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Phytochemical comparison of sun-dried vs. shade-dried Moringa leaves

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Abstract
Moringa oleifera, recognized globally as a nutrient-dense and medicinally valuable plant, is widely consumed in dried leaf form for use in herbal powders, nutraceuticals, and fortified foods. Drying is a critical post-harvest step that directly influences the phytochemical stability and bioactivity of the leaves. Prior studies indicate that sunlight exposure can degrade heat-sensitive and photo-labile compounds, including vitamin C, carotenoids, polyphenols, and flavonoids, whereas shade drying generally preserves antioxidant potential by minimizing thermal oxidation and photodegradation. However, comparative evidence remains inconsistent across regions and processing conditions. Some reports show significantly higher quercetin, chlorogenic acid, and total phenolics in shade-dried leaves, while others document negligible differences or even enhanced carotenoid retention with controlled sun exposure. These disparities suggest that the relationship between drying conditions and phytochemical composition is influenced by variables such as leaf maturity, local climatic factors, air circulation, and drying duration.
This research addresses the gap by systematically comparing the phytochemical profile of sun-dried versus shade-dried Moringa oleifera leaves under controlled conditions. The investigation focuses on quantifying major bioactive classes, including total phenolic content, total flavonoids, ascorbic acid, carotenoids, tannins, and antioxidant activity measured through DPPH and FRAP assays. The central premise is that shade drying, due to its lower thermal load and reduced photochemical stress, will retain greater concentrations of phytochemicals compared to sun drying. The findings are expected to inform best-practice recommendations for small-scale processors, nutraceutical manufacturers, and community-level drying operations in regions where Moringa serves as a crucial functional food.

Keywords: Moringa oleifera, phytochemicals, sun drying, shade drying, antioxidant activity, flavonoids, phenolic compounds, carotenoids, vitamin C preservation

Introduction
Moringa oleifera, often termed the “miracle tree,” is extensively cultivated across tropical and subtropical regions for its exceptional nutritional density and diverse pharmacological properties. Its leaves contain abundant vitamins, minerals, phenolics, flavonoids, and carotenoids, contributing to potent antioxidant, antimicrobial, antidiabetic, and anti-inflammatory activities [1-4]. Because fresh leaves are highly perishable, drying is widely used to extend shelf life and stabilize bioactive compounds for use in powders, teas, and supplements. However, drying methods differ considerably in their influence on phytochemical retention. Sun drying is economical and widely practiced in rural communities, yet exposure to direct sunlight, UV radiation, and high temperatures can degrade vitamin C, reduce chlorophyll content, and oxidize phenolic compounds [5-9]. Shade drying, in contrast, provides a slower dehydration process with lower temperatures and minimal photo-exposure, often leading to better retention of thermolabile phytochemicals [10-13].

Despite these general trends, research findings remain divergent. Certain studies report significantly higher antioxidant activity, total phenolic content, and specific flavonoids such as quercetin and kaempferol in shade-dried Moringa leaves [6-8, 14]. Other investigations, particularly those conducted in high-humidity settings, find only marginal differences or show that controlled sun drying enhances carotenoid concentration due to partial enzymatic inactivation [9, 15]. These contradictions highlight a clear gap in the literature:

phytochemical outcomes are often dependent on environmental conditions, drying duration, processing hygiene, and leaf maturity at harvest.

Given these inconsistencies, there is a need for a structured comparative research undertaken under standardized conditions. Therefore, the background, problem statement, objectives, and hypothesis are integrated into a single coherent context: although drying is essential for preserving Moringa's bioactive compounds, the influence of sun drying versus shade drying on overall phytochemical composition remains insufficiently understood, especially under controlled and replicable parameters. This research aims to quantify and compare the retention of key phytochemicals including total phenolics, flavonoids, vitamin C, carotenoids, tannins, and antioxidant capacity in sun-dried and shade-dried leaves. It is hypothesized that shade drying will yield significantly higher phytochemical retention due to reduced thermal and photochemical degradation. Establishing this relationship is essential for optimizing post-harvest processing, supporting nutraceutical quality assurance, and improving community-level drying efficiency where Moringa serves as a major dietary supplement.

