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ENHANCING NUTRIENT AND PHYTOCHEMICAL RETENTION IN *MORINGA* LEAF POWDER: AN ASSESSMENT ON DRYING METHODS AND LEAF AGE USING MULTIVARIATE ANALYSES

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ABSTRACT

Moringa (*Moringa oleifera*), a tropical tree originating from India and Africa, is renowned for its modest utility as timber and its significance as a crucial vegetable crop. Notably, *Moringa* leaves serve as a concentrated source of vital nutrients, encompassing iron, calcium, proteins, vitamins (A, C, and E), dietary fiber, phosphorous, and potassium, all of which are pivotal for human well-being. Moreover, their substantial content of antioxidants, such as flavonoids and phenolics, imparts significant medicinal properties. The sporadic cultivation patterns of *moringa*limits their global availability. Nevertheless, the utilization of *moringa* leaf powder presents a viable solution, enhancing its potential for global exportation. This research seeks to assess the suitability of different dryers for the production of *moringa* leaf powder while retaining its nutritional quality. Conducted at the Post-Harvest Technology Laboratory, Department of Horticulture, Rajasthan College of Agriculture, and the Department of Processing and Food Engineering, College of Technology and Agricultural Engineering, Maharana Pratap University of Agriculture and Technology in Udaipur, Rajasthan, India, the study delves into various quality parameters of *moringa* leaf powder subjected to diverse drying methods and leaf age. Our investigation reveals that the fluidized bed dryer outperformed tray and heat pump dryers, maintaining superior nutrition and quality. Additionally, our findings indicate that heat pump dryers are not conducive to producing high-quality *moringa* leaf powder. Principal component analysis supports and reinforces these conclusions.

Keywords: Moringa, leaf powder, drying, fluidized bed dryer, quality, nutritional profile

Introduction

Moringa (*Moringa oleifera*) is a tropical tree known for its low-quality timber and as a vital vegetable crop originating from India and Africa. Referred to as a "superfood" due to its rich nutrient content, particularly in its leaves, it has gained popularity among marginal farmers (Balakumbahan *et al.*, 2020). India is the leading producer, annually yielding around 2.2 million tonnes of tender fruits from an approximate 38,000-hectare cultivation area.

Moringa leaves represent a highly concentrated reservoir of essential nutrients, including iron, calcium, proteins, vitamins (A, C, and E), dietary fiber, phosphorous, and potassium, pivotal for human well-being. Additionally, their richness in antioxidants, such as flavonoids and phenolics, endows them with significant medicinal properties. The nutritional profile of *moringa* leaves addresses global concerns related to malnutrition in children and anemia, while also serving as a traditional remedy for hypertension. Furthermore, the dried leaves of *moringa* serve as raw materials for pharmaceutical, confectionary, animal feed, and nutraceutical industries (Balakumbahan *et al.,* 2020). Their versatility extends to culinary applications, where fresh leaves can be incorporated into various dishes, including soups, salads, fried foods, and curds (Yameoga *et al.,* 2011).

Moringa stands out as an exceptionally rich plant source of fat-soluble vitamins A, D, E, and K, along with water-soluble vitamins B and C. Essential minerals, including calcium, copper, iron, potassium, magnesium, manganese, and zinc, are also abundant. With over 40 natural antioxidants, dried *moringa* leaves exhibit remarkable micronutrient content, boasting ten times the vitamin A of carrots, 17 times the calcium of milk, 15 times the potassium of bananas, 25 times the iron of spinach, and nine times the protein of curd (Mahmood *et al.,* 2010). Drying, an ancient preservation method dating back to prehistoric times, continues to play a crucial role in today's food supply chain.

Drying processes, such as air/contact drying, freeze drying, and vacuum drying, operate on the principle of reducing the water content in food to prevent or slow down spoilage by microorganisms (Ahmed *et al.,* 2013). Moisture removal inhibits the growth of spoilage microorganisms, reduces damaging reactions associated with moisture, and results in decreased weight and volume. This, in turn, lowers packaging, storage, and transportation costs, allowing for extended ambient temperature storage. Various types of dryers, including mechanical hot air dryers (tray dryers, tunnel dryers, drum dryers), microwave dryers, solar dryers, freeze dryers, heat pump dryers, fluidized bed dryers, and vacuum dryers, are employed for this purpose. Each drying process involves specific parameters, such as selective variety, slice size, drying time, microwave power rates, and dryer temperatures, to ensure the highest quality of finished products. The primary objectives of crop drying are to enhance shelf life, improve quality, facilitate handling, storage, and transportation, and prepare the product for subsequent processing.

The tray dryer is commonly used in agricultural drying due to its simple design and high-volume drying capacity. However, its main drawback is uneven drying caused by inadequate airflow distribution in the drying chamber. Fluidized bed dryers (FBD) are widely utilized in various industries for drying particulate solids, offering advantages such as effective solids mixing, high heat and mass transfer rates, and ease of material handling. Efficient operation of FBD requires regular monitoring and control of fluidization regime, particle size distribution (PSD), moisture content, bulk density and product chemical properties (Sivakumar *et al.,* 2016). Heat pump systems, extensively researched for applications like space heating, cooling, and dehumidifying, have been modified and combined with other mechanisms to enhance performance. The heat pump dryer, particularly beneficial for preserving the quality of food and agricultural products, allows control over drying parameters such as temperature, relative humidity, moisture extraction, air velocity, and drying period (Goh *et al.,* 2011).

