Comparative Assessment of Drying Technologies to Minimize Postharvest Losses in Turmeric

Thinley Gyeltshen[j], Tenzin Rabgay[j], Tshering Penjor[j], Pema Yangdon[j], Tshering Pem[j], Domang[j], Kinzang Thinley[j], Kinley Sithup[j], Kinley Wangmo[k]

ABSTRACT

Turmeric, a valuable spice with high medicinal value, is highly perishable due to its high moisture content (70-80%), necessitating the need for efficient postharvest technologies to minimize losses. Drying is a proven method to extend shelf life and reduce losses, but no comprehensive studies on turmeric drying have been conducted in Bhutan. This study, conducted at the Agriculture Research and Development Centre, Wengkhar, evaluated three drying methods; Open Sun Drying (control), a Fabricated Electric Dryer, and a Solar Dryer integrated with IoT technology, to determine their efficacy in reducing turmeric postharvest losses. Using stratified and random sampling, 450 turmeric rhizomes were sliced and dried across treatments. Significant differences were observed in weight loss and water activity between the methods at a 5% significance level. Although, the Electric Dryer had the shortest drying duration (7.76 hours), it retained higher water activity (58.05), increasing the risk of microorganism growth. In contrast, the IoT-based Solar Dryer required the longest drying time (71.05 hours) but achieved the lowest water activity (39.7) and superior product quality in texture and color. Therefore, given its ability to handle larger volumes, the IoT-based Solar Dryer is recommended for commercial operations. Future research should focus on biochemical composition, particularly curcumin content, and the economic viability of different drying methods.

Keywords: *Drying technologies; Dry weight; Post harvest loss; Turmeric; Water Activity*

1 Introduction

Turmeric (*Curcuma longa*) has been recognized as a valued medicinal herb throughout history (Malik & Kumar, 2022). Its medicinal use is so well-established that the European Medicines

Corresponding author: thinleyg@moal.gov.bt

[j] Agriculture Research and Development Centre-Wengkhar, Department of Agriculture, Ministry of Agriculture and Livestock

[k] National Post Harvest sub-centre, Lingmethang, Department of Agricultural Marketing and Cooperatives, Ministry of Agriculture and Livestock

Agency (EMA) approved turmeric-based products, including herbal teas, in 2019 for addressing mild digestive disorders such as flatulence and indigestion (EMA, 2019). In Bhutan, Turmeric is widely used for the treatment of Diabetes Mellitus (Choden & Erdene, 2014). The primary bioactive component of turmeric, curcumin, has been extensively studied for its wide range of therapeutic effects. These include anti-inflammatory, antioxidant, anti-cancer, anti-mutagenic, and anticoagulant properties, as well as its ability to regulate fertility and blood sugar levels (Krishi et al., 2018).

Besides its medicinal significance, turmeric holds substantial economic importance in the economy of India, which remains the world's leading producer and exporter of turmeric, accounting for over 46% of the global market (Mirjanaik & Vishwanath, 2020). In Bhutan, turmeric has emerged as a prominent spice crop alongside cardamom, ginger, and garlic. According to the (National Statistis Bureau, 2023), around 143.1 acres of land were used for turmeric cultivation in Bhutan, yielding approximately 134.7 metric tons annually. However, Bhutan recorded a negative trade balance in turmeric during 2022 and 2023, with imports valued at Nu 10.8 million and Nu 9.7 million respectively, while exports were limited to Nu 1.4 million and Nu 0.99 million (Department of Revenue Customs, 2023). This trade imbalance underscores a significant potential for enhancing domestic turmeric production, presenting a promising opportunity for Bhutanese farmers to reduce import dependency and improve income generation.

