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Refractance Window versus Oscillatory Drying: Effects on *Vernonia amygdalina* Nutritional, Bioactive, and Techno-Functional Properties

***[1]Mayowa Saheed Sanusi, [2]Hafsat Funmilayo Bankole, [1]Sodiq Ayinde Olaleye, [1]Joyce Titilayo Madamori and [1]Musiliu Olushola Sunmonu**

[1]Department of Food Engineering, Faculty of Engineering and Technology, University of Ilorin, Ilorin, Kwara State, Nigeria.
[2]Shelterbelt Research Station, Forestry Research Institute of Nigeria, Kano State, Nigeria.

*Corresponding authors' email: sanusi.ms@unilorin.edu.ng

ABSTRACT
The preservation of nutritional and bioactive compounds during the drying of leafy vegetables remains a major challenge, as conventional drying methods often cause quality deterioration due to thermal degradation. This study compared the effects of Refractance Window drying (RWD) and oscillatory hot-air drying (OD) on the nutritional composition, bioactive compounds, colour characteristics, and techno-functional properties of *Vernonia amygdalina* (bitter leaf). Fresh leaves were dried under controlled conditions using both techniques, and the resulting powders were analyzed using standard methods. RWD produced a lower residual moisture content (6.57%) than OD (9.04%) and resulted in higher retained levels of protein (15.60%), fat (3.34%), fiber (4.57%), and ash (7.24%). The technique also demonstrated superior preservation of bioactive compounds, yielding a total phenolic content of 40.54 mg GAE/100 g, total antioxidant capacity of 54.39 mg AAE/g, and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity of 58.65%. Furthermore, RWD better maintained colour quality by preserving leaf greenness compared with OD. Improved techno-functional properties were also observed, including higher water absorption capacity, a rehydration ratio of 3.51, and a bulk density of 0.42 g/cm³, indicating enhanced structural integrity and reconstitution characteristics. This study demonstrates that RWD is a promising drying technology for producing high-quality *V. amygdalina* powders with improved nutritional, functional, and bioactive properties, making it suitable for application in functional foods and nutraceutical formulations.

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INTRODUCTION

Vernonia amygdalina (bitter leaf) is a leafy vegetable widely consumed in tropical Africa, particularly Nigeria, valued for its nutritional, bioactive, and health-promoting properties (Okolie et al., 2021). The leaves are rich in proteins, dietary fiber, minerals, vitamins, and phytochemicals such as flavonoids, alkaloids, saponins, tannins, and phenolic compounds, which contribute to their antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and anticancer activities (Eraga, 2020; Uchegbu et al., 2022; Ofodile, 2025). However, *V. amygdalina* has a high moisture content of about 84–86%, making it highly perishable (Tamala et al., 2025). Although drying is commonly used to extend its shelf life and availability, traditional methods often result in substantial nutrient losses and deterioration of quality attributes (Okolie et al., 2021).

Conventional drying techniques such as sun drying and hot-air drying as simple but usually subjects plant tissues to prolonged exposure to elevated temperatures and oxygen. These conditions often lead to the degradation of heat-sensitive nutrients like vitamins, and phenolics due to non-enzymatic browning (ElGamal et al., 2023; Jadhav, 2024). Also, there may be colour change due to biochemical and chemical responses caused by heat and oxidation during drying (Agomuo et al., 2022). These issues are of particular concern for *V. amygdalina* because its nutritional and antioxidative properties are dependent on the thermolabile bioactive compounds, and traditional drying of *V. amygdalina* has been associated with nutrient depletion and deterioration of quality attributes (Okolie et al., 2021).

Refractance window drying (RWD) has emerged as a promising contact-based thermal drying technology. In RWD, heat is transferred from hot water through a transparent polymeric film to a thin layer of wet material by a combination of conduction, convection and infrared radiation (Rurush et al., 2022; Eapen et al., 2025). This configuration allows high heat flux while maintaining relatively low product temperatures, typically below 70°C (Zalpouri et al., 2023). As a result, RWD has been linked to better retention of colour, flavor, vitamins, and antioxidants compared with conventional convective drying methods (Puente-Diaz et al., 2020; Nansereko et al., 2022; Mwaurah et al., 2022).

Oscillatory hot-air drying (OD) is a modification of conventional convective drying where the product bed is mechanically agitated to improve airflow distribution within the drying chamber (Sanusi et al., 2023). Whether this modification translates into substantial improvements in the nutritional, bioactive, and techno-functional quality of leafy vegetables, however, has not been fully established.

To the best of our knowledge, there is limited information in the literature on the effects of RWD and OD on the nutritional, bioactive, and techno-functional properties of *V. amygdalina*, despite the potential of these drying technologies to preserve product quality. Due to the significant contribution of heat-sensitive compounds to the nutritional and functional properties of *V. amygdalina*, establishing this comparison would provide valuable insight into the effects of the drying techniques on its processing and quality attributes. Therefore, the objective of this study was to evaluate and compare the effects of refractance window drying and oscillatory hot-air drying on the nutritional, bioactive, and techno-functional properties of *V. amygdalina.*

MATERIALS AND METHODS

Raw Material Preparation

Fresh *V. amygdalina* leaves were harvested from an agricultural research farm in Ilorin, Kwara State, Nigeria (8°29′ N, 4°32′ E). The plant material was authenticated at 105°C the Herbarium, Department of Plant Biology, University of Ilorin, where a voucher specimen was deposited. Harvested leaves were transported to the laboratory in insulated polyethylene bags within 2 h, sorted to remove defective samples, washed with potable water, and blotted dry. Initial moisture content was determined gravimetrically using the hot-air oven method at until constant weight, and expressed on both wet and dry bases. All reagents used for proximate composition and antioxidant assays were of analytical grade and purchased from Biofare analytical laboratory (Ilorin, Nigeria).