Moringa leaf powder, known for its nutritional importance, must be stored in air-tight containers, away from direct heat, humidity, and light. Improper drying or storage can lead to the growth of harmful molds or mildews, posing various issues, from unpleasant odors to the production of chemicals affecting human health. Given the nutritional significance of *moringa* leaves and the various drying methods, this study aims to standardize drying techniques for both fresh and 2-month-old *moringa* leaves and evaluate the quality of the stored dried *moringa* leaf powder.

Materials and Methods

The experiment took place in the Post-Harvest Technology Laboratory at the Department of Horticulture, Rajasthan College of Agriculture, and the Department of Processing and Food Engineering, College of Technology and Agricultural Engineering, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan. Newly emerged (7-10 days) and two-month-old leaves of *Moringa oleifera* were gathered from the Horticulture Farm of Rajasthan College of Agriculture, MPUAT, Udaipur, Rajasthan, India. The drying process was carried out in three different dryers namely the tray dryer, heat pump dryer and fluidized bed dryer. In tray dryer, moringa leaves of 100 g were spread on a tray in a single layer at a temperature of 60°C under a fixed air velocity of 2 ms^{-1}. In the fluidized bed dryer, *moringa* samples (100 g) were dried at 60°C with an air velocity of 10 $m\ s^{-1}$. The dried leaves from each method were ground using a mortar and pestle and a Cyclotech grinder, followed by filtration through a 32-mesh sieve to obtain a fine powder. The resulting powder was packed in 80-micron LDPE (Low-density polyethylene) and stored for 90 days under ambient conditionsat the Post-Harvest Technology Laboratory.

The methodologies employed for the physical and biochemical analyses are outlined as follows. The drying rate of the samples was computed using the equation proposed by Kadam *et al.*, (2011). The moisture content of *moringa* leaves was determined through the standard hot air oven method as per AOAC (1999). The dehydration ratio was calculated by measuring the initial and final mass of *moringa* leaves, representing the ratio of the weight of the dehydrated sample to the initial weight of fresh leaves. Bulk density values were determined by the ratio of the mass of the powder to the volume occupied in the cylinder, as per Goula *et al.*, (2004). Furthermore, the total ash and crude fiber contents of *moringa* leaves were assessed using a muffle furnace. Crude protein content was determined through the micro Kjeldahl's method (Steyermark *et al.*, 1958), while the ascorbic acid content was evaluated following the procedure suggested by Serban *et al.*, (1993). The carotenoid content was determined using the colorimetric method outlined by Ranganna (1986).

TSS was determined utilizing a hand refractometer within the range of 0–45° Brix (QA Supplies, LLC). The samples underwent thorough mixing, and a few drops were placed on the refractometer's prism, with direct readings obtained by interpreting the scale in meters. The results were expressed in °Brix at a temperature of 20°C (AOAC, 1994). Phenols were assessed by their reaction with an oxidizing agent phosphomolybdate in Folin-Ciocalteu reagent under alkaline conditions, forming a blue-colored complex, molybdenum blue, which was measured at 650nm colorimetrically (Bray and Thorpe, 1954). The contents of calcium, phosphorous, and potassium were analyzed using the methods recommended by AOAC (1999). The Water Solubility Index (WSI) determined the amount of polysaccharides or polysaccharide release from the granule upon the addition of excess water, as outlined by Anderson and Griffin (1969). WSI represented the weight of dry solids in the supernatant from the water absorption index test, expressed as a percentage of the original weight of the sample. A digital water activity meter measured the water activity of *moringa* leaf powder, with the powder samples in contact with the sensor probe, and the recorded water activity values. The color of the dried *moringa* samples was assessed using a Hunter Lab Colorimeter. The lightness index of color, denoted as L*, a*, and b* scales, were employed for color determination in the Hunter Lab Colorimeter. The color values L*, a*, and b* indicated lighter (+L) *vs*. darker (-L), red (+a) *vs*. green (-a), and yellow (+b) *vs*. blue (-b), respectively. Color evaluation was conducted for both dried *moringa* leaves and *moringa* powder.

The study was conducted using a completely randomized design. Data collected on various characteristics underwent statistical analysis through analysis of variance techniques as recommended by Gomez and Gomez (1984). The appendices provide the analysis of variance results for different parameters. The critical difference (CD) was computed to determine the significance or non-significance of differences between treatment means.

Results and Discussion

Effect of different dryers on the nutritional quality of moringa leaf powder

Among the fresh leaf samples, D3 (fluidized bed drying) exhibited the highest drying rate at 9.50 g-w/g dm-h, while D1 (tray drying) showed the lowest at 4.16 g-w/g dm-h. In the case of old leaf samples, D3 again had the maximum drying rate at 7.81 g-w/g dm-h, and D1 had the minimum at 3.21 g-w/g dm-h. Throughout all experiments, drying rates consistently decreased, following a typical falling rate during the drying period. This reduction in drying rate towards the end may be attributed to the diminishing moisture availability as the drying process advances. These findings align with those reported by Taheri-Garavand and Meda (2018) for savory leaves and Shravya *et al.*, (2019) for guava leaves.

