. In summary, dried avocado seeds are a valuable source of macronutrients and bioactive compounds, highlighting their potential as functional ingredients in the food industry. Furthermore, the implications of this research finding is to produce stable products with better quality from plant by-products using the proper drying methods and promoting a circular economy.

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1. Introduction

Avocados (*Persea americana* Mill) are a popular plant fruit widely cultivated and consumed all over the world. It is a dicotyledonous plant classified as a flowering plant belonging to the genus *Persea* and *Lauraceae* family. The avocado is a tropical and subtropical climacteric fruit indigenous to Central America, specifically Mexico [1,2].

Ethiopia is the top avocado-producing nation in sub-Saharan Africa (SSA), behind South Africa and Kenya, and is ranked 20th globally [3]. Among avocado varieties, the Hass avocado variety has been given priority and is the focus of government and private investors, particularly for agro-processed food owing to its nutritional quality, processing potential, and yields per hectare, which contribute to poverty reduction and economic growth [4]. As a result, this large volume of fruit generates large quantities of by-products, mainly avocado seeds representing approximately 33–45 % of the total fruit weight, which is discarded as waste and environmental burden at the same time [5]. However, no attention has been given to the conservation of avocado seeds throughout the supply chain owing to limited information and research technology.

This residue, however, has a considerable nutritional value and is a rich source of bioactive chemicals [6]. For example, avocado seeds have 15 % higher phenolic content [7] and exhibit more antioxidants (70 %) than the fresh edible parts (pulp) [8], however, their chemical compositions can differ because of the variation in geographical settings, soil chemistry, and agronomic practices [6]. Furthermore, fresh and lyophilized extracts of avocado seeds have been shown to exhibit sizable physiological health and functional properties, including cholesterol-lowering [9], antidiabetic [10] antioxidant, anti-inflammatory [11,12] and anti-microbial activities [13]. These unique qualities are in high demand for valorization such as for commercial use in the production of healthy functional ingredients for food and non-food processing applications, which is critical for minimizing by-product waste. Thus, it is crucial to develop green technologies that enhance conservation efforts and preserve the beneficial compounds found in fruit and vegetable waste, such as avocado seeds.

Drying is the primary preservation method. It is the most practical and efficient method used for industrial processing to preserve foods with high moisture content in agricultural products including fruits and vegetable crops, which improves the safety of products by preventing microbial growth [14]. Consequently, drying reduces postharvest losses, ensures year-round product availability, reduces volume, and facilitates storage and transport. Previous studies have reported that drying avocado seeds using conventional drying methods often yields poor quality dried products and negatively affects their nutritional value [15]. Pre-treatment drying is a vital process that preserves heat-sensitive components, such as vitamins, enhances the dried product's appearance, inactivates enzyme activity, and accelerates the overall drying rate. In this context, pre-treatment drying techniques such as soaking in ascorbic acid and

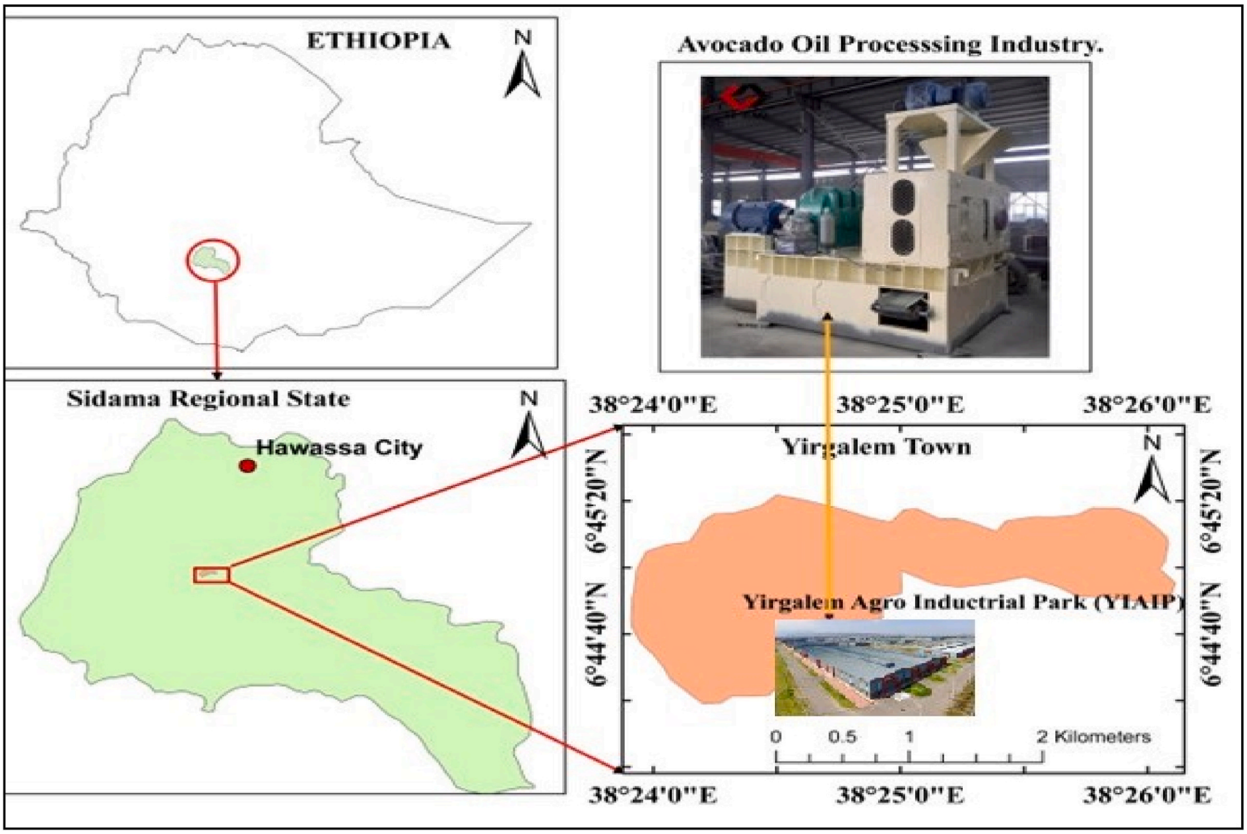

Fig. 1. Map of the study area.

hot water blanching serve as effective alternatives prior to drying methods. These approaches enhance the quality of fresh food properties while also contributing to energy conservation [16,17]. However, the chemical effects of different pretreatment techniques in combination with various drying methods on the functional quality of dried foods are not well documented, particularly for unconventional food materials like avocado seeds.

The mathematical model is one of the main approaches used to understand drying kinetics, which allows the measurement of the time required to reduce the moisture content of food materials [18]. Hence, it is also a useful tool for the design of new dryer equipment to improve process efficiency to predict the performance fitness for the final product quality by reducing the drying time under various settings. Four semi-theoretical thin layer models, the Page model, Logarithmic model, Lewis model, and Henderson and Pabis model, are the most widely used in drying kinetics for agro-based food products. These models are preferred because they do not require any assumptions about the geometry or diffusivity of food materials, resulting in improved accuracy in predicting drying behaviors [19,20]. In addition to the drying kinetics, understanding the thermodynamic properties of agricultural products during the drying process is vital because this information can be used to determine the degree of physical change occurrences and characteristics of the adsorbed water [21]. Nevertheless, to the best of our knowledge, information on the detailed description of the prediction of thermal profiles, thermodynamic behavior, drying kinetics by mathematical modeling, and the functional aspects of dried avocado seeds using different drying methods are not commonly found in published data.

The main purpose of this study was to study the drying features of avocado seed slices subjected to pretreatments (ascorbic acid, blanching, and roasting) and three drying methods: fluidized bed dryer (FBD), hot air dryer (HAD), and solar dryer (SD) the mathematical drying modeling, and determine the physicochemical and functional quality of avocado seeds. Freeze drying was used as a control in this study.

2. Methods and materials

2.1. Description of the study area

In this study, raw avocado seed samples were collected from a local avocado oil company, Sunvado Agro-Processing Plc, which is located near the Yirgalem Integrated Agro-Industrial Park (Yirgalem IAIP), Yirgalem Town, Hawassa. The area is situated far from 40 km in south-central Sidama regional state, Hawassa, and 315 km south of Addis Ababa, the capital city of Ethiopia. Fig. 1. The map of the study area shows that the latitude and longitude of the study area lie between 6 ${}^{\circ}$45 20″ N and 38 ${}^{\circ}$25 E, respectively.

2.2. Preparation of the sample

Fully ripened purplish-black mature avocado (Hass variety) fruit, free from mechanical damage, uniform size, color, and defects were obtained from a local agro-processing company (Sunvado). The ripened fruit Hass variety was manually separated into peel, pulp, and seed. The seed samples were manually washed with distilled water, dried using tissue paper at room temperature, and transported in an ice-box plastic pack to the laboratory. Subsequently, the avocado seed by-products were carefully de-coated and kept at 5 °C until the drying process was carried out. Before processing, six fresh avocado seeds were randomly selected. The initial moisture content of 57.45 ± 0.02 % (wb) and an average weight of 65.14 ± 2.69 g was sliced into thin slices of 3.5 ± 0.01 mm using a laboratory-scale machine slicer (model: robot coupe-CL30, France). The uniformity of the sliced samples was evaluated using a hand digital vernier caliper (Mitutoyo, Japan). Then, the sliced avocado seeds were divided and subjected to three different pretreatment settings. Condition one: ascorbic acid was diluted in distilled water at a dilution ratio of 0.5 % (w/v). The sample was submerged in the prepared solution at room temperature for 60 min. Condition two: Sliced samples were blanched for 3 min at a temperature of 71.5 ± 0.01 °C in boiling water. After blanching, the samples were removed and immediately dipped in cold water at 25 °C for 2 min to prevent overcooking. Condition three: The sliced avocado seeds were roasted at 160°C for 10 min in an oven (model: Comet-F3222AERW, China). On the other hand, samples treated with distilled water serving as control or untreated were labelled with three-digit codes.

2.3. Drying process and equipment

In this study, a fluidized bed dryer, solar dryer, and hot air dryer were employed as drying techniques while a freeze dryer served as control. Briefly, two hundred grams (200 ± 0.5 g) of treated or untreated avocado seed slice samples were weighed using a digital balance (model: WT10001×, China) with a precision sensitivity of ±0.001, in preparation for further drying procedures. Moisture loss was recorded by removing the tray from each experimental dryer at 30-min intervals and weighing it along with the sample on a digital balance [22]. This procedure was continued until a condition of low water activity (aw) of less than 0.7 was reached, which can inhibit microbial growth on the dried product [23]. The experimental drying procedure was performed in triplicates.