Description of the Drying Systems

Description of Dual-Powered Refractance Window Dryer

A laboratory-scale refractance window dryer was designed and fabricated at the Department of Food Engineering, University of Ilorin, for this study as shown in Figure 1. The system consisted of a stainless-steel hot water bath (HWB), a transparent polyester (mylar) film stretched over the bath, a product feed tray, a water circulation system, and dual heating units. The HWB had internal dimensions of (1.42 × 0.66 × 0.06) m, with a working water depth of 0.05 m. The mylar film thickness was 50 µm and was selected based on its high infrared transmittance and thermal stability. Heating was provided by two alternative energy sources: (i) an electric immersion heater rated at 2 kW and (ii) a liquefied petroleum gas (LPG) burner. The system was insulated with 25 mm thick glass wool lagging around the bath walls and base to minimize heat losses. Water circulation was achieved using a 0.5 hp centrifugal pump that recycled approximately 11 L of hot water every 10 min, corresponding to an average flow rate of 1.1 L/min. Temperature of the HWB was monitored using calibrated K-type thermocouples connected to a digital data logger. The system was operated at a target water temperature of 90±2°C for all experiments.

(A) (B)

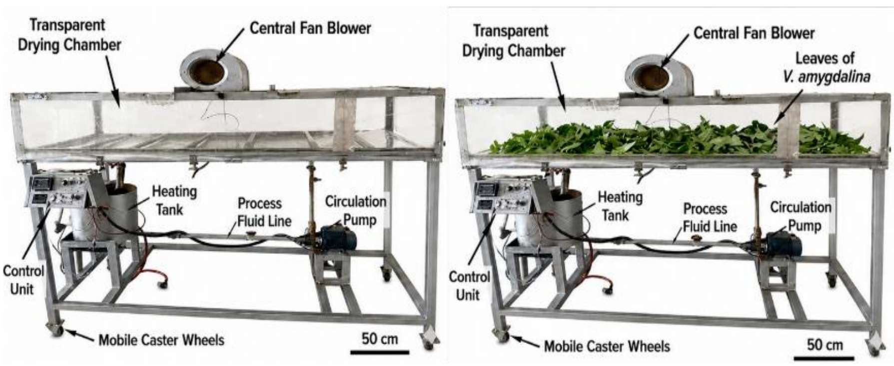


Figure 1: Dual-Powered Refractance Window Dryer Without *V. amygdalina* (A) and with *V. amygdalina* (B)

Description of Oscillatory **Hot-Air** *Dryer*

The oscillatory hot-air dryer was designed and fabricated at the Department of Food Engineering, University of Ilorin. The oscillatory hot-air dryer without and with *V. amygdalina* are shown in Figure 2. The apparatus consists of a stainless-steel mesh screen, an oscillatory electric motor, a drying chamber, a digital temperature controller with a thermocouple sensor, a 2000 W electric heating element, a centrifugal blower, and a removable galvanized steel cover equipped with a chimney and handle, all supported by a structural frame. To accommodate green leafy vegetables, the drying bed utilizes a stainless-steel screen with a 1.5 mm mesh aperture. This design optimizes interstitial airflow and uniform thermal penetration through the *V. amygdalina* leaf matrix, accelerating the moisture desorption rate. Dynamic agitation is driven by the oscillatory electric motor, which transfers mechanical energy via an articulated linkage arm to impart a reciprocating motion to the bed. The system can operate in either a continuous oscillation or a stationary mode. Thermal regulation is managed via a closed-loop feedback system. The digital controller modulates the 2000 W heating element based on real-time data from the temperature sensor inside the chamber, preventing thermal overshoot to preserve heat-sensitive bioactives. The blower continuously circulates this hot air across the leaf bed. The removable top cover minimizes heat loss, while its integrated chimney allows the unhindered escape of evaporated water vapor during the drying process.

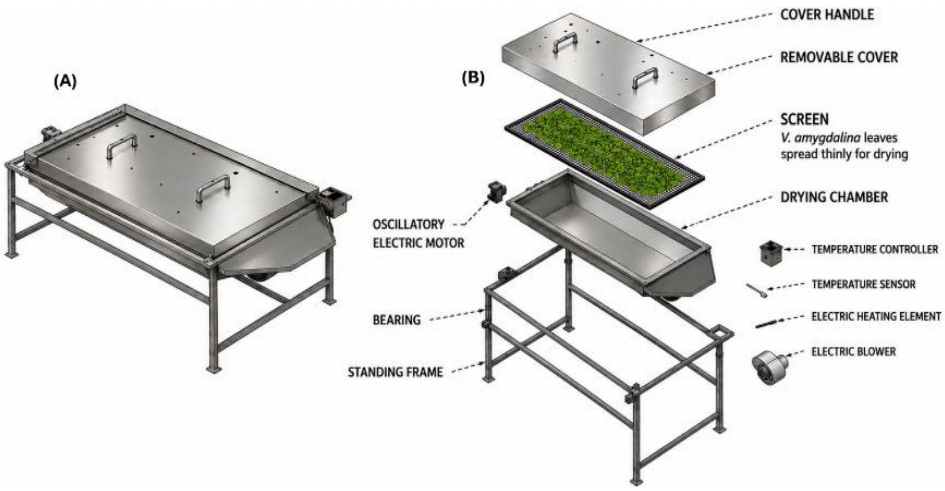


Figure 2: Oscillatory Hot-Air Dyer without *V. amygdalina* (A) and with *V. amygdalina* (B)