Among fresh leaf samples, initial moisture contents averaged 264.96%, 267.65%, and 267.65% (db) for tray drying, heat pump drying, and fluidized bed drying, respectively. For old leaf samples, corresponding averages

Table 1: Effect of different dryers on dehydration ratio and total ash content.

Dryers	Dehydration ratio		Total ash content							
			0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	0.33	0.29	13.50	14.00	12.00	13.00	11.50	12.50	11.00	11.50
D2	0.28	0.31	11.50	12.00	11.00	11.00	10.50	10.50	9.50	10.00
D3	0.28	0.33	10.50	12.50	10.00	11.50	9.50	11.00	9.00	10.50
CD (5%)	0.09	0.01	0.53	0.32	0.67	0.80	0.45	0.83	0.52	0.66
SEM	0.01	0.02	0.15	0.09	0.19	0.23	0.13	0.23	0.15	0.19

Low ⬛ High 🟦

Table 2: Effect of different dryers on bulk density and crude protein content.

Dryers	Bulk density (g/cm3)								Crude protein (%)							
	0 DAS		30 DAS		60 DAS		90 DAS		0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	0.44	0.41	0.39	0.38	0.36	0.34	0.33	0.30	26.39	27.48	26.18	27.26	26.04	27.05	26.91	26.87
D2	0.43	0.39	0.38	0.35	0.34	0.30	0.28	0.27	25.68	26.73	25.49	26.51	25.33	26.32	25.18	26.13
D3	0.46	0.43	0.41	0.39	0.37	0.36	0.34	0.32	27.43	28.53	27.21	28.29	27.03	28.09	26.89	27.92
CD (5%)	0.02	0.02	NS	0.02	0.02	0.02	0.01	0.02	NS	NS	1.27	NS	1.22	1.29	1.28	1.07
SEM	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.54	0.48	0.36	0.44	0.35	0.37	0.36	0.30

were 217.46%, 238.98%, and 214.47% (db). Final moisture contents decreased to 5.75%, 4.10%, and 4.43% (db) after drying for tray, heat pump, and fluidized bed drying, respectively. The diminishing moisture content is attributed to continuous moisture evaporation into the air during the drying process. The shortest drying time was observed at the highest drying air temperature (60ºC). These findings align with results from previous studies on various leafy vegetables and drumstick leaves, such as tray drying by Gernah *et al.,* (2011) and curry leaves by Vijayan *et al.,* (2017). Among fresh leaf samples, D1 (tray drying) exhibited the highest dehydration ratio at 0.33, while D3 (fluidized bed drying) showed the lowest at 0.28. For old leaf samples, D3 again had the maximum dehydration ratio at 0.33, and D1 had the minimum at 0.29 (Table 1). This outcome aligns with similar findings reported by Kushwaha and Mustafa (2012) for fenugreek leaves and Kaur *et al.,* (2006) for coriander leaves.

The ash content was initially highest on 90 DAS of storage and gradually decreased over time. Among drying methods, D1 (Tray drying) retained the highest ash content, and old leaves exhibited higher ash values compared to fresh ones. The maximum ash content (14.00%) was observed on 90 DAS for old leaves under D1 (Tray drying), while the lowest value (9.00%) occurred on day 90 for fresh leaves under D3 (Fluidized bed drying) (Table 1). Throughout storage, there was a slight decrease in ash content, likely attributable to increased moisture content with prolonged storage, a phenomenon reported similarly in carrot and onion slices by Gupta and Shukla (2017).

The bulk density of moringa leaf powder declined consistently throughout the storage period. Among different drying methods, the highest bulk density (0.46g/cm^3) was observed in D3 (Fluidized bed drying) on 90 DAS for fresh leaves, decreasing over time (Table 2). The lowest value (0.27g/cm3) occurred in D2 (Heat pump drying) on day 90 for old leaves. This decline in bulk density throughout storage is attributed to changes in particle size and an increase in moisture content. Similar findings were reported by Bandral (2021) in amaranthus, radish, and chickpea leaves.

The crude protein content decreased consistently throughout the storage period, regardless of drying methods and leaf type. The highest crude protein content was observed on day 90 after storage, diminishing over time. Among drying methods, D3 (Fluidized bed drying) retained the highest crude protein content, and old leaves had a higher crude protein content compared to fresh ones. The maximum crude protein content (28.53%) was recorded on day 0 for old leaves under D3, while the minimum value (25.18%) occurred on day 90 for fresh leaves under D2 (Heat pump drying) (Table 2). The data indicates a reduction in crude protein of *moringa* leaf powder with the progression of storage, possibly attributed to increased water activity activating certain enzymes due to respiration. This finding aligns with similar results reported by Khan *et al.,* (2016) in soybean.

The crude fiber content was highest on 90 days after

Table 3: Effect of different dryers on crude fibre and ascorbic acid contents.