Solar dryer (SD): this is based on direct exposure to a sun-drying system. The experiment was conducted by laying the sliced avocado seed samples on a plastic-covered wire mesh consisting of a fan attached to the top of the drying chambers that supplied airflow at the solar collector input for drying. Air conditions including relative humidity (RH %) and temperature (°C) at drying chamber entrances was collected and monitored using a digital hygrometer (Thermo pro, China). The RH had mean values of 70.1 ± 0.01 %, and the average temperature within the drying chamber was 28.7 ± 0.27°C under air conditions.

Hot-air dryer (HAD): *a* ventilated laboratory-scale hot-air dryer (model: Binder-ED53, Germany) was used for a drying system. It contained a drying chamber and exhaust system with an axial flow fan. Once the dryer reached the preset temperature, it was maintained at 65 °C with an air velocity of 1 m/s. The avocado seed slice sample was then weighed, spread evenly in a rectangular aluminum tray, and left to dry. The weight loss of the sample was weighed and recorded by removing the tray from a hot-air dryer at 30-min intervals and weighing it along with the sample on a digital balance until a constant weight was achieved.

Fluidized bed dryer (FBD): avocado seed slice samples were dried using a laboratory-scale fluidized bed drier (model: Sherwood Scientific-14851, Germany) with a digital setting at a temperature of 65 °C and an airflow rate of 4.5 ms^{-1}. Then, the weight loss (g) was measured at a 30-min interval until a constant weight of the dried sample (±0.01 g) was achieved.

Freeze dryer (FD): in this experiment, a tabletop laboratory-scale freeze dryer (model: Biobase, BK-FD10P, China) was used, operating at a cold trap temperature of −61 °C and maintaining a constant vacuum pressure in the drying chamber of 5 kg m^{-1} s^{-2}. It is comprised of a transparent drying chamber that is visual and safe, a condensing unit-condenser trap, and an operational panel made of stainless steel with an attached vacuum pump. The shelves (trays) are stainless steel, which can be adjusted as needed, along with the connected vacuum pump. The prepared slices were put into a freeze-drying chamber after being arranged in a single layer on trays. The tray temperature was managed and controlled with the use of a thermocouple probe. The weight loss of the samples was recorded every 4 h during the drying process, with an accuracy of ±0.01 g.

2.4. Drying characteristics of avocado seed slices

Moisture ratio (MR): MR of the avocado seed slice was determined as described by Ref. [18] using the following Eq. (1).

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

where *MR* represents the dimensionless moisture ratio, 'M_t' is the instantaneous moisture content at any given time, 'M_o' is the initial moisture content (% w.b, wet basis), and 'M_e' is the equilibrium moisture content (EMC). Since *equilibrium moisture content (M_e)* is very small compared to *instantaneous moisture content* (M_t) and *initial moisture content* (M_o) for all drying methods, then, the moisture ratio (*MR*) was also simplified as (M_t/M_o).

2.5. Effective moisture diffusivity, activation energy, and thermodynamic properties

2.5.1. Effective moisture diffusivity coefficient (D_{eff})

Fick's second rule of diffusion was designated to estimate effective moisture diffusivity [24], which can be used to determine the moisture movement within the sample drying characteristics to define the falling rate period using Eq.(2). In this study, the effective diffusivity was determined as described by Ref. [25] in most food products assumed as one-dimensional and has a uniform initial moisture content, negligible external resistance to heat and mass transfer, and constant moisture diffusivity. The solution of Fick's is stated formula below:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(-(2n+1)\pi^2 \frac{D_{eff}t}{4L^2}\right) \tag{2}$$

Briefly, the exponential function shows a significant decrease as 'n' increases. Therefore, it is sufficient to determine the effective diffusivity (D_{eff}) value of the avocado seed sample using the first term of the series in Eq.(2). This can be achieved by plotting the natural logarithm of the experimental drying data, specifically the moisture ratio (MR) against drying time (t), as described by the following formula [26]:

$$\ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L_o^2} t\right)$$

$$D_{eff} = \left(\frac{4L_O^2}{\pi^2}\right) slope$$

$$slope = \frac{(lnMR_2 - \ln MR_1)}{(t_2 - t_1)}$$

where 'D_{eff}' represents effective moisture diffusivity, 'L' denotes the thickness (cm) of the sample initial size before drying, and 't' stands for drying time in (min).

2.5.2. Activation energy (E_a)

E_a of the avocado seeds was determined from D_{eff} using the Arrhenius equation, as described by Ref. [27]. The activation energy (E_a) was calculated as described by Ref. [28] plotting ln D_{eff} against 1/T with slope K, which is expressed formula as Eq. (3).

$$\text{Slope K} = E_a/R$$

$$D_{eff} = D_o exp\left(\frac{-E_a}{RT}\right) \tag{3}$$

where: 'T' is the absolute temperature (T + 273.15) in Kelvin (K), D_0 is the pre-exponential factor (m^2s^{-1}), 'E_a' is denoted by the activation energy ($kJmol^{-1}$) and 'R' represents the ideal gas constant (8.3143 $kJmol^{-1}$). The relationship between E_a and diffusivity coefficients was determined using linear regression analysis.

2.5.3. Thermodynamics characteristics

The thermodynamic parameters of the drying process, such as the specific enthalpy, entropy, and Gibbs free energy were determined [29] using Eqs. (4, 5, 6), respectively.

$$\Delta H = E_a - RT \tag{4}$$

$$\Delta S = R\left(ln\, D_{o-}\; ln\frac{k_b}{h_p} - lnT\right) \tag{5}$$

$$\Delta G = \Delta H - T\Delta S \tag{6}$$

where: 'ΔH' is denoted by the change in enthalpy (J mol−1), A change in entropy is used to indicate 'ΔS' (J mol−1 K−1), the change in Gibbs free energy (J/mol) is used to represent 'ΔG', Boltzmann constant (1.38 % $\times 10^{-23}$ J K−1) is represented by the symbol 'kb', the Planck constant (6.626 $\times 10^{-34}$ J s) is symbolized as 'h_P,' and the temperature is denoted by 'T' (K).

2.6. Mathematical modeling for fitting drying curves

The thin-layer mathematical drying models commonly used for agro-food crops, as described by Ref. [30], are presented in Table 1. These mathematical models were fitted to the drying kinetics data of avocado seeds to effectively model their drying behaviour.

2.7. Physicochemical properties of dried avocado seeds

2.7.1. Water activity (a_w)

One important criterion in determining the safety and quality of food products is achieving low water activity, which is dimensionless. The water activity was measured as described by Ref. [34]. The dried avocado seed sample (2 g) was placed directly into a water activity meter (model: AquaLab-Pre000776, China) at a temperature of 27.7 °C, until the instrument finished the measurement. The data were recorded in triplicate.

2.7.2. Total acidity level

The pH of the extract samples was determined according to the Association of Official Analytical Chemists International, Official method 981.12 [35]. The pH meter was calibrated using buffer solutions of pH 4.0, 7.0, and 9.2. The pH was measured in a 3 % aqueous solution prepared from avocado seed sample extracts by dipping the glass electrode into the sample solutions using a digital pH meter (model: EI-7011, Taiwan) at a temperature of 21.7 ± 0.01 °C. Readings were taken in triplicate. The titratable acidity (TA) of the samples was determined as described by AOAC(1995) [35] Official method 942.15 by titrating the aliquot against standard 0.1 N NaOH solution using phenolphthalein (3–5 drops) as an indicator until the first appearance endpoint reached pink (persisting for 15 s) at room temperature. The results were expressed as a percentage of (g of malic acid per 100 g sample) with 1 mL of NaOH (0.1N), which is equivalent to 0.0067 g of malic acid of milliequivalent weight.

2.7.3. Color measurements

The color parameters of fresh and dried avocado seed samples (L_o, a_o, and b_o) and (L*, a*, and b*) were measured as described by Ref. [36] using an instrumental hand-held chroma meter (model: CM-A177, Konica Minolta, Japan). The scale of lightness to darkness (0–100) is indicated by L*, the scale of positive (redness) and negative (greenness) is indicated by a* (± ve a*), and b* indicates yellowness (positive) and negative (blueness), expressed as (± ve b*). The magnitude of the total color difference (**Δ**E) was documented by placing the samples on the port of the color measuring system and calculated by using Eqn. (7).

Table 1
Mathematical models fitted to the drying avocado seed drying kinetics data.

Model name	Model equation	References
Lewis	$MR = \exp(-k.t)$	[31]
Page	$MR = \exp(-k.t^n)$	[30]
Henderson and Pabis	$MR = a \bullet \exp(-k.t)$	[32]
Logarithmic	$MR = a \bullet exp(-k.t) + c$	[33]

$$\Delta E = \sqrt{\left[(L - L_o)^2 + (a - a_o)^2 + (b - b_o)^2\right]} \tag{7}$$

2.7.4. Measurement of vitamin C content

The vitamin C (ascorbic acid) concentration was determined using the standard protocol AOAC method [35]. The sample and standard L-ascorbic acid were prepared using a 3 % meta-phosphoric acid solution and thereafter titrated against 2, 6-dichloropheno-l-indophenol dye-DIP until a light pink color lasted for at least 15 s. The following formula was used to determine the vitamin C content Eqn.(8).

$$Vitamin\ C\left(\frac{mg}{100g}\right) = \frac{Titre\ value\ x^{*}dye\ factor\ x\ volume\ madeup\ x\ 100}{Weight\ of\ sample\ x\ volume\ of\ aliquot\ taken} \tag{8}$$

$$^{*}Dye\ factor = {}^{0.5}/_{titre\ value\ of\ standard}$$

2.8. Proximate analysis and mineral profiling

The proximate compositions: moisture, crude protein, crude fat, total ash, and crude fiber contents of dried avocado seeds were examined using the Association of Official Analytical Chemists (AOAC 2000) standard method. Moisture content was determined by a gravimetric method using an oven dryer (method 925. 09), fat content was determined by the Soxhlet extraction (method 920.39), and total ash content was determined after carbonization, and ignition in a muffle furnace (Method 942.05), fiber content was determined by assisted-neutralization (Method 962.09). The samples were diluted in 100 mL of 1.25 % H_2SO_4 solution and digested for 30 min, followed by washing with distilled water. Subsequently, 100 mL of 1.25 % NaOH solution was added for alkali hydrolysis, and digested for an additional 30 min. Then, the sample was dried in an oven dryer and ashed in a muffle furnace. The crude fiber content was determined based on the loss of mass during ignition. The crude protein content was determined by micro Kjeldahl (method 979.09) method of nitrogen content analysis from which % protein content was evaluated as % N*6.25. Total carbohydrate content was calculated using the "difference method" [37]. Total energy was determined by calculation from fat, carbohydrate and protein contents using Atwater's conversion factors: 4 kcal/g for protein, 9 kcal/g and 4 kcal/g for carbohydrates and calories, respectively [38]. Gross energy (GE) (kcal/100 g, db) = 4 × protein % + 4 × carbohydrate% + 9 × fat %.

