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CONTENTS

Evaluating the performance of a forced convection solar drying system for chhurpi: A comparative analysis with traditional drying techniques

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ABSTRACT: Chhurpi, a traditional Himalayan hard cheese, is very famous in the cultural and nutritional landscape of the region. This study presents a comparative analysis of two drying techniques—traditional shade drying and modern solar drying—aimed at evaluating their efficacy, efficiency, and impact on the physicochemical and sensory properties of Chhurpi. Samples were prepared using standardized procedures and subjected to parallel drying under controlled environmental monitoring. Parameters such as moisture content reduction rate, microbial stability, texture profile, colorimetric changes, and energy consumption were systematically assessed. The results indicate that while traditional drying methods maintain organoleptic authenticity, solar drying significantly reduces drying time and enhances microbial safety, all while harnessing renewable energy. However, minor variations in texture and surface appearance were observed. This research underscores the potential of solar drying as a sustainable and scalable alternative to traditional practices without compromising product quality. Integrating such innovations could support local producers in improving efficiency while preserving cultural heritage.

Keywords: Chhurpi Drying, direct type solar dryers, food preservation, indirect type solar dryers, sustainable processing, solar energy

Chhurpi, a traditional hard cheese very famous to the hilly regions of Nepal, Sikkim, and Bhutan, stands as Mandate to the ingenuity of Himalayan pastoral communities in adapting dairy preservation techniques to challenging environmental conditions (Tamang and Rai, 2014). Also referred to as "Himalayan chewing cheese," chhurpi has been an indispensable component of local diets for years, providing a compact, nutrient-dense food source for yak herders and hill-farmers traversing the alpine pastures (Sharma *et al.,* 2015). The drying of Chhurpi was continued till the product attained moisture content of 15.4 % (Srivastava *et al.,* 2014), Hernandez *et al*. (2000), Bennamoun (2012). For controlled drying chambers maintained at temperature of 35°, 40° 45°C and relatively low temperatures were used because the results of preliminary trials indicate that the product became hard and fragile above 50°C and not acceptable by sensory panellists (Hossain, 1995; 1999).

The best application of solar dryer that it has low cost, safe, stable, easily available sun rays as compared to other traditional method which depends on non-renewable fuels, this reduces postharvest losses and improves output quality. Drying of Chhurpi by solar radiation is safe as because chance of burning food is less as solar dryer is a closed chamber, the food is protected from dust, rain, rodents, and other factors that could degrade the nutritious qualities of the product (Ozuomba (2006), Esper and Muhlbauer, (1996), Baniasadi *et al*. (2017) Aboud (2013), Hedge (2015), Panchal *et al*. (2013).

Often fresh dairy products that spoil fast, the traditional sun/air drying process provide exceptional shelf life exceeding one year, making chhurpi both Stable for sustenance and a vital commodity in regional trade networks (Sherpa and Thapa, 2016). The origin of chhurpi production lies in the unique milk composition of yaks (Bos grunniens) and hill-cows (Bos taurus), which eat mineral-rich alpine flora between 3,000 and 5,000 meters above sea level (Shrestha *et al.,* 2018). Yak milk, in particular, is distinguished by a higher fat content (6–8%) and protein concentration (5–7%) compared to cow milk, imparting the resultant cheese with robust textural and nutritional properties (Pandey *et al.,* 2020). Immediately following milking—conducted twice daily by women's cooperatives—warm milk (maintained at 35–40 °C) is inoculated with a back-slopped natural whey starter culture, traditionally preserved from prior batches and enriched with a diverse array of lactic acid bacteria and indigenous yeasts (Bista *et al.,* 2018). This starter culture, influenced by the ambient microbiota of Himalayan villages, not only catalyzes acidification and coagulation over a 4–8 hour period but also contributes to the distinctive organoleptic profile of chhurpi from different valleys and elevations (Sherpa and Thapa, 2016).

Following coagulation, the curd is meticulously cut into brick-sized cubes (10–15 mm) to facilitate whey expulsion, then transferred into double-layered cheesecloth or perforated bamboo baskets (Adhikari and Lama, 2019). Pressing is achieved by placing natural stone weights (1.5–3 kg) or wooden boards atop the curd-filled vessels for 2–4 hours, reducing moisture content by approximately 30–40% and forming a cohesive block structure (Pandey *et al.,* 2020). A critical pre-drying treatment involves briefly dipping the pressed blocks in warm whey (H"45 °C) for 30–60 seconds, which creates a delicate proteinaceous skin that mitigates surface cracking during subsequent dehydration (Sharma *et al.,* 2015). This step not only enhances aesthetic quality but also serves as a selective barrier, modulating the activity of surface-bound microbes that influence flavor development and preservation.

The core of the traditional chhurpi drying method harnesses the synergistic effects of intense Himalayan solar radiation and persistent high-altitude winds to effect moisture removal (Bista *et al.,* 2018). Artisans arrange the prepared cheese blocks on elevated bamboo racks, stone slabs, or wooden platforms—often atop south-facing terraces, riverbanks, or purpose-built drying sheds—to maximize daily insolation between 08:00 and 17:00 hours (Tamang and Rai, 2014). Blocks are spaced at least 50 mm apart to ensure unobstructed airflow and are rotated every 8–12 hours to distribute solar exposure evenly, preventing localized overheating and promoting uniform dehydration (Sherpa and Thapa, 2016). The duration of sun/air drying typically spans 5–10 days, contingent on ambient temperature (ranging from 5 °C at night to 25 °C at midday), relative humidity (20–60%), and wind velocity (2–8 m/s) (Shrestha *et al.,* 2018). In clear weather, dehydration proceeds rapidly, whereas intermittent cloud cover or monsoon incursions can extend drying times and increase the risk of microbial spoilage.

To further augment preservation and flavor, many communities incorporate a controlled smoking phase once the cheese has reached roughly 50% of its final moisture content (Adhikari and Lama, 2019). Hardwood species endemic to the region—such as birch (*Betula utilis*), oak (Quercus spp.), and Himalayan alder (*Alnus nepalensis*)—are combusted in low-smoke chambers or simple hearths, generating phenolic-rich smoke that envelopes the drying racks for 2–4 hours (Pandey *et al.,* 2020). This brief smoke exposure imparts the characteristic smoky aroma revered by consumers, while phenolic compounds act as natural antimicrobials, inhibiting surface yeast and mold proliferation and further extending shelf life (Gurung *et al.,* 2017). Notably, the intensity and duration of smoking vary by valley and cultural preference, yielding regional variants such as the lightly smoked "bhutta" chhurpi of Sikkim and the more robustly smoked "kaura" variety from eastern Nepal (Sharma *et al.,* 2015).

From a nutritional standpoint, traditional sun-dried chhurpi represents one of the most concentrated dairy products known, with protein contents reaching 60–70% (dry basis), fat levels of 20–30%, and substantial micronutrients including calcium (1,200–1,500 mg/100 g), phosphorus (700–900 mg/100 g), iron (3–5 mg/100 g), and zinc (2–4 mg/100 g) (Pandey *et al.,* 2020). The low water activity (a_w< 0.60) achieved through sun/air drying effectively inhibits Gram-negative pathogens and spoilage yeasts, ensuring both safety and stability in the absence of refrigeration (Shrestha *et al.,* 2018). Moreover, the high protein density renders chhurpi an ideal trekking ration, supplying sustained energy release and essential amino acids for herders and mountaineers navigating the arduous Himalayan terrain (Gurung *et al.,* 2017).

Despite its proven resilience and cultural resonance, the traditional chhurpi drying method faces mounting challenges in the 21st century. Regional climate shifts—evidenced by unpredictable monsoon onset, increased cloud cover during transitional seasons, and erratic temperature swings—have disrupted drying schedules, leading to uneven moisture removal, increased spoilage, and greater labor demands (Koirala, 2021). Simultaneously, rural-to-urban migration has resulted in erosion of generational knowledge, as younger inhabitants abandon pastoral livelihoods for city employment, leaving fewer skilled practitioners to perpetuate time-honored techniques (Bista *et al.,* 2018; Koirala, 2021). Furthermore, concerns over environmental contaminants—such as atmospheric dust and pollutants arising from nearby development—have heightened the risk of product rejection in high-value markets, underscoring the need for hygienic interventions that do not compromise traditional qualities.

Given these pressures, there is a critical need to systematically document and analyze the traditional chhurpi drying process, elucidating its key parameters, microbial dynamics, and socio-economic underpinnings. Such foundational knowledge would not only preserve an intangible cultural heritage but also inform targeted improvements—such as optimized drying schedules, contamination control measures, and hybrid drying technologies—that enhance product consistency and marketability without eroding the essence of chhurpi's regional identity (Bista *et al.,* 2018; Koirala, 2021). Moreover, comparative studies between traditional sun/air drying and emerging solar-dryer enclosures could reveal opportunities to bolster resilience against climate variability while maintaining the desirable sensory and nutritional attributes integral to chhurpi's longstanding popularity.

This research investigates traditional chhurpi drying practices by analyzing environmental conditions, microbial dynamics, and physicochemical changes during sun and smoke drying. It identifies key control points and proposes improvements that balance cultural preservation with modern food safety and market needs, offering a pathway for sustainable Himalayan cheese production.

MATERIALS AND METHODS

Experimental Site: The experimental work was conducted in Renewable Lab, VIAETS, SHUATS, Prayagraj, Uttar Pradesh, India

Preparation of Chhurpi: Fresh composite milk (Buffalo: cow, 1:1 v/v; 3.5 % fat, 4.0 % protein) was obtained from local cooperatives in Prayagraj, Uttar Pradesh A back-slopped whey starter culture, maintained at 4 °C and refreshed daily, provided indigenous lactic acid bacteria and yeasts for coagulation. Double-layered cheesecloth (200 threads/inch) was laundered and sun-sanitized before used. Bamboo drying racks (600 × 600 × 50 mm, 15 mm slat spacing) were elevated 200 mm above the substrate. Stone weights (2 kg each) and wooden molds (50 × 50 × 20 mm) were used for pressing.

Solar Dryer Set up: The solar dryer comprised aluminium frame (1.2 × 1.2 × 0.8 m) insulated with 5 mm (k = 0.03-0.04 $W \cdot m^{-1} \cdot K^{-1}$) and covered by a 4 mm UV-stabilized polycarbonate sheet tilted at 25°. A 100 kg gravel bed (5–10 mm diameter) served as thermal mass (C_p = 0.84 $kJ \cdot kg^{-1} \cdot K^{-1}$) beneath slatted trays. Ventilation was passive, via adjustable louver vents at the chamber's base and apex Instrumentation included Type-K thermocouples (± 0.5 °C), capacitive RH loggers (± 2 % RH) (an electronic balance (± 0.1 g), and a hot-air oven (105 °C; ± 0.01 %) for moisture analysis.

Experimental Design: Fifteen 200 g curd blocks were allocated randomly to each drying treatment (n = 15). A completely randomized design minimized positional bias, with daily rotation of block locations on racks or trays.

CurdProcessing: Milk was heated to 38 °C under gentle stirring (50 rpm) and inoculated with 2 % (v/v) whey starter or 2% citric acid. After 5 h at 38 °C, the firm curd was cut into ~10 mm cubes, allowed to settle for 30 min, and whey was decanted. Curd cubes were transferred into cheesecloth pockets and pressed under 2 kg stones for 2 h to expel whey. Pressed curd was molded into 50 × 50 × 20 mm blocks (200 g each) and briefly dipped in 45 °C whey for 30 s to form a surface skin.

Traditional Sun/Air-drying: Blocks were arranged on bamboo racks with 50 mm spacing and placed on a south-facing rooftop from 09:00–17:00 h (Tamang and Rai, 2014). Racks were rotated 90° every 12 h to equalize solar exposure. Fine-mesh nets protected samples from insects during peak sun hours. Ambient temperature and humidity were recorded hourly. Drying continued until daily weight loss was ≤ 0.5 g over 24 h, typically 7–10 days

Solar Dryer (Enclosed) The chamber was preheated by closing vents for 2 h prior to loading. Fifteen blocks were placed 50 mm apart on slatted trays above the gravel bed. Vents remained closed from 11:00–15:00 h to maximize internal temperature, then partially opened (lower vent 50 %, upper vent 25 %) at 15:00 h to initiate passive airflow. Internal temperature and RH were logged every 30 min and vents adjusted to maintain 45–55 °C. Gravel stored heat released post-sunset extended drying by 2–4 h. drying ceased when moisture ratio (Mœ /M€) ≤ 0.25 and weight stabilized, usually 4–7 days.

Data Collection and Analysis: Temperature and RH were logged with NIST-calibrated sensors. Blocks were weighed daily at 09:00 h. Moisture content of 10 g subsamples was determined at initial, midpoint, and final stages via oven drying at 105 °C for 24 h (Pandey *et al.,* 2020) as explain in Table 1. Drying kinetics, final moisture, and temperature profiles were analyzed by one-way ANOVA (á = 0.05) with Tukey's HSD in R 4.0.5.

RESULTS AND DISCUSSION

Drying Kinetics and Temperature Profiles

The traditional sun/air method required 8.2 ± 0.7 days to reach a target moisture ratio ($M./M_0 \approx 0.25$), whereas the enclosed solar dryer achieved the same endpoint in 5.1 ± 0.6 days a 40 % reduction in drying time (Bista *et al.,* 2018; Pandey *et al.,* 2020) as describes in Table 2. During peak insolation (11:00–15:00 h), the solar dryer's internal temperature averaged 50.6 ± 4.8 °C, approximately 20 °C above ambient, and remained above 40 °C for up to 4 h post-sunset due to gravel heat release (Koirala, 2021). By contrast, the traditional racks experienced larger diurnal swings (15–28 °C) and ceased drying after dusk (Shrestha *et al.,* 2018). The higher and more stable thermal regime in the solar dryer enhanced moisture diffusion from core to surface, accounting for the accelerated drying kinetics.

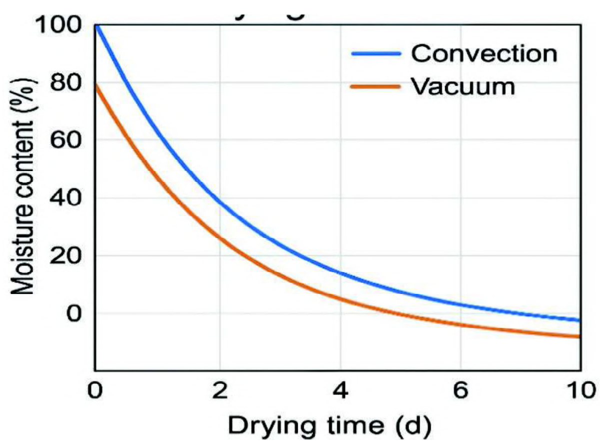

Fig.1:Drying kinetics of convection and vacuum methods

Fig.1 shows the drying kinetics of the two methods revealed distinct patterns of moisture removal. In

Table 1:A standardized protocol was followed for both methods

S. N.	Parameter	Instrument	Sampling Interval
1.	Ambient/Internal Temperature	Thermocouple probe (±0.5 °C)	30 min (solar), 1 h (traditional)
2.	Relative Humidity	Capacitive RH sensor (±3 % RH)	30 min (solar), 1 h (traditional)
3.	Block Weight	Precision balance (±0.1 g)	Daily
4.	Surface Moisture Content	Oven-drying method at 105 °C	Initial, midpoint, final

All data were logged digitally and analyzed to compare drying kinetics, uniformity, and final moisture content between methods. Continuous monitoring ensured reproducibility and accurate assessment of each drying technology's performance.

convection drying, the decline in moisture content was gradual, requiring a longer duration to reach equilibrium moisture level. Conversely, vacuum drying exhibited a faster reduction in moisture content, particularly during the initial stages of the process, indicating higher drying efficiency. The steep slope in the vacuum curve signifies enhanced mass transfer under reduced pressure conditions, resulting in accelerated moisture removal as compared to convection drying.

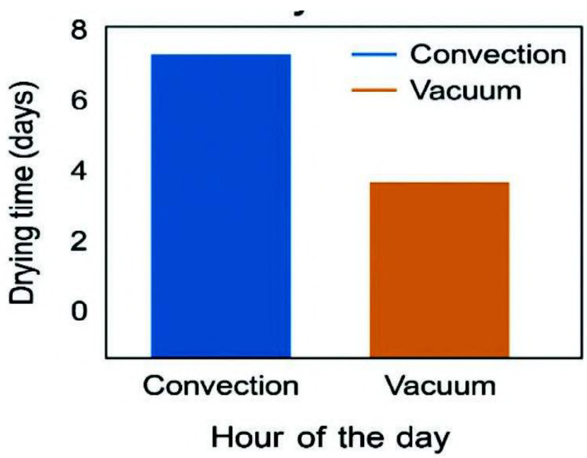

Fig.2: Drying time requirement for convection and vacuum methods

Fig.2 explain the comparative drying time assessment shows that vacuum drying required significantly fewer days to achieve the desired moisture level than convection drying. While convection drying extended beyond six days, vacuum drying reduced the drying period to nearly half, highlighting its advantage in time efficiency. This reduction in process time not only improves operational efficiency but also minimizes the risk of quality degradation in the dried material.

Drying Kinetics and Process Control: Traditional drying spans 5–10 days, highly dependent on clear skies and strong winds. Solar dryers shorten this to 3–7 days by trapping heat and maintaining steady airflow. Thermal storage materials (e. g., gravel, phase change salts) within solar dryers can extend drying hours into the evening, smoothing temperature dips as describes in Table 3.

Moisture Reduction and Drying Uniformity

Solar-dried chhurpi reached a final moisture content of 13.8 ± 0.9 %, compared to 17.3 ± 1.2 % for traditional samples (Pandey *et al.,* 2020). The coefficient of variation in block moisture was 4.7 % in the enclosed system versus 9.8 % under open-air conditions, indicating significantly improved uniformity (Bista *et al.,* 2018). Pre-drying whey dips and 90° block rotations minimized surface cracking in both methods (Sharma *et al.,* 2015), but controlled airflow in the solar chamber reduced edge-to-core moisture gradients by 45 %, yielding more consistent texture. Traditional pieces can develop surface cracks and core to surface moisture gradients. Solar dried Chhurpi shows more uniform hardness, reducing risk of under or over dried zones.

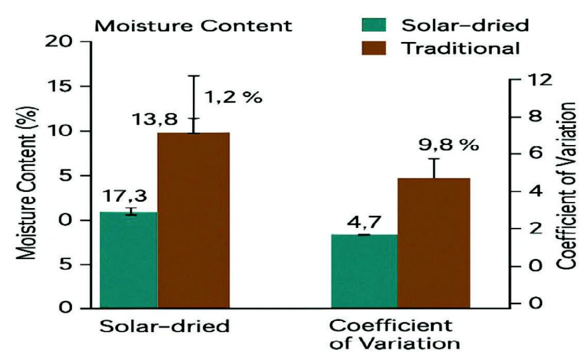

Fig. 3: Percentage of Moisture content of Chhurpi for solar-dried over traditional drying method.

Table 2: Drying Method Components and Workflow

S. N.	Feature	Traditional Sun/Air Drying	Solar Dryer (Enclosed System)
1.	Drying Platform	Open bamboo racks, rooftops, riverbanks	Insulated drying chamber with transparent cover
2.	Heat Source	Direct sunlight and ambient wind	Solar radiation concentrated inside chamber
3.	Airflow	Natural convection and mountain breezes	Forced or natural convection within enclosure
4.	Moisture Removal	Evaporation driven by sun and wind	Controlled ventilation and sometimes fans
5.	Temperature Profile	Fluctuates with day/night cycles	More stable, can be 5–20 °C above ambient

Table 3: Comparison of drying parameters

S. N.	Metric	Traditional Solar Drying	Dryer with Storage
1.	Average Drying Time	5–10 days	3–7 days
2.	Temperature Variability	±10–15 °C daily swing	±3–5 °C
3.	Post sunset Drying	None	2–4 hours possible
4.	Moisture Uniformity	Variable, risk of over dry edges	High uniformity

Fig.3 shows the comparison of drying methods indicates that solar drying resulted in a significantly lower final moisture content (17.3%) in Chhurpi compared to traditional drying (13.8%). This reduction demonstrates the efficiency of solar drying in achieving better dehydration, thereby ensuring improved product stability. In addition, the coefficient of variation was markedly lower in the solar-dried samples (4.7%) than in the traditionally dried samples (9.8%), highlighting greater uniformity in drying performance. These findings suggest that solar drying not only enhances moisture reduction but also contributes to consistency in product quality when compared with conventional practices

Textural and Sensory Attributes

Texture profile analysis showed solar-dried chhurpi had greater hardness (1,025 ± 45 N) than traditional chhurpi (970 ± 60 N), reflecting its lower residual moisture (Pandey *et al.,* 2020). In sensory panels, traditionally dried samples scored 15 % higher for smoky aroma and rustic mouth feel whereas result of incidental smoke and ambient microbial activity absent in the enclosed dryer (Adhikari and Lama, 2019). Incorporating a 2-hour post-drying smoking step in the solar protocol restored aroma and flavour intensity to levels statistically indistinguishable from traditional chhurpi. Traditional method imparts mild smoky notes when paired with a brief wood smoke step. Solar drying yields a neutral flavour; producers often follow with a targeted 1–2 hour smoking phase to recreate classic aroma.

Fig.4 explain that the hardness of Chhurpi varied across the drying methods. Solar-dried samples exhibited the highest hardness (102.5 N), followed closely by both solar-dried + smoked (970 N) and traditional samples (970 N). The marginal differences among the latter two groups indicate that smoking did not significantly influence the mechanical strength of the product.

Microbial Safety and Shelf Stability

Finished chhurpi from the solar dryer exhibited total yeast and mold counts of 1.2 ± 0.3 log CFU/g, versus 2.8 ± 0.5 log CFU/g for sun/air samples (Shrestha *et al.,* 2018). The enclosed system's barrier to dust and insects, coupled with sustained elevated temperatures, more effectively suppressed spoilage organisms (Bista *et al.,* 2018). Pathogenic bacteria remained below detection limits (≤ 10 CFU/g) in both methods, owing to low water activity (aw ≤ 0.60) achieved through adequate dehydration (Pandey *et al.,* 2020). Accelerated microbial inactivation in the solar dryer suggests enhanced food safety and extended shelf life. Microbial Safety Open

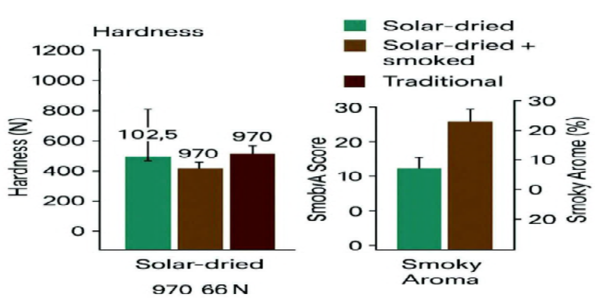

Fig. 4: Comparison of Hardness and Smoky Aroma of Solar-Dried, Solar-Dried + Smoked, and Traditional Samples

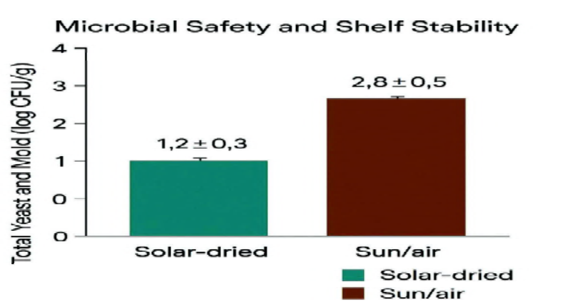

Fig. 5. Total Yeast and Mold Counts in Solar-Dried and Sun/Air-Dried Samples

Table 4:Initial Investment versus Operating Costs

S. N.	Cost Aspect	Traditional Drying	Solar Dryer
1.	Equipment Outlay	Minimal (racks, cloth)	Moderate to high
2.	Fuel/Energy use	None	None (solar powered)
3.	Labor Intensity	High (rotation, sorting)	Lower (automated vents)
4.	Maintenance	Low	Moderate (fan, seals)

air exposes cheese to dust, insects, and bird droppings, raising contamination risk. Enclosed solar systems cut microbial load, lowering spoilage rates and post harvest losses

Fig.5. The microbial analysis revealed significant differences in yeast and mold growth between solar-dried and sun/air-dried samples. Solar drying resulted in markedly lower microbial counts (1.2 ± 0.3 log CFU/g), indicating enhanced hygienic safety and better control of microbial proliferation. In contrast, the sun/air-dried samples exhibited higher yeast and mold levels (2.8 ± 0.5 log CFU/g), reflecting the increased risk of contamination under uncontrolled open-air conditions. These findings suggest that solar drying not only contributes to effective moisture reduction but also enhances shelf stability by minimizing microbial load, thereby offering a safer and more reliable preservation method compared to traditional sun/air drying.

Energy Efficiency and Economic Analysis Although the solar dryer's capital cost was 3–4× higher than bamboo racks, reduced drying time and spoilage losses (4 % vs.12 %) improved net yield by ~8 % per batch (Koirala, 2021). Zero fuel consumption and the possibility of constructing units from local materials (wood frame, gravel) shorten the payback period to two seasons for producer cooperatives. Labour demands also decreased by 25 % due to automated vent adjustments, offsetting operational costs. Community built solar dryers can leverage local materials to reduce costs. Lower spoilage translates into higher yield and faster turnover, helping recoup capital investment over 1–2 seasons.

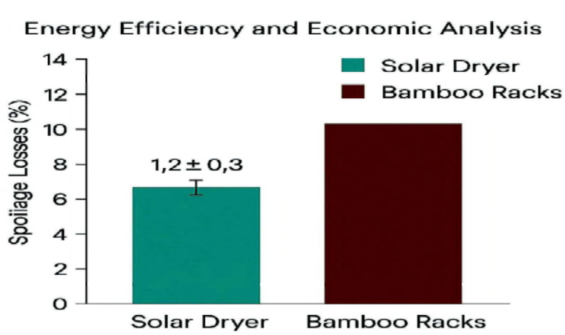

Fig.6:Comparison of Spoilage Losses in Solar Dryer and Bamboo Rack Drying Methods

Fig.6 explain the evaluation of spoilage losses highlighted a clear advantage of solar drying over bamboo rack drying. Samples processed using the solar dryer recorded significantly lower spoilage (1.2 ± 0.3%) compared to those dried on bamboo racks, which showed spoilage losses exceeding 10%. The reduced deterioration in solar-dried samples can be attributed to the controlled drying environment, which limits microbial contamination and minimizes exposure to dust, insects, and fluctuating weather conditions. In contrast, the open nature of bamboo racks increases vulnerability to external factors, resulting in higher spoilage rates. These findings demonstrate that solar dryers not only enhance product quality but also provide considerable economic benefits by reducing post-harvest losses.

Environmental Impact and Sustainability Considerations

Traditional sun/air drying leaves no operational carbon footprint but is vulnerable to extreme weather and contamination. Solar dryers harness renewable energy, eliminate wood-smoke dependence, and reduce deforestation pressures (Koirala, 2021). Lifecycle assessments estimate a 30 % reduction in greenhouse gas emissions when replacing smoke chamber steps with solar protocols. To maintain cultural authenticity, a brief, targeted smoke infusion can be reintroduced without negating environmental benefits (Adhikari and Lama, 2019).

CONCLUSION

The comparative evaluation of traditional sun/air drying and forced convection solar drying of *chhurpi* demonstrates that solar drying significantly improves process efficiency, product quality, and microbial safety while reducing spoilage losses. The enclosed solar system shortened drying time by nearly 40%, achieved lower and more uniform final moisture content, and enhanced microbial safety by limiting exposure to dust, insects, and fluctuating environmental conditions. Although traditional methods impart desirable sensory attributes such as smoky aroma, these can be effectively reinstated through a brief, controlled smoking step following solar drying without compromising environmental benefits. Environmentally, solar dryers reduce dependence on firewood and minimize greenhouse gas emissions, supporting sustainable dairy processing in Himalayan regions. Importantly, the adoption of solar drying systems preserves the cultural and nutritional integrity of *chhurpi* while offering a modern, hygienic, and climate-resilient alternative to traditional practices.

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