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Comparative Analysis of Traditional and Solar Drying Techniques for Red Chilli

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Abstract

This study compared the performance of direct solar dryer, indirect solar dryer, and open-sun drying methods for red chilli. The solar dryers consisted of collectors, drying chambers, and airflow systems, while open-sun drying involved spreading chilies on polyethylene sheets under direct sunlight. Drying occurred from 9:00 am to 3:00 pm until the desired moisture content was reached. Average ambient conditions included a temperature of 31.04°C, relative humidity of 63.68%, air velocity of 3.45 m/s, and solar radiation of 365 W/m². The highest temperature was recorded in the direct solar dryer (57.6°C), followed by the indirect solar dryer (55.4°C) and open-sun drying (38.1°C). The direct solar dryer had the lowest relative humidity (41.2%) compared to the indirect solar dryer (43.1%) and open-sun drying (53.2%). Solar radiation was lowest in the indirect solar dryer (230 W/m²). Drying time was 32 hours for the direct solar dryer, 36 hours for the indirect solar dryer, and 50 hours for open-sun drying. The highest drying rate (6.1 g/hr) was observed in the direct solar dryer, followed by the indirect solar dryer (5.9 g/hr) and open-sun drying (2.4 g/hr). The direct solar dryer proved to be the fastest and most efficient for drying red chili while maintaining quality.

Keywords: Storage, Relative humidity, Temperature, Quality, Radiation

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Introduction

Red Chilli, a significant crop in Pakistan, is a crucial ingredient in the production of essential culinary items. Red chili is an excellent source of antioxidants since it is abundant in vitamins such as A and C, phytochemicals (Maqbool et al., 2023), and other minerals that serve as an essential source of nourishment in the human diet (Devianti et al., 2023). Chillies are one of the most widely sold spices on the global market. Pakistan is the fourth-largest producer of chilli peppers after China, India, and Mexico. Chilli, covering an area of 157.9 thousand acres with a production of 142.9 thousand tonnes, was cultivated in Pakistan in 2017-18, with Sindh province contributing approximately 85% (Government of Pakistan, 2018). Red chilli is perishable agricultural produce, often spoiling a few days after being harvested (Olatunji & Afolayan, 2018). Foods are preserved by drying, thereby eliminating sufficient moisture to prevent deterioration and spoilage (Panhwar et al., 2020). A prolonged delay in drying leads to the development of microorganisms, resulting in a loss of quality during storage (Amit et al., 2017). Drying and dehydrating chillies are necessary to minimize their overall moisture content before processing, thereby extending their shelf life (Azlan et al., 2022).

Sun drying is the most cost-effective traditional method. However, the quality of the items produced using this process falls far short of international requirements. Many developing countries extensively utilize sun-drying methods (Kotu et al., 2019; Mobolade et al., 2019). This drying technique is highly weather-sensitive and prone to contamination, infestation, and microbial assaults, among other issues, thereby reducing the product's quality (Agbede et al., 2023). The drying pace depends on many characteristics, including sun radiation, wind speed, ambient temperature, relative humidity, initial moisture content, crop type, crop absorption, and product mass per unit of exposed surface (Arunkumar et al., 2024). This drying method has several disadvantages, including product contamination from wind, dirt, rain, insect infestation, and human and animal intervention. The evaporation rate will decrease due to intermittent sunlight, interruption, and precipitation (Ahmed et al., 2016). Solar drying is a well-established food preservation method that reduces the moisture content of agricultural produce, thereby preventing quality loss over extended storage periods (Loemba et al., 2024). Solar dryers can produce higher-quality products, reducing the time required for drying. Several types of solar dryers have been designed and are used to dry various agricultural goods. To address these issues, solar dryers employing natural convection or forced circulation have been studied (Calín-Sánchez et al., 2020). For commercial operations, the dryer's capacity to operate continuously throughout the day is crucial for drying items to safe storage levels and preserving their quality (Müller et al., 2022).

Chilli drying often occurs in the open air, resulting in significant losses in the quality and quantity of the product. Considering these losses, this research was conducted to evaluate the performance of various methods for drying chillies and identify an approach suitable for drying red chillies.