The elemental analysis (calcium, phosphorus, magnesium, iron, zinc, aluminum, copper, lead, and Nickle) contents were determined according to the [35] (AOAC, 1995) method 985.35 using flame atomic absorption spectrophotometer (model: 240FSAA, Malaysia) with air-acetylene flame as a source of energy for atomization while the phosphorus contents of the ground sample was determined by Ref. [39] using the UV-spectrophotometer method.

2.9. Determination of anti-nutritional factors

The quantitative determination of condensed tannin, phytate, oxalate, and total alkaloid contents in were determined using standard protocol. The condensed tannin contents were analyzed by a modified vanillin-HCl methanol protocol [40] using a spectrophotometer. The phytate content of the samples was determined by colorimetric method using a UV-spectrophotometer and the absorbance was measured at 500 nm as described by Ref. [41]. Total alkaloid content was determined by gravimetric method after precipitation from the solution [42]. According to the protocol AOAC (2000) standard method no. 974.24, the oxalate content was determined by titration.

2.10. Determination of bioactive compounds

2.10.1. Preparation of sample extract

The extract from avocado seeds was used to determine the total phenolic content (TPC) and total flavonoid content (TFC) using a solid-liquid extraction procedure, as described by Ref. [43] with slight modifications. Briefly, 5 g of avocado seed flour (d.b) was carefully weighed and mixed in 50 mL of solvent mixtures of the solutions (absolute methanol 99.9 % grade: acetone) with a non-polar solvent (n-hexane) at a ratio of (75:15:10, v/v). The suspensions were homogenized in a homogenizer at 5000 rpm for 30s and left in an incubator shaker (model: ZHWY-103B, Shanghai, China) for 24 h at 150 rpm at a temperature of 35 °C, which was used to improve the extraction efficiency of the samples. The mixtures were centrifuged (10000×g, 10 min) and carefully filtered through filter paper (Whatman No.42,110 mm). The leftover residue was combined once again, cleaned with 5 mL of solutions, and then placed in a shaker at 35 °C for 120 min. This process was repeated three times. The supernatant was collected in a pre-weight petri-plate and then concentrated using a rotary evaporator (model: Stuart-RE300DB, UK) at 60 °C to obtain semisolid extracts, which were re-dissolved in absolute methanol. The semi-crude extract obtained was stored in a micro-centrifuge tube and placed in a refrigerator at −20 $^{\circ C}$ until being used for further experiments. The analysis was performed in triplicate.

2.10.2. Preparation of standard solutions

In a 25 mL volumetric flask, 0.025 g of gallic acid and 0.0125 g of quercetin were dissolved in 99.9 % methanol was used to serve as standards for the determination of total phenol and flavonoids content, respectively. Solutions were prepared using distilled water as follows: 7.5 % sodium carbonate (Na_2CO_3, w/v), 5 % sodium nitrite ($NaNO_2$, 5 g/100 mL, w/v), 10 % aluminum chloride (ACl_3, 10 g, w/v), and 1M sodium hydroxide (NaOH, 4 g/100 mL, w/v).

2.10.3. Determination of total phenolic content

The total phenolic content of the sample extract was determined spectrophotometrically using a modified Folin-Ciocalteu method [44], with gallic acid serving as the standard. The reaction mixture was prepared by combining 100 μL of the extract (2 mg pellet dissolved in 2 mL methanol), 900 μL of methanol, and 1 mL of Folin-Ciocalteu reagent in a 10 mL test tube. The mixture was then thoroughly vortexed for 60 s at room temperature. After being stored in the dark for 10 min, 1.5 mL (mL) of 7.5 % Na_2CO_3 was added, followed by the addition of 7 mL of distilled water. The mixture was then allowed to stand in a dark area at room temperature for 60 min. Absorbance was measured at a wavelength of 765 nm using UV spectrophotometer (model: PerkinElmer Lambda 950) against the prepared reagent blank using methanol. The standard curve was prepared using gallic acid (0.025 g/25 mL, dissolved in a 99.9 % of methanol) concentrations of (20–120 μg/mL). The total phenolic content was evaluated from gallic acid standard regression line ($y = 0.0141x + 0.0095$ and $R^2 = 0.9959$). The results were expressed as milligrams of gallic acid equivalent per 100 g of sample extract (mg GAE/100 g of sample extract).

2.10.4. Determination of total flavonoid content

The total flavonoid content (TFC) of the samples was determined using an aluminum chloride assay [45]. Briefly, an aliquot (0.5 mL) of the extract was thoroughly mixed with 4.5 mL of methanol in a 10-mL (mL) test tube. At each step, the mixture was vortexed, and 0.3 mL of 5 % $NaNO_2$ was added to a 10 mL test tube.After 5 min, add 0.3 mL of 10 % $AlCl_3$, and then, after 6 min, 2 mL of 1 % M NaOH was added to the mixture, and gently mixed. The mixed solution was incubated in the dark at room temperature. The absorbance of the developed yellowish-orange color was measured at a wavelength of 415 nm with a quercetin reference using a UV spectrophotometer. The concentrations for the standard quercetin (0.0125 g of quercetin, dissolve 99.9 % of methanol in 25 mL flask) and calibration curve range (0.00, 25, 50, 75, 100, and 125 μg/mL) were used for calibration line (($y = 0.0096x + 0.1002$, where $R^2 = 0.9981$). The concentration of TFC was expressed as mg of quercetin equivalent per gram (mg of QE/g of sample extract). Calculations were made using a standard curve.

2.11. Statistical analysis

In this study, a completely randomized factorial design was employed for physiochemical analysis. The experimental analysis of the parameters was performed in triplicates. The data were analyzed by analysis of variance (ANOVA) by using statistical software package SAS-JMP Pro (version 17.0.2, Statistical Analysis of Software Institute Inc., Cary, North Carolina, USA). The mean differences among samples were evaluated using Tukey's test at a 5 % ($p < 0.05$) level of significance. Results were expressed as the mean ± standard deviation (SD). The goodness of fit for the drying kinetics samples was assessed based on the models with the lowest root mean square error (RMSE), the lowest reduced chi-square ($\chi 2$), and the highest correlation coefficient (R^2) values, in order to accurately represent the thin-layer drying characteristics of avocado seed slices [46]. Statistical parameters, including the determination of R^2, RMSE, and $\chi 2$, were calculated as follows.

$$RMSE = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)\right]}$$

$$x^2 = \sum_{i=1}^{N}\frac{\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \quad and$$

$$R^2 = 1 - \left(\frac{\sum MR_{pre} - \sum MR_{exp}}{\sum MR_{pre,av} - \sum MR_{exp}}\right)^2$$

In the context of this study, 'MR_{pre}' indicates the predicted dimensionless moisture ratio, 'MR_{exp}' is the experimental dimensionless moisture ratio, and '$MR_{pre, av}$' stands for the average moisture ratio. During the drying process, the observed data and constants of the thin-layer models are denoted by the letters, 'N' and 'n,' respectively.

3. Result and discussions

3.1. Drying kinetics

The experimental moisture ratio versus drying time depicts the experimental drying data obtained from various drying methods (hot air dryer, freeze dryer, fluidized bed dryer, and solar dryer). This data was collected for avocado seed slice samples subjected to different pretreatments (ascorbic acid treatment, blanching, and roasting), using a mathematical logarithmic model. Fig. 2. Represents experimental moisture ratio versus drying time using hot air dryer (HAD), Fig. 3. Experimental moisture ratio versus drying time using freeze-dryer (FD). Fig. 4. Experimental moisture ratio versus drying time using fluidized bed dryer (FBD). Fig. 5. Experimental moisture ratio versus drying-time using solar dryer (SD). The findings indicate that in every setup, there was a significant decrease in the exponential moisture ratio curve as drying time increased. This phenomenon has been documented in the drying of various agricultural food materials [20,47]. Furthermore, the treated samples exhibited a drying rate that was 70 % higher throughout the drying process compared to the untreated/control samples.

Perhaps increasing the average kinetic energy of moisture migration from the product sample into the environment by applying pretreatments, makes the process easier and results in a higher rate of evaporation [48]. Comparable results have been observed when drying potato slices with ethanol [46] peeled bananas pretreated with blanching, chilling, or combinations [49] and grapes with ethyl oleate and potassium carbonate solutions [50]. Mostly, pretreatment samples often showed a higher drying rate in comparison to control samples, which helps to facilitate moisture loss transit rate from the center to its surface [51]. The present result showed the drying time of the samples varied among the dryer methods used. In this case, the fluidized bed dryer had 83 % faster drying time than the solar dryer. This may be because solar dryers are dependent on unpredictable climatic conditions, including relative humidity, temperature, and solar radiation, which slow down the diffusion of moisture from the food matrix into the surrounding environment. On the other hand, the maximum drying time of the fluidized bed dryer was 92.1 % times higher than that of the freeze-dryer drying for the avocado seed slice. This indicates that the fluidized bed dryer achieved a significant improvement in the quality of the final dried product in less time. This result is consistent with past findings on the drying of date fruits [51], which indicated that date samples dried significantly faster using a microwave dryer, achieving a 95.3 % reduction in drying time compared to freeze-drying. Another report revealed that comparable results were obtained in an experiment using microwave drying on banana slices, which reduced the drying time by 90 % when compared to hot air drying [52].

3.2. Analysis of the drying curve-fitting models

Experimental MR data was obtained and performed with the four mathematical models, which were used to describe the drying kinetics behavior of the avocado seed slice samples. The parameters of models and statistical values are presented in Table 2. Parametric models and statistical values for the drying of avocado seed slices. The most suitable models that fit the experimental data of the drying curve were evaluated by comparing statistical metrics, validated by the highest R^2 (approaches 1.00), lowest chi-square ($\chi 2$), and root mean square error (RMSE) values (approaches 0.00) of the statistical parameters as described by Refs. [24,53]. According to the statistical analysis of the data, the R^2 -values for the Newton, Henderson and Pabis, Page, and Logarithmic models ranged from 0.9495 to 0.9984, 0.9476 to 0.9998, 0.9569 to 0.9986, and 0.9949 to 0.9999, respectively for different pre-treatment samples. The RMSE-values were 0.0123–0.095, 0.008 to 0.0901, 0.0018 to 0.0192, and 0.0116 to 0.0551, while the $\chi 2$-values were 0.0001–0.0074, 0.0001 to 0.0084), 0.0003 to 0.0049, and 0.0008 to 0.0086, respectively. In all cases, the models exhibited a strong correlation with the drying experimental data. According to the high-quality literature and our findings, the drying kinetics model for the experimental data of avocado seed slices was shown to have the best fit with the Logarithmic model when compared to the other models. This finding is in agreement with the previously reported on a range of drying processes, such as the use of freeze dryers for persimmon puree drying [54], laboratory scale convective dryers for bell pepper drying [55], hot air dryers for banana slice drying [56], apple pomace drying [24], and solar dryers for apricot drying [33]. In this research study, the empirical drying models including the Newton/Lewis model, Page model, Henderson and Pabis, and Logarithmic model were relevant due to their practical and effective way of predicting drying behaviour, saving time and energy, and improving product quality. On the other hand, parametric models play a key role in describing moisture movement from food materials in a specific drying environment which gives better results for predictions of moisture loss [57].