Dryers	Crude fibre (%)								Ascorbic acid (mg/100g)							
	0 DAS		30 DAS		60 DAS		90 DAS		0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	11.86	12.01	11.75	11.91	11.67	11.83	11.61	11.76	81.97	84.26	79.02	81.57	76.98	78.93	75.08	76.28
D2	10.98	11.15	10.88	11.08	10.80	11.02	10.74	10.95	80.92	82.93	77.89	79.83	74.98	77.13	73.18	75.05
D3	11.96	13.03	11.85	12.94	11.78	12.87	11.72	12.81	83.54	86.43	80.79	83.82	78.28	81.15	76.05	78.97
CD (5%)	0.80	0.55	1.58	0.50	0.66	0.48	0.65	0.35	NS	NS	NS	NS	NS	NS	NS	NS
SEM	0.23	0.16	0.16	0.14	0.19	0.14	0.19	0.10	0.94	1.55	1.13	0.89	1.23	0.94	1.48	1.06

Table 4: Effect of different dryers on vitamin A and TSS.

Dryers	Vitamin A (mg/100g)								TSS (°Brix)							
	0 DAS		30 DAS		60 DAS		90 DAS		0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	23.15	26.58	21.28	24.88	19.80	23.88	18.92	22.29	2.90	5.20	2.70	4.90	2.40	4.70	2.10	4.40
D2	21.98	24.70	20.35	23.02	18.97	21.73	17.89	20.63	2.50	4.50	2.20	4.30	1.90	3.90	1.70	3.70
D3	25.37	28.38	23.48	26.79	21.88	25.42	20.48	24.12	2.00	2.50	1.80	2.20	1.50	1.90	1.30	1.90
CD (5%)	1.50	1.17	1.19	1.80	1.31	1.05	1.22	1.64	0.16	0.23	0.07	0.24	0.07	0.10	0.09	0.20
SEM	0.43	0.33	0.32	0.51	0.37	0.30	0.35	0.47	0.05	0.07	0.02	0.07	0.02	0.03	0.03	0.06

storage and declined during the storage period. Among various drying methods, the maximum crude fiber content (13.03%) occurred in D3 (Fluidized bed drying) on 90 days for old leaves, decreasing over time. The minimum value (10.74%) was observed in D2 (Heat pump drying) on day 90 for fresh leaves (Table 3). The reduction in crude fiber during storage may be attributed to the degradation of hemicelluloses and other polysaccharides, along with the breakdown of pectic substances by heat and moisture solubilizers. Similar observations were reported by Sharon and Usha (2007) in breadfruit and Singh *et al.,* (2022) in pearl millet. The ascorbic acid content of *moringa* leaf powder was not significantly influenced by different drying methods, but it decreased over the storage period. The highest ascorbic acid content (86.43 mg/100g) was observed in D3 (Fluidized bed drying) on day 0 for old leaves, decreasing with storage, reaching a minimum value (73.18 mg/100g) in D2 (Heat pump drying) on day 90 for fresh leaves (Table 3). The data in Table 3 indicates a consistent decrease in ascorbic acid content throughout the storage period, likely attributed to the oxidation of ascorbic acid, forming dehydro-ascorbic acid due to the enzyme ascorbinase activity during storage. This observation aligns with similar findings by Seevaratnam *et al.,* (2012) in green leafy vegetables and Udikala *et al.,* (2017) in *moringa* leaves.

The highest vitamin A content (28.38 mg/100g) was observed in D3 (Fluidized bed drying) on day 0 for old leaves, decreasing with storage to a minimum value (17.89 mg/100g) in D2 (Heat pump drying) on day 90 for fresh leaves (Table 4). The decline in vitamin A content during the storage period is attributed to thermal treatment, causing thermal degradation. This observation is consistent with findings by Gupta and Shukla (2017) in carrot and onion slices, where thermal degradation led to reduced vitamin A content. The reduction in vitamin A during storage is likely influenced by oxidative and non-oxidative changes, given its sensitivity to heat. Similar results were reported by Seevaratnam *et al.,* (2012) in green leafy vegetables during storage. The TSS content was highest on day 0 after storage and declined throughout the storage period. Among drying methods, D1 (Tray drying) retained the highest TSS content, and old leaves exhibited a higher TSS value compared to fresh ones. The maximum TSS content (5.20 °Brix) was recorded on day 0 for old leaves under D1 (Tray drying), while the minimum value (1.30 °Brix) was observed under D3 (Fluidized bed drying) on day 90 for fresh leaves (Table 4). The decrease in TSS content during storage may be attributed to an increased rate of respiration. Similar findings have been reported by Gil *et al.,* (1997) and Pelayo *et al.,* (2003) in strawberry fruit. Among different drying methods, the highest total phenol content (196.40 mg/100g) was observed in D3 (Fluidized bed drying) on day 0 for old leaves, decreasing with storage to a minimum value (168.81 mg/100g) in D2 (Heat pump drying) on day 90 for fresh leaves (Table 5). The reduction in total phenol content during the entire storage period is attributed to the oxidation of polyphenols by polyphenol oxidase and

Table 5: Effect of different dryers on total phenol and potassium contents.