Experimental Design

Fresh *V. amygdalina* leaves, with an initial moisture content of approximately 82.4% (wet basis), were dehydrated using RWD and OD in this study. All drying experiments were conducted in triplicate to ensure reproducibility. For each run, a 10 kg batch of fresh leaves was evenly distributed as a thin layer on the mylar film of the refractance window dryer and on the mesh screen of the oscillatory hot-air dryer. Drying was carried out under the respective operating conditions of each system, combining conductive and convective heat transfer mechanisms, for approximately 2 h until moisture reduction was attained. Following 2 h drying, the samples were cooled to room temperature and milled into powder. The powders were then packaged in airtight, moisture-resistant polyethylene bags, hermetically sealed to minimize moisture reabsorption and oxidative deterioration, and stored under ambient conditions prior to the determination of nutritional composition, bioactive compounds, colour characteristics, and techno-functional properties.

Proximate Composition

Moisture, ash, crude protein, crude fat, crude fiber, and carbohydrate contents of the dried samples were determined using standard AOAC methods (AOAC, 2019). Carbohydrate was calculated by finding the difference the sum of moisture, ash, crude protein, crude fat, crude fiber, and 100.

Bioactive Contents

Total Phenolic Content (TPC)

The TPC of the dried *V. amygdalina* samples was determined using the Folin-Ciocalteu method, as described by Sanusi et al. (2023) with slight modifications. Approximately 500 mg of the finely ground sample was extracted in 12.5 mL of an acetone–water mixture of 4:1(v/v). The mixture was stirred continuously for 2 h using a magnetic stirrer, followed by centrifugation at 3000 rpm for 10 min. For the assay, 0.2 mL of the resulting supernatant was mixed with 1.5 mL of a freshly prepared 10-fold diluted Folin-Ciocalteu reagent. After allowing the mixture to stand for 5 min, 1.5 mL of sodium carbonate solution (60 g/L) was added to the mixture. The reaction mixture was incubated in the dark at room temperature for 90 min. The absorbance was subsequently measured at 725 nm using a UV-Vis spectrophotometer (Cary 3500 Flexible, Agilent Technologies, California, USA). An acetone-water solution of 4:1(v/v) served as the blank, and gallic acid was employed as the standard. The TPC results were expressed as milligrams of gallic acid equivalents (GAE) per gram of dry sample (mg GAE/100 g).

Total Antioxidant Capacity (TAC)

The TAC was evaluated using the Phosphomolybdenum method according to the method described by Yumita et al. (2023). An aliquot of the sample extract was combined with the phosphomolybdenum reagent solution (0.6 M sulfuric acid, 28 mM sodium phosphate, and 4 mM ammonium molybdate). The reaction mixture was incubated at 95°C for 90 min. After cooling to room temperature, the absorbance was measured at 695 nm using a UV-Vis spectrophotometer (Cary 3500 Flexible, Agilent Technologies). A standard curve was prepared using ascorbic acid, and the TAC of the samples was expressed as mg of ascorbic acid equivalents per gram of sample (mg AAE/g).

2,2-Diphenyl-1-Picrylhydrazyl (DPPH) Radical Scavenging Activity

The DPPH radical scavenging activity was measured following the method described by Baliyan et al. (2022). 1 mL of the sample extract was mixed with 3 mL of 0.1 mM DPPH solution prepared in 80% methanol. After 30 min of incubating the mixture in a dark room, absorbance was read at 517 nm using a UV-Vis spectrophotometer (Cary 3500 Flexible, Agilent Technologies). The inhibition percentage was calculated in Equation (1) (Baliyan et al., 2022).

$$Inhibition\ (\%) = \frac{A_{control} - A_{sample}}{A_{control}} \times 100 \qquad (1)$$

Colour

Colour characteristics were determined using a digital colourimeter (CR-400, Konica Minolta, Inc., Tokyo, Japan) based on the CIELAB colour system, following the method of Uchegbu et al. (2022). The instrument was calibrated with a standard white tile before each measurement. Approximately 5 g of the sample was placed in a flat-bottomed Petri dish, and colour readings were taken at three randomly selected points on the sample surface. The L* value represents lightness (0 = black, 100 = white), a* denotes the red/green axis (positive values indicate redness, negative values indicate greenness), and b* corresponds to the yellow/blue axis (positive values indicate yellowness, negative values indicate blueness). Mean values were reported.

Techno-Functional Properties

Bulk Density (BD)

BD was evaluated according to the procedure reported by Uchegbu et al. (2022). Ten grams (10 g) of the powdered sample was carefully transferred into a 50 mL graduated measuring cylinder. The cylinder was gently tapped until no further volume change was observed, after which the settled volume was recorded. BD was calculated in Equation (2) (Uchegbu et al. 2022).

$$BD\ (g/cm^3) = \frac{Mass\ of\ sample\ (g)}{volume\ occupied\ (cm^3)} \quad (2)$$

Water absorption capacity (WAC)

WAC of *V. amygdalina* powder was assessed using the method described by Uchegbu et al. (2022). One gram (1 g) of the powdered sample was weighed into a centrifuge tube, and 10 mL of distilled water was added. The mixture was allowed to stand at ambient temperature for 30 min, followed by centrifugation at 3000 rpm for 15 min. The supernatant was carefully decanted, and the residue was weighed. WAC was calculated in Equation (3) (Uchegbu et al. 2022).