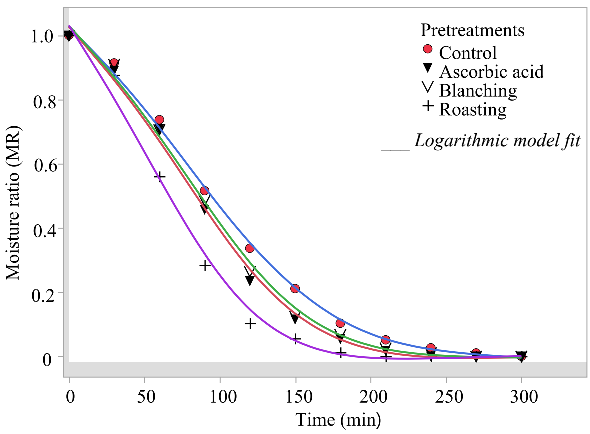

Fig. 2. Experimental moisture ratio versus drying-time using hot-air dryer.

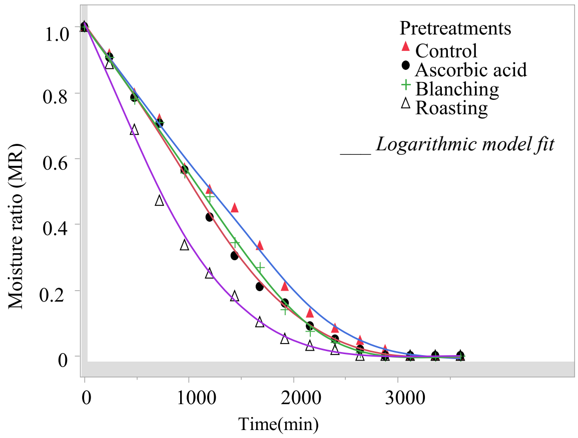

Fig. 3. Experimental moisture ratio versus drying-time using a freeze-dryer freeze dryer.

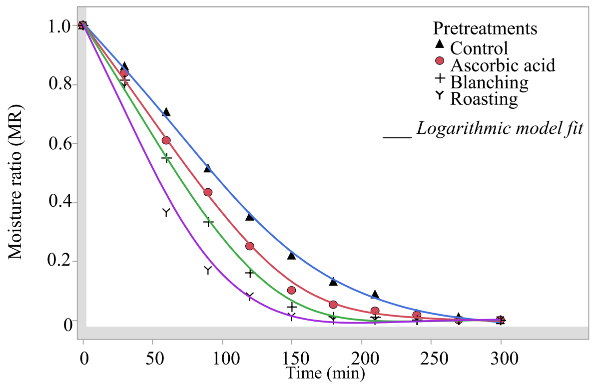

Fig. 4. Experimental moisture ratio versus drying-time using fluidized bed dryer.

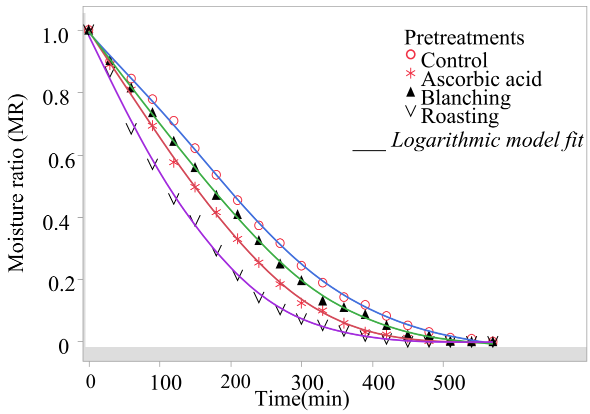

Fig. 5. Experimental moisture ratio versus drying-time using a solar dryer.

3.3. Effective moisture diffusivity, activation energy, and thermodynamic properties and desirability profiles

3.3.1. Moisture diffusivity (D_{eff})

Understanding the thermal properties of food components is critical for processing and prolonging shelf-life since it depends on the moisture content and chemical compositions of the food. D_{eff} values were significantly ($p < 0.05$) different for samples of

Table 2
Mathematical drying models, parameter definitions, and statistical values for avocado seed.

Models	Drying methods	Pretreatment	Parameters of models				Statistical values		
			k	a	n	c	R^2	RMSE	$\chi 2$
Newton/Lewis	FBD	Control	0.074	–	–	–	0.9952	0.0118	0.0012
		Soaking[a]	0.0108	–	–	–	0.9967	0.0138	0.0011
		Blanching	0.0135	–	–	–	0.9983	0.0111	0.0007
		Roasting	0.0225	–	–	–	0.9972	0.0141	0.0011
	HAD	Control	0.078	–	–	–	0.9971	0.095	0.0001
		Soaking[a]	0.0099	–	–	–	0.9963	0.0123	0.0011
		Blanching	0.0092	–	–	–	0.9958	0.0127	0.0009
		Roasting	0.0204	–	–	–	0.9954	0.0172	0.0045
	SD	Control	0.0096	–	–	–	0.9495	0.0315	0.0009
		Soaking[a]	0 0.009	–	–	–	0.9455	0.0206	0.0009
		Blanching	0.0084	–	–	–	0.9541	0.0263	0.0069
		Roasting	0.0059	–	–	–	0.9708	0.0136	0.0074
	FD	Control	0.0002	–	–	–	0.9945	0.0097	0.0006
		Soaking[a]	0.0021	–	–	–	0.9984	0.0099	0.0006
		Blanching	0.0003	–	–	–	0.9977	0.0076	0.0003
		Roasting	0.0004	–	–	–	0.9929	0.0152	0.0012
Henderson and Pabis:	FBD	Control	0.0079	0.71	–	–	0.9973	0.0118	0.0011
		Soaking[a]	0.0076	0. 68	–	–	0.9998	0.0144	0.0012
		Blanching	0.0003	0.95	–	–	0.9958	0.0132	0.0012
		Roasting	0.0072	0.61	–	–	0.9784	0.0251	0.0031
	HAD	Control	0.0074	0.73	–	–	0.9985	0.0901	0.0016
		Soaking[a]	0.0115	0.69	–	–	0.9996	0.0141	0.0001
		Blanching	0.0066	0.68	–	–	0.9933	0.0160	0.0021
		Roasting	0.009	0.62	–	–	0.9933	0.0190	0.0021
	SD	Control	0.0096	1.05	–	–	0.9476	0.0289	0.0084
		Soaking[a]	0.0091	1.03	–	–	0.9656	0.0151	0.0051
		Blanching	0.0084	0.99	–	–	0.9543	0.0256	0.0049
		Roasting	0.0094	1.01	–	–	0.9609	0.0181	0.0013
	FD	Control	0.0002	0.97	–	–	0.9878	0.0101	0.0006
		Soaking[a]	0.0002	0.96	–	–	0.9931	0.0114	0.0006
		Blanching	0.0003	0.94	–	–	0.9965	0.0081	0.0004
		Roasting	0.0002	0.96	–	–	0.9904	0.0168	0.0014
Page	FBD	Control	0.0331	–	0.82	–	0.9903	0.0148	0.0021
		Soaking[a]	0.024	–	0.84	–	0.9949	0.0154	0.0014
		Blanching	0.0211	–	0.85	–	0.9977	0.0135	0.0009
		Roasting	0.018	–	0.93	–	0.9981	0.0119	0.0009
	HAD	Control	0.007	–	0.83	–	0.9925	0.0125	0.0016
		Soaking[a]	0.0125	–	0.82	–	0.9986	0.0192	0.0006
		Blanching	0.0196	–	0.83	–	0.9909	0.0146	0.0013
		Roasting	0.0266	–	0.92	–	0.9933	0.0166	0.0014
	SD	Control	0.0023	–	0.73	–	0.9739	0.0103	0.0022
		Soaking[a]	0.0025	–	0.76	–	0.9716	0.0135	0.0011
		Blanching	0.0022	–	0.7	–	0.9696	0.0154	0.0049
		Roasting	0.0022	–	0.68	–	0.9569	0.0105	0.0019
	FD	Control	0.0051	–	0.93	–	0.9955	0.0098	0.0005
		Soaking[a]	0.005	–	0.92	–	0.9979	0.0071	0.0003
		Blanching	0.0045	–	0.91	–	0.9959	0.0098	0.0005
		Roasting	0.0046	–	0.92	–	0.9993	0.0018	0.0004
Logarithmic	FBD	Control	0.0094	1.02	–	3.66	0.9995	0.0321	0.0082
		Soaking[a]	0.0054	0.98	–	3.13	0.9999	0.0291	0.0012
		Blanching	0.0046	0.97	–	2.91	0.9998	0.0463	0.0013
		Roasting	0.0021	0.92	–	2.36	0.9993	0.0542	0.0018
	HAD	Control	0.012	1.02	–	3.41	0.9994	0.0291	0.0086
		Soaking[a]	0.0068	0.99	–	3.29	0.9999	0.0263	0.0009
		Blanching	0.005	0.99	–	3.11	0.9949	0.0444	0.0012
		Roasting	0.004	0.93	–	2.48	0.9998	0.0551	0.0015
	SD	Control	0.009	1.04	–	−10.88	0.9958	0.0288	0.0017
		Soaking[a]	0.001	1.05	–	−11.18	0.9968	0.0319	0.0010
		Blanching	0.008	0.99	–	−9.87	0.9959	0.0266	0.007
		Roasting	0.006	0.98	–	−8.46	0.9798	0.0427	0.0015
	FD	Control	0.0043	1.24	–	8.36	0.9999	0.0116	0.0008
		Soaking[a]	0.0041	1.23	–	8.06	0.9999	0.0137	0.0009
		Blanching	0.004	1.21	–	7.51	0.9998	0.0123	0.0008
		Roasting	0.0042	1.22	–	8.02	0.9999	0.0182	0.0016

Where: FBD-fluidized bed dryer, HAD-hot air dryer, SD -solar dryer, and FD-freeze dryers, respectively. MR-moisture ratio, and.
[a] ascorbic acid (0.5 %, w/v) was used as pretreatments.

Table 3
Thermal properties of dried avocado seed using various pretreatments and drying methods.