Materials and Methods

Experimental Site

The research was conducted at the Department of Farm Structures and Postharvest Engineering, Sindh Agriculture University, Tandojam, Pakistan. The red chilli *(C. annuum L.)* samples were obtained from the local farm of Tando Allahyar, Sindh, Pakistan. The red chillies were subjected to three different drying methods: direct solar drying, indirect solar drying, and open sun drying. The red chilli was loaded in the dryer on trays and dried till the moisture content reached a desired value. The drying experiment was conducted in good sunny conditions from 9:00 am to 3.00 pm. The performance of the solar dryers was compared with open sun drying, which is the standard method of drying red chillies in the area.

Direct Solar Dryer

The direct solar dryer consisted of a drying chamber with a transparent glass cover. (Figure 1). The drying chamber consisted of an insulated, shallow box with air openings that allowed air to enter and leave the box freely. The agricultural produce samples were laid on a perforated tray to enable air to circulate freely through the material and the tray. Solar radiation penetrated the see-through cover and was then transformed into a lower-grade form of heat when it came into contact with an opaque wall. The greenhouse effect caused this low-grade heat to be trapped within the container, which in turn caused the temperature to rise. In addition, the glass cover helped minimize direct convective heat loss to the surrounding environment, which was ultimately advantageous for both increasing the product temperature and maintaining a stable chamber temperature.

Indirect Solar Dryer

This type of dryer does not involve direct solar energy impact on the product being dried. The air was first heated in a solar collector to dry the product and then routed into the drying chamber (Figure 1). The insulator, absorber plate, and cover plate, all made of glass, are the components that make up the solar collector. The cover plate was made of clear glass, 4 mm thick, and had no color. It was positioned 10 cm higher than the absorber plate, which was responsible for gathering solar light. The absorber plate was manufactured of an aluminium sheet coated black, and the cover plate was placed below. Its purpose was to absorb incoming solar radiation transmitted through the glass cover plate and heat the air moving between it and the cover plate. Insulation, which was placed behind the absorber plate, was used to reduce the amount of heat lost from the system. The solar collector was angled at 45° from the horizontal to receive the maximum amount of radiation and was linked to a separate drying chamber where the product was stored on perforated trays. To prevent the wood from being wet and soaked if it was to be utilized during the rainy season, the drying chamber was constructed of plywood and covered with emulsion paint. A vent was installed at the top of the drying chamber, and it was via this vent that the exhaust air and moisture were expelled.

Open Sun Drying

The product in this method was distributed evenly throughout the black polyethylene sheets and exposed directly to the sun. Solar light with a short wavelength struck the surface, partially reflecting the energy, while the surface absorbed the remainder. The absorbed radiation was transformed into thermal energy, and the product's temperature rose. This resulted in the loss of long-wavelength radiation from the product's surface to the ambient air via damp air. Besides long-wavelength radiation loss, there is also convective heat loss due to wind moving through wet air over the material's surface. The product was dried due to evaporative losses involving the evaporation of moisture (Handayani et al., 2022).