$$WAC\ (g/g) = \frac{Weight\ of\ water\ absorbed}{Weight\ of\ dry\ sample} \quad (3)$$

Rehydration Ratio (RR)

RR was determined following the method described by Uchegbu et al. (2022). Five grams (5 g) of the dried leaf sample was immersed in 100 mL of hot water (90°C) and allowed to soak for 20 min. The rehydrated sample was then drained, blotted to remove excess surface water, and reweighed. RR was calculated in Equation (4) (Uchegbu et al. 2022).

$$RR = \frac{Weight\ of\ rehydrated\ sample\ (g)}{Weight\ of\ dry\ sample\ (g)} \quad (4)$$

Statistical Analysis

All experiments were performed in triplicate (n=3). Data were expressed as mean±standard deviation. Analysis of variance (ANOVA) was performed using IBM SPSS software (version 20.0, IBM Corp., Armonk, NY, USA) at a significance level of $p<0.05$. Differences between means were separated using Duncan's multiple range test.

RESULTS AND DISCUSSION

Effect of RWD and OD on Proximate Composition of V. *amygdalina*

Table 1 presents the effect of RWD and OD on the proximate composition of *V. amygdalina*. The moisture content ranged from 6.57% (RWD) to 9.04% (OD), crude fat (3.34% (RWD)) to (2.31% (OD)), crude fiber (4.57% (RWD)) to (3.35%(OD)), ash (7.24 (RWD)) to (5.64% (OD)), protein (15.60% (RWD)) to (12.73% (OD)), and carbohydrate (66.93% (OD)) to (62.70% (RWD)). The lower moisture content observed in RWD-dried samples (6.57%) compared to the OD (9.04%) could be attributed to the synergistic effect of conductive, convective, and radiative heat transfer, facilitated by the Mylar film. This mechanism creates a uniform thermal flux that prevents the formation of a dry surface crust, common in connective systems, thereby ensuring continuous internal moisture diffusion and more thorough dehydration. The observations reported by Padhi et al. (2022) on the effects of RWD on unripe green banana flour are similar with this present study. The reduction of the moisture content below 10% corroborates with Silva et al. (2024), who investigated the effects of RWD on brewer's spent grain. Samples dried with RWD showed higher crude fat content (3.34%), reflecting the milder drying environment and reduced oxidative stress. The indirect conductive-radiative heat transfer of RWD minimizes thermal and oxygen-induced lipid degradation, which is more pronounced in high-velocity hot-air systems like drying. Comparable improvements in fat retention under RWD was also reported by Padhi et al. (2022).

Crude fiber content was significantly higher in RWD-dried samples (4.57%) compared to OD (3.35%), likely due to gentler heat transfer and minimized structural degradation. The indirect conductive-radiative heating mechanism of RWD maintains lower product temperatures, thereby preserving cell wall polysaccharides and fibrous matrix integrity that are prone to thermal breakdown under prolonged convective hot-air exposure.

Table 1: Effect of RWD and OD on the Proximate Composition of Dried *V. amygdalina*

Sample	Moisture %	Crude fat %	Crude fiber %	Ash %	Protein %	Carbohydrate %
RWD	6.57±0.64^b	3.34±0.01^a	4.57±0.05^a	7.24±0.04^a	15.60±0.03^a	62.70±0.03^b
OD	9.04±0.21^a	2.31±0.06^b	3.35±0.12^b	5.64±0.12^b	12.73±0.13^b	66.93±0.66^a

RWD, Refractance Window Drying; OD, Oscillatory Hot-Air Drying. All Values are Mean±SD (n=3). Means with Different Superscript Letters ($^{a-b}$) in the Same Column are Significantly Different ($p<0.05$) by Duncan's Multiple Range Test

This observation is consistent with the findings of Dadhaneeya et al. (2023), who reported higher crude fiber retention in RWD-dried banana pulp compared with hot-air drying, indicating improved preservation of structural components under RWD conditions. RWD-dried samples exhibited higher ash content (7.24%), indicating superior retention of inorganic minerals. The controlled temperature profile in RWD reduces losses that can occur during convective drying due to uneven airflow, promoting effective concentration of mineral matter. Similar trends have been observed by Puente-Díaz et al. (2020), thus showing the effectiveness of RWD in preserving mineral components. The higher crude protein content in RWD-dried *V. amygdalina* (15.60%) compared to OD (12.73%) is attributed to the superior thermal regulation of the RWD system. In OD, high-intensity convective heat and turbulent airflow can elevate surface temperatures, leading to thermal denaturation of proteins and loss of nitrogenous compounds. In contrast, RWD's indirect conductive-radiative heat transfer maintains lower, uniform product temperatures, protecting the amino acid profile from degradation. This observation is consistent with Waghmare (2021), who reported that RWD minimizes thermal stress on bio-origin products, ensuring higher retention of thermolabile nutrients than conventional convective methods. Furthermore, this finding aligns with Zalpouri et al. (2025), who noted that RWD prevents "hot spots," thereby preserving nutritional quality. The total carbohydrate fraction was higher in OD samples by mass balance (66.93%), than in RWD samples (62.70%), thereby demonstrating a more stable nutrient density relative to the higher protein and ash concentrations. The regulated heat flux in RWD effectively reduces the rates of caramelization and Maillard browning, preserving the chemical integrity of the sugar and starch matrix despite variations in total fraction calculations.