Drying methods	D_{eff} (x 10^{-10}m^{2}s^{-1} ± x 10^{-11})	E_a (kJmol^{-1})	Thermodynamics quality		
			ΔH (kJmol^{-1})	ΔS (kJmol^{-1} K^{-1})	ΔG (kJK^{-1})
FBD	4.78 ± 1.18^a	78.58 ± 1.19^a	−21.91 ± 0.02^a	−2.31 ± 0.01^a	6.3 ± 0.01^c
HAD	4.36 ± 1.02^a	72.92 ± 1.02^a	−21.96 ± 0.01^a	−2.32 ± 0.01^a	7.07 ± 0.01^a
SD	3.74 ± 1.07^b	62.53 ± 2.01^b	−22.07 ± 0.01^b	−2.34 ± 0.03^b	7.03 ± 0.01^b
FD	2.51 ± 3.03^c	41.82 ± 0.02^c	−22.28 ± 0.03^c	−2.37 ± 0.01^c	6.24 ± 0.01^d
Pretreatments					
Ascorbic acid	4.55 ± 4.04^a	76.13 ± 0.01^a	−21.88 ± 0.02^a	−2.31 ± 0.01^a	6.68 ± 0.01^a
Blanching	3.99 ± 3.03^b	66.74 ± 0.01^b	−22.03 ± 0.02^b	−2.33 ± 0.01^b	6.67 ± 0.01^a
Roasting	4.86 ± 1.01^a	81.27 ± 0.04^a	−21.94 ± 0.02^a	−2.32 ± 0.01^a	6.69 ± 0.01^a
Control	1.89 ± 2.04^c	31.71 ± 0.04^c	−22.38 ± 0.04^c	−2.39 ± 0.01^c	6.59 ± 0.01^b

Arithmetic mean ($\bar{x}$) ± standard deviation (SD) with the three replications (n = 5), Tukey's posthoc test ($p < 0.05$) means in the same column that is followed by different superscript letters are statistically different and: FBD stands for fluidized bed dryer, HAD-hot air dryer, SD-solar dryer, and FD-signifies freeze dryer.

pretreatments with drying methods when compared to the control samples. The thermal properties of dried avocado seed using various drying methods are shown in (Table 3). This result demonstrates the impact of the drying methods on the moisture diffusivity of the avocado seed slice sample. Statistically, there was a significant difference ($p < 0.05$) among the drying methods in D_{eff} value. The samples were dried using different drying procedures in the following order of effectiveness: fluidized bed drying (FBD) > hot air drying (HAD) > solar drying (SD) > freeze drying (FD). The maximum D_{eff} value recorded was for the fluidized bed dryer at 4.78 × 10^{-10} m^{2}s^{-1} (FBD) while the lowest D_{eff} value recorded was 2.51 × 10^{-10} m^{2}s^{-1} for the freeze dryer (FD). The potential cause of this variance could be attributed to the way food materials are dried in dryers and the operational circumstances. The pretreated sample with the highest D_{eff} values (4.86 × 10^{-10} m^{2}s^{-1}) was noticed by the roasted samples, followed by ascorbic acid (4.55 × 10^{-10} m^{2}s^{-1}). For samples that were not treated, the lowest D_{eff} values (1.89 × 10^{-10}m^{2}s^{-1}) was observed. According to this result, roasting appears to have a more robust influence on the disintegration of the cell membrane and free drive of water in the cell than the other pretreatment methods used in this study. These marks were in the range from 10^{-12} m^{2}s^{-1} to 10^{-6} m^{2}s^{-1} which was specified for agricultural products such as fruits and vegetables [19,58]. This finding is consistent with various research reports, on the impact of pretreatments on moisture diffusivity during air dryings such as banana slices [49], blackberries [59], apple slices [60], and carrot pomace [61] revealed that the use of pretreatment technologies prior to drying was very important for enhancing the product quality and appearance.

3.3.2. *Activation energy (E_a)*

Activation energy is the minimum energy required to initiate the drying process which can be used to evaluate the performance of dryers, design new dryer equipment, and monitor the final dried quality product. The effect of various drying methods and pretreatments on the activation energy (Ea) values of avocado seeds is presented in Table 3. The maximum E_a value was 78.58 kJmol^{-1} for FBD whereas a minimum value of 41.83 kJmol^{-1}for FD was observed.

Conversely, significant differences in E_a values were observed between the control (untreated) and the pretreated samples ($p < 0.05$). This may be due to changes in the product's texture and the formation of microscopic pore surface structures that facilitate moisture loss. This suggests that the E_a value decreased at a higher rate compared to the control sample. The activation energy (E_a) values for the pretreated samples were as follows: roasting at 81.27 kJmol^{-1}, ascorbic acid at 76.13 kJmol^{-1}, blanching at 66.74 kJmol^{-1}, and the control sample at 31.71 kJmol^{-1} These values are consistent with those typically observed in food products. According to Ref. [62], 12 to 110 kJmol^{-1} were the best E_a value ranges for agricultural food products.

3.3.3. *Thermodynamics properties of avocado seed*

The chemical content of food products is substantially impacted by drying behavior. Therefore, it is critical to understand thermodynamic properties, such as specific enthalpy, specific entropy, and Gibbs free energy, which help to enhance the efficiency of the drying process, select the precise operating conditions, improve the quality control of the finished product, and optimize the process design for food material. Table 3 presents the thermodynamic properties including the E_a and D_{eff} of the avocado seed sample. The result shows that there were notable differences in thermodynamic parameters between the various drying methods. The value of Gibbs free energy (ΔG) was positive in all drying techniques and pretreatment procedures. This describes that an endergonic reaction occurred, requiring more energy in the medium containing the product for drying to occur under specific conditions. However, the negative values for entropy (ΔS) and specific enthalpy (ΔH) suggested that the adsorbent underwent structural changes and experienced chemical adsorption [29,63]. In this regard, it suggests that dried avocado seed should be further investigated for potential applications as an adsorbent material in the processing industry.

3.3.4. *Prediction of optimal thermal profiles*

Thermal profile prediction is crucial in the drying of food materials, as it provides valuable insights into the drying process, enhances the quality of the final product, and optimizes drying conditions in the food industry. On the other hand, desirability determines when the response variable attains optimum conditions and is subsequently confirmed for the design and quality result. The typical desirability scale ranges from 0 to 1, allowing for either a 1-best fit with approaching value or a 0-undesirable or less fit in the experimental data. In this instance, predicting desirable profiles of the thermal coefficient for the avocado seed waste based on thermal characteristics is essential to designing dryers and enhancing the final quality of the dried product.

In this study, the prediction of desirability profiles of thermal coefficient for avocado seed using different drying techniques is presented in Fig. 6. The results clearly show that samples treated with roasting and dried under a hot air dryer (HAD) achieved the highest desirability score of 0.9256 that indicate efficient responses drying conditions. This was followed by samples treated with ascorbic acid and dried in a fluidized bed dryer, which had a desirability score of 0.8975. The thermal profile coefficients for the activation energy and effective moisture diffusivity of avocado seeds were predicted to range from 80.91 to 97.02 $kJmol^{-1}$ (with optimum value 88.96 $kJmol^{-1}$), and $4.8 \times 10^{-10} m^2 s^{-1}$ to $5.8 \times 10^{-10} m^2 s^{-1}$ (optimum value $5.32 \times 10^{-10} m^2 s^{-1}$), respectively. The optimal values of thermodynamics profile prediction for enthalpy, entropy, and gibs free energy of the avocado seed sample were -21.81 $kJmol^{-1}$, -2.31 $kJmol^{-1}$ K^{-1}, and 7.18 kJK^{-1}, respectively.

3.4. Physicochemical quality

Understanding the physicochemical quality of dried agro-food products plays a fundamental role in determining the final quality of the product as well as product design and quality control during processing. Thus, one of the most important metrics for evaluating food safety, shelf-life, sensory qualities, oxidation, and browning is the measurement of the water activity (a_w) and pH of dried food

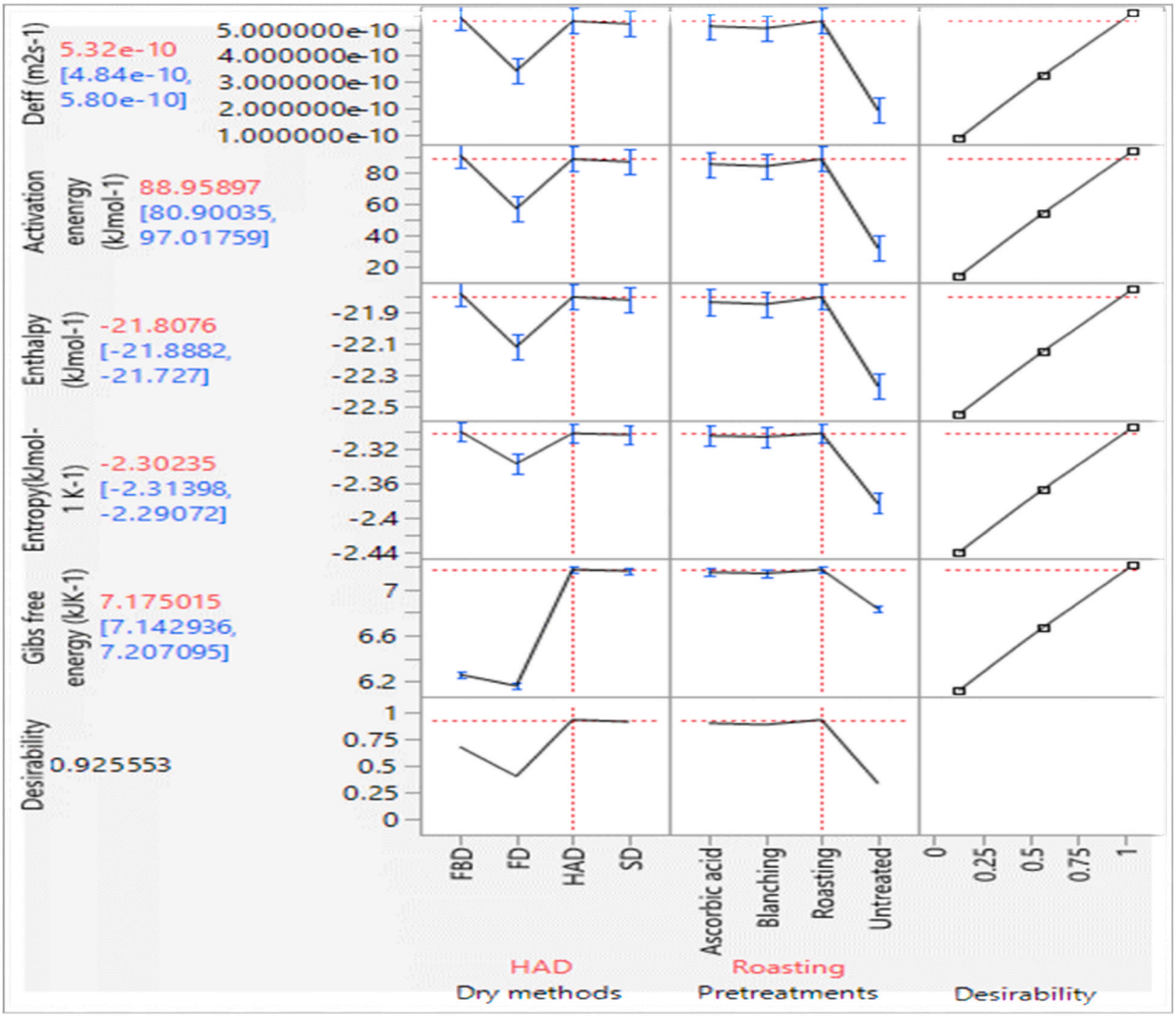

Fig. 6. Prediction of desirability profiles of thermal coefficient for avocado seed.