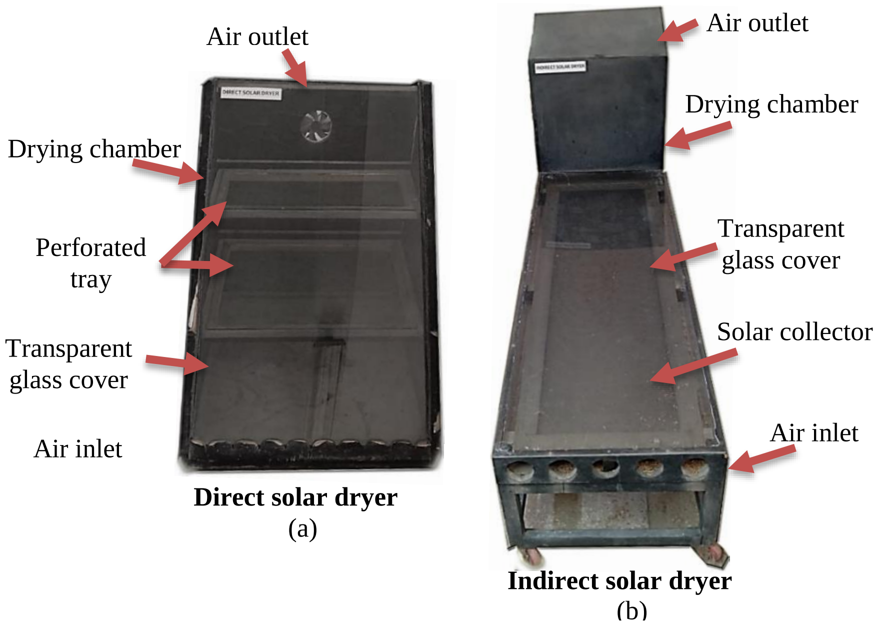

Figure 1. Direct solar dryer (a), and Indirect solar dryer (b)

Samples Collection and Analysis

Data on the dryer's performance and the product's quality were observed for all three drying methods. The chili samples were dried in an oven at 105 °C to determine their moisture content, which was then calculated using Eq. 1 (Soomro et al., 2020). The drying rate (DR) was determined by dividing the moisture loss per unit of time during the drying process (Eq. 2). The amount of moisture that was lost due to evaporation per unit of time is the drying rate (Raj et al., 2018). The temperatures (°C) inside and outside were measured using a digital thermometer. The relative humidity (%) was recorded using a hygrometer (Chattha et al., 2020). The air velocity (m/s) was determined using the anemometer. The solar radiations (W/m^2) were measured using a pyrometer.

$$\text{MC}\ (\%) = \frac{\text{Wi - Wf}}{\text{Wi}} \times 100 \quad \text{(Eq. 1)}$$

$$\text{DR}\ (\text{g/hr}) = \frac{\text{Mi - Md}}{\text{t}} \quad \text{(Eq. 2)}$$

Statistical Analysis

An analysis of variance using a two-factor factorial design was conducted with SPSS (version 23) software to determine the effect of drying methods and drying time on dryer performance.

Results and Discussion

Moisture Content

The moisture content results differed statistically for drying methods and times (Table 1). The initial moisture content of red chilli was 70.30% (Figure 2). The sun drying method, indirect solar dryer, and direct solar dryer took 50, 36, and 32 hrs to dry the red chilies at the desired moisture content. The direct solar dryer showed rapid moisture removal compared to the indirect solar dryer and open sun drying. Initially, a rapid decrease in moisture content was observed due to the free moisture from the outer layers of the red chilli, which then decreased as the moisture migrated from the internal structure (Naveed et al., 2023). Akoy (2014) designed and tested a natural convection direct-type sun drier that reduced the moisture content of mangoes in two days. This is because a greater degree of drying temperature was observed in the dryer due to direct exposure to sunlight or a direct kind of solar dryer (El-Sebaey et al., 2023).