Effect of RWD and OD on the TPC of V. *amygdalina*

Figure 3 (A) shows the effect of RWD and OD on the TPC of dried *V. amygdalina*. The TPC of RWD-dried samples (40.54 mg GAE/100 g) was significantly higher than that of OD-dried samples (30.95 mg GAE/100 g), indicating superior phenolic retention in the former. The enhanced TPC observed in RWD-dried bitter leaves is attributed to the mild and controlled heat transfer mechanism of RWD, which minimizes thermal and oxidative degradation of heat-sensitive phenolic compounds through rapid moisture removal and restricted oxygen exposure. In contrast, OD utilizes convective hot air, which accelerates phenolic degradation due to intensified thermal and mechanical stress. This finding aligns with Santos et al. (2022), who reported significantly higher phenolic retention in RWD-dried amaranth vegetables compared to conventional drying methods, attributing the preservation to the maintenance of controlled product temperature. Likewise, the work of Padhi et al. (2022) further supports the ability of RWD to preserve phenolics better than hot air drying of unripe green banana.

Effect of RWD and OD on the TAC of V. *amygdalina*

Figure 3 (B) illustrates the effect of RWD and OD on the TAC of dried *V. amygdalina*, where TAC values were 54.39 mg AAE/g for RWD-dried samples and 43.39 mg AAE/g for OD-dried samples. This indicates a significantly higher antioxidant retention in the leaves dried using RWD. The superior TAC observed in RWD-dried bitter leaves could be attributed to the RWD mechanism, which employs indirect conductive–radiative heat transfer through a thin polymeric film in contact with hot water. This process minimizes direct exposure of plant tissues to high temperatures and oxygen, thereby reducing oxidative degradation of heat-sensitive antioxidant compounds such as polyphenols, flavonoids, and ascorbic acid. This finding is consistent with the work of Martínez-Sánchez et al. (2024), who reported that RWD preserved antioxidant activity, colour, and bioactive compounds in beetroot more effectively than conventional tray drying. Similarly, Nansereko et al. (2022) observed enhanced antioxidant retention in jackfruit pulp dried using RWD, attributing this to rapid moisture removal and reduced thermal stress.

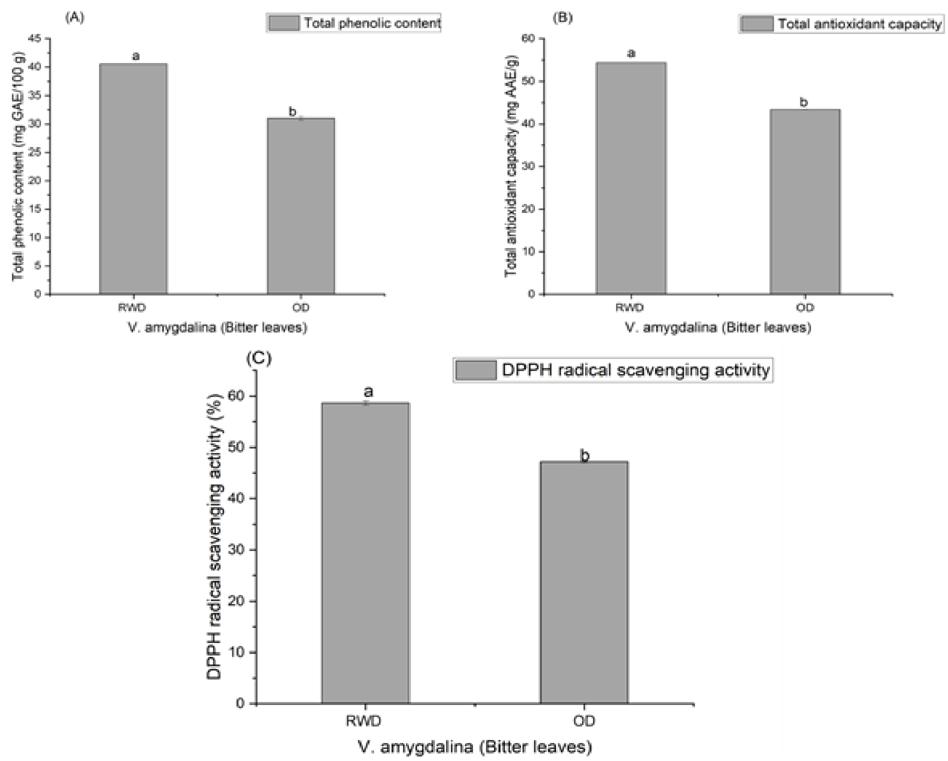


Figure 3: Effect of RWD and OD on the Total Phenolic Content (A) Total Antioxidant Capacity (B) and DPPH (C) of *V. amygdalina* (Bitter Leaves). All Values are Mean±SD (n=3). Means with Different Superscript Letters ($^{a\text{-}b}$) on the Bars for the Same Variable (TPC, TAC or DPPH) Indicate Significant Difference Between Drying Methods by Duncan's Multiple Range Test ($p<0.05$)

Effect of RWD and OD on the DPPH Radical Scavenging Activity of V. *amygdalina*

Figure 3 (C) illustrates the effect of RWD and OD on the DPPH radical scavenging activity of dried *V. amygdalina*, where DPPH values were 58.65% for RWD-dried samples and for 47.20% OD-dried samples. The mild and indirect heating associated with RWD minimize oxidative and thermal degradation of these compounds, which are often compromised by the high-velocity hot air and mechanical stress of OD. The scavenging activity obtained from this study is close to the value of Kaveh et al. (2024) during the experimentation of drying of mint leaves using RWD, relating the increased value to the release of antioxidative cellular compounds. These findings are consistent with Kaveh et al. (2025), who reported that RWD-treated rose flowers exhibited the highest DPPH activity when compared with infrared and convective drying methods. These results further support the suitability of RWD for preserving functional antioxidant properties in leafy vegetables such as V. amygdalina.