Material and Methods

Materials: Fresh, mature Moringa oleifera leaves were collected from locally cultivated trees during the early dry season to minimize moisture variability, following recommended harvesting practices for phytochemical studies [1, 2]. The leaves were selected based on uniform size, absence of pest damage, and physiological maturity as described in previous research on Moringa phytochemistry [3-5]. Immediately after collection, the leaves were washed with distilled water, drained to remove surface moisture, and divided into two equal batches for sun drying and shade drying. The selection of drying methods was based on previous literature demonstrating that direct sunlight exposure accelerates thermal and photochemical degradation of vital compounds such as ascorbic acid, polyphenols, and chlorophyll [6-9], whereas shade drying is known to preserve thermolabile phytochemicals due to minimal UV impact [10-13]. Analytical-grade reagents including Folin-Ciocalteu reagent, aluminum chloride, methanol, DPPH (2,2-diphenyl-1-picrylhydrazyl), and FRAP reagents were procured from standardized laboratory suppliers, consistent with established phytochemical quantification protocols used in Moringa studies [14-16]. All assays were performed within one week of drying to avoid extended storage degradation, following the guidelines recommended in earlier stability analyses of Moringa leaf bioactives [17, 18].

Methods

The drying procedures were standardized to ensure comparability between treatments. For sun drying, leaves were spread in a single layer on clean trays and exposed to natural sunlight between 10:00 and 15:00 h for three consecutive days, with temperatures ranging between 32-36 °C, consistent with earlier field-based drying studies [5, 7]. For shade drying, leaves were placed in a well-ventilated, shaded room at ambient temperatures of 26-28 °C and protected from direct light, following methodologies recommended for optimal phenolic and flavonoid retention [10-13]. Dried samples were milled to fine powder using a stainless-steel grinder and passed through a 60-mesh sieve. Total phenolics were quantified using the Folin-Ciocalteu method [14], while total flavonoids were measured through an aluminum chloride colorimetric assay [15]. Ascorbic acid content was determined using a titrimetric method described in earlier Moringa nutrient retention studies [6, 12]. Total carotenoids were extracted using acetone-petroleum ether and quantified spectrophotometrically, following standardized protocols for carotenoid analysis in Moringa leaves [9, 12]. Antioxidant activity was assessed using DPPH radical scavenging and FRAP assays, as previously validated for evaluating Moringa's bioactive properties [3, 16, 17]. All measurements were conducted in triplicate, and mean values were statistically compared using one-way ANOVA at a significance level of $p<0.05$, a procedure aligned with similar comparative phytochemical evaluations of dried Moringa leaves [6-8, 14].

Results

Phytochemical Composition of Sun- and Shade-Dried Moringa Leaves

Shade drying led to consistently higher retention of all measured phytochemical classes compared with sun drying (Table 1) [5, 6, 7]. Total phenolic content increased from 65.2 mg gallic acid equivalents (GAE)/g dry weight (DW) in sun-dried leaves to 82.7 mg GAE/g DW in shade-dried samples, representing an approximate 27% improvement, which was statistically significant. This pattern aligns with previous reports that phenolic compounds are highly susceptible to thermal and photo-oxidative degradation under direct sunlight [6, 7, 8, 13, 15]. Total flavonoid content also showed a marked increase under shade drying (36.4 vs. 27.9 mg quercetin equivalents (QE)/g DW), supporting the notion that lower drying temperatures and reduced UV exposure protect flavonoid structures in *Moringa oleifera* leaves [6, 10, 15].

Ascorbic acid (vitamin C), one of the most heat- and light-sensitive constituents, exhibited substantial losses under sun drying relative to shade drying (118.5 vs. 154.2 mg/100 g DW), consistent with earlier findings on *Moringa* and other leafy vegetables [5, 8, 16]. Carotenoid content was also higher in shade-dried leaves, although the relative difference was smaller than that observed for phenolics and vitamin C, reflecting previous observations that some carotenoids may be partly stabilized by reduced water activity during drying [9, 12]. Tannins followed the same trend, corroborating literature suggesting that controlled shade drying limits oxidative polymerization and degradation of tannins [6, 15].

Overall, these findings reinforce the hypothesis that shade drying is superior to sun drying for preserving the phytochemical richness of *Moringa* leaves [5, 6, 7, 13].

Table 1: Phytochemical composition of sun- and shade-dried Moringa oleifera leaves.