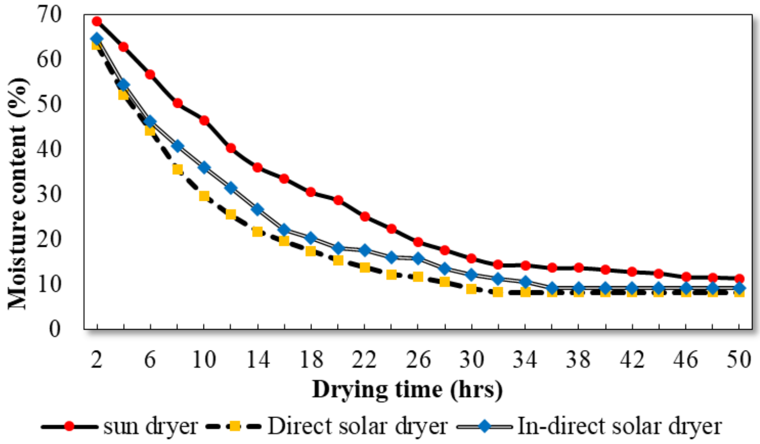

Figure 2. Variation in moisture content under different drying methods over time

Drying Rate

Statistical analysis of variance indicated a significant difference in drying rate for different drying methods and times (Table 1). The drying rate of chili showed a decreasing trend throughout the drying period (Figure 3). The highest drying rate of chili (6.1 g/hr) was observed in the direct solar dryer, compared to the indirect solar dryer (5.9 g/hr) and sun drying (2.4 g/hr). A high drying rate was observed during the initial stages of drying, resulting in a higher moisture content in the fresh chili. The lower drying rate in sun drying was attributed to variations in temperature, humidity, and wind velocity. The results agree with the findings of Mainil et al. (2020). Similarly, Bolaji and Olalusi (2008) evaluated a mixed-mode solar drier using yam chips. Their results showed a higher drying rate for the dryer, which dried the product rapidly to a safe moisture level, compared to the sun drying method. Irtwange and Adebayo (2009) developed and tested a passive solar dryer for food grains. They also found a higher average drying rate under passive solar driers than traditional sun drying. Ambrose et al. (2024) studied the influence of drying techniques and pre-treatments on the quality attributes of red chilli. They reported that solar tunnel drying proved to be the most efficient method for reducing drying time while retaining quality parameters. On the other hand, open sun drying requires more extended drying periods.

Table 1. Mean squares of drying parameters under different drying methods and drying times

SOV	DF	Temperature ^{0}C	Humidity %	Solar radiation W/m^2	Moisture content %	Drying rate g/hr
Replication	2	0.00385	0.00976	0.3	0.00516	0.00118
Drying methods (DM)	2	3563.47*	3467.43*	10067.7*	997.945*	9.65885*
Drying time (DT)	24	239.829*	97.1987*	86521.4*	1553.41*	14.4988*
DM x DT	48	6.77938*	5.9858*	17.1*	10.7078*	1.01334*
Error	74	6.688E-05	6.039E-04	1.7	1.802E-04	1.789E-05
Total	150					

* = Highly significant at $p<0.01$

Temperature (℃)

The ambient temperature was recorded between 24.2 ℃ and 37.3 ℃ throughout the experiment, with an average value of 31.04 ℃. The maximum and minimum ambient temperature of 37.0 ℃ and 24.2 ℃ was noted at the 30th and 2nd hour of drying time (Figure 4). The temperature change was statistically different for different drying methods (Table 1). The temperature around the product followed the pattern of the ambient temperature in sun drying, direct solar drying, and indirect solar drying throughout the experiment. The highest temperature around the red chili (57.6°C) was recorded in the direct solar dryer, followed by an indirect solar dryer (55.4 °C) and sun drying method (37.3 °C) at the 30th hour of drying time. However, the lowest temperature of 24.2 °C, 33.2°C, and 35.3 °C was noted in the sun drying, indirect solar dryer, and direct solar dryer, respectively, at the 2nd hour of the drying period. The maximum rise in average temperature around the red chilli under sun drying, indirect solar dryer, and direct solar dryer was observed to be 0.84 °C, 13.88 °C, and 16.64 °C, respectively, when compared with the ambient temperature. The temperature reached its peak at noon, then declined. This is because the intensity of solar radiation is at its lowest in the morning, while it is at its peak around midday. A similar variation in the increase and decrease of temperature has also been reported by Ennissioui et al. (2023). Alonge and Adeboye (2012) experimented with a no-load indirect-type dryer, which resulted in a maximum temperature increase of 48 ℃, despite an ambient temperature of 39 ℃. Bolaji (2005) designed an indirect crop dryer with a higher drying chamber. They found that the maximum average temperature acquired in the drying chamber was 57.0 °C, while the ambient air temperature was 33.5 °C.