Effect of RWD and OD on the Colour Attributes of V. *amygdalina*

Table 2 presents the effect of RWD and OD on the colour attributes of dried *V. amygdalina*. The colour parameters, expressed as lightness (L*), redness–greenness (a*), and yellowness–blueness (b*), showed distinct variations between the two drying methods. The RWD samples recorded higher L* values (29.78) compared to OD samples (16.77), indicating better retention of brightness and reduced browning. Higher L* values are commonly associated with minimal thermal degradation and reduced non-enzymatic browning reactions during the drying process. This improved lightness observed in RWD-dried *V. amygdalina* may be attributed to relatively low product temperatures and rapid moisture removal facilitated by the thin-film heat transfer mechanism of the RWD system. Similar trends were reported by Puente-Díaz et al. (2020), who observed higher L* values in RWD-dried Physalis fruit purée due to reduced thermal stress. Minuye et al. (2024) also observed higher values of L* in mango, avocado, and tomato, dried with RWD, compared to a conventional oven drying.

The a* values further distinguished the drying methods, with RWD samples exhibiting negative a* values (–0.28 ± 4.09), indicating a retention of the green spectrum, while OD samples showed positive a* values (0.87 ± 3.83), suggesting a shift towards redness and browning. The preservation of green colour in RWD-dried *V. amygdalina* suggests reduced chlorophyll degradation, which is often accelerated in convective drying systems. The lower a* values observed in RWD samples support the ability of this technique to maintain the natural green pigment of leafy vegetables. Similar findings were reported by Nemzer et al. (2018), who observed lower a* value in cherries and strawberries dried with RWD, attributing the effect to reduced pigment degradation compared to hot-air drying. Largo-Avila et al. (2024), also reported that RWD of peach recorded lower a* value when compared to conventional oven drying method. The b* values were also higher in RWD-dried samples (25.07 ± 1.83) than in OD-dried samples (19.30 ± 2.81), indicating superior retention of yellow pigments such as carotenoids. This enhanced b* retention reflects improved pigment stability under the mild, indirect conductive–radiative heating characteristic of RWD, which limits thermal and oxidative degradation. This observation is consistent with the findings of Zamani et al. (2023), who reported significantly higher b* values in *Dracocephalum kotschyi* samples dried with RWD compared with other drying techniques (shade and sun drying).

Table 2: Effect of RWD and OD on the Colour (L*, a*, b*) of *V. amygdalina*

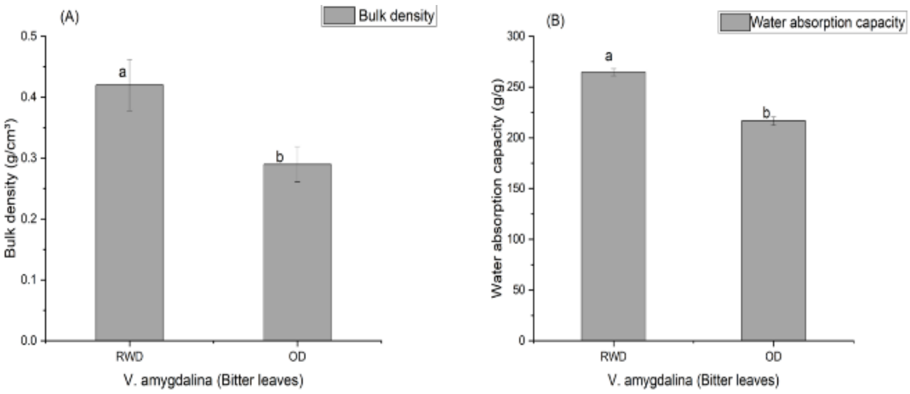
Samples	L*	a*	b*
RWD	29.78 ± 1.98^{a}	0.28 ± 4.09^{b}	25.07 ± 1.83^{a}
OD	16.77 ± 1.63^{b}	0.87 ± 3.83^{a}	19.30 ± 2.81^{b}

RWD, Refractance Window Drying; OD, Oscillatory Hot-Air Drying. All Values are Mean±SD (n=3). Means with Different Superscript Letters ($^{a-b}$) in the Same Column are Significantly Different ($p<0.05$) by Duncan's Multiple Range Test

Effect of RWD and OD on the Techno-Functional Properties of V. *amygdalina*

Figure 4 shows the effect of RWD and OD on the BD, RR and WAC of the *V. amygdalina*. The RWD-dried samples exhibited superior functional properties compared with samples dried using OD. BD values were higher for RWD-dried *V. amygdalina* (0.42 g/cm³) compared with OD-dried samples (0.29 g/cm³), suggesting improved structural compactness and reduced excessive porosity. Higher BD is advantageous for packaging, transportation, and storage efficiency. The uniform heat distribution and gentle drying conditions of RWD likely contributed to reduced structural damage and better matrix integrity. Similar results were reported by Zomorodi and Hedayat (2023), who observed higher BD in RWD-dried tomato and plant-based powders compared with conventionally dried samples, attributing this to reduced tissue collapse and improved particle packing. The water absorption capacity of RWD-dried *V. amygdalina* (264.10 ± 3.68 g/g) was significantly higher than that of OD-dried samples (216.42 ± 5.06 g/g). Higher WAC values indicate improved hydration ability, which is desirable for reconstituted vegetable products. This enhanced water absorption may be attributed to the preservation of hydrophilic functional groups and a more intact microstructure resulting from the mild and indirect thermal conditions of RWD. Nansereko et al. (2022) similarly reported higher WAC in RWD-dried jackfruit pulp compared with oven- and solar-dried samples, linking this effect to reduced cellular collapse and improved structural integrity.