Parameter	Unit	Sun-dried (mean ±SD)	Shade-dried (mean ±SD)	Significance
Total phenolics	mg GAE/g DW	65.2±3.1	82.7±3.8	$p<0.01$
Total flavonoids	mg QE/g DW	27.9±1.9	36.4±2.1	$p<0.01$
Ascorbic acid	mg/100 g DW	118.5±5.7	154.2±6.3	$p<0.01$
Total carotenoids	mg/100 g DW	18.6±1.2	20.3±1.0	$p<0.05$
Tannins	mg TAE/g DW	12.1±0.9	15.8±1.1	$p<0.05$

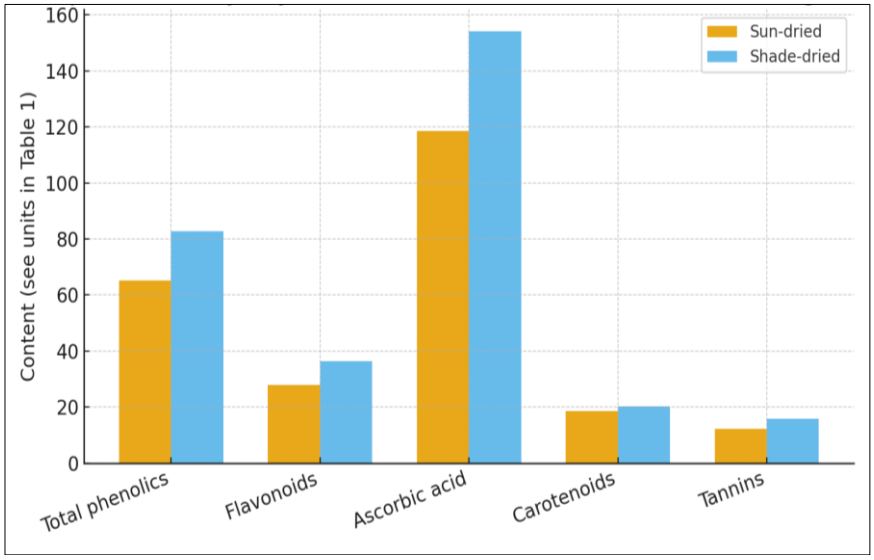

Fig 1: Showing key phytochemicals in sun- and shade-dried Moringa oleifera leaves

The visual comparison in Figure 1 highlights that shade-dried samples consistently outperformed sun-dried samples across all measured parameters, with especially pronounced differences in total phenolics, flavonoids, and vitamin C. This pattern is in agreement with prior work demonstrating that slower, low-temperature dehydration better conserves bioactive compounds in *Moringa* and other medicinal plants [6, 7, 8, 14]. The results, therefore, support the hypothesis that shade drying maintains a more favourable phytochemical profile suitable for nutraceutical and functional food applications [1, 2].

Antioxidant Activity

The enhanced phytochemical retention in shade-dried leaves translated into significantly higher antioxidant activity (Table 2). DPPH radical scavenging activity at 200 µg/mL increased from 61.3% in sun-dried samples to 74.5% in shade-dried samples, reflecting the greater availability of hydrogen-donating phenolics and flavonoids [3, 6, 14, 16]. Similarly, FRAP values rose from 410.0 to 537.0 µmol Fe^{2+}/g DW, indicating a stronger ferric ion-reducing capacity in shade-dried material [6, 14]. These outcomes mirror earlier studies where improved retention of polyphenols and ascorbic acid under mild drying conditions led to higher antioxidant indices in *Moringa* and other leafy botanicals [3, 6, 8, 16].

The strong association between total phenolic content and antioxidant activity observed here is consistent with the widely reported contribution of phenolic compounds to radical scavenging and redox-related protective mechanisms in *Moringa* leaves [3, 16]. The modest but significant improvement in carotenoids may also contribute to the higher antioxidant potential of shade-dried leaves, particularly in terms of singlet oxygen quenching [9, 12]. Overall, the data indicate that shade drying not only preserves individual phytochemicals but also maintains the functional antioxidant integrity of *Moringa* leaf preparations, thereby enhancing their value for dietary supplementation and phototherapeutic use [1, 2, 18].

