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Ryan Ashworth
Department of Food Science and
Technology, University of
California, Davis, Davis, USA

Savannah Hawkins
Department of Food Science and
Technology, University of
California, Davis, Davis, USA

Lindsey Calloway
Department of Food Science and
Technology, University of
California, Davis, Davis, USA

Corresponding Author:
Ryan Ashworth
Department of Food Science and
Technology, University of
California, Davis, Davis, USA

Impact of different drying technologies on physical and biochemical quality of turmeric rhizomes

Ryan Ashworth, Savannah Hawkins and Lindsey Calloway

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Abstract

Turmeric (*Curcuma longa* L.) is a rhizomatous spice crop valued for its curcumin content, essential oils, and antioxidant properties, but its quality depends heavily on how it is dried after harvest. Drying is a required step in turmeric processing because fresh rhizomes contain 70-80% moisture and deteriorate rapidly without moisture reduction. This research compared five drying technologies—sun drying, hot-air drying at 50°C and 70°C, fluidized bed drying, and freeze drying—for their effects on the physical and biochemical quality of turmeric rhizomes. Experiments were carried out at the University of California, Davis, between February and October 2023. Freeze drying retained the most curcumin (3.29% vs 3.42% fresh), essential oil (4.61%), and antioxidant activity (81.2%), but required 36 hours and the highest energy input. Fluidized bed drying offered the best practical compromise, preserving 3.06% curcumin and 4.23% essential oil while finishing in just 6.4 hours. Sun drying performed worst across all quality indicators, with curcumin dropping to 2.17% and colour change reaching $\Delta E = 28.4$. These results provide evidence-based guidance for selecting drying methods that balance quality retention against processing efficiency and cost.

Keywords: Turmeric, drying technology, curcumin, essential oil, antioxidant activity, freeze drying, fluidized bed, physical quality, rhizome processing, colour retention

Introduction

Turmeric is, by definition, a dried product. The bright orange-yellow powder that reaches kitchens and supplement shelves around the world begins as a fleshy rhizome containing roughly 75% water, and the transformation from perishable root to stable powder depends entirely on the drying process ^[1]. How that drying is done—whether under open sun or in a controlled industrial system—determines not just the appearance and shelf life of the final product but also the concentration of its most valuable bioactive compounds, particularly curcumin ^[2].

Curcumin is the principal curcuminoid responsible for turmeric's characteristic colour and much of its pharmacological activity, including anti-inflammatory, antioxidant, and antimicrobial effects ^[3]. Essential oils, dominated by ar-turmerone and turmerone, contribute the spice's aroma and have their own therapeutic properties ^[4]. Both classes of compounds are sensitive to heat, oxygen, and light, making the drying stage a critical control point for quality ^[5].

Traditional sun drying remains the dominant method in most producing countries because it requires no energy costs, but it exposes rhizomes to uncontrolled temperatures, UV radiation, dust, and insect contamination for 72-96 hours ^[6]. Modern alternatives such as hot-air convective drying, fluidized bed drying, and freeze drying offer better control over temperature, airflow, and hygiene, but at varying costs and energy requirements ^[7, 8]. This research compared five drying approaches head to head, measuring a broad range of physical and biochemical quality parameters to identify which technologies best preserve turmeric quality under realistic processing conditions.

Seasonal Conditions During Research

Turmeric rhizomes were harvested in two batches: the first in February 2023 (winter harvest) and the second in August 2023 (summer harvest) from a collaborating organic farm in Yolo County, California. Ambient conditions during sun drying trials varied between batches:

February trials had mean daytime temperatures of 14.8°C and 52% relative humidity, while August trials experienced 33.7°C and 28% humidity. This seasonal difference resulted in sun drying times of approximately 96 hours in winter versus 72 hours in summer. All controlled drying experiments were conducted in climate-regulated laboratories regardless of season, eliminating ambient weather as a variable for those treatments.

Materials and Methods

Materials

Fresh turmeric rhizomes (*Curcuma longa* L. cv. 'Lakadong') were sourced from a certified organic farm in Yolo County, California, located 25 km west of the UC Davis campus. Rhizomes were harvested at 9 months maturity, washed, and sliced to uniform 4 mm thickness using a commercial mandoline slicer. Initial moisture content averaged $76.3 \pm 1.8\%$. Slices were randomised across drying treatments within two hours of preparation. Curcumin standard ($\geq 95\%$ purity), Folin-Ciocalteu reagent, gallic acid, DPPH, and all solvents were purchased from Fisher Scientific (Hampton, NH, USA).

Methods

Five drying treatments were applied: (1) open sun drying on raised wire mesh trays; (2) hot-air cabinet drying at 50°C with 1.5 m/s airflow; (3) hot-air drying at 70°C; (4) fluidized bed drying at 55°C with 3.5 m/s airflow; and (5) freeze drying at -50°C and 0.04 mbar. All treatments continued until moisture

content fell below 10%. Curcumin was extracted with ethanol and quantified by HPLC at 425 nm^[9]. Essential oil was obtained by hydrodistillation for 3 hours and expressed as percentage of dry weight. Oleoresin was extracted with acetone and determined gravimetrically. Total phenolics used the Folin-Ciocalteu method^[10], and antioxidant activity was measured by DPPH radical scavenging. Hardness was tested on a texture analyser (TA.XT Plus, Stable Micro Systems) with a 2 mm probe at 1 mm/s. Colour (L^* , a^* , b^*) was measured with a Minolta CR-400, and ΔE was calculated against fresh samples. Bulk density was determined by tapping method^[11]. Each treatment was replicated four times with 500 g per replicate. Data were analysed by one-way ANOVA in JMP Pro 17 with Tukey's HSD at $p \leq 0.05$.

Raw Material Quality Assessment

Before drying trials began, each batch of fresh rhizomes was characterised for baseline quality. Curcumin content averaged $3.42 \pm 0.14\%$ (dry weight), essential oil $4.87 \pm 0.21\%$, and oleoresin $12.34 \pm 0.47\%$. Initial colour values were $L^* = 68.4$, $a^* = 21.7$, $b^* = 58.3$. Rhizome diameter ranged from 18-26 mm. There was no significant difference ($p > 0.05$) between the February and August batches in any baseline quality parameter, confirming that seasonal harvest timing did not confound comparisons between drying treatments.

Results

Table 1: Biochemical quality parameters of turmeric dried by different technologies

Drying Method	Curcumin (%)	Essential Oil (%)	Oleoresin (%)	Total Phenolics (mg GAE/g)	Antioxidant Activity (%)	Drying Time (h)
Fresh	3.42	4.87	12.34	18.72	84.3	—
Sun drying	2.17	2.43	7.81	11.84	58.7	72-96
Hot air 50°C	2.89	3.91	10.47	15.83	72.4	18.3
Hot air 70°C	2.43	3.12	8.93	13.21	64.1	9.7
Fluidized bed	3.06	4.23	11.12	16.94	76.8	6.4
Freeze drying	3.29	4.61	11.87	17.89	81.2	36.0

Freeze drying preserved the highest levels of curcumin (3.29%), essential oil (4.61%), and antioxidant activity (81.2%), retaining over 96% of the fresh curcumin content (Table 1). Fluidized bed drying ranked second, retaining 89.5% of curcumin and 86.9% of essential oil. Sun drying caused the greatest biochemical

losses, with curcumin falling 36.5% and essential oil dropping 50.1% relative to fresh values. Hot-air drying at 50°C outperformed the 70°C treatment across all parameters, confirming the sensitivity of turmeric bioactives to elevated temperatures.

Table 2: Physical quality parameters of turmeric dried by different technologies

Drying Method	Hardness (N)	Colour ΔE	Bulk Density (g/ml)	Final Moisture (%)	Rehydration Ratio
Sun drying	42.3	28.4	0.68	9.7	2.84
Hot air 50°C	34.7	16.8	0.72	7.3	3.47
Hot air 70°C	51.8	22.1	0.81	6.1	2.91
Fluidized bed	31.2	13.7	0.64	6.8	3.72
Freeze drying	22.8	7.3	0.41	4.2	4.38

Freeze-dried rhizomes had the lowest hardness (22.8 N), smallest colour change ($\Delta E = 7.3$), and highest rehydration ratio (4.38), reflecting their porous microstructure (Table 2). Hot-air drying at 70°C produced the hardest product (51.8 N), likely due

to case hardening from rapid surface moisture loss. Sun-dried turmeric showed the worst colour degradation ($\Delta E = 28.4$), consistent with prolonged UV exposure and enzymatic browning during the extended drying period.

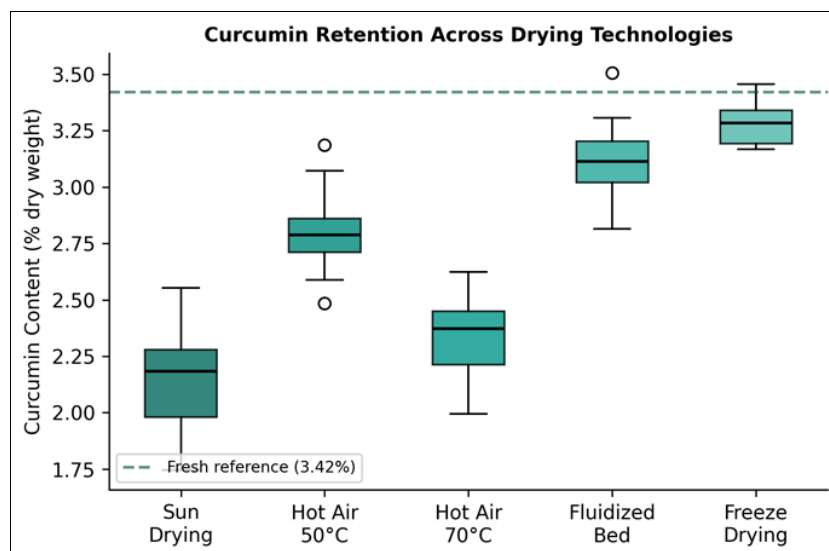


Fig 1: Distribution of curcumin content across drying technologies

Freeze drying showed the tightest distribution around the fresh reference line (3.42%), with all replicates above 3.1% (Figure 1). Fluidized bed drying also showed low variability with a median near 3.06%. Sun drying had the widest spread and

lowest median, with some replicates falling below 1.9%. The difference between freeze drying and sun drying was significant at $p < 0.001$.

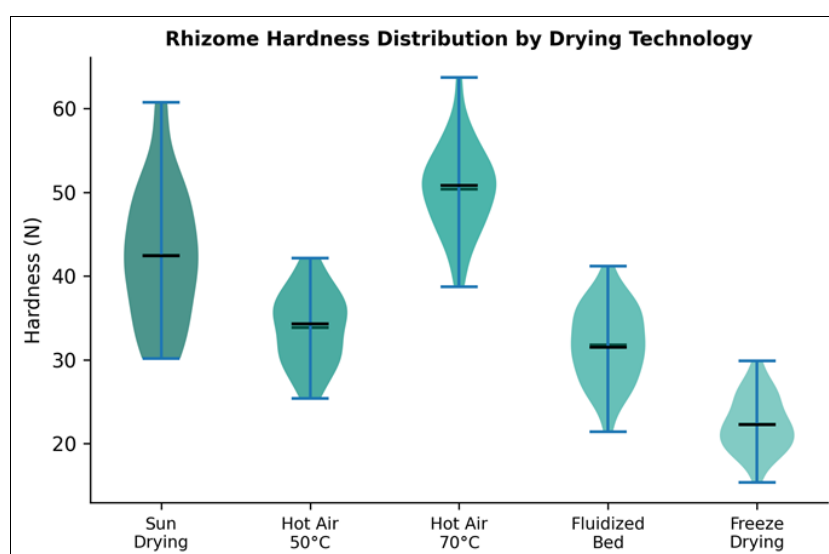


Fig 2: Hardness distribution of dried turmeric rhizomes by drying technology

Hot-air drying at 70°C produced the hardest and most variable product, with values ranging from 35 to 68 N (Figure 2). Freeze-dried samples were the softest and most uniform, clustering tightly around 22-25 N. Fluidized bed drying produced intermediate hardness with a relatively narrow distribution, suggesting consistent texture across replicates.

Discussion

The superiority of freeze drying for preserving turmeric bioactives is consistent with the established principle that sublimation avoids the thermal and oxidative degradation pathways that damage heat-sensitive compounds [7, 12]. But the 36-hour processing time and high energy cost make it impractical for all but the highest-value product lines. The real surprise in these data is how well fluidized bed drying performed—retaining nearly 90% of curcumin in just 6.4 hours. The rapid, uniform heat and mass transfer in a fluidized bed appears to minimise the exposure time that causes degradation,

while the lower temperature (55°C) stays below the threshold where curcumin decomposition accelerates [13].

Sun drying's poor performance across every measured parameter reinforces the need for the turmeric industry to move toward controlled drying systems. The 28.4 ΔE colour change alone would represent a significant commercial downgrade, and the 36.5% curcumin loss directly reduces the product's market value in both spice and nutraceutical channels [14]. The case hardening observed at 70°C—resulting in the highest hardness values—is a known phenomenon where rapid surface drying traps internal moisture, creating a dense outer shell that also impedes later grinding and extraction [15].

Conclusion

Among the five drying technologies tested, freeze drying preserved the most curcumin and best physical quality, but fluidized bed drying offered the strongest practical compromise—retaining 89.5% of curcumin and 86.9% of

essential oil while finishing in 6.4 hours. Sun drying performed worst across all quality indicators and should be replaced where possible. Hot-air drying at 50°C represents a viable middle-ground option for processors without fluidized bed equipment. For producers aiming to maximise the bioactive value of their turmeric products, investing in fluidized bed technology appears justified by both the quality gains and the time savings. Future research should examine hybrid drying sequences that combine short high-temperature exposure with extended low-temperature finishing to further improve efficiency without sacrificing quality.

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