RR followed a similar trend, with RWD-dried samples exhibiting higher values (3.51 ± 0.00) than OD-dried samples (2.89 ± 0.04). A higher RR reflects better restoration of the dried product to its original state upon water uptake and is indicative of minimal structural damage during drying. The efficient heat transfer associated with RWD helps preserve capillary pathways within plant tissues, thereby enhancing rehydration performance. This observation agrees with the findings of Ayala-Aponte et al. (2021), who reported excellent rehydration characteristics in RWD-dried aloe vera gel due to minimal tissue shrinkage and collapse. Zalpouri et al. (2021) reported that potato flakes dried with RWD had higher RR than convective tray drying, which supports this present study's outcome.



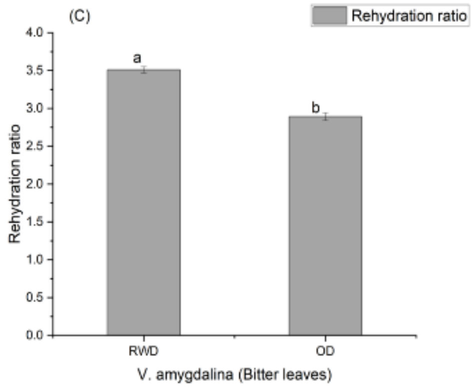


Figure 4: Effect of RWD and OD on the BD (A) WAC (B) and RD (C) of the *V. amygdalina.* All values are mean±SD (n=3). Means with different superscript letters ([a-b]) on the bars for the same variable (BD, WAC or RR) indicate significant difference between drying methods by Duncan's multiple range test ($p<0.05$)

CONCLUSION

This study demonstrated that RWD is more effective than OD in preserving the nutritional, antioxidant, colour, and techno-functional quality of *V. amygdalina.* RWD produced leaves with lower residual moisture content and superior retention of protein, fat, fiber, ash, and bioactive compounds, resulting in enhanced antioxidant capacity and improved colour preservation. In addition, RWD-dried samples exhibited better functional properties, including higher WAC, RR and BD, indicating reduced structural degradation during drying. Therefore, this study established RWD as a promising low-temperature drying technology for leafy vegetables and other heat-sensitive plant materials, offering significant potential for producing high-quality functional foods and nutraceutical ingredients.

REFERENCES

AOAC. *Official Methods of Analysis of the Association of Official Analytical Chemists: Official Methods of Analysis of AOAC International*. 21st ed, AOAC, Washington DC, USA (2019)

Agomuo JK, Nasiru BU, Ifeka C. Effect of different drying methods on the nutritional and sensory attributes of Abelmoschus esculentus (okra). *FUDMA Journal of Sciences*, *6*(3), 70-75 (2022)

Ayala-Aponte AA, Cárdenas-Nieto JD, Tirado DF. Aloe vera gel drying by Refractance Window®: Drying kinetics and high-quality retention. *Foods,* 10, 1445 (2021)

Baliyan S, Mukherjee R, Priyadarshini A, Vibhuti A, Gupta A, Pandey RP, Chang CM. Determination of antioxidants by DPPH radical scavenging activity and quantitative phytochemical analysis of Ficus religiosa. *Molecules,* 27, 1326 (2022)

Dadhaneeya H, Nayak PK, Saikia D, Kondareddy R, Ray S, Kesavan RK. The impact of refractance window drying on the physicochemical properties and bioactive compounds of malbhog banana slice and pulp. *Appl Food Res*, 3, 100279 (2023)

Eapen AS, Bhosale YK, Roy S. A Review on Novel Techniques Used for Drying Medicinal Plants and Its Applications. *Int J Biomater*, 2025, 4533070 (2025)

ElGamal R, Song C, Rayan AM, Liu C, Al-Rejaie S, ElMasry G. Thermal degradation of bioactive compounds during drying process of horticultural and agronomic products: A comprehensive overview. *Agronomy*, 13, 1580 (2023)

Eraga LI. Determination and comparison of total flavonoid and phenol content amongst Vernonia amygdalina varieties collected from Southern Nigeria. *Direct Res J Health Pharm,* 8, 7–15 (2020)

Jadhav PD. Refractance Window Drying (RWD) in Food Processing and Preservation: A Comprehensive Review. Vigyan Varta an International E-Magazine for Sci. Enthusiasts, 5 9, 265 - 268 (2024)

Kaveh M, Zomorodi S, Ghaysari B, El-Mesery HS, Sharifian F, ElMesiry AH, Salem A. Impact of various drying technologies for evaluation of drying kinetics, energy consumption, physical and bioactive properties of Rose flower. *Sci Rep*, 15, 9245 (2025)

Kaveh M, Zomorodi S, Mariusz S, Dziwulska-Hunek A. Determination of drying characteristics and physicochemical properties of mint (Mentha spicata L.) leaves dried in refractance window. *Foods*, 13, 2867 (2024)