Dryers	Total phenol (mg/100g)								Potassium (g/100g)							
	0 DAS		30 DAS		60 DAS		90 DAS		0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	182.10	190.20	178.40	186.60	175.70	182.90	173.20	179.50	1.23	1.26	1.21	1.24	1.19	1.22	1.18	1.20
D2	179.30	187.20	174.60	183.30	171.20	179.80	168.81	177.50	1.19	1.22	1.17	1.20	1.15	1.18	1.14	1.16
D3	188.50	196.40	184.30	191.20	180.70	187.50	178.10	183.60	1.28	1.30	1.26	1.28	1.24	1.27	1.22	1.25
CD (5%)	5.29	4.74	NS	NS	NS	NS	NS	NS	0.04	0.05	NS	NS	NS	NS	NS	0.05
SEM	1.50	1.34	3.14	3.13	3.02	2.21	2.87	3.61	0.01	0.01	0.02	0.02	0.03	0.02	0.02	0.01

Table 6: Effect of different dryers on calcium and phosphorus contents.

Dryers	Calcium (g/100g)								Phosphorus (g/100g)							
	0 DAS		30 DAS		60 DAS		90 DAS		0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	2.27	2.28	2.25	2.26	2.23	2.23	2.21	2.21	0.20	0.21	0.20	0.20	0.19	0.20	0.18	0.19
D2	2.23	2.24	2.20	2.22	2.18	2.20	2.17	2.18	0.20	0.21	0.19	0.20	0.18	0.19	0.18	0.19
D3	2.29	2.31	2.27	2.28	2.27	2.26	2.25	2.24	0.21	0.22	0.20	0.21	0.19	0.20	0.19	0.19
CD (5%)	NS	0.04	NS	NS	NS	NS	NS	NS	NS	0.01	NS	NS	NS	NS	0.01	NS
SEM	0.03	0.01	0.05	0.03	0.03	0.03	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

increased polymerization of tannins. Similar observations were reported by Mokhtar *et al.,* (2021) in pumpkin.

The potassium content of *moringa* leaf powder consistently decreased throughout the entire storage period. Among various drying methods, the highest potassium content (1.30g/100g) was observed in D3 (Fluidized bed drying) on day 0 for old leaves, decreasing with storage to a minimum value (1.14g/100g) in D2 (Heat pump drying) on day 90 for fresh leaves (Table 5). Comparable findings were reported by Verma *et al.,* (2015) in guava powder and Mensah *et al.,* (2012) in *moringa* leaves. Among the drying methods, D3 (Fluidized bed drying) retained the highest calcium content, and old leaves exhibited a higher calcium value compared to fresh ones. The maximum calcium content (2.31 g/100g) was recorded on day 0 for old leaves under D3 (Fluidized bed drying), while the minimum value (2.17 g/100g) was observed on day 90 for fresh leaves under D2 (Heat pump drying) (Table 6). Comparable findings were reported by Adsure and Chavan (2021) in fenugreek, spinach, and coriander leaves, as well as by Verma *et al.,* (2015) in guava powder. The phosphorus content was highest on day 0 after storage and declined during the storage period. Among drying methods, D3 (Fluidized bed drying) retained the highest phosphorus content, and old leaves exhibited a higher phosphorus value compared to fresh ones. The maximum phosphorus content (0.22 g/100g) was recorded on day 0 for old leaves under D3 (Fluidized bed drying), while the minimum value (0.18 g/100g) was observed on day 90 for fresh leaves under D2 (Heat pump drying) (Table 6). Similar findings were reported by Verma *et al.,* (2015) in guava powder and Mensah *et al.,* (2012) in *moringa* leaves.

The water absorption index was highest on day 0 after storage and declined throughout the storage period. Among drying methods, D1 (Tray drying) retained the highest water absorption index, with fresh leaves having a higher value compared to old ones. The maximum water absorption index (3.82 g) was recorded on day 0 for fresh leaves under D1 (Tray drying), while the minimum value (3.12 g) was observed on day 90 for old leaves under D3 (Fluidized bed drying) (Table 7). The decrease in the water ;Yousf *et al.,* (2017) in rice. The water solubility index was highest on day 0 after storage and decreased throughout the storage period. Among drying methods, D1 (Tray drying) retained the highest water solubility index, with fresh leaves having a higher value compared to old ones. The maximum water solubility index (3.92%) was recorded on day 0 for fresh leaves under D1 (Tray drying), while the minimum value (3.41%) was observed on day 90 for old leaves under D3 (Fluidized bed drying) (Table 7). Similar results were indicated by Looi *et al.,* (2019) in *moringa* leaf powder and Yousf *et al.,* (2017) in rice. Among drying methods, D3 (Fluidized bed drying) retained the highest water activity, with old leaves having a higher value compared to fresh ones. The maximum water activity (0.30) was recorded on day 90 for old leaves under D3 (Fluidized bed drying), while the minimum value (0.23) was observed on day 0 for fresh leaves under D2 (Heat pump drying) (Table 8). Throughout storage,

Table 7: Effect of different dryers on water absorption and water solubility indices.

Dryers	Water absorption index (g)								Water solubility index							
	0 DAS		30 DAS		60 DAS		90 DAS		0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	3.82	3.64	3.71	3.55	3.59	3.43	3.46	3.29	3.92	3.86	3.84	3.79	3.73	3.69	3.66	3.60
D2	3.73	3.56	3.62	3.45	3.51	3.31	3.42	3.18	3.83	3.77	3.72	3.67	3.65	3.56	3.58	3.49
D3	3.63	3.43	3.49	3.33	3.34	3.21	3.22	3.12	3.70	3.68	3.61	3.57	3.54	3.49	3.45	3.41
CD (5%)	NS	NS	NS	0.77	1.47	0.50	1.13	NS	NS	NS	0.07	0.16	NS	NS	NS	0.15
SEM	0.07	0.06	0.06	0.02	0.04	0.01	0.03	0.05	0.06	0.05	0.02	0.05	0.06	0.06	0.08	0.04

Table 8: Effect of different dryers on water activity and CIE L* color coordinates.

Dryers	Water activity								CIL L* color coordinate							
	0 DAS		30 DAS		60 DAS		90 DAS		0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	0.24	0.25	0.25	0.26	0.26	0.27	0.27	0.27	59.71	54.62	57.95	54.29	56.13	53.86	55.09	53.12
D2	0.23	0.24	0.24	0.25	0.25	0.25	0.26	0.26	59.37	56.24	58.59	51.57	57.76	48.76	55.65	44.73
D3	0.27	0.28	0.28	0.29	0.29	0.29	0.29	0.30	60.04	57.15	58.34	54.54	56.13	51.98	53.96	50.96
CD (5%)	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	NS	NS	NS	1.91	NS	3.12	NS	2.45
SEM	0.005	0.004	0.004	0.005	0.003	0.003	0.002	0.003	0.83	0.89	0.99	0.54	0.83	0.88	1.15	0.70

the water activity increased, likely due to the absorption of moisture during storage in *moringa* leaf powder, and the uptake of moisture from the environment contributing to the increase in water activity. Comparable findings were reported by Bandral *et al.,* (2021) in amaranthus, radish, and chickpea leaves.

The product's color is a crucial quality parameter influencing consumer appeal and market price. Various drying methods significantly impacted the initial color of the dehydrated product in this study. Moreover, the color value of the dehydrated product decreased with prolonged storage. In fresh leaf samples, the maximum L* value (60.04) was observed in D3 (fluidized bed drying) on day 0, and the minimum L* value (53.96) was noted in D3 (fluidized bed drying) on day 90 (Table 8). The maximum CIE a* color coordinate (-7.08) was found in D2 (heat pump drying) on day 0, while the minimum (-1.91) was in D3 (fluidized bed drying) on day 90. Similarly, the maximum CIE b* color coordinate (35.98) was in D3 (fluidized bed drying) on day 30, and the minimum (25.45) was in D3 (fluidized bed drying) on day 90 (Table 9). Similarly, the maximum CIE b* color coordinate (36.97) was in D1 (tray drying) on day 0, and the minimum (23.55) was in D3 (fluidized bed drying) on day 90 (Table 9). These findings align with results reported by other researchers, such as Ali *et al.,* (2014) for moringa leaves, Kaur *et al.,* (2006) for coriander leaves, and Donkar *et al.,* (2013) for *moringa* leaves.

Principal component analysis for evaluating the effects of dryers on moringa leaf powder physical and nutritional quality

Principal Component Analysis (PCA), a method utilized for reducing dimensionality, was implemented to evaluate the impact of treatments on a set of 12 biochemical parameters linked to tamarind pulp. Spectral decomposition was conducted to examine the interdependencies among these variables. The PCA results on variances of the components are shown in Fig. 1. In the context of these loadings, it is crucial to note that higher absolute values signify a stronger association between the variable and the respective principal component. Examining the factor loadings, the dehydration ratio exhibits a noteworthy positive loading on PC2 (0.426), implying a substantial correlation with this principal component. Similarly, the total ash content displays a significant positive loading on PC2 (0.394), suggesting a pronounced association with this particular component. Bulk density demonstrates positive loadings on both PC1 (0.239) and PC2 (0.228), indicating its contribution to the variance in both principal components. Likewise, variables such as crude protein, crude fibre, and ascorbic acid exhibit positive loadings on both PC1 and PC2, suggesting their influence on the variation captured by these components. Therefore, the above-mentioned variables are highly influenced by the different types of dryers.

The variables exhibiting the greatest influence on PC1 are deemed more diverse and significantly impacted by

Table 9: Effect of different dryers on CIE a* and b* color coordinates.

Dryers	CIE a* color coordinate								CIE b* color coordinate							
	0 DAS		30 DAS		60 DAS		90 DAS		0 DAS		30 DAS		60 DAS		90 DAS	
	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf	New leaf	Old leaf
D1	-5.77	-6.50	-4.58	-4.95	-3.42	-3.43	-2.65	-2.32	32.96	36.97	31.31	35.45	29.96	33.26	28.34	32.13
D2	-7.08	-8.51	-6.00	-4.12	-5.83	-2.98	-4.96	-1.67	30.18	35.53	29.06	30.31	27.87	27.79	26.56	24.51
D3	-6.42	-6.52	-3.49	-4.06	-2.46	-3.14	-1.91	-2.09	30.15	29.47	29.55	26.94	27.06	24.89	25.45	23.55
CD (5%)	0.44	0.41	0.14	0.30	0.21	0.18	0.06	0.11	0.84	2.87	1.13	1.38	1.31	1.80	1.58	1.18
SEM	0.12	0.12	0.39	0.09	0.06	0.05	0.02	0.03	0.24	0.81	0.32	0.39	0.37	0.51	0.44	0.33

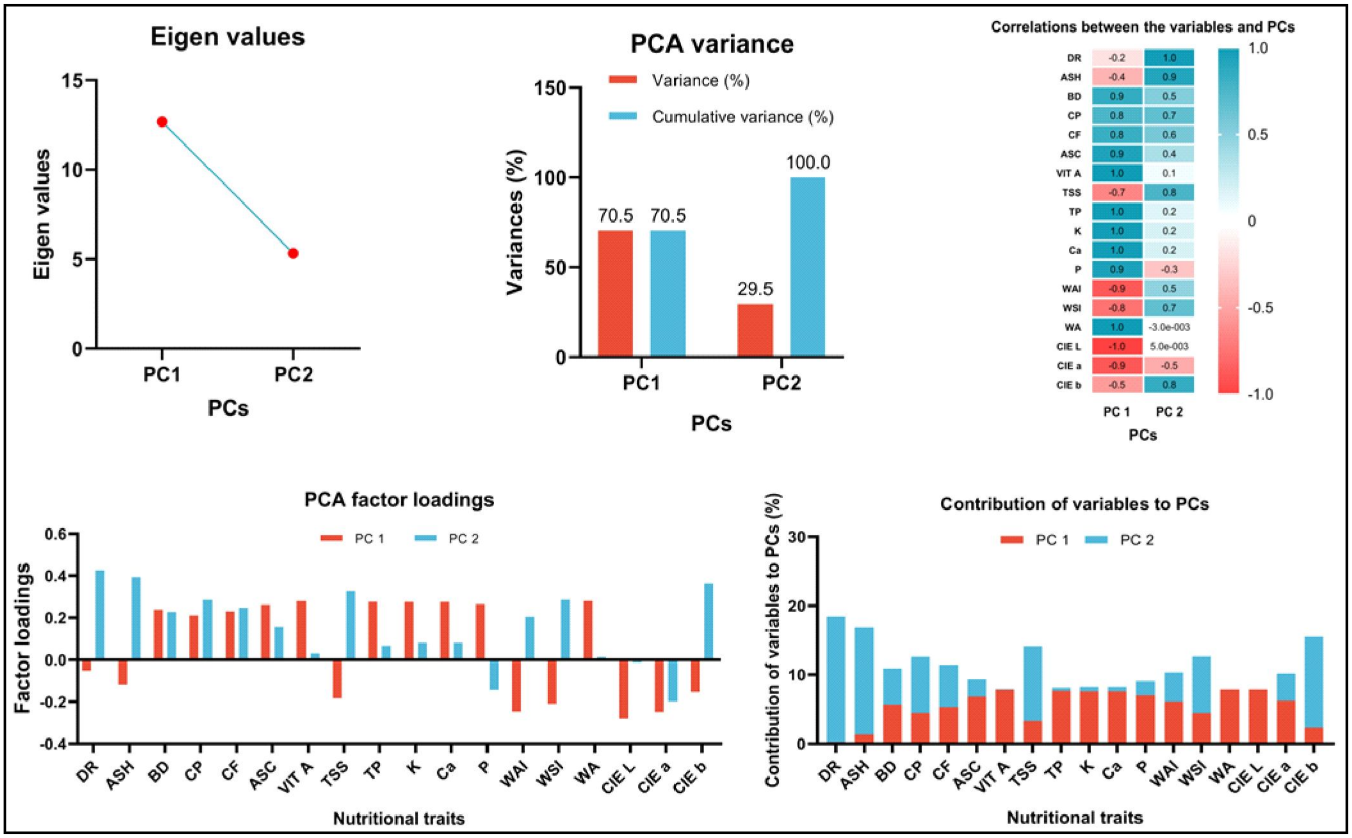

Fig. 1: PCA results explaining eigen values, variances (%), correlation between the variables and PCs, PCA factor loadings and contribution (%) of variables to PCs.

the treatment effect, representing various types of dryers. As delineated in Fig. 1, water activity and CIE L* color collectively make the most substantial contribution to the overall variability (7.885), succeeded by vitamin A (7.847), total phenol content (7.969), and potassium and calcium contents (7.613). The same table elucidates the correlation between the variables and principal components (PCs). The most pronounced positive correlation is observed with total phenol content (0.988), followed by potassium and calcium contents (0.983), and ascorbic acid (0.932). These variables have played a

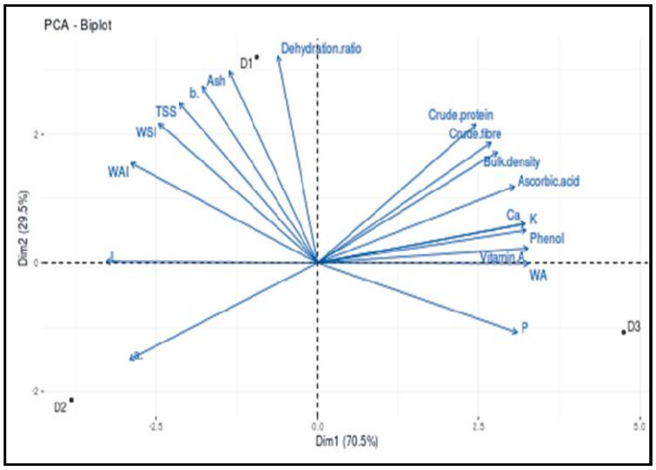

Fig 2: PCA- Biplot.

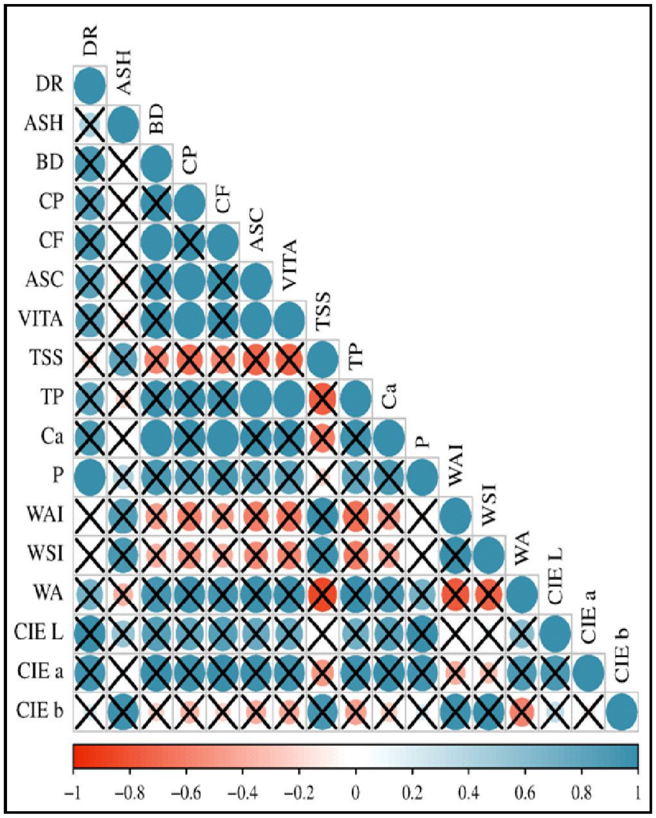

Fig. 3: Pearson correlation among various physical, biochemical and color attributes of moringa leaf powder effected by the different dryers

pivotal role in both the overall variation and the effects associated with the utilization of distinct dryers.

The PCA biplot (Fig. 2) visually represents a distinct clustering of essential nutritional quality drivers, including crude protein, crude fiber, bulk density, ascorbic acid, calcium, potassium, total phenol, vitamin A, phosphorus, and water activity, within the context of *moringa* leaf powder. This cluster is specifically associated with treatment D3 (fluidized bed dryer) implying the superior retention of these quality attributes by this drying method. Conversely, parameters such as water absorption index, water solubility index, TSS, CIE L*, total ash content, and dehydration ratio form a secondary cluster linked to D1 (tray dryer). This suggests a greater influence of the tray dryer on these parameters. However, these traits are of lesser consideration in controlling the quality and nutritional profile that consumers anticipate from *moringa* leaf powder. Consequently, it is advisable to prioritize the utilization of D3 (fluidized bed dryer) in the manufacturing process of *moringa* leaf powder.

Pearson correlation analysis

The Pearson correlation plot explains the association, its direction and magnitude, of the moringa leaf attributes (Fig. 3). Most of the traits showed insignificant and only the significant traits are discussed below. The hydration ratio was positively correlated with phosphorus content; bulk density with calcium and crude fibre contents; crude protein with ascorbic acid, vitamin A and TSS; crude fibre with calcium content; ascorbic acid with vitamin A, total phenol content; and vitamin A with total phenol content. None of the negative associations were found significant.

Conclusion

This study extensively analyzes the efficacy of different drying methods, namely tray drying, heat pump drying, and fluidized bed drying, in preserving the physical and chemical characteristics of *moringa* leaf powder. Among these methods, fluidized bed drying emerges as the most effective in maintaining superior qualities such as vitamin A, ascorbic acid, total phenol, crude fiber, crude protein, calcium, potassium, phosphorus, and color. Notably, old leaves exhibit a higher retention of quality characteristics compared to fresh leaves. Despite the chosen drying method and leaf type, a marginal reduction in quality parameters is observed with the progression of storage. This comprehensive investigation sheds light on the nuanced impact of drying techniques on the nutritional and chemical composition of *moringa* leaf powder, emphasizing the superior performance of fluidized bed drying in preserving its essential attributes.

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Authors' contribution: Conceptualization - KRA, AKD; Methodology - RS; formal analysis and investigation - RS, JJ; Writing (orginal draft preparation) - RS, JJ ; Writing (review and editing) - KRA, AKD, SPK; Resources - KRA ; Supervision - KRA.

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