# Comparative Analysis of Cardamom Drying Technologies: Energy Efficiency, Quality Retention, Capacity and Cost-Effectiveness

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**Abstract -** *Incorrect drying of cardamom significantly impacts quality, quantity, and economic viability, resulting in a 10-20% loss in quality and quantity and a 5-10% loss in market value. Causal factors include inadequate techniques, insufficient training, and poor handling and storage practices. Implementing optimal drying technologies and proper training can mitigate these losses. Cardamom drying is a crucial step in preserving the quality and aroma of this valuable spice. Various drying technologies are employed in India, but their efficiency, capacity, quality retention, and cost- effectiveness vary significantly. This review evaluates cardamom drying technologies to bring to light the potential of current technologies and future direction for growth. The results indicate that Solar and Heat Pump dryers offer the fastest drying times, ranging from 6 to 12 hours, and superior quality retention. In contrast, Biomass dryers demonstrate low energy consumption and moderate drying times of 14-19 hours. Conversely, Electric dryers and Traditional Bhattis exhibit high energy consumption and compromised quality retention. A comprehensive cost analysis reveals Solar dryers as the most economical option, closely followed by Biomass dryers. This review provides critical insights for cardamom stakeholders, policymakers, and researchers, underscoring the potential of energy-efficient and cost-effective drying technologies to enhance the competitiveness of India's cardamom industry. To boost both quality and productivity in cardamom production, India must prioritize the adoption of efficient and cost-effective drying technologies.*

***Key Words***: Cardamom drying, energy efficiency, quality retention, cost-effectiveness, solar drying, heat pump drying, biomass drying

## 1.INTRODUCTION

Cardamom (*Elettaria cardamomum* (L.) Maton) (Fig 1), aptly referred to as the "Queen of Spices," is a highly valued spice crop native to the tropical regions of India and Southeast Asia [1][2]. This aromatic crop is widely cultivated for its seeds, which are enclosed in a green, pod-like fruit, prized for their unique flavour, aroma, and medicinal properties [3]. Cardamom production in India significantly contributes to the global market, accounting for approximately 40% of worldwide production [4]. India produces around 40,000-50,000 tons of cardamom annually, with major producing states including Karnataka, Kerala, Tamil Nadu, and NE region [4] [5].

Source: NIF database; https://innovation.nif.org.in

**Fig -1:** *Elettaria cardamomum* (L.) Maton

The main cardamom varieties cultivated in India are Alleppey Green, Coorg Green, and Naga Jhaal [1] along with Njallani variety [6][7]. However, the industry faces several challenges, including climate change, diseases, and pests [3]. Rising temperatures and changing rainfall patterns affect yield and quality, while fungal diseases and insect infestations result in significant losses [8]. To address these issues, the Government of India (GoI) has initiated programs like the National Horticulture Mission and the Spice Board of India [9].

India's cardamom exports are predominantly directed to the Middle East, Germany, Europe, the USA, and Southeast Asia [10] [11]. While these established markets remain strong, there are significant opportunities for growth in emerging markets and a rising demand for organic and specialty cardamom [12]. Domestically, the cardamom industry is witnessing increased demand for cardamom-based products [13], alongside the potential for value-added products like cardamom oil and powder [1], which offer promising avenues for market expansion.

To grab these opportunities, the Indian cardamom industry needs to prioritize improvement in productivity, quality, and sustainability through focused research and development, farmers' training, and the adoption of innovative technologies. One such area of innovation lies in post-harvest processing, particularly drying technologies. For instance, the benefits of solar drying systems should be highlighted, which reduce drying time by approximately 50% compared to traditional open sun drying methods,[14]. Similarly, a comprehensive performance analysis of solar and heat pump dryers, demonstrating their effectiveness in preserving the greenness and essential oil content of cardamom [15]. Further emphasizes the importance of adopting advanced drying techniques to address inefficiencies in traditional methods and reduce the excessive consumption of fuelwood [16].

This integrated approach for enhancing both the market strategies and processing technologies can help ensure that India remains competitive in both the global and domestic cardamom markets while adhering to sustainable practices.

### 1.1 Area And Production of Cardamom Crops in India

Cardamom cultivation in India has seen fluctuating trends in area and production over the years (Chart 1). From 2009–10 to 2014–15, both area and output generally increased, with a peak of 100,000 hectares and 24,000 tonnes in 2014–15. Although the area declined in subsequent years, production continued to rise, reaching 28,000 tonnes by 2017–18. A dip occurred in 2018–19, with both area and production falling. However, from 2019–20 to 2022–23, the cultivated area remained stable around 85,000–86,000 hectares, while production showed significant growth, peaking at 37,000 tonnes in 2021–22. These trends reflect the adaptability of cardamom farming in India, with production improving despite varying cultivation areas.


**Chart -1:** Area of India under Cardamom Crop Production [4]

### 1.2 Overview of the Cardamom Harvest and Post-Harvest Process

Cardamom harvesting typically occurs between August and November, depending on the region and variety [1][17]. The ideal harvesting stage is when the capsules are mature, green, and slightly soft to the touch. Hand-picking and stem-cutting are the two primary harvesting methods, with hand-picking being more labour-intensive but resulting in minimal damage to the capsules. After harvesting, cardamom undergoes a series of post-harvest processes to preserve its quality and flavour. Cleaning is the first step, which involves removing impurities, dirt, and debris from the harvested capsules [3]. This can be done through hand-sorting, air-jet cleaning, or mechanical cleaning. Drying is a critical step in the post-harvest process, reducing the moisture content to 10-12% to prevent spoilage and Mold growth [8]. Various drying methods are employed, including sun drying, solar drying, electric drying, and fuel-based drying like biomass and fossil fuel [17]. Curing is another essential step, which involves treating the cardamom capsules with heat, steam, or chemicals to inhibit Mold growth, preserve colour and flavour, and reduce moisture content [9]. Grading and packaging follow, with cardamom sorted by size, colour, and quality, then stored in airtight containers or bags. Proper storage is essential, typically in a cool, dry place (temperature: 10–20°C, humidity: 60–70%) for up to two years [10]. However, post-harvest losses remain a significant challenge both in the field and the market, with estimated losses ranging from 30% to 50% [13][18].

## 2. IMPORTANCE OF DRYING

Drying is a critical step in preserving cardamom's quality, ensuring its longevity and viability for storage and export. Fresh cardamom pods have a high moisture content of around 80%, making them susceptible to spoilage, Mold growth, and insect infestation [1][19]. To prevent these issues, it is essential to reduce the moisture content to 10-12% through proper drying. Proper drying prevents spoilage by inhibiting microorganism growth, minimizing yeast fermentation, and preserving cardamom's natural flavour and aroma [3]. Reduced moisture content creates an unfavourable environment for microorganisms, reducing the risk of mycotoxin production, contamination, and spoilage [8]. Drying also plays a vital role in maintaining cardamom's distinctive flavour and aroma by retaining its essential oils [1]. Proper drying preserves cardamom's sweet, pungent, and aromatic flavour, maintaining its distinctive aroma and enhancing the overall sensory experience [3]. Furthermore, proper drying extends cardamom's shelf life, enabling storage for extended periods without significant quality loss [9]. Reduced moisture content prevents re-absorption of moisture from the environment, minimizes oxidation, and preserves cardamom's natural colour and flavour [8]. Finally, dried cardamom meets international quality standards, enabling export to global markets [10]. Compliance with international regulations, such as ISO and ASTM, enhances market access and competitiveness.

### 2.1 Indian Quality Standards for Dried Cardamom

In India, the quality standards for dried cardamom are specified by the Bureau of Indian Standards (BIS). According to IS 1907:1984, large cardamom should have a maximum moisture content of 10% and a minimum volatile oil content of 5% [20]. For small cardamom, IS 13446:2009 stipulates a maximum moisture content of 12% and a minimum volatile oil content of 6% [21]. Additionally, IS 1797:1985 provides general specifications for cardamom (Elettaria cardamomum (L.) Maton), including requirements for colour, flavour, and aroma [22]. Furthermore, IS 13145:1993 outlines standards for dried cardamom capsules, covering aspects such as packaging and labelling [23]. Adherence to these standards ensures that dried cardamom meets the required quality parameters for domestic consumption and export.

### 2.2 Losses Incurred Due to Incorrect Drying of Cardamom

Losses incurred due to incorrect drying of cardamom can be substantial, affecting quality, quantity, and economic viability. Incorrect drying can lead to flavour and aroma degradation, colour changes, texture changes, and reduced shelf life [1]. Additionally, moisture content fluctuations can result in weight loss, shrinkage, or breakage during drying, leading to inconsistent quality [3]. The economic implications of incorrect drying are significant, with reduced market value due to inferior quality, decreased export potential, and increased energy costs associated with re-drying or re-processing [9]. Estimates suggest that incorrect drying can result in a 10-20% loss in quality and quantity [9], with a 5-10% loss in market value due to inferior quality [9, 24]. Factors contributing to incorrect drying include inadequate drying techniques or equipment, insufficient training or expertise, inconsistent temperature and humidity control, and poor handling and storage practices [8]. To mitigate these losses, implementing optimal drying technologies, training farmers and processors on proper drying techniques, monitoring temperature, humidity, and moisture levels, and improving handling and storage practices are essential.

## 3. DRYING METHODS AND THE PROCESS

Following six types of drying methods are used for drying cardamom Fig. 2 shows these methods.

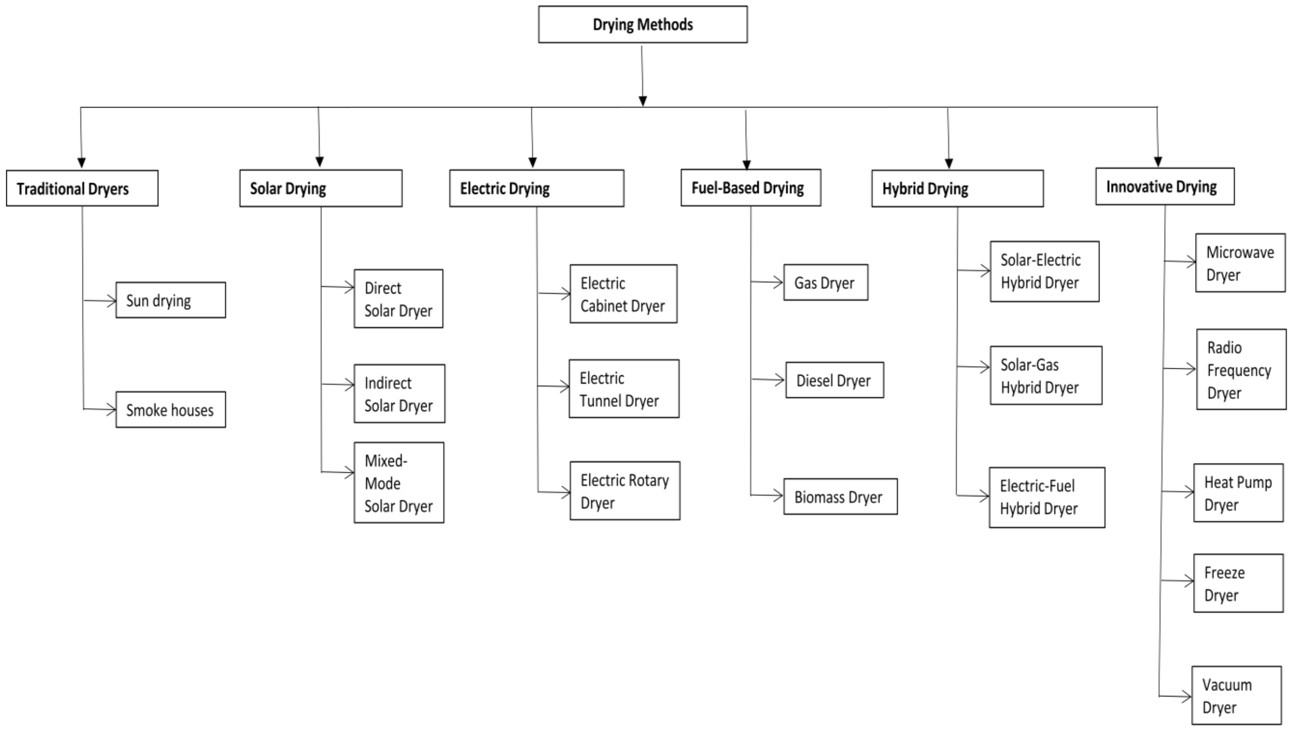


**Fig -2:** Flowchart of Cardamom Drying Methods

*Traditional Dryers*

Traditional drying methods, such as sun drying and smoke houses, remain widely practiced due to their simplicity and low initial costs [1]. Sun drying involves spreading cardamom on mats or concrete floors under direct sunlight. Although simple and cost-effective, this method is highly weather-dependent, labour-intensive, and susceptible to contamination. It often results in inconsistent drying quality and quantity losses due to birds and pest infestations. Smoke houses, on the other hand, use smoke from burning wood or biomass to dry cardamom. Although this imparts a distinctive flavour and aroma to the spice, it introduces health risks and environmental concerns due to smoke exposure. Despite widespread use, these methods exhibit several inefficiencies. High energy consumption, uneven drying, and the loss of essential oils—crucial for cardamom's flavour and market value—are common drawbacks. As emphasizes, these traditional practices often fail to meet modern efficiency and quality standards, highlighting the need for innovative and sustainable drying technologies, [14].

*Solar Drying*

Solar drying is an effective method that utilizes natural sunlight to evaporate moisture from cardamom, offering energy efficiency and low-cost benefits. Solar dryers can be categorized into direct, indirect, or mixed-mode types, each designed with components such as solar collectors, drying chambers, air circulation systems, and temperature control mechanisms. This eco-friendly alternative significantly reduces drying time by approximately 50% compared to traditional open sun drying. As demonstration on solar dryers are particularly effective in preserving the greenness and essential oil content of cardamom, making them a sustainable and practical option for drying processes [25].

*Electric Drying*

Electric drying offers advantages, such as enhanced product quality and reduced energy consumption. This method ensures that cardamom retains its natural green colour, a critical factor for its market value. Studies, emphasize the effectiveness of electric drying in overcoming the inefficiencies of traditional methods, particularly uneven drying and contamination, which often compromise the quality of the final product, [24]. The process of electric drying relies on electric heat sources to remove moisture from cardamom efficiently [12]. Common types of electric dryers include cabinet dryers, tunnel dryers, and rotary dryers. These systems are designed for easy operation and provide uniform drying conditions, addressing the challenges associated with traditional practices. Key components of electric dryers typically include electric heating elements, drying chambers, air circulation mechanisms, and temperature control systems, ensuring a controlled and consistent drying environment.

*Fuel-Based Drying*

Fuel-based drying uses fuels like gas, diesel, or biomass to generate heat for drying cardamom [13]. Fuel-based drying systems for cardamom rely on energy sources such as wood, diesel, gas, or biomass to produce heat for the drying process. These systems are widely used in regions where electricity or solar energy is less accessible. With components including a heating chamber, drying chamber, and air circulation system, fuel-based dryers ensure uniform and efficient drying conditions.

*Hybrid Drying*

Hybrid drying technologies integrate multiple drying methods, such as solar-electric, solar-gas, and electric-fuel systems, to achieve optimal drying results [10]. These systems offer distinct advantages, including improved energy efficiency, reduced operational costs, and enhanced flexibility in adapting to varying environmental conditions. By combining solar and auxiliary energy sources, hybrid drying systems ensure consistent performance even during adverse weather conditions, such as cloudy days. A notable example is the hybrid mixed-mode solar dryer, which efficiently utilizes solar energy supplemented by auxiliary power sources. These dryers optimize energy use, maintaining consistent temperature levels crucial for drying high-quality products. As a result, they not only reduce energy consumption but also preserve the product's essential properties, ensuring superior quality [16].

*Innovative Drying*

Innovative drying employs advanced technologies to dry cardamom efficiently [13]. Innovative drying technologies for cardamom are transforming traditional practices by enhancing efficiency, quality, and sustainability. Among these advancements, the Microwave Cardamom Drying Machine stands out as a revolutionary solution [26]. This technology uses microwave radiation to expedite the drying process while preserving the essential oils and volatile compounds that contribute to cardamom's distinctive aroma and flavour. Unlike conventional methods, it ensures uniform drying and significantly reduces processing time. Innovative dryers include microwave, radio frequency, heat pump, freeze, and vacuum dryers, with advantages such as fast drying rates and energy efficiency.

## 3.1 Different Types of Dryers Used to Dry Cardamom

Over a hundred research papers and articles were reviewed, of which approximately three dozen were found to be relevant. The findings on various types of dryers used for cardamom, along with their comparative analysis, are presented in Table 1.

**Table -1:** Comparative Analysis of Cardamom dryers

| Dryers | Drying Time | Capacity | Energy Consumption | Quality | Cost | Space | Efficiency | References |
|---|---|---|---|---|---|---|---|---|
| Traditional large-cardamom curing chambers (*Bhattis*) in Sikkim | 24-48 hours | 100-500 kg per batch | Energy Source: Firewood<br>Power Consumption: NA | Moisture content: 15-20 %<br>Colour retention: Poor | High (firewood consumption) | Medium-Small | NA | [34] |
| ICRI Improved Bhatti for large cardamom curing | 12-24 hours | 200-500 kg per batch | Energy Source: Firewood and Biomass<br>Power Consumption: NA | Moisture content: 10-12 %<br>Colour retention: Excellent (Natural colour) | NA | Medium-Small | Bhatti operates with very poor operating thermal efficiency of the order 5-15% resulting in wastage of huge quantities | [35] |

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|---|---|---|---|---|---|---|---|---|
| LPG fired small cardamom drier | 22-23 hours | NA | Energy Source: LPG<br>Fuel: LPG (Liquefied Petroleum Gas) Energy Consumption:<br>1.43 kg LPG/kg cardamom (approx.) | Moisture content: 8% (w.b.)<br>Colour retention: Good | Rs. 2.10/- per kg cardamom | Small-Medium | Thermal efficiency of the dryer: 75.74 per cent. | [25] [27] |
| Abraham Low Pressure Cardamom Drying Chamber | 6-8 hours | 50-100 kg per batch | Energy Source: Electricity and LPG<br>Power Consumption: 1 HP (0.75 kW) motor | Moisture content: NA<br>Colour retention: Good | Rs. 20,000/- per unit | Small | NA | [6] |
| Cardamom Dryer developed By UAS, Bangalore | 10 hours | 50-100 kg per batch | Energy Source: Electricity<br>Power Consumption: NA | Moisture content: 12%<br>Colour retention: Good | Rs. 0.3 Lakh | Small | NA | [28] |
| Low-Cost portable biomass fired dryer for cardamom drying | 14-19 hours | 20-30 kg per batch | Energy Source: Biomass (firewood)<br>Energy Consumption (SEC): 0.67 kg firewood/kg cardamom (average) | Moisture content: 10%<br>Colour retention: Good | NA | Small | NA | [19] [29] |
| Solar- biomass hybrid dryer (SBHD) for small cardamom | 19 hours | NA | Energy Source: Solar and Biomass (hybrid) Specific<br>Energy Consumption (SEC): NA | Moisture content: 9.1% (w.b)<br>Colour retention: Good (better in SBHD than biomass mode)<br>Highest percent of oil content. | NA | Small | Drying efficiency of 28.63% and 23.98% were obtained for the SBHD and biomass mode | [30] |
| Solar dryer for large cardamom | 24 hours (3 sunny days) | 20-50 kg per batch | Energy Source: Solar Energy<br>Power Consumption: 0 kW (Passive solar drying) | Moisture content: 10.1% (w.b)<br>Colour retention: Excellent | NA | Small-Medium | Collector efficiency of solar dryer for drying large cardamom was 40.02 % in the month of December | [31] |
| Solar and heat pump dryer for small cardamom | 10-15 hours (Solar) | 20-50 kg per batch | Energy Source: Solar Energy<br>Power Consumption: 0 kW (Passive solar drying) | Moisture content: 10-12%<br>Colour retention: Poor (greenness value: -0.8 to -3.25) | NA | Small-Medium | NA | [15] |
| | 12-15 hours (heat pump dryer) | 50-200 kg per batch | Energy Source: Electricity<br>Power Consumption: NA | Moisture content: 10-12%<br>Colour retention: Excellent (greenness value: higher) | NA | Small-Medium | NA | [15] |

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|---|---|---|---|---|---|---|---|---|
| Indirect type flat plate collector solar dryer for black cardamom | 24 hours | 20-50 kg per batch | Energy Source: Solar Energy Power Consumption: 0 kW (passive solar drying) | Moisture content: 8.2% Colour retention: Excellent | NA | Small-Medium | Daily energy efficiency of the solar energy accumulator reached 35.8%, while the daily exergy efficiency reached 13.84%. Exergy efficiency of the drying chamber was in the range of 47–97% | [32] |
| Hot air convective drying for small cardamom | 6-12 hours | 50-200 kg per batch | Energy Source: Electricity Power Consumption: NA | Moisture content: 10-12% Colour retention: Excellent | NA | Small-Medium | NA | [33] |

Note: 'NA' indicates information not available.

Cardamom drying technologies vary significantly in terms of drying time, capacity, energy source, energy consumption, costs, space requirements, and efficiency, catering to different needs and scales of production (Table 1). The LPG-fired small cardamom dryer, for instance, operates within 22-23 hours, consuming approximately 1.43 kg of LPG per kg of cardamom with a thermal efficiency of 75.74%. This method achieves good color retention, an 8% moisture content (w.b.), and costs Rs. 2.10 per kg, making it a viable option for small to medium spaces. On the other hand, the Abraham Low Pressure Drying Chamber is faster, requiring only 6-8 hours to dry 50-100 kg batches using electricity and LPG. It is ideal for small spaces, ensuring good color retention, and costs Rs. 20,000 per unit. Similarly, the cardamom dryer developed by UAS Bangalore, which also caters to small-scale operations, takes 10 hours to dry 50-100 kg batches, maintains a 12% moisture content with good color retention, and is priced at Rs. 0.3 Lakh. For lower-cost options, the portable biomass-fired dryer processes 20-30 kg of cardamom within 14-19 hours by consuming 0.67 kg of firewood per kg of cardamom, ensuring 10% moisture content and good color retention.

The solar-biomass hybrid dryer (SBHD) exemplifies a hybrid approach, drying cardamom in 19 hours with improved color retention, a moisture content of 9.1% (w.b.), and the highest oil content, though its drying efficiencies stand at 28.63% for SBHD mode and 23.98% for biomass mode. The solar dryer for large cardamom relies solely on solar energy, requiring 24 hours (three sunny days) for a batch of 20-50 kg. This method achieves excellent color retention, a 10.1% moisture content (w.b.), and a collector efficiency of 40.02% during December. For small cardamom, the solar and heat pump dryers offer two distinct modes. The solar mode, although eco-friendly, requires 10-15 hours, processes 20-50 kg batches, and yields poor color retention (greenness value: -0.8 to -3.25). In contrast, the heat pump mode is more efficient, handling 50-200 kg batches in 12-15 hours, ensuring excellent color retention and a moisture content of 10-12%.

## 3.2 Evolutionary Journey of Dryers used for cardamom drying:

The evolutionary journey of dryers used for cardamom drying has undergone significant transformations over the years (Figure 2). Initially, traditional methods such as sun drying, smoke drying, and Bhatti drying were employed. However, with the advent of mechanization, electric dryers, gas dryers, and hot air dryers emerged, improving drying efficiency. Advanced dryers were developed, including solar dryers, heat