Largo-Avila E, Rico-Rodríguez F, Peñaloza-Figueroa JK, López-Padilla A. Effect of Refractance Window™ and oven drying on physicochemical and sensory properties of peach (Prunus persica L.) surplus. *Front Nutr*, 11, 1307423 (2024)

Martínez-Sánchez CE, Torres-Niño MS, Ramírez-Figueroa E, Rodríguez-Miranda J, Gallegos-Marín I, Calderón-Chiu C, Herman-Lara E. Evaluation of energy efficiency and quality parameters by drying beets with a refractive window (Beta vulgaris). *LWT*, 206, 116589 (2024)

Minuye M, Yenasew A, Belew S. Effect of drying method on the nutritional and antioxidant properties of mango, avocado, and tomato. *J Hortic Res*, 32, 75-83 (2024)

Mwaurah PW, Setlhoka MD, Malik T. Refractance Window Drying: Principles and Applications. In: *Thermal Food Engineering Operations*, Publisher Info, City, Country, p 237-260 (2022)

Nansereko S, Muyonga J, Byaruhanga YB. Influence of drying methods on jackfruit drying behavior and dried products physical characteristics. *Int J Food Sci*, 8432478 (2022)

Nemzer B, Vargas L, Xia X, Sintara M, Feng H. Phytochemical and physical properties of blueberries, tart cherries, strawberries, and cranberries as affected by different drying methods. *Food Chemistry*, 262, 242-250 (2018)

Ofodile SN. Assessing the phytochemical contents and antimicrobial activity of bitter leaf (Vernonia amygdalina) on micro-organisms. *Int J Funct Res Sci Eng*, 3, 1 (2025)

Okolie H, Ndukwe O, Obidiebube E, Obasi C, Enwerem J. Evaluation of nutritional and phytochemical compositions of two bitter leaf (Vernonia amygdalina) accessions in Nigeria. *Int J Res Innovation Appl Sci*, 6, 2454-6194 (2021)

Padhi S, Murakonda S, Dwivedi M. Investigation of drying characteristics and nutritional retention of unripe green banana flour by refractance window drying technology using statistical approach. *J Food Meas Charact*, 16, 2375-2385 (2022)

Puente-Díaz L, Spolmann O, Nocetti D, Zura-Bravo L, Lemus-Mondaca R. Effects of infrared-assisted refractance window drying on the drying kinetics, microstructure, and colour of physalis fruit purée. *Foods*, 9, 343 (2020)

Rurush E, Alvarado M, Palacios P, Flores Y, Rojas ML, Miano AC. Drying kinetics of blueberry pulp and mass transfer parameters: Effect of hot air and refractance window drying at different temperatures. *J Food Eng*, 320, 110929 (2022)

Sanusi MS, Sunmonu MO, Alasi SO, Adebiyi AA, Tajudeen AA. Composition, bioactive constituents and glycemic index of brown rice-watermelon seeds extruded snacks as stimulated by extrusion conditions. *Appl Food Res*, 3, 100287 (2023)

s VCS, Souza RLD, Figueiredo RT, Alsina OLSD. A review on refractance window drying process of fruits and vegetables: its integration with renewable energies. *Braz J Food Technol*, 25, e2021153 (2022)

Silva NC, Santos AO, Duarte CR, Barrozo MA. Refractance window drying as an alternative method for brewer's spent grain preservation. *Appl Biosci*, 3, 71-86 (2024)

Tamala Y, Yani M, Sailah I, Halimatushadyah E, Tallei TE. Comparative study of drying techniques on the anti-inflammatory content of bitter leaf simplicia (Vernonia amygdalina Del.). *Adv Food Sci Sustainable Agr Agroind Eng*, 8, 492-502 (2025)

Uchegbu NN, Oni K, Olagunju TM. Vernonia amygdalina processing as a functional ingredient: Oil-thermal influence on antioxidant, vitamin, mineral, and functional group retention. *J Food Process Preserv*, 46, e16846 (2022)

Waghmare R. Refractance window drying: A cohort review on quality characteristics. *J Food Sci Technol*, 110, 652-662 (2021)

Yumita A, Hanani E, Agustina A, Damayanti F, Priani KN, Fadila SIN. Total phenolic content and antioxidant activities of leaves and bark extract of Adenanthera pavonina L. *Nat Prod Sci*, 29, 24-30 (2023)

Zalpouri R, Kaur P, Kaur A, Sidhu GK. Comparative analysis of optimized physiochemical parameters of dried potato flakes obtained by refractive and convective drying techniques. *J Food Process Preserv*, 45, e15077 (2021)

Zalpouri R, Singh M, Kaur P, Kaur A, Gaikwad KK, Singh A. Drying kinetics, physicochemical and thermal analysis of onion puree dried using a refractance window dryer. *Processes*, 11, 700 (2023)

Zalpouri R, Singh M, Kaur P, Singh S, Kumar S, Kaur A. Mathematical and artificial neural network modelling for refractance window drying kinetics of coriander (Coriandrum sativum L.) followed by the determination of energy consumption, mass transfer parameters and quality. *Biomass Conversion Biorefinery*, 15, 967-983 (2025)

Zamani S, Bakhshi D, Sahraroo A, Ebadi MT. Improvement of phytochemical and quality characteristics of Dracocephalum kotschyi by drying methods. *Food Sci Nutr*, 11, 4246-4262 (2023)

Zomorodi S, Hedayat A. Impact of Refractance Window drying method on physical properties and phenolic antioxidants of tomato powder. *Research Square*, https://doi.org/10.21203/rs.3.rs-2961093/v1 (2023).