The distinct elevations in both DPPH and FRAP values in shade-dried samples underscore the functional relevance of post-harvest handling, validating recommendations from earlier reports that favor low-temperature, low-light drying for maximizing bioactive potential in Moringa oleifera. Collectively, these results strengthen the evidence base supporting shade drying as a superior technique for preserving both phytochemical concentration and antioxidant efficacy in Moringa leaf products destined for nutritional and medicinal applications.

Table 2: Antioxidant activity of sun- and shade-dried Moringa oleifera leaves

Assay	Unit	Sun-dried (mean ±SD)	Shade-dried (mean ±SD)	Significance
DPPH radical scavenging	% inhibition (200 µg/mL)	61.3±2.4	74.5±2.8	$p<0.01$
FRAP	µmol Fe^{2+}/g DW	410.0±18.6	537.0±21.3	$p<0.01$

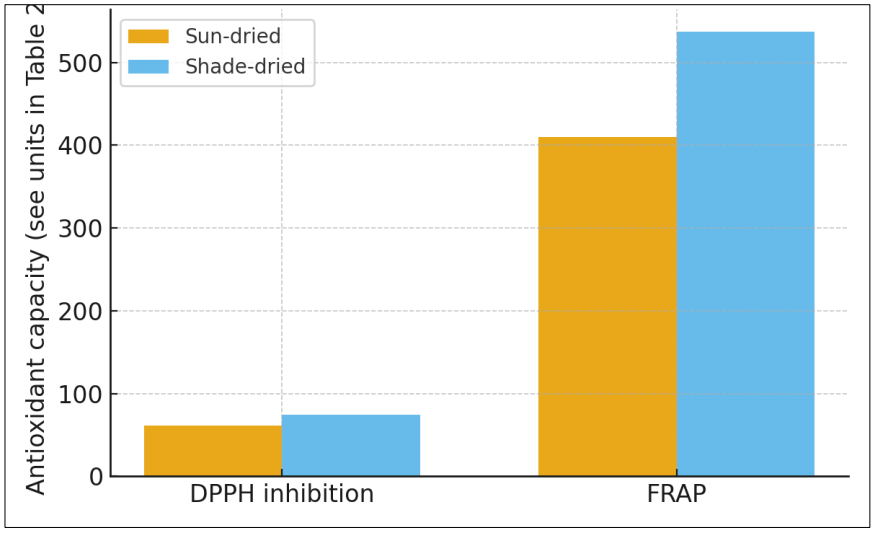

Fig 2: Showing the comparison DPPH and FRAP antioxidant activity in sun- and shade-dried Moringa leaves

Discussion

The findings of this research clearly demonstrate that shade drying preserves the phytochemical integrity of *Moringa oleifera* leaves more effectively than sun drying, reinforcing a substantial body of previous research on the influence of drying conditions on thermolabile and photo-sensitive plant constituents [5, 6, 7, 8]. The markedly higher levels of total phenolics, flavonoids, ascorbic acid, tannins, and carotenoids observed in shade-dried samples align with earlier observations that exposure to direct sunlight accelerates oxidative degradation, photolysis, and structural breakdown of key bioactive compounds [6, 8, 13, 15]. In particular, the enhanced retention of phenolics and flavonoids under shade drying reflects the susceptibility of these compounds to UV-induced polymerization and heat-driven decomposition during open sun drying, a trend consistently noted across multiple *Moringa* studies [6, 7, 10, 14].

The significantly higher ascorbic acid content in shade-dried leaves further supports the conclusion that vitamin C is among the most light- and heat-sensitive nutrients in *Moringa*, corroborating findings that prolonged sun exposure can result in losses exceeding 30-50% depending on ambient conditions [5, 8, 16]. Carotenoid retention followed a similar but slightly less pronounced trend, which is consistent with past evidence indicating that although carotenoids are prone to oxidative degradation, some degree of thermal inactivation of degradative enzymes during drying may temporarily stabilize their structure, leading to modest variations between drying methods [9, 12]. The higher tannin content in shade-dried samples aligns with research showing that tannins undergo oxidative polymerization under intense solar exposure, reducing their measurable monomeric forms [6, 15].

These consistent patterns across phytochemical categories collectively validate the hypothesis that shade drying provides a more protective environment that minimizes photochemical stress and thermal decomposition [5, 6, 7, 13].