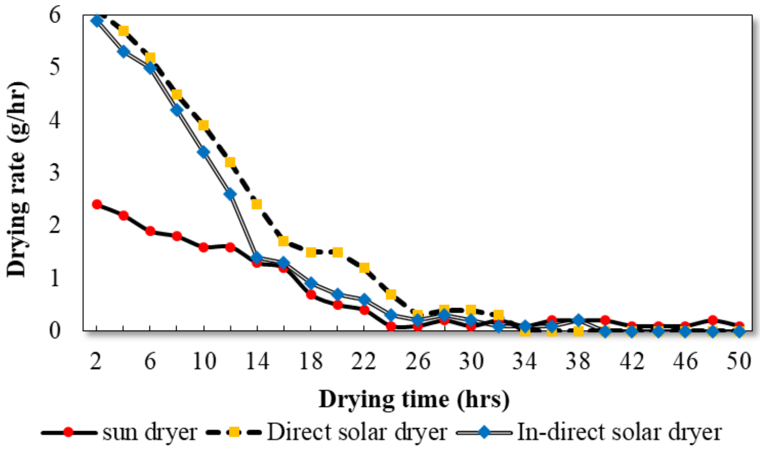

Figure 3. Variation in drying rate under different drying methods concerning time

Relative Humidity

The ambient relative humidity was recorded between 55.8% and 71.4% during the experiment, with an average value of 63.68%. The maximum ambient relative humidity (71.4%) was noted at the 36th hour of drying. However, the lowest ambient relative humidity of 55.8% was observed at the 26th hour of drying (Figure 5). Statistical analysis showed a significant effect of drying time and drying methods on relative humidity (Table 1). The relative humidity around the product followed the pattern of the ambient relative humidity in all the dryers, namely, sun drying, indirect solar dryer, and direct solar dryer, throughout the drying experiment. The results also showed that the relative humidity of the air around the red chilli in the direct and indirect solar dryers was lower than that of the ambient relative humidity. The lowest relative humidity around the red chilli (41.2%) was recorded in the direct solar dryer when compared to the indirect solar dryer (43.1%) and traditional sun dryer (53.2%) at the 26th hour of drying time. However, the highest relative humidity of 69.0%, 55.3%, and 54.1% was noted in the sun dryer, indirect solar dryer, and direct solar dryer, respectively, at the 36th hour of the drying period. The differences in average relative humidity around the red chili during sun drying, indirect solar drying, and direct solar drying were observed to be 1.67%, 15.25%, and 16.8%, respectively, compared to the ambient relative humidity. The relative humidity decreased from morning to noon, attained a minimum at noon, and then increased. This was due to the increasing temperature from morning to noon, increasing the drying air's water-holding capacity.

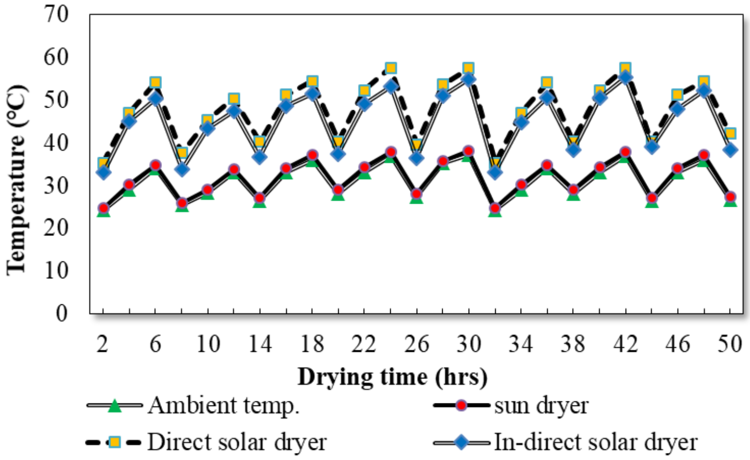

Figure 4. Variation in temperature under different drying methods over time

Solar Radiation

Statistical analysis revealed a significant effect of drying methods and drying time on solar radiation during the drying process (Table 1). The ambient solar radiation was recorded between 264.0 W/m² and 558.0 W/m², with an average value of 365.0 W/m² throughout the drying experiment. The maximum ambient solar radiation (558.0 W/m^2) was noted at the 46th hour of drying. However, the lowest ambient solar radiation of 264 W/m^2 was observed at the 6th hour of drying (Figure 6). The solar radiation around the product followed the pattern of the ambient solar radiation during the sun-drying, indirect solar-drying, and direct solar-drying phases of the drying experiment. The results also indicated that the solar radiation around the chili in the sun-drying process, as well as in the indirect solar dryer and direct solar dryer, was lower than ambient solar radiation. The minimum solar radiation around the chili (230 W/m^2) was recorded in the indirect solar dryer, followed by 245 W/m^2 in the direct solar dryer and 256 W/m^2 in the sun drying method at 6 hours of drying time. The highest solar radiation with 545 W/m^2, 527 W/m^2, and 508 W/m^2 was observed in sun drying, direct solar dryer, and indirect solar dryer at the 46th hour of drying. The differences in average solar radiation around the chili under the sun drying, direct solar dryer, and indirect solar dryer were 8.28 W/m^2, 20.24 W/m^2, and 36.84 W/m^2, respectively, as compared with the ambient solar radiation. The solar radiation around the product followed the pattern of the ambient solar radiation in all the drying methods throughout the drying experiment. Similar results have also been reported by Karthikeyan and Murugavelh (2018). Similarly, Khama et al. (2016) designed and evaluated an indirect solar dryer for tomato fruit. They observed an increase in the drying efficiency of the drier with solar radiation varying between 400 and 800 W/m².

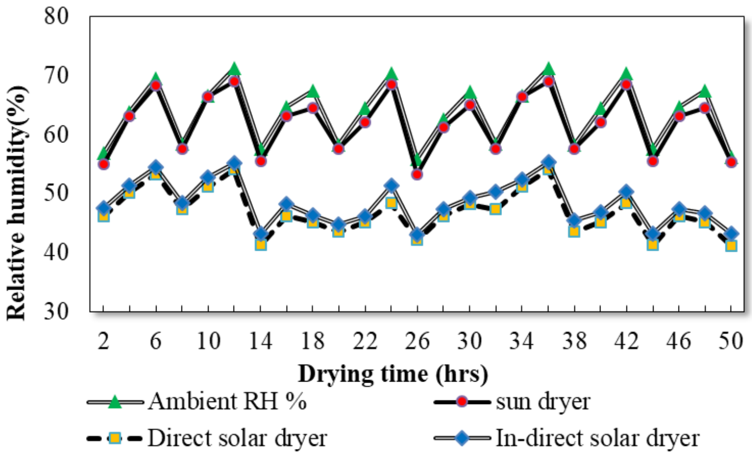

Figure 5. Variation in relative humidity under different drying methods concerning time

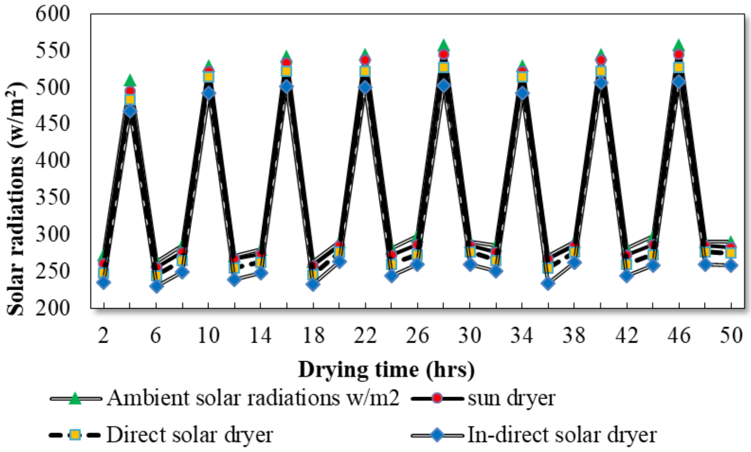

Figure 6. Variation in solar radiation under different drying methods concerning time

Air Velocity

The ambient air velocity was recorded between 1.7 m/s and 4.5 m/s, with an average value of 3.45 m/s throughout the drying experiment. The maximum ambient air velocity (4.5 m/s) was noted at the 18th hour of drying, whereas the lowest 1.7 m/s ambient air velocity was observed at the 48th hour of drying (Figure 7). The results indicated that the air velocity around the red chilli during sun drying, in the indirect solar dryer, and the direct solar dryer was lower than the ambient air velocity. The average differences in air velocity around the chili under the sun drying method, indirect solar dryer, and direct solar dryer were 0.58 m/s, 1.22 m/s, and 1.08 m/s, respectively, when compared with the ambient air velocity. The minimum air velocity around the chilli (2.0 m/s) was recorded under the indirect solar dryer, as compared to a direct solar dryer (2.1 m/s) and sun drying (1.3 m/s). The results also revealed that the air velocity around the chilli in all dryers was lower than that of the ambient air velocity. Various researchers have reported that increasing air movement by utilising fans or wind ventilation enhances the drying process (Amedorme et al., 2013; Nukulwar & Tungikar, 2021). Gutti et al. (2012) constructed a solar dryer utilizing forced convection. They reported that the drying capacity of the forced convection drying technique was much greater than that of natural convection drying. Hegde et al. (2015) developed and evaluated an indirect solar dryer utilising banana slices. They reported that the quality of the banana was better when dried at an airflow rate of 1 m/s, when compared to 0.5 m/s.

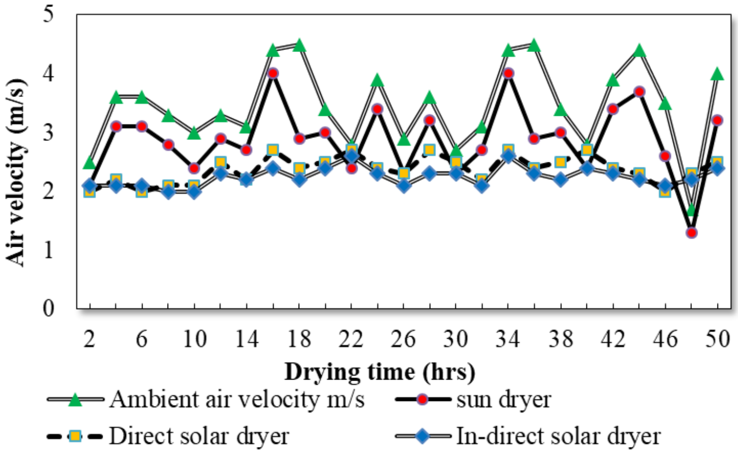

Figure 7. Variation in air velocity under different drying methods concerning time

Conclusions

Solar dryers, both direct and indirect, resulted in significantly faster drying of chili to the desired moisture content level, ensuring a higher-quality dried product. The dryers proved useful for minimising postharvest losses and preserving agricultural products. The air temperature inside the dryers was more than the ambient temperature during the whole drying period. The highest temperature around the red chili (57.6 °C) was recorded under the direct solar dryer, followed by the indirect solar dryer and the traditional sun drying method. The relative humidity of air inside the dryers was lower than the ambient relative humidity. The lowest relative humidity around the chili (41.2%) was recorded under a direct solar dryer, followed by an indirect solar dryer and sun drying. The solar radiation and air velocity around the red chilli in all the selected dryers were lower than the ambient solar radiation and air velocity, respectively. The highest drying rate of red chilli (6.1 g/hr) was observed under a direct solar dryer, followed by an indirect solar dryer (5.9 g/hr) and sun drying method (2.4 g/hr). The results concluded that the direct solar dryer significantly accelerated the drying of red chili to an acceptable moisture level, ensuring better quality. Considering the losses incurred during the open sun drying method, farmers and related processing industries are highly recommended to use a direct solar dryer for drying red chillies, resulting in better quality and minimal loss.

Competing Interests

The authors declare that the research was conducted without any commercial or financial relationships that could be perceived as a potential conflict of interest.

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Code availability: Not applicable.
Consent to participate: All authors participated in this research study.
Consent for publication: All authors submitted consent to publish this research.
Data availability statement: The data presented in this study are available on request.

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