Table 4
Interaction effect of pre-treatment with drying methods on physicochemical parameters and recoveries of dried avocado seed.

Sample code		Water activity	pH	Toal acidity (g/100 g)	Lightness (L*)	Redness (a*)	Yellowness (b*)	Total color difference (ΔE)
Fresh sample[a]		0.92 ± 0.03^{a}	5.71 ± 0.01^{d}	1.16 ± 0.09^{a}	67.96 ± 0.01^{a}	2.92 ± 0.01^{q}	25.67 ± 0.02^{a}	36.35 ± 0.01^{a}
Pretreatments *drying								
C_o	FBD	0.4 ± 0.09^{hi}	5.74 ± 0.38^{d}	0.89 ± 0.29^{c}	47.67 ± 0.01^{g}	16.01 ± 0.01^{a}	20.18 ± 0.03^{l}	27.09 ± 0.09^{f}(74.53)
$AA_{0.5}$	FBD	0.35 ± 0.01^{jk}	5.56 ± 0.19^{fg}	0.69 ± 0.26^{fg}	56.09 ± 0.05^{c}	10.75 ± 0.09^{e}	25.55 ± 0.06^{b}	31.28 ± 0.03^{b}(86.06)
B_l	FBD	0.46 ± 0.11^{ef}	5.37 ± 0.25^{j}	0.61 ± 0.17^{h}	45.97 ± 0.01^{h}	13.08 ± 0.01^{c}	23.09 ± 0.01^{e}	26.54 ± 0.01^{h}(73.02)
R_o	FBD	0.43 ± 0.06^{fgh}	5.31 ± 0.09^{k}	0.54 ± 0.08^{i}	40.65 ± 0.06^{k}	8.67 ± 0.09^{l}	24.89 ± 0.08^{c}	24.22 ± 0.08^{k}(66.63)
C_o	HAD	0.41 ± 0.01^{gh}	5.85 ± 0.48^{b}	0.83 ± 0.39^{d}	39.16 ± 0.01^{m}	13.12 ± 0.09^{b}	19.23 ± 0.04^{n}	22.79 ± 0.01^{m}(62.67)
$AA_{0.5}$	HAD	0.37 ± 0.01^{ij}	5.40 ± 0.17^{i}	0.75 ± 0.16^{e}	48.17 ± 0.01^{f}	9.07 ± 0.07^{j}	20.73 ± 0.01^{k}	26.61 ± 0.01^{g}(73.21)
B_l	HAD	0.4 ± 0.07^{hi}	5.18 ± 0.19^{m}	0.51 ± 0.06^{i}	39.32 ± 0.01^{l}	9.89 ± 0.09^{h}	22.75 ± 0.06^{g}	23.25 ± 0.06^{l}(63.95)
R_o	HAD	0.41 ± 0.01^{h}	5.54 ± 0.17^{g}	0.41 ± 0.16^{k}	36.01 ± 0.01^{p}	7.67 ± 0.07^{n}	20.87 ± 0.01^{j}	21.16 ± 0.01^{p}(58.22)
C_o	SD	0.57 ± 0.07^{b}	5.77 ± 0.41^{c}	0.95 ± 0.33^{b}	37.98 ± 0.02^{o}	12.78 ± 0.01^{d}	15.83 ± 0.01^{q}	21.55 ± 0.01^{o}(59.27)
$AA_{0.5}$	SD	0.47 ± 0.01^{de}	5.58 ± 0.58^{f}	0.81 ± 0.23^{d}	45.11 ± 0.02^{i}	8.71 ± 0.08^{k}	19.98 ± 0.01^{m}	25.09 ± 0.03^{i}(68.91)
B_l	SD	0.42 ± 0.01^{fgh}	5.55 ± 0.18^{g}	0.67 ± 0.07^{g}	38.11 ± 0.01^{n}	10.39 ± 0.08^{f}	19.05 ± 0.07^{o}	21.93 ± 0.07^{n}(60.33)
R_o	SD	0.40 ± 0.01^{hi}	5.44 ± 0.08^{h}	0.59 ± 0.11^{h}	33.71 ± 0.01^{q}	5.67 ± 0.08^{p}	21.87 ± 0.01^{h}	20.29 ± 0.01^{q}(55.82)
C_o	FD	0.52 ± 0.07^{c}	5.89 ± 0.51^{a}	0.72 ± 0.01^{e}	54.71 ± 0.07^{d}	10.18 ± 0.01^{g}	18.97 ± 0.01^{p}	29.41 ± 0.01^{d}(80.88)
$AA_{0.5}$	FD	0.49 ± 0.09^{cd}	5.43 ± 0.06^{h}	0.54 ± 0.09^{i}	57.46 ± 0.01^{b}	9.69 ± 0.06^{i}	21.81 ± 0.09^{i}	31.11 ± 0.09^{c}(85.59)
B_l	FD	0.45 ± 0.01^{efg}	5.62 ± 0.25^{e}	0.45 ± 0.23^{j}	48.37 ± 0.01^{e}	7.45 ± 0.05^{o}	24.17 ± 0.03^{d}	27.29 ± 0.03^{e}(75.09)
R_o	FD	0.42 ± 0.06^{fgh}	5.26 ± 0.12^{l}	0.36 ± 0.26^{l}	43.03 ± 0.06^{j}	8.07 ± 0.02^{m}	22.95 ± 0.06^{f}	24.72 ± 0.01^{j}(67.99)

Where the value data presented as arithmetic mean ($\overline{x}$) ± standard deviation (SD) (n = 5), means subscript letters indicating significant differences in the same column are determined using Tukey's post-hoc test at 5 % probability (P < 0.05). The numbers in the bracket represent the proportion of the samples' total color difference (ΔE) that is retained. Where: FBD C_o-fluidized bed dryer with control, FBD AA $_{0.5}$ - fluidized bed dryer with ascorbic acid (0.5 %, w/v), FBD B- fluidized bed dryer with blanching, FBD R_o-fluidized bed dryer with roasting, HAD C_o -heat air dryer with control, HAD AA $_{0.5}$- hot air dryer with ascorbic acid (0.5 %, w/v), HAD B_l-hot air dryer with blanching, HAD R_o-hot air dryer with roasting, SD C_o-solar dryer with control, SD AA $_{0.5}$ - solar dryer with ascorbic acid (0.5 %, w/v), SD B_l - solar dryer with blanching, SD R_o-solar dryer with roasting, FD C_o - freeze dryer with control, FD AA $_{0.5}$ – freeze dryer with ascorbic acid (0.5 %, w/v), FD B_l – freeze dryer with blanching, FD R_o-freeze dryer with roasting.
[a] Values are expressed on a wet basis.

products [64]. Interaction effect of different drying methods using pretreatments on the physicochemical quality of the dried avocado seed samples is presented in Table 4. The water activity (a_w) and pH values of a fresh avocado seed were 0.92, and 5.71, respectively, indicating favorable conditions for microbial safety. Hence, by employing pretreatment conditions and drying methods, it is possible to reduce a_w of the avocado seed samples from 0.92 to 0.35. The food product had an ideal water activity of 0.3, which is good for microbiological safety [65]. Results indicate that there were statistically significant differences (P < 0.05) in water activity (a_w) between treated or untreated samples dried under different drying methods. As depicted in Table 4, the highest a_w value for samples untreated and dried by solar dryer was (0.57), whereas the lowest a_w value for samples treated with ascorbic acid and dried by fluidized bed dryer was (0.35). In this case, the dried avocado seeds exhibited a desirable range of water activity, from 0.57 to 0.35. This indicates that it extends the shelf-life and allows for a wider range of applications in the food industry. In another case, pH value for dried avocado seeds ranged from 5 to 5.89, which indicates a low pH value of the sample. Comparatively, it was reported that the pH values of vegetable waste (potato, carrot, and cabbage peels) ranged from 6.0 to 6.5, while the pH of fruit waste (banana and apple peels) was found to be approximately pH 5.0. However, fruit waste (oranges, and kiwi peels) had an acidic level below pH 4.0 [66].

The prevalence of food adulteration and food fraud has increased along with the demand for food, which poses a risk to public health issues. Food color is thought to be the most important factor in determining food quality [67]. Therefore, color is an essential physical quality parameter of food products that significantly influences consumer acceptance. In this study, the color parameter values L*, a*, b*, and total color difference for values of fresh avocado seed were 67.95, 2.92, 25.67, and 36.35, respectively. This study showed that during the drying trials, color value of a* parameter for dried samples was increased in comparison to the fresh avocado seed samples. This is consistent with findings in a report on dried mango chips [68]. The increase in a* values in the dried samples could be attributed to both enzymatic and non-enzymatic reactions that contribute to browning in agricultural products, such as fruits and vegetables [36]. However, the dried avocado seed samples processed using the freeze and solar dryers showed a decrease in color a* value, indicating a loss of red hue in the finished product. Comparing freeze-dried fruit to those processed with various dryers [69] reported that freeze-dried fruit had the lowest level of redness (a*) color. In contrast, the treated samples consistently displayed lower a* values in comparison to the control samples across all drying methods. This study found that the control sample, which was dried with a fluidized bed drier, had the highest a* value of 16.01. A possible explanation can be the inactivation of the enzymes that induce enzymatic browning, due to pretreatments using ascorbic acid, blanching, and roasting. In all cases, the a* parameter value was positive, indicating that the sample exhibited redness, which is used to assess the quality of the dried product [70]. In light of the results, it is recommended that dried avocado seeds be utilized as a food coloring in the food industry in future, rather than being discarded. In comparison to fresh avocado seed samples, dried samples showed a decrease in yellow hue (b*) with significant ($p < 0.05$) changes within the various drying processes, as shown in Table 4. This is in agreement with past studies on dried mango chips [68], and dried date fruit [51] where it was found that the drying process reduced the color b* values parameters. The ascorbic acid and roasting procedures yielded maximum b* values of 25.55 and 24.89 for the dried samples by fluidized bed dryer, respectively. These were followed by the freeze-dryer with blanching treatments, which had a b*value of 24.17, while the sample dried by solar dryer without treatment had a minimum color b*value of 15.83. On the other hand, the positive b* values in all samples exhibited their yellowness. Moreover, products with high b*values have more yellow color, which suggests that they contain more carotenoids for dried products [71].

The total color difference value (ΔE) is highly useful for representing the overall amount of color change caused by the process [68, 72]. In comparison to fresh samples with a total color difference value of 36.35, samples dried using a freeze-dryer and fluidized bed dryer showed comparatively strong recovery and low total color difference values, indicating minimal color loss throughout the drying process. Providing color stability during freeze-drying procedures is linked to the removal of water through ice sublimation, which helps to reduce enzymatic browning reactions. The findings of this study generally supported previous research on date fruit [51], and pineapple slices [36], which indicates that the freeze-dryer maintained the color quality of the dried samples. Our study showed that samples treated with ascorbic acid and dried using a fluidized bed drier and freeze-dryer had greater recoveries with 31.28 (86.06 %), and 31.11 (85.59 %) being the highest percentages, respectively, whereas the samples subjected to roasting and dried using solar dryer exhibited the lowest recoveries of 20.29 (55.82 %). Despite the statistically significance decline in physicochemical values across various drying methods, more than 55.8 % of these values were retained in all dried samples, including those dried using a solar dryer. However, in comparison to convectional dryer technologies, solar dryer technology proves to be more affordable and operationally cost-effective for preserving agricultural products, especially in developing countries like Ethiopia. These findings can be strengthened

Table 5
Interaction effect of pretreatments with drying methods on proximate compositions avocado seed by dry basis per 100 g.

Pretreatments*drying Code		Proximate analysis (dry basis, % w/w)						
		Moisture	Ash	Fiber	Protein	Fat	Total carbohydrate	Energy value (kcal/100 g)
FBD	C_o	11.63 ± 0.018^{l}	3.23 ± 0.07^{a}	4.76 ± 0.09^{d}	3.76 ± 0.01^{g}	4.97 ± 0.04^{de}	71.68 ± 0.05^{cdef}	321.56 ± 0.08^{e}
FBD	$AA_{0.5}$	10.97 ± 0.018^{n}	3.11 ± 0.26^{a}	4.92 ± 0.01^{c}	4.04 ± 0.02^{d}	5.47 ± 0.85^{c}	71.53 ± 0.01^{e}	324.03 ± 0.08^{c}
FBD	B_l	11.49 ± 0.03^{m}	2.81 ± 0.08^{e}	4.75 ± 0.11^{d}	3.98 ± 0.04^{e}	5.44 ± 0.01^{c}	71.55 ± 0.02^{def}	323.86 ± 0.11^{c}
FBD	R_o	11.86 ± 0.29^{k}	2.69 ± 0.15^{gh}	5.08 ± 0.06^{a}	3.78 ± 0.02^{g}	5.98 ± 0.35^{b}	70.61 ± 0.11^{g}	321.47 ± 0.01^{e}
HAD	C_o	12.71 ± 1.14^{g}	2.92 ± 0.01^{d}	4.22 ± 0.01^{i}	3.29 ± 0.01^{i}	5.14 ± 0.05^{d}	71.72 ± 0.68^{bcde}	320.61 ± 0.08^{f}
HAD	$AA_{0.5}$	12.05 ± 0.47^{j}	2.76 ± 0.01^{f}	4.43 ± 0.07^{g}	3.87 ± 0.01^{f}	5.5 ± 0.03^{c}	71. 41 ± 0.11^{f}	323.07 ± 0.17^{d}
HAD	B_l	12.56 ± 0.98^{h}	2.61 ± 0.01^{k}	4.51 ± 0.01^{f}	3.41 ± 0.04^{h}	4.98 ± 0.12^{de}	71.95 ± 0.15^{b}	321.23 ± 0.13^{e}
HAD	R_o	11.61 ± 0.04^{l}	2.65 ± 0.06^{jk}	4.30 ± 0.01^{h}	3.19 ± 0.01^{j}	6.49 ± 0.84^{a}	71.77 ± 0.01^{bcd}	325.77 ± 0.08^{a}
SD	C_o	13.83 ± 0.25^{a}	2.81 ± 0.01^{e}	4.01 ± 0.07^{k}	3.09 ± 0.08^{k}	4.48 ± 0.01^{f}	71.78 ± 0.07^{bcd}	317.45 ± 0.07^{i}
SD	$AA_{0.5}$	13.39 ± 1.57^{b}	2.74 ± 0.1^{f}	4.01 ± 0.01^{k}	3.21 ± 0.09^{j}	5.01 ± 0.04^{de}	71.64 ± 0.01^{def}	319.41 ± 0.1^{g}
SD	B_l	13.29 ± 1.72^{cd}	2.66 ± 0.19^{ij}	4.11 ± 0.01^{j}	3.21 ± 0.01^{j}	4.82 ± 0.02^{e}	71.91 ± 0.05^{bc}	319.77 ± 0.07^{g}
SD	R_o	12.37 ± 0.79^{i}	2.55 ± 0.01^{k}	3.95 ± 0.01^{l}	2.98 ± 0.05^{l}	4.49 ± 0.01^{f}	73.66 ± 1.87^{a}	324.54 ± 0.28^{b}
FD	C_o	13.35 ± 1.79^{bc}	2.96 ± 0.01^{c}	4.19 ± 0.07^{i}	4.91 ± 0.87^{b}	4.51 ± 0.04^{f}	70.07 ± 0.05^{h}	317.87 ± 0.11^{h}
FD	$AA_{0.5}$	13.15 ± 0.14^{e}	2.73 ± 0.11^{fg}	5.01 ± 0.09^{b}	5.17 ± 1.13^{a}	4.96 ± 0.01^{de}	68.98 ± 0.04^{j}	316.47 ± 0.08^{j}
FD	B_l	13.21 ± 1.71^{de}	2.68 ± 0.23^{hi}	4.6 ± 0.01^{e}	4.94 ± 0.07^{b}	5.02 ± 0.03^{de}	69.57 ± 0.07^{i}	318.03 ± 0.01^{h}
FD	R_o	12.98 ± 1.09^{f}	2.61 ± 0.06^{k}	4.31 ± 0.06^{h}	4.61 ± 0.63^{c}	5.45 ± 0.05^{c}	70.03 ± 0.04^{h}	320.38 ± 0.07^{f}

Results are presented as arithmetic mean ($\overline{x}$) ± standard deviation (SD) of three replications ($n = 7$), means followed by different superscript letters in the same column are significantly different by Tukey's post-hoc test at 5 % probability ($P < 0.05$). Where: FBD C_o-fluidized bed dryer with control, FBD $AA_{0.5}$ - fluidized bed dryer with ascorbic acid (0.5 %, w/v), FBD B- fluidized bed dryer with blanching, FBD R_o-fluidized bed dryer with roasting, HAD C_o -heat air dryer with control, HAD $AA_{0.5}$- hot air dryer with ascorbic acid (0.5 %, w/v), HAD B_l-hot air dryer with blanching, HAD R_o-hot air dryer with roasting, SD C_o-solar dryer with control, SD $AA_{0.5}$ - solar dryer with ascorbic acid (0.5 %, w/v), SD B_l - solar dryer with blanching, SD R_o-solar dryer with roasting, FD C_o - freeze dryer with control, FD $AA_{0.5}$ – freeze dryer with ascorbic acid(0.5 %,w/v), FDB_l–freeze dryer with blanching, FD R_o-freeze dryer with roasting.

by other research work [73,74].

3.5. Proximate analysis

Proximate analysis is a critical technique in the food industry for determining the nutritional value and quality of food samples by examining their primary constituents, including moisture, fiber, ash, protein, fat, and carbohydrate levels. Furthermore, it provides valuable information on the composition of food samples and regulatory requirements, including the use of underutilized agro-food by-products, like avocado seeds, in various sectors of the food industry [75]. The results of the proximate compositions of dried avocado seeds employing various drying techniques and pretreatments are shown in Table 5. There a was significant difference ($P < 0.05$) in the proximal values between treated and untreated samples dried by various methods. Interactions with drying techniques and pre-treatments had a substantial impact on the moisture content, which varied from 10.97 to 13.83 %. The results of this observation showed that the untreated (control) avocado seed dried in a solar dryer (SD Co) had a higher moisture content value (13.83 %), while the sample dried in a fluidized bed dryer after being treated with ascorbic acid had the lowest moisture content (10.97 %), with a significant difference ($P < 0.05$). This could be because the avocado seed slices showed evidence of moisture loss due to a higher interaction impact between the drying method and pretreatments, as well as good contact between the particles and the drying gas.

In this study, the overall interaction effect of different drying methods and pretreatments on the proximate compositions for dried avocado seed were revealed. The total ash content ranged from 2.55 to 3.23 %, while the crude fiber varied between 3.95 and 5.08 %. Crude protein levels were found to be between 2.98 and 5.17 %, and crude fat content ranged from 4.49 to 6.49 %. Additionally, total carbohydrate content was 68.98–73.66 %, with an energy value of 316.47–325.77 kcal per 100 g on a dry basis. Past reports have shown, that carbohydrates make up a significant fraction of macromolecules, ranging from 44.5 % [76] to 81.1 % [77]. Furthermore, the proportion of protein found in the avocado seed varies from 2.64 % [77] to 23.0 % [76], while the crude fat ranges from 0.65 % [78] to 15.73 % [79], and total ash ranges from 0.89 % [80] to 3.83 % [77]. These fundamental compositional quality of avocado seeds are different might be due to environmental factors and origin [6]. In contrast, our research used pretreatment conditions followed by various drying methods, which helped retain the nutritional value and produce a high-quality dried final product for a wide range of applications.

3.6. Mineral profiling

The avocado seed contains a variety of micronutrients, including essential minerals such as phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), and other trace minerals iron (Fe), zinc (Zn), copper (Cu), lead (Pb), manganese (Mn), and Nickle (Ni). In our findings, the major nutrient element in the avocado seeds were Ca (643.62 mg/100 g), Mg (303.77 mg/100 g), K (421.34 mg/100 g) followed by P (11.31 mg/100 g). Among the trace nutrient minerals, there was high Fe (18.49 mg/100 g), followed by Zn (9.09 mg/100 g), Cu (8.5 mg/100 g), Mn (0.62 mg/100 g) and low in Pb, and Ni (0.05, and 0.01 mg/100 g), respectively (Table 6). In contrast, a high potassium content of (1202 mg/100 g) was reported by Ref. [81]. This difference might be due to environmental factors. This indicates that avocado seeds could supply significant amounts of calcium and magnesium, which are essential for the development and maintenance of healthy bones and teeth in human nutrition. The high potassium content in avocado seed flour suggests its potential to help lower blood pressure. Therefore, the minerals found in avocado seeds may contribute to addressing micronutrient deficiencies, making them a preferable choice for human nutrition.

3.7. Bioactive compounds and anti-nutrient qualities of avocado seed

The results of this study demonstrated that samples dried using different drying methods had levels of total phenol and flavonoids ranging from 75.04 to 106.59 mg GAE/100 g dried matter and 39.24–67.36 mg QE/100 g dried matter, respectively. In contrast, the fresh avocado seed sample contained a total phenol content of 112.42 (mg GAE/100 g fresh sample) and total flavonoids of 81.06 (mg QE/100 g fresh sample) (Table 7). These findings indicate that the drying parameters significantly ($p < 0.05$) reduced the total phenolic and flavonoid content in the dried samples.

This discovery is most likely the result of bound phenolic compounds potentially releasing their bonds and forming free phenolic compounds from the components of cells [83]. Our results, however, were still slightly higher than those reported in previous studies on the total phenol content of freeze-dried avocado seeds, which ranged from 51 mg GAE/100 g dried matter [84] to 88 mg GAE/100 g

Table 6

Mineral content profiles of avocado seed in comparison to previous studies.

Mineral analysis (mg/100 g)											References
Ca	Mg	K	Na	Cu	Fe	Mn	Zn	P	Ni	Pb	
434.9[1]	55.8	1202.6	39.4	16.7	3.7	1.5	1.8	NR	NR	NR	[81]
36.78[1]	20.81	57.35	40.04	1.09	19.56	NR	6.47	20.53	NR	NR	[79]
0.43[2]	1.19	14.5	0.2	0.01	0.55	0.01	0.05	NR	NR	NR	[82]
0.82[2]	0.10	4.16	1.41	NR	NR	NR	0.18	0.10	NR	NR	[76]
643.62[2]	**303.77**	**421.34**	**NR**	**8.50**	**18.49**	**0.62**	**9.09**	**11.31**	**0.01**	**0.05**	(Present Authors, 2024)

Whereas NR, is not reported,[1] and [2] wet basis (wb) and dry weight basis (db), respectively.

Table 7
Interaction with drying methods using pretreatments on bioactive and anti-nutrient qualities of the avocado seed.

Sample code		Total phenol (mg GAE/100 g)	Total flavonoids (mg QE/100 g)	Condensed tannin (mg/100 g)	Phytate content (mg/100 g)	Oxalate content (mg/100 g)	Total alkaloids (mg/100 g)	Vitamin C (mg/100 g
Fresh sample*		112.42 ± 4.21^{a}	81.06 ± 3.56^{a}	6.04 ± 0.11^{a}	12.92 ± 0.24^{a}	9.03 ± 0.08^{a}	4.89 ± 0.32^{a}	12.75 ± 0.63^{a}
Pretreatments * drying								
C_o	FBD	86.99 ± 4.21^{bcd}	47.47 ± 4.38^{bcdef}	1.71 ± 0.06^{ef}	8.75 ± 0.12^{def}	6.01 ± 0.03^{c}	1.78 ± 0.17^{bc}	5.68 ± 0.36^{bcd}
$AA_{0.5}$	FBD	106.59 ± 3.98^{ab}	41.95 ± 2.19^{ef}	1.39 ± 0.05^{fg}	5.93 ± 0.13^{j}	4.27 ± 0.06^{g}	1.34 ± 0.13^{bcd}	9.82 ± 0.12^{a}
B_l	FBD	82.91 ± 4.37^{cd}	56.29 ± 3.25^{bcdef}	1.07 ± 0.02^{ghi}	7.83 ± 0.13^{gh}	2.29 ± 0.05^{k}	1.23 ± 0.18^{bcd}	6.25 ± 0.36^{bc}
R_o	FBD	86.87 ± 4.16^{bcd}	44.99 ± 3.09^{cdef}	1.08 ± 0.06^{gh}	7.06 ± 0.19^{i}	1.45 ± 0.05^{m}	1.45 ± 0.19^{bcd}	5.68 ± 0.32^{a}
C_o	HAD	89.44 ± 3.02^{abcd}	39.24 ± 3.48^{ef}	2.39 ± 0.01^{c}	8.93 ± 0.09^{de}	5.48 ± 0.04^{d}	1.45 ± 0.2^{bcd}	4.45 ± 0.62^{cd}
$AA_{0.5}$	HAD	105.58 ± 4.43^{abc}	56.06 ± 3.17^{bcdef}	1.29 ± 0.06^{g}	8.09 ± 0.17^{fgh}	4.78 ± 0.05^{f}	1.22 ± 0.21^{bcd}	5.57 ± 0.36^{bcd}
B_l	HAD	104.96 ± 4.07^{abc}	55.28 ± 2.19^{bcdef}	0.79 ± 0.06^{hij}	8.84 ± 0.23^{def}	2.85 ± 0.06^{j}	1.01 ± 0.06^{cd}	5.42 ± 0.11^{bcd}
R_o	HAD	75.04 ± 5.31^{d}	57.27 ± 3.17^{bcde}	0.79 ± 0.02^{hij}	7.71 ± 0.14^{ghi}	1.95 ± 0.01^{l}	0.45 ± 0.01^{d}	5.08 ± 0.22^{cd}
C_o	SD	101.75 ± 4.01^{abc}	52.64 ± 4.41^{bcdef}	2.83 ± 0.06^{b}	9.46 ± 0.2^{bcd}	6.56 ± 0.05^{b}	1.89 ± 0.18^{bc}	4.73 ± 0.43^{cd}
$AA_{0.5}$	SD	103.94 ± 4.21^{abc}	67.36 ± 5.18^{ab}	0.79 ± 0.02^{hij}	8.81 ± 0.14^{def}	5.11 ± 0.05^{e}	1.56 ± 0.19^{bc}	5.82 ± 0.37^{bcd}
B_l	SD	85.55 ± 3.89^{bcd}	46.46 ± 3.18^{abc}	0.49 ± 0.01^{jk}	8.39 ± 0.18^{efg}	3.67 ± 0.07^{h}	1.23 ± 0.17^{n}	4.44 ± 0.09^{cd}
R_o	SD	97.29 ± 2.87^{abcd}	64.78 ± 3.08^{abc}	0.79 ± 0.01^{hij}	8.17 ± 0.13^{efgh}	2.29 ± 0.05^{k}	1.23 ± 0.15^{bcd}	3.98 ± 0.36^{de}
C_o	FD	87.73 ± 3.07^{bc}	64.51 ± 5.11^{abcd}	2.14 ± 0.07^{cd}	10.03 ± 0.14^{b}	5.89 ± 0.05^{c}	2.12 ± 0.19^{b}	7.68 ± 0.32^{b}
$AA_{0.5}$	FD	77.35 ± 4.09^{de}	50.26 ± 3.56^{bcdef}	2.01 ± 0.06^{de}	9.19 ± 0.18^{cd}	4.95 ± 0.09^{ef}	2.01 ± 0.18^{bc}	10.32 ± 0.36^{a}
B_l	FD	82.75 ± 4.01^{cd}	64.09 ± 2.85^{abcd}	0.56 ± 0.06^{jk}	9.74 ± 0.13^{bc}	3.21 ± 0.03^{i}	1.78 ± 0.13^{bc}	5.68 ± 0.52^{bcd}
R_o	FD	92.12 ± 3.11^{abcd}	49.07 ± 5.12^{bcdef}	0.41 ± 0.06^{k}	8.75 ± 0.12^{def}	2.54 ± 0.05^{jk}	1.78 ± 0.18^{bc}	5.62 ± 0.36^{bcd}

Tukey's posthoc test with 5 % probability ($P < 0.05$) indicates that means in the same column that is followed by different superscript letters are significantly different from one another. The findings were shown as arithmetic means ± standard deviation (SD) with three replications. Values for total phenol content are expressed as mg GAE/100 g sample (milligram gallic acid equivalent per 100 g of fresh sample), for flavonoids contents expressed as mg QE/100 g (milligram quercetin equivalent per 100 g of sample), other parameters condensed tannin, phytate, oxalate, and total alkaloids are expressed as milligram per 100 g of sample (mg/100 g).

of dry matter [85]. A potential reason for the differences in results from previous research studies may be attributed to variations in drying pretreatments, green extraction processes, and the origins of the sample collections. The anti-nutrient factor contents for fresh avocado seed samples were measured as follows: condensed tannins at 6.04 mg/100 g, phytates at 12.92 mg/100 g, oxalates at 9.03 mg/100 g, and total alkaloids at 4.89 mg/100 g (on a wet basis). In this context, the levels of these anti-nutrients were significantly influenced by the pretreatment and drying methods, which resulted in a decrease in their concentrations in the dried samples as compare to the fresh samples.

In this study, the vitamin C (ascorbic acid) content of dried avocado seeds ranged from 3.98 mg/100 g to 11.00 mg/100 g. It is important to note that these levels contribute to meeting vitamin C requirements. The dietary reference intake for vitamin C (mg/day) varies by age group. For example, infants aged 7–12 months require 50 mg, while those aged 1–3 years need 15 mg. For pregnant women, the recommended intake is estimated at 80 mg for those aged 18 years and younger and 85 mg for those aged 19–30 years [86]. Assuming that 20 g of dried avocado seedsare added to complementary foods for children aged 1–3 years, this could significantly increase the vitamin C content. The sample treated with ascorbic and dried under a fluidized bed dryer showed the highest increase of vitamin C at 13 %, followed by an 8 % increase for the samples dried in a solar dryer with ascorbic acid. This recent study provides a comprehensive evaluation of various drying methods and pretreatments on the retention of nutritional and bioactive compounds, particularly in comparison to freeze-drying, which aligns closely with the expected true values.

4. Conclusion

Drying kinetics can effectively reveal the behavioral characteristics of food materials. Mathematical drying models are useful tools for determining the necessary drying time while simultaneously illustrating the drying patterns of food. The results indicated that the logarithmic model of drying kinetics provided the best statistical fit for the experimental data obtained from drying of avocado seed slices, exhibiting a typical falling exponential curve. Additionally, the fluidized bed dryer (FBD) demonstrated the fastest drying time, processing 80 % more efficiently when compared to other drying methods. Furthermore, pretreatments proved to be effective for preserving the nutritional value and color stability of dried avocado seeds. According to the findings, the application of an ascorbic acid pretreatment followed by drying with a fluidized bed dryer or freeze-drying resulted in high-quality dried avocado seed slices. These slices were found to be good sources of macronutrients and bioactive compounds, making them a wholesome, high-energy, and nutritious option that can be incorporated into other breakfast cereals and snacks for various food applications. Moreover, establishing optimum pretreatment conditions like time and temperature, is critical for unconventional food materials like avocado seeds.

CRediT authorship contribution statement

Desta Dugassa Fufa: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Tilahun Bekele:** Writing – review & editing, Supervision, Resources, Investigation. **Aynadis Tamene:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization. **Geremew Bultosa:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Data availability statement

Data will be provided upon request.

Ethical statement

This research experiment did not involve human or animal study.

Declaration of competing interest

The authors declare that none of the work reported in this study could have been influenced by any known competing financial interests or personal relationships that any of the authors have disclosed in this study.

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