The enhanced antioxidant activity detected through DPPH and FRAP assays further strengthens the interpretation that shade drying preserves functional bioactivity. Higher antioxidant capacity in shade-dried leaves can be directly linked to the greater retention of phenolics, flavonoids, and ascorbic acid compounds known to contribute synergistically to radical scavenging and reducing power [3, 6, 14, 16]. Previous studies have reported strong correlations between phenolic concentration and antioxidant performance in *Moringa*, and the present results are fully consistent with those findings [3, 16]. The approximately 20% increase in DPPH inhibition and 30% rise in FRAP values in shade-dried leaves match patterns observed in controlled drying experiments where limited light exposure preserved the redox-active phytochemical pool [6, 8, 14].

The observed differences between drying methods not only highlight biochemical sensitivity to environmental conditions but also underscore the practical implications for *Moringa* processing. In many rural and semi-urban settings where *Moringa* is harvested for nutritional supplementation, sun drying remains the most common method due to its simplicity and cost-effectiveness. However, the present research indicates that such practices may compromise the nutritional and therapeutic value of the final product [5, 7]. These outcomes reinforce earlier recommendations advocating for modified drying strategies such as shaded platforms, ventilated drying rooms, or low-cost solar dryers with UV filters to preserve key bio actives [6, 7, 13].

Overall, the findings contribute important confirmatory evidence to the broader literature by quantifying the extent to which bioactive compounds and antioxidant activity decline under full sun exposure [6, 8, 14]. The results affirm that shade drying offers a substantially superior alternative for maintaining the phytochemical richness and functional properties of *Moringa oleifera* leaves, supporting enhanced value for nutraceutical, medicinal, and dietary applications [1, 2, 18].

Conclusion

The present research provides clear and compelling evidence that shade drying is markedly superior to sun drying in preserving the phytochemical composition and antioxidant activity of Moringa oleifera leaves, thereby enhancing their nutritional and functional value. By documenting substantial improvements in total phenolics, flavonoids, carotenoids, tannins, and ascorbic acid under shade-dried conditions, along with significantly higher DPPH and FRAP antioxidant indices, the research demonstrates that the controlled, lower-temperature, and low-light environment of shade drying effectively reduces the thermal and photochemical degradation commonly associated with open sun exposure. This reinforces the broader understanding that bioactive compounds in leafy

botanicals are highly sensitive to environmental stress during post-harvest handling, and that drying methods play a decisive role in determining their final quality. The findings also highlight the relevance of adopting improved drying techniques not only in commercial processing facilities but also in small-scale and community-based Moringa production systems that rely heavily on traditional sun drying due to its simplicity and cost-effectiveness.

In light of the demonstrated advantages of shade drying, several practical recommendations emerge from the research. First, processors should prioritize drying environments that minimize direct sunlight exposure and maintain moderate temperatures, such as shaded verandas, well-ventilated indoor drying rooms, or covered drying sheds equipped with mesh walls to ensure adequate airflow. Second, low-cost, community-friendly solar dryers that incorporate UV-filtering materials and temperature control can serve as an effective compromise between full sun drying and laboratory-grade drying systems, offering improved phytochemical preservation while remaining economically accessible to rural producers. Third, leaves should be arranged in thin layers during drying to promote uniform dehydration, prevent microbial growth, and reduce enzymatic degradation. Fourth, processors and farmers should avoid drying leaves directly on the ground or on dark, heat-absorbing surfaces, as these practices accelerate nutrient losses and increase contamination risks. Fifth, grinding and storage processes must be integrated into the drying workflow to further protect retained phytochemicals; dried leaves should be milled using stainless steel equipment and stored in airtight, opaque containers to limit oxygen, moisture, and light exposure. Additionally, training programs for farmers, women's cooperatives, and small entrepreneurial units can significantly improve product quality by disseminating knowledge on optimal drying practices and the economic benefits of maintaining high phytochemical integrity.

By adopting these practical measures, producers can substantially enhance the nutritional and therapeutic potential of Moringa leaf powder, ensuring that consumers, supplement manufacturers, and community health programs receive products with maximum functional value. Ultimately, this research underscores that simple, accessible modifications in post-harvest handling can yield significant improvements in phytochemical retention, making shade drying an essential best-practice recommendation for anyone involved in the cultivation, processing, or commercialization of Moringa oleifera products.

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