Similar to other agricultural commodities, turmeric requires proper post-harvest technologies to minimize economic losses. Due to its inherently high moisture content of 70-80%, turmeric is highly perishable (Prasad et al., 2006). In the northeast hill regions, post-harvest losses of fresh turmeric range between 535 kg and 1,480 kg, resulting to an estimated 10.5% loss of the total production, emphasizing the need for improved preservation techniques (Singh et al., 2020). Drying is a common method used globally to extend the shelf life of turmeric, reducing moisture content below critical levels to prevent spoilage (Prasad et al., 2006). While traditional sun drying techniques are still commonly used, advanced drying technologies is increasingly promoted to reduce post-harvest losses and enhance the quality of the product. These modern techniques aim to minimize moisture content while preserving curcumin levels, which is essential for maintaining the medicinal and economic value of turmeric (Damale & Patil, 2018).

Several studies have explored the effectiveness of different drying techniques for turmeric. For instance, Kumar et al. (2016) has examined the performance of solar dryers for various agricultural products, while Borah et al. (2015) evaluated the solar conduction dryers for both sliced and whole turmeric rhizomes. However, these studies focused only on one type of drying technology, and the evaluation was limited to the chemical composition of the final product. There is a notable gap in comprehensive research on turmeric drying methods in Bhutan. Hence, the study was undertaken to assess different drying methods with the objective of identifying and promoting appropriate technologies that can effectively minimize post-harvest losses in turmeric production.

The study assessed three different drying methods: open sun drying (control), electric drying using a locally fabricated dryer, and solar drying method integrated with Internet of Things (IoT) automation within a greenhouse. The methods were evaluated based on drying time, weight loss, water activity, and colour changes of the product. The study aimed to reduce post-harvest loss of turmeric and improve the quality through appropriate and efficient drying technology.

2 Materials and Method

2.1 Study area

The study was carried out in 2023 at the Agriculture Research and Development Centre, Wengkhar, in Mongar Dzongkhag (Figure 1), situated at an altitude of 1720 meters above sea level. During the study period, the area received an annual rainfall of 695.3 mm and recorded maximum and minimum temperatures of 22.3°C and 13.8°C, respectively (National Center for Hydrology and Meterology, 2023).

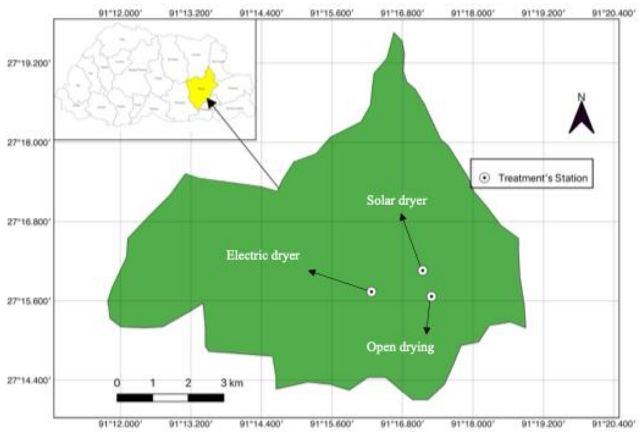

Figure 6: Study Location at ARDC-Wengkhar

2.2 Treatments

The study incorporated three treatments for drying turmeric: T1- Open Sun Drying (Control), T2- Electric Dryer, and T3- Solar Dryer. The electric dryer, developed by the National Post-Harvest Center (NPHC), Paro, is fabricated using locally available materials such as plywood and bamboo. The dryer measures 2 x 1 m and is equipped with four bamboo trays to accommodate the turmeric samples. A heater installed at the base generates hot air, while an exhaust fan positioned at the top ensures uniform air circulation throughout the drying chamber. The internal drying temperature was consistently maintained at 35°C to ensure controlled and standardized drying conditions.

The solar dryer used in the study is a fabricated greenhouse structure measuring 10 x 5 m. Within the structure, two rows of wooden shelve, each measuring 8 × 4 meters, were installed to hold the turmeric. The internal environment is regulated through IoT-based automation system consisting of temperature and humidity sensors to maintain a constant temperature of 35°C and a relative humidity of 50%. It has four exhaust fans positioned at both the front and rear of the greenhouse, programmed to activate automatically when humidity levels exceed the set threshold of 50%. Additionally, two electric fans were installed to ensure uniform air circulation which automatically activates when temperatures rise above 35°C.

The Open Sun Drying method followed the conventional approach of drying turmeric in open areas without any protective enclosure, subjecting the product to ambient environmental conditions.

The drying temperatures in both T2 (Electric Dryer) and T3 (Solar Dryer) were standardized at 35°C to ensure uniformity across treatments and to avoid skewness in data collection.

2.3 Sampling Method

A two-stage sampling method was applied. In the first stage, stratified sampling was used to classify the turmeric samples into three different size categories; Large, Medium, and Small. In the second stage, simple random sampling was employed to select 50 samples from each category, resulting in 150 rhizomes per treatment and a total sample size of 450 fresh turmeric rhizomes.

2.4 Data Collection

Each selected turmeric rhizome was initially weighed to record the fresh weight in grams and its initial water activity (aw) was measured after peeling. The rhizomes were then uniformly sliced using a mechanical slicer to ensure consistency in slice thickness and uniform drying across all treatments. The prepared slices were arranged on drying trays corresponding to their respective drying methods. The drying process was continuously monitored, and the final drying time was determined when the turmeric slices reached a water activity level of 6%. A digital weighing balance was used to measure the fresh and dry weights of turmeric, while a Pawkit water activity meter was employed to determine its water activity. Following the completion of the drying process, the final weight of each sample was recorded to determine weight loss, which was calculated using the following formula:

Weight loss = Fresh weight- dry weight

The quality of the dried turmeric was assessed based on colour, texture, and odour. All data were recorded and organized using MS Excel for further analysis.

2.5 Data Analysis

Data analysis was performed using R software (version 4.3.2) and STAR software. The descriptive statistics including mean, minimum, maximum, and standard deviation were also computed. For inferential analysis, a two-way Analysis of Variance (ANOVA) was conducted to evaluate the significance of differences among treatments at a 95% confidence level. Post-hoc analysis was conducted using the Tukey HSD test to evaluate pairwise differences between treatments. In addition, a correlation test was also performed to assess the relationship between drying time and weight loss among the different treatments.

Prior to conducting ANOVA, the normality of the data was confirmed through visual inspection using histograms and boxplots.

3 Results and Discussion

3.1 Descriptive statistics of variables of interest

The descriptive analysis of drying time, weight loss, and post-drying water activity (aw) revealed notable trends across the three drying methods. The electric dryer demonstrated the shortest average drying time, with a mean duration of 7.76 hours, while the IoT-based solar dryer exhibited the longest, averaging 71.05 hours. In terms of weight loss, the electric dryer resulted in the highest mean weight loss of 58.05 grams, while the open sun drying method showed the lowest mean weight loss of 36.45 grams (Table 1).

The variation in drying time was most pronounced in the electric dryer, as reflected by its highest standard deviation of 1.59 hours, suggesting inconsistent drying performance. In contrast, both the IoT-based solar dryer and the open sun drying method showed no variation in drying time, with standard deviations of 0, indicating consistent drying durations (Table 1).

Regarding weight loss, standard deviations were relatively uniform across treatments, showing minimal variability. However, the standard deviation for water activity post-drying was highest in the electric dryer (0.12), compared to the solar dryer, which had the lowest variability of 0.06 (Table 1).

The notable differences in drying time variation for the electric dryer suggest the need for continuous monitoring once the turmeric is placed inside the chamber. The high variability likely indicates uneven air circulation, as the exhaust fan may not uniformly distribute warm air within the dryer. This observation highlights the potential for further optimization of the electric dryer. Future modifications could include improving air circulation or avoiding the placement of products on shelves close to the heater, particularly if continuous monitoring is not feasible.

Table 11. Descriptive statistics of Fresh and Drying weight, Drying time, Weight loss, and Water activity after drying across different treatments.

Treatment	Variable	Minimum	Maximum	Mean	SD
Electric Dryer	Fresh weight (g)	48	170	105.9	33.6
	Dry weight (g)	10	31	17.7	6.14
	Drying time (hrs)	6.49	10.28	7.76	1.59
	Weight loss (g)	27	89	58.05	16.42
	Water activity after drying (%)	0.31	0.53	0.4	0.12
Solar Dryer	Fresh weight (g)	34	142	74.05	27.43
	Dry weight (g)	4	21	10.05	4.32
	Drying time (hrs)	71.05	71.05	71.05	0
	Weight loss (g)	20	75	39.7	16.4
	Water activity after drying (%)	0.44	0.56	0.49	0.06
Control (Open)	Fresh weight (g)	33	128	67.25	27.59
	Dry weight (g)	3	14	7.35	3.92
	Drying time (hrs)	27.46	27.46	27.46	0
	Weight loss (g)	15	68	36.45	16.15
	Water activity after drying (%)	0.42	0.55	0.47	0.07

3.2 **Assessment of Weight Loss of Turmeric**

The two-way ANOVA revealed a statistically significant difference in the weight loss of dried turmeric across the treatment groups, leading to the rejection of the null hypothesis at the 0.05 significance level (Table 2). A Tukey HSD post-hoc analysis further indicated significant differences between the Open Sun Drying and Electric Dryers as well as between Solar and

Electric Dryers at the 5% confidence level. However, no significant difference was observed between the Solar and Open Dryers within the 95% confidence interval (Table 2).

Table 12. Two-way ANOVA output of weight loss between the treatments

	Degree of Freedom	Sum of squared	Mean of squared	F value	P Value
Treatment	2	5426	2712.8	10.18	0.000^{***}
Residuals	57	15192	266.5		

*Notes: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05*

In both significant comparisons, the weight loss was higher in the Electric Dryer relative to the other treatments. Specifically, the Electric Dryer resulted in an average additional weight loss of 21.6 grams when compared to the Open Sun Drying method. Likewise, in comparison to the Solar Dryer, the Electric Dryer exhibited an increased mean weight loss of 18.35 grams (Table 3).

Table 13. Significant differences between treatments with Tukey HSD post-hoc test

Treatment	Difference	Lower	Upper	P value
Open-Electric Dryer	-21.6	-34.02	-9.18	0.000^{***}
Solar-Electric Dryer	-18.35	-30.77	-5.93	0.002^{***}
Solar - Open Dryer	3.25	-9.17	15.67	0.81

*Notes: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05*

Based on these findings, the Electric Dryer was the most effective in reducing turmeric weight during the drying process. However, from a practical perspective for commercial-scale operations, the Solar Dryer is recommended due to its substantially larger volume capacity, accommodating approximately ten times the capacity of the Electric Dryer. Additionally, the Solar Dryer yielded superior quality in terms of texture and colour. These findings align with the study by Mirjanaik & Vishwanath (2020), who reported that solar tunnel drying was more efficient than open sun drying, preserving higher levels of curcumin (5.83%), volatile oils (4.74%), and oleoresin (12.4%), while also reducing drying time. However, unlike their study, which utilized a solar tunnel dryer, the present research employed a protected greenhouse solar dryer with IoT-based automation, offering a more advanced and modern technological solution.

However, due to the absence of data on curcumin content and other biochemical quality parameters in the current study, future research should include these critical assessments to enhance the robustness of findings and support evidence-based recommendations for optimal turmeric drying technologies. Such comprehensive evaluations will be essential for promoting the broader adoption of efficient and high-quality post-harvest drying practices.

3.3 **Assessment of Water activity and Duration of drying time**

Water activity and drying time are crucial parameters when determining the most suitable drying technology for turmeric. Roos 2002 defined water activity as, "an equilibrium property of water in foods and other materials". Water activity measures the availability of water for biological reactions and is a key factor in determining the potential for microorganism growth (Canovas et al., 2020).

A two-way ANOVA was performed to assess the significant differences among the drying technologies. The analysis revealed statistically significant differences between the Electric Dryer and Open Sun Dryer, as well as between the Electric Dryer and Solar Dryer for water activity, but no significant differences were observed between the Open Sun Dryer and Solar Dryer at the 0.05 significance level. The electric dryer recorded the highest water activity, 58.05%, compared to the open sun dryer and the solar dryer (Table 4). These results suggest that the Electric Dryer maybe associated with increased postharvest losses, as the higher water activity indicates an increased potential for microorganism growth. Similar findings were reported by the Borah et al. (2015); Chumroenphat et al. (2021); Huang et al. (2021); and Singh et al. (2020). However, Bourdoux et al. (2016); and, Pittia & Antonello (2016) contested the direct correlation between higher water activity (a_w) and postharvest losses emphasizing that susceptibility to losses is more dependent on the intrinsic characteristics of the agricultural product. For instance, starch-rich foods are highly prone to microbial growth regardless of the water activity level in dried products. The ideal water activity for spice crops such as turmeric, garlic, and ginger must be maintained at 20-30% to inhibit microbial growth (Canovas et al., 2020).

Regarding drying time, the null hypothesis was rejected at the 5% significance level, indicating statistically significant differences among all three treatments. The Electric Dryer demonstrated the shortest drying time, completing the process in 7.76 hours, whereas the Solar Dryer took the longest at 71.05 hours. The Electric Dryer was 63.29 hours faster than the Solar Dryer and 19.7 hours faster than the Open Sun Dryer (Table 4). These findings suggest that, based on drying time alone, the Electric Dryer is the most efficient technology. The substantial variation in drying time across treatments raises concerns regarding the lack of environmental control mechanisms specifically, the inability to regulate ambient air movement, temperature, and relative humidity in both the Solar Dryer and Open Sun drying conditions. This limitation may have contributed to extended drying durations in these treatments due to less stable microclimatic conditions.

Table 14. ANOVA output of duration of drying time and water activity between the treatments

Treatment	Water Activity (%)	Duration of Drying time (hrs)
Electric Dryer	58.05^{a}	7.76^{c}
Open	36.45^{b}	27.46^{b}
Solar	39.7^{b}	71.05^{a}
P value	0.000^{***}	0.000^{***}

*Notes: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05*

Although the Electric Dryer demonstrated the fastest drying, it was associated with higher water activity, indicating a higher potential for microorganism growth. Moreover, its limited capacity makes it inefficient for handling large scale turmeric processing as repeated drying cycles would substantially increase labour and energy costs. In contrast, the Open Sun Dryer depends on optimal sunlight conditions, making it unreliable during periods of poor weather. Furthermore, the open exposure of turmeric during this method increases the risk of contamination from dust and other environmental pollutants, adversely affecting product quality and hygiene.

In comparison, the Solar Dryer emerged as the most effective drying method, producing turmeric with lower water activity levels, although requiring a longer drying duration. These findings are consistent with previous studies; for instance, Borah et al. (2015) reported that the Solar Conduction Dryer (SCD) reduced the moisture content of sliced turmeric samples from 78.65% to 5.5% within 12 hours, whereas Open Sun drying required 25.5 hours to achieve comparable results. The SCD was also noted for its effectiveness in minimizing mould growth, particularly under humid conditions, due to its ability to dry wet samples more rapidly. Although the SCD utilized stainless steel components and was designed for small-scale operations, the present study's Solar Dryer features a larger structure, offering improved economies of scale. Similarly, Kumar et al. (2016) it the suitability of Solar Dryers as the most efficient and cost-effective drying solution, especially in developing countries, where affordability and performance are critical factors for processing agricultural commodities.

3.4 Association between weight loss and duration of drying time among the treatments

The relationship between weight loss and drying time for the various treatments was analyzed using a Pearson correlation test, a statistical method used to determine the strength and direction of the linear relationship between two continuous variables. The findings revealed a negative correlation coefficient of -0.4, indicating a moderately weak inverse relationship between drying time and the weight loss experienced by turmeric.

This outcome signifies that as the drying time increases, the weight loss of turmeric tends to decrease. This trend can be observed in Figure 1. The implications of these results are significant, leading to the conclusion that drying methods requiring extended durations, such as solar drying technology, maybe the most effective. After a certain point in the drying process, the weight loss of turmeric reaches a plateau, suggesting that prolonged drying times do not yield further reductions in weight loss. Therefore, these findings highlight the need to evaluate more efficient drying techniques that optimize weight loss within an appropriate time frame.

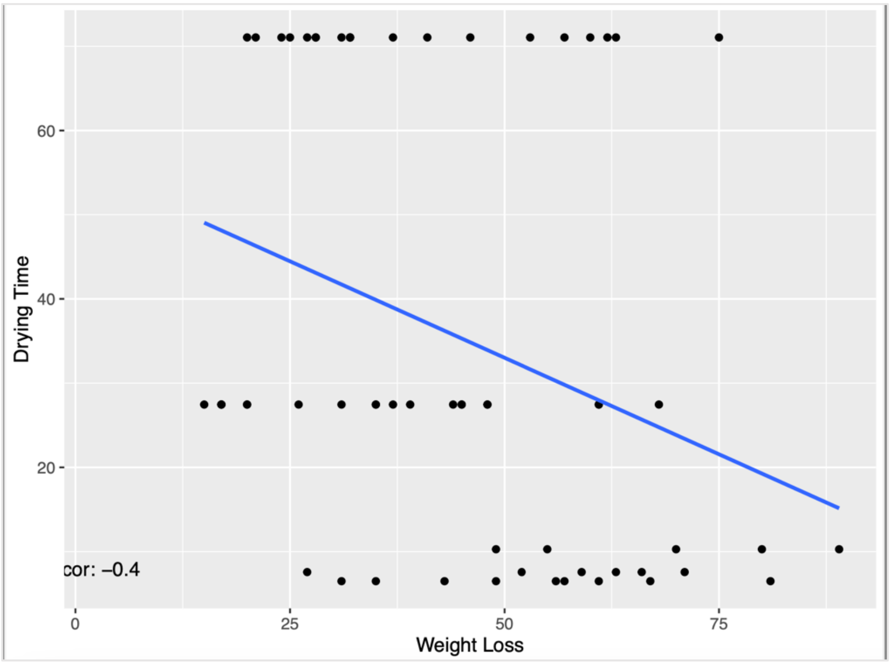

Figure 7: Correlation between weight loss and drying time

4 Conclusion

In conclusion, this study highlights the significant influence of various drying methods on the physical attributes, rehydration capacity, sensory quality, bioactive composition including the antioxidant characteristics of turmeric. Among the methods tested, turmeric dried using the

Solar Dryer integrated with IoT-based climate control technology exhibited superior physical qualities, including vibrant color, minimal shrinkage, and reduced hardness. However, this method required the longest drying duration.

In contrast, the Electric Dryer achieved the highest weight loss, and the shortest drying time compared to Open Sun Drying and Solar Drying. Despite its efficiency, the Electric Dryer has limitations, including high water activity, limited capacity, increased labor demands, and high energy consumption, making it less suitable for commercial-scale operations.

Considering scalability and product quality, the IoT-enabled Solar Dryer is recommended due to its larger operational capacity and ability to retain desirable physical quality parameters such as color and texture. To encourage broader adoption of Solar Drying technology, future research should focus on evaluating its impact on the chemical composition of turmeric, particularly curcumin, which is vital for its medicinal and therapeutic properties. Additionally, further studies are needed to examine the effect of drying temperature on drying duration and economic analysis of Solar Dryer technology to optimize their performance and application for commercial uses.

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6 Authors' contribution statement

Thinley Gyeltshen, Tenzin Rabgay, Tshering Penjor, and Domang- Study conception and design; Implementation of research, data analysis and interpretation of result and drafting of manuscript**.** Pema Yangdon, Tshering Pem, Kinzang Thinley, Kinley Sithup and Kinley Wangmo- Implementation of research and data collection; data cleaning; and data analysis and interpretation of result.

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