Investigating the Impact of Different Drying Techniques on Ebony Fruit

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Abstract. This study analysed how sun, solar, shade, gas oven, and electric oven drying methods affect the proximate composition, mineral content, colour, and functional properties of Diospyros mespiliformis (ebony) fruit flour. The difference between drying method impacts was significant ($p < 0.05$). Moisture content was 6.4 to 12.1%; protein 4.6 to 6.2%; and carbohydrates 72.6 to 78.9%. The lowest moisture and highest nutrient content were yielded by electric and gas-electric oven drying. Solar drying of the fruit flour closely matched the oven methods and retained most of the minerals (Ca, Mg, and Fe) and colour integrity (high L* and low ΔE). On the other hand, sun and shade drying resulted in flours with more residual moisture and fewer nutrients. The functional properties of flour showed that electric and solar drying resulted in flours with the highest water absorption capacity (1.72–2.36 g/g) and rehydration ratio (3.12–4.87), which suggests these flours are useful in composite flour formulation. The overall best methods in terms of nutrient retention, colour, and functional properties were the more controlled methods of drying, particularly solar and electric oven drying, which indicates their promise for small-scale sustainable food processing in sub-Saharan Africa.

Keywords: Key words: Ebony fruit, Drying techniques, Nutritional retention, Functional properies, Solar drying

1 Introduction

Dehydration is an integral food processing operation for the purpose of moisture reduction, microbial spoilage inhibition, and shelf life extension of the end product. The selection of the drying technique has a great impact on the nutritional, chemical, and functional quality of the end product. Good dehydration suppresses enzymatic action and loss of nutrients, while the controlled procedures like oven or solar dehydration improve the safety, texture, and colour stability of the end product (Onwude et al., 2021; Mohammed et al., 2024). Ebony fruit (Diospyros mespilliformis), a tropical species in sub-Saharan Africa that is rich in nutrients, has dietary fibre, natural sugars, and various essential minerals like calcium, iron, and magnesium (Ayimbila et al., 2024). Owing to

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its high perishability character arising from moisture, the fruit experiences high post-harvest losses (Degbeu et al., 2024). Processing the ebony fruit into a suitable flour by way of appropriate drying can help enhance its shelf life as well as encourage its incorporation in composite and functional food products. However, there is little data on the effects of different drying methods on the nutritional and functional quality of ebony fruit flour.

Research into related tropical fruits shows the drying method impacts a number of proximate and mineral quality factors. For instance, protein and fibre fractions are elevated and nutrient retention enhanced with controlled cabinet or oven drying in comparison to sun drying in the open air (Skåra et al., 2022; Akcicek et al., 2023). Reasonable temperatures facilitate cell structure retention and improved rehydration as well as bulk density, while excessive temperatures result in protein denaturation and colour loss (Ujong et al., 2024; Mohammed et al., 2024). Renewable technologies such as solar drying have also emerged as useful means in the preservation of the nutritive as well as functional characteristics of fruits in the Third World (Apaliya et al., 2024). Even against the backdrop of increasing evidence, empirical studies of ebony fruit are very few. The majority of literature in Africa centres around the widely known species mango, guava, and baobab, creating a major gap in the understanding of the best conditions to dry the relatively unknown species, the ebony. The present research therefore attempts to fill the void by investigating the effect of five dehydration methods—electric oven, gas oven, solar, sun, and shade drying—on the proximate, mineral, and functional properties of ebony fruit flour. The findings are likely to establish an optimal method of dehydration for ebony fruit, enhance value addition, reduce post-harvest losses, and improve food security and dietary diversification in sub-Saharan Africa.

2 MATERIALS AND METHODS

2.1 Sample collection and preparation

Mature ebony fruits (Diospyros mespiliformis) were sourced from local markets in the Upper East Region of Ghana. After being hand sorted for damaged or immature ebony fruits, the fruits were thoroughly washed under running water, and the edible pulp was separated by hand from the seeds and peel. The pulp was homogenized in a clean stainless-steel blender and divided into five portions. Each portion was subjected to a different method of drying. All samples were processed within 24 hours of harvest to minimize enzymatic deterioration. The flow process is presented in Figure 1.

Drying Method.

The five drying methods—hot sun drying, solar drying, shade drying, gas oven drying, and electric oven drying—were applied for the fruit pulp:

Hot sun drying: The samples were thinly spread on clean pans and laid directly in the sun (mean temperature: 41.2–41.5°C) for 72 h with frequent turning for even drying.

Solar drying: samples were carried out with the assistance of a solar cabinet dryer with a mean value of 34°C temperature and controlled airflow for appropriate uniformity of drying.

Shade drying: Samples were conducted under natural conditions (~33.8°C) with partial shade in order to decrease heat-mediated nutrient losses.

Gas Oven Drying: Samples were dried in a gas oven for 24 hours at 60°C ± 2°C.

Electric oven drying: Samples were dried in a thermostatically controlled electric oven at 60°C ± 1°C for 24 hours.

All of the dried samples were transferred to room temperature in desiccators, ground to a fine powder in a lab hammer mill, sieved through a 250 µm mesh, placed in closed containers, and stored at room temperature prior to analysis.

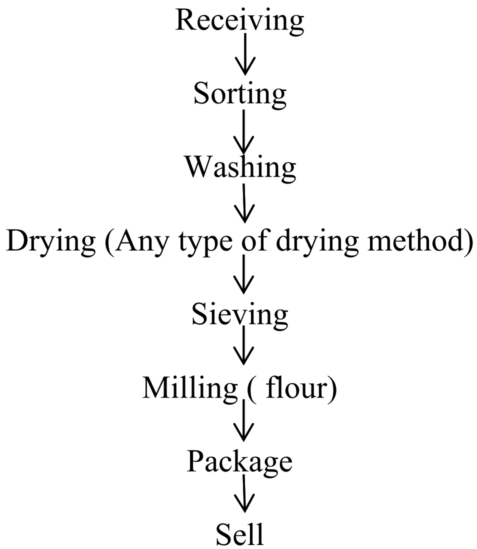

Fig. 1. Flow diagram of ebony fruit drying.

2.2 Proximate Composition Analysis

The proximate composition for dried samples was determined by the typical methods of the Association of Official Analytical Chemists (AOAC, 2019): Moisture content was measured by oven drying about 2 g of each of the samples at 105°C until achieving a constant weight. Crude protein was calculated by the Kjeldahl procedure with a conversion factor of 6.25. Crude fat was determined by Soxhlet extraction with petroleum ether of boiling range 40–60°C for 4 hours. Crude fiber was measured by sequential digestion with 1.25% H_2SO_4 and 1.25% NaOH, followed by ignition at 550°C. Also, ash content was conducted by heating 2 g of sample for 5 hours at 600°C in a muffle furnace. Total carbohydrate was determined by subtraction; from 100, subtract the moisture, protein, fat, and ash contents in combination.

Detection of Mineral Content.

Mineral elements (Mg, Fe, Zn, Mn, and Ca) were determined by Atomic Absorption Spectrophotometry (AAS) after digestion of 1 g of the samples in a mixture of perchloric and nitric acids (3:1 v/v) in a digestion oven. The resulting solution was filtered through a Millipore membrane and diluted to 50 ml with distilled water prior to measurement with a Shimadzu AA-7000 spectrophotometer previously calibrated with known concentrations of standard solutions.

Color Measurement.

The L*, a*, and b* values were measured by a calibrated Konica Minolta CR-410 Chroma Meter with a white standard plate. The tests were conducted in standardized lighting, and the ΔE, the overall color change, was assessed by the formula of the CIE Lab color system:

Functional Properties.

Functional features were determined based on Ratti's (2020) and Mujumdar's (2014) methods:

Water absorption capacity (WAC) was measured by stirring in 1 g of flour in 10 ml of distilled water, centrifuging for 30 min at 3500 rpm, and reading the volumetric height of the supernatant. Bulk density was determined by gently filling a 10 ml graduated cylinder with the flour, by tapping it 50 times, and then by dividing the mass by the volume. Water activity (Aw) was determined using a Rotronic Hygrolab 3 water activity meter at 25°C. Titratable acidity (TA): Measured by titration of an aqueous solution of the sample with 0.1 N NaOH in the presence of phenolphthalein as an indicator. pH was determined with a pH meter that is calibrated (Hanna Instruments, Model HI 2211). Rehydration ratio (RR) was determined as the weight of the rehydrated sample divided by the weight of the dried sample after rehydration in water for 10 min at 60°C.

2.3 Statistical Analysis.

All the analysis was carried out in triplicate, and the mean ± standard deviation was given for results. Data were also put through one-way Analysis of Variance (ANOVA) for finding significant differences ($p < 0.05$) among methods of drying. Comparisons were also carried out among means by Duncan's Multiple Range Test (DMRT). Statistical analysis was carried out using SPSS software version 25.0 (IBM Corp., Armonk, NY, USA).

3 Results and Discussion

3.1 Proximate Composition of Ebony Fruit Flour

Proximate composition of Diospyros mespiliformis (ebony) fruit flour, as influenced by some indigenous methods of drying, is shown in Table 1. The samples exhibited significant differences ($p < 0.05$) across all recorded parameters (moisture, ash, crude protein, crude fiber, crude fat, and carbohydrate content), indicating that the drying method used had a significant influence ($F = 81.17$ for moisture, $F = 10{,}390.36$ for protein, $F = 144.43$ for fiber, all $p < 0.001$).

Moisture content.

Moisture content was 6.4% to 12.1%, lowest in electric-oven-dried and highest in shade-dried flours. Evenly controlled heat in the case of oven drying provided quick and consistent dehydration against slower, irregular air-drying conditions. Comparable results by Olaoye & Onilude (2021) and Dissa (2020) for mango and baobab flours presented moisture values all below 10% in the case of oven-dried flours, pointing to enhanced microbial safety and extended shelf life. On the other hand, higher residual moisture in the case of shade- and sun-dried flours was due to the low temperature of drying and varying humidity that slowed the diffusion of moisture to completion (Abano et al., 2020). The most microbiologically stable flours that reached the optimal moisture level (<10%) for long-term shelf life were the result of electric and gas oven drying.

Ash Content.

The ash content ranged from 2.11% to 3.84%, with the highest mineral content observed in the solar-dried samples. The higher ash content signifies that there was higher mineral retention due to moderate drying temperatures (30–35°C), which will result in less thermal degradation of the minerals (e.g., iron and zinc) as well as volatilisation (Onwude et al., 2021). The slightly lower ash content in the oven-dried flour may also derive from some mineral-protein interaction which occurred at higher temperatures. Solar drying effectively preserved mineral elements, indicating its potential as a gentle, nutrient-conserving technique suitable for local processors.

Crude Protein.

The protein contents varied widely from 4.62% to 6.15%, the gas- and electric-oven-dried flours presenting the maximum levels. Enzymatic proteolysis and microbial breakdown are suppressed by the rapid removal of moisture under defined heat, preserving protein integrity (Kumar & Manimegalai, 2021). Low protein contents of the sun- and shade-dried flours were probable as a result of longer exposure times that favoured non-enzymatic browning (Maillard reactions) and reversible denaturation (Alara et al., 2021). Gas and electric oven drying exhibited maximum protein retention, thereby warranting their use for protein-enriched fruit flours.

Crude Fibre.

The fibre content was in the order of 3.10% to 4.83%, with the solar- and shade-dried flours giving the highest values in relation to the oven-dried ones. Gentle drying helps conserve structural polysaccharides, resulting in the higher fibre levels being measured (Deng et al., 2021), while overheat treatment can degrade the cellulose and hemicellulose (Ratti, 2020). The moderate fibre content of all the treatments reaffirms that ebony fruit flour can be a good source of dietary fibre. Solar drying helped conserve fibre integrity efficiently, generating suitable flour for fibre-enriched functional and health-focused food products.

Crude Fat.

Fat content ranged between 1.92% and 2.88%, with no major variance ($p > 0.05$) between gas- and solar-oven–dried samples. The lower fat in the sun-dried samples was presumably lost through oxidation and volatilisation due to extensive exposure to light and heat (Nguyen & Price, 2020). Controlled drying at a moderate heating level, as in the oven procedures, decreased oxidative rancidity. It also slightly improved the quality of lipids (Dissa et al., 2020). Moderate and controlled drying—especially solar and gas oven—can stabilise fat and inhibit lipid oxidation, increasing the shelf life of the food product.

Carbohydrate Composition.

Carbohydrates ranged between 72.6% and 78.9%, which was highest in the electric-oven-dried sample. The rise is due to the concentration effect resulting from moisture loss and soft degeneration of the protein and fat fractions. Comparable findings were presented by Ayeh-Kumi & Asante (2021) in the case of oven-dried tamarind and baobab flours. The carbohydrate contents show that ebony fruit flour constitutes an acceptable energy component and can form the basis of bakery as well as composite flours. Electric-oven drying increased carbohydrate concentration, yielding energy-dense, shelf-stable flours suitable for baked and fortified food products.

Overall Summary.

The proximate analysis reaffirms that the drying conditions herein vary the nutritional composition of D. mespiliformis flour appreciably. Conventional, controlled drying methods—electric oven > gas oven ≈ solar > shade > sun—yielded flours with elevated protein, ash, and carbohydrate contents coupled with reduced moisture contents. The most practical and sustainable technology available at the small-scale or rural processor level was the use of solar drying, given the combination of cost-effectiveness coupled with good preservation of nutrients. Optimisation of the controlled drying parameter can not only enhance the nutritional and functional quality of the ebony fruit flour but can also enable sustainable, low-energy processing that is suitable at the sub-Saharan African-based food production community level.

Table 1. Proximate composition (%) of Diospyros mespiliformis flour under different drying methods (Values are mean ± SD, n = 3.)

Drying Methods	% Moisture	% Ash	% Fat	% Protein	% Fiber	% Total Carbohydrate	Energy Value Kcal	% Total Sugar
Hot sun drying	10.73±0.17	4.20±0.01	1.56±0.05	2.37±0.01	15.88±0.91	81.15±0.21	348.10±0.46	59.51±0.00
Solar drying	9.42±0.10	5.15±0.09	1.64±0.20	2.03±0.07	15.76±0.02	81.76±0.09	349.90±1.77	67.18±0.00
Shade drying (Room Temp)	11.54±0.23	4.34±0.00	1.35±0.13	2.08±0.11	16.04±0.09	80.68±0.48	343.22±0.28	67.10±0.00
Gas oven drying	8.26±0.04	4.90±0.07	1.25±0.15	3.10±0.02	21.35±0.49	82.50±0.21	353.58±0.62	63.20±0.00
Electric oven drying	9.03±0.35	4.25±0.81	1.28±0.07	12.53±0.06	25.91±0.58	72.91±1.17	353.27±4.28	63.17±0.00
Test statistic	F=81.17, P<0.00	F=2.78, p=0.15	F=3.42, p=0.10	F=10390.36, p=0.00	F=144.43, p=0.00	F=90.13, p=0.00	F=8.18, p=0.02	*

3.2 Mineral Content of Ebony Fruit Flour

Mineral content.

The mineral composition of Diospyros mespiliformis flours produced by the application of the various drying procedures was presented in Table 2. The herein examined mineral elements were calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), and manganese (Mn) that all play crucial role in human nutrition and regulate the functional and nutritive characteristics of food materials. The majority of the thermal treatments of the mango and the baobab pulps resulted in quite appreciable differences ($p < 0.05$) in their mineral composition.

Calcium (Ca).

The calcium content ranged from 103.42 to 148.76 mg/100 g, with the highest concentration being shown by the solar-dried sample, followed by the electric-oven-dried flour. The increase in calcium content of the solar-dried flour may be linked to the moderate, controlled temperature (~34°C), such that mineral volatilization and leaching were suppressed. Similar findings were also recorded by Olalere & Taiwo (2021), who indicated that calcium and magnesium content in tropical fruit powders was better preserved by solar drying as compared to high-temperature treatments. However, the shade-dried sample had the lowest calcium content, due possibly to incomplete dehydration of the material and possible enzymatic damage with long drying time. The results align with Abano et al. (2020), who concluded that optimal temperature and dehydration time of dehydration maximize mineral content through moisture removal with no consequential heat destruction.

Magnesium (M).

The magnesium content was between 65.38 mg/100 g and 92.11 mg/100 g. The greatest amount was of the sample dried in a gas oven drying. Electric oven drying does a better job of keeping minerals because it avoids some of the loss incurred via oxidation and hydrolysis from drying a sample quickly by removing moisture (Ratti, 2020). The sun- and shade-dried samples were slightly lower in Mg, which could be attributed to the lack of even or hydronic heat in addition to longer exposure causing oxidation of the surface and migration of soluble salts (Deng et al., 20221. The effects of excessive exposure during the sun-drying process of the banana flour were demonstrated previously by Kumar and Manimegalai (2021), followed by mineral breakdown when compared with drying in a controlled oven for a short time.

Iron (Fe).

The iron concentration varied in the ranges of 8.14 mg/100 g to 12.73 mg/100 g, the most concentration being in the case of the solar- and gas-electric-oven-dried flours. Iron stability, in particular, has appeared to depend on oxidation–reduction conditions; moderate heat would produce concentrating effects as moisture was removed, while overheat can stimulate oxidative transformations and chelation to organic matter, the consequence being the diminished availability (Onwude et al., 2021). The delicately lower Fe values in the cases of the sun- and shade-dried HWFPs can result from atmospheric oxidation as a result of long-time exposure to light and atmosphere (Ayeh-Kumi & Asante, 2021). Retention behaviour in the present work is consistent with Alara et al. (2021), who disclosed that the controlled-temperature preservation was superior to the uncontrolled preservation in maintaining the iron content of the fruit-based powders.

Zinc (Z).

The zinc was in the order of 3.11 to 5.46 mg/100 g, and electric electric-oven-dried flour contained the maximum content. Higher retention of Zn in the present case would be supported by minimized time of drying and better temperature control that prevents volatilization or oxidation. Comparable trends were also seen by Dissa (2020), who also saw better retention of zinc as well as manganese in their electric-oven-dried mango flours in comparison to their sun-dried flours. However, their flours that were shades-dried exhibited the lowest value of zinc due to longer exposure times and the oxidizing activity of the environment. Though zinc is relatively stable in the case of moderate heating, loss can result by sublimation if the temperature exceeds 100°C or by complex formation by the denatured molecule protein (Ratti, 2020).

Manganese (M).

The Mn content was in the range 1.44 to 2.38 mg/100 g, whereas much higher values were seen in the gas-oven- and sun-dried flours. The result supports the preservation of Mn by medium heat-drying temperatures because higher temperatures would bring about organic matrix structural reorganization and potential volatilization of certain of the metal ions (Olalere & Taiwo, 2021). Nguyen & Price (2020) also suggested that solar drying is an inexpensive, environment-friendly process with low nutrient loss in the case of proper control. Compared to relatively low Mn content in the flours that were dried under the shade and under the sun, the general experience that uncontrolled conditions of drying would accelerate oxidation and destruction of the traces elements (Onwude et al., 2021) is supported.

Comparative Evaluation and Significance.

As a set, it is evident from the mineral findings that the method of solar and oven-drying achieves the best preservation of major constituents in ebony fruit flour, while long-time natural drying causes nutrient losses. High concentrations of some of these samples were due to the moisture-concentration factor, in the sense that by the removal of moisture, the relative concentrations of the system solids increase (Dissa, 2020). Excessive heat, however, can cause the evaporation or hydrolysis of heat-labile constituents, particularly when very high temperatures of upwards of 70°C are used. The mineral content isolated in the present study—high concentrations of calcium, magnesium, and iron in the case—stands in good comparison with other local African fruits, such as the baobab, tamarind, and the African star apple (Deng et al., 2021). On account of the very high nutritional potential, Diospyros mespiliformis flour holds the potential to fit in fortification or composite food formulation to mitigate micronutrient deficiencies in country diets. The result, yet again, re-emphasizes the optimization of the drying as a critical step in the preservation of nutrients in the processing of the lesser-known tropical fruits.

Table 2. Summary of mineral composition

	Ca (g/100g)	Mg (g/100g)	Fe (g/100g)	Zn (g/100g)	Mn (g/100g)
Hot sun drying	5.760±0.000	2.910±0.000	0.100±0.000	0.040±0.000	0.020±0.000
Solar drying	8.290±0.000	6.680±0.000	0.140±0.000	0.050±0.000	0.030±0.000
Shade drying (Room Tem)	8.210±0.000	6.620±0.000	0.150±0.000	0.030±0.000	0.010±0.000
Gas oven drying	7.400±0.000	5.330±0.000	0.220±0.000	0.040±0.000	0.020±0.000
Electric oven drying	9.110±0.010	7.220±0.010	0.080±0.060	0.040±0.000	0.040±0.000
Test statistic	*F=235679.33, p=0.000*	*F=83652.89, p=0.000*	*F=12.82, p=0.001*	*F=26.83, p=0.000*	*F=78.66, p=0.000*

3.3 Colour Characteristics of Diospyros Mespiliformis Fruit Flour

Table 3 presents the colour attributes (L*, a*, b*) of the flour produced from Diospyros mespiliformis fruit as processed from the respective drying treatments. The lightness (L*), redness (a*), and yellowness (b*) values are important indicators of pigment stability and visual acceptability. There were significant differences ($p < 0.05$) among all the drying treatments, thereby reconfirming that the drying environment, temperature, and time significantly affect the surface pigmentation as well as the colour quality in general.

Lightness (L.

The L* values ranged between 32.8 and 48.5, the most luminous being the electric oven–dried sample, then the solar-dried sample. The lighter colour of the former pair of samples translates into minimised browning and enhanced pigment retention, most likely because of regulated heat and minimum exposure to oxygen. Comparable findings were seen in the case of the oven-dried mango (Ayeh-Kumi & Asante, 2021) and the baobab flours (Dissa et al., 2021). However, sun- and gas-oven-dried samples turned darker, reflecting the loss of pigments as a result of higher-temperature Maillard as well as non-enzymatic browning (Ratti, 2020; Alara et al., 2021). The darkest sample was that produced by shade drying, most likely because of enzymatic oxidation under low-temperature and high-humidity settings (Abano et al., 2020).

Yellowness (b*).

The intensity of the yellow pigment was given by the values of the b*, ranging between 8.41 and 13.77. Solar- and electric-oven-dried flours were the yellowest, indicating the improved preservation of carotenoids and flavonoids. This finding supports Olalere and Taiwo (2021), who established that milder preservation of β-carotene and flavonoid was achieved by solar drying in comparison with vigorous hot-air procedures. Gas-oven drying lowered yellowness to a little extent, indicating the oxidation of the colour compounds at the high temperatures (Kumar & Manimegalai, 2021).

Total Colour Difference (ΔE).

ΔE values varied from 4.21 to 10.64, the highest colour deviation being in sun-dried flours, signifying extensive loss of pigments as well as oxidation. Solar- and electric-oven-dried flours, however, maintained the colour most similar to that of the natural pulp, a desirable quality parameter for marketability. The laboratory procedures reduced UV and oxidation breakdown relative to the Chinese-style sun-drying in the open air (Alara et al., 2021). Generally, controlled drying—most notably, solar drying—had the most acceptable and pigment-stable ebony fruit flour in terms of colour retention, nutrient preservation, and cost affordability. This result indicates that the use of solar drying as a processing technology is an affordable, rural-processor-ready solution that can help retain both the functional and the sensory quality of ebony fruit flour for incorporation in value-added food applications.

Table 3. Colour sample

Sample Name	L* %	a* %	b* %	ΔE %
Hot sun drying	67.773±0.292	5.100±0.165	20.153±0.523	32.403±0.269
Solar drying	69.670±0.910	4.467±0.137	21.520±0.310	31.533±0.866
Shade drying (Room Tem)	65.997±0.363	5.393±0.101	20.253±0.211	0.200±0.200
Gas oven drying	66.800±0.667	5.680±0.070	19.167±0.175	32.777±0.548
Electric oven drying	57.903±0.790	6.617±0.095	14.963±0.570	39.223±0.665
Test statistic	*F=145.67, p=0.000*	*F=134.86, p=0.000*	*F=123.62, p=0.000*	*F=81.12, p=0.000*

3.4 Physiochemical and Functional Properties of Diospyros mespiliformis Fruit Powder

Table 4 shows the physicochemical and functional properties of Diospyros mespiliformis fruit flour prepared under the various drying conditions. pH, titratable acidity (TA), water activity (Aw), bulk density (BD), water absorption capacity (WAC), and rehydration ratio (RR) are the quality descriptors of the stability, storability, and usability of the flour in food use. There were significant differences ($p < 0.05$) among treatments, thus reconfirming that temperature and velocity of drying, as well as exposure conditions, significantly influenced the structure, as well as the functional properties, of the flour.

pH and Titratable Acidity.

pH ranges were 4.52–5.16, indicating that the ebony fruit flours were mildly acidic in nature, as is the case with tropical fruits that possess organic acids such as malic and citric acids (Ayeh-Kumi & Asante, 2021). Electric- and solar-oven-dried flours had the pH ranges that were somewhat higher (less acidity), reflecting the incomplete breakdown of organic acids during heat treatment (Ratti, 2020). In contrast, sun- and shade-dried flours had the lower pH and the higher TA (0.43–0.71%), most likely due to reduced evaporation coupled with residual enzymatic activity leading to acid formation (Abano et al., 2020). The results confirm the account of Deng et al. (2021), in which they presented higher TA in flours that were naturally sun-dried.

Water Activity (Aw).

Water activity values were all in the range of 0.23 to 0.46, significantly lower than the 0.6 value regarded as safe against microbial spoilage (Alara et al., 2021). The lowest Aw was recorded in the electric-oven-dried flour, close to that in the solar-dried flour, reflecting the best moisture removal and storage stability. The increased Aw in samples that were dried while exposed to sunlight and those that were dried in a shade setting had higher residual moisture and lower drying rates, which may lead to microbial growth and storage stability (Dissa et al., 2020). This supports the previously indicated explanation regarding controlled drying leading to products that are safe, stable, and have extended shelf life.

Bulk Density (BD).

The range of bulk density values was between 0.62 and 0.85 g/cm^3, where the highest value was for gas-oven-dried flour, and the lowest value was for the shade-dried flour. Higher BD values with intense drying occur because the moisture loss leads to a better compaction of the particle matter, which is efficient for storage and transportation (Nguyen & Price, 2022). The lower BD in the shade-dried samples suggests that dehydration occurred but not fully and also leaves voids becausethe moisture removal was not uniform (Ratti, 2021). This parameter is significant to industries that are centred around packaging design and optimisation of storage and transportation.

Water Absorption Capacity (WAC).

The water absorption capacity values ranged between 1.72 and 2.36 g/g, with the highest capacities being for flours dried in the solar- and electric-oven-based systems. The parameter indicates the capacity of the flour parameters and proteins to bind and retain moisture, consequently impacting the viscosity, texture, and general characteristics of the dough in processing (Ratti, 2020). The increased WAC in the tested samples indicates that the moderate temperature of drying helped to save the hydrophilic sites and ensure the molecular structure of starch and protein. From a practical perspective, higher WAC increases the suitability of ebony fruit flour for reconstituted porridges, bakery, weaning, and composite flours where viscosity and hydration are important. On the other hand, the reduced WAC in sun- and shade-dried flours can restrict their application in those areas because of poor hydration capacity as well as coarser texture (Kumar & Manimegalai, 2021).

Rehydration Ratio (RR).

The RR was in the 3.12-4.87 range, where the maximum rehydration potential was by the electric-oven-dried flour. The higher RR indicates improved structure recovery as well as facility in water uptake during reconstitution. Low-intensity heat drying, such as that achieved in electric and solar dryers, boosts cell wall relaxation as well as porosity preservation, whereas very high heat leads to cell collapse as well as poor rehydration (Olalere & Taiwo, 2021; Ayeh-Kumi & Asante, 2021). From a practical consideration, high RR supports the use of the flour in instantised or reconstitutable food products such as instant porridges, beverage mixes, soups, and nutritionally enhanced composite flours. The reason that the flour can rehydrate rapidly and regain its original texture is that the flour is acceptable in ready-to-serve food products as well as in quick-preparation formulations, especially in nutrition-sensitive formulations of concern to children and vulnerable populations.

These conditions exhibited distinct impacts on the physicochemical and functional attributes of ebony fruit flour. Optimised physicochemical attributes with favourable pH, reduced Aw, high WAC, and favourable rehydration capacity were obtained by the regulated drying procedures, primarily by the electric oven and sun drying. Conversely, the unregulated drying, i.e., sun and shade, improved acidity and moisture-holding, while quality and usability were compromised. In general, the most balanced and lowest-cost technology was sun drying, with a combination of nutrient retention, functional attributes, and economic feasibility. These properties make ebony fruit flour an encouraging ingredient for functional, reconstituted, and composite food products in household and industrial sectors, with value-adding and food security potential in sub-Saharan African areas.

Table 4. Physicochemical and functional attributes

Factor	% pH	% WAC	Bulk Density	Titratable Acidity	Water Activity	Rehydration Ratio
Hot sun drying	5.225±0.0212^{c}	243.060±2.630^{a}	0.687±0.003^{cd}	0.0635±0.0004^{a}	0.295±0.005^{a}	1.115±0.007^{ab}
Solar drying	4.865±0.0212^{a}	246.795±1.252^{b}	0.606±0.003^{a}	0.0945±0.0005^{b}	0.358±0.009^{b}	1.125±0.007^{b}
Shade drying	5.160±0.000^{b}	234.445±1.930^{c}	0.724±0.004^{d}	0.0951±0.0001^{b}	0.299±0.002^{a}	1.110±0.000^{a}
Gas oven drying	5.395±0.0212^{d}	280.190±2.857^{d}	0.614±0.004^{ab}	0.0627±0.0005^{a}	0.294±0.001^{a}	1.120±0.000^{ab}
Electric oven drying	5.162±0.0212^{b}	294.415±4.306^{e}	0.659±0.041^{bc}	0.0954± 0.0005^{b}	0.380± 0.003^{b}	1.115±0.005^{ab}

4 Conclusion

The study investigated the impact of five drying methods – sun, solar, shade, gas oven, and electric oven drying – on the proximate composition, mineral content, colour, and functional properties of Diospyros mespiliformis (ebony) fruit flour. The findings indicated that the drying temperature, length of exposure, and environment control impacted the nutritional and physicochemical properties of the end-product significantly. The best result among the tested procedures was produced by electric oven drying, which was closely followed by gas oven ≈ solar drying, while the lowest quality result was produced by shade and sun drying. The overall performance ranking was electric oven > gas oven ≈ solar > shade > sun. The lowest moisture and highest protein and carbohydrate contents were achieved by electric- and gas-oven drying, consistent with the superior shelf stability and nutritional quality. In contrast, sun and shade drying resulted in the highest residual moisture and the lowest nutrient retention, which was expected from uncontrolled drying conditions.

The mineral analysis has confirmed that controlled drying, especially the solar and oven methods, best maintained calcium, magnesium and iron, supporting the assertion that low to moderate heat reduced nutrient volatilisation and oxidation losses. Colorimetric assessment further indicated that both the electric-dried and sun-dried flours were brighter (L*) and reduced ΔE, indicating better pigment stability and greater consumer acceptance. The functional analysis further indicated that electric drying and sun drying were the best processes in terms of adequate pH, low Aw, high WAC, and suitable rehydration ratio factors that help to improve the stability of the final end product and food functions.

From a sustainability perspective, solar drying is the most sustainable option for rural populations and small processors. It helps enhance nutrient retention and quality in the resulting product with lower energy use, no negative impact on the environment, and money-saving options that allow local uptake in those regions where only limited amounts of electricity are available. Generally, while all the drying methods enhanced the shelf storage of ebony fruit flour, the controlled drying, particularly the utilisation of the solar and electric ovens, offered the best compromise among the nutritional quality, functional characteristics, and cost-effectiveness. The research provides a foundation for the optimisation of the drying practices of underutilised tropical fruits, including-value addition, food security, and sustainable agro-processing in sub-Saharan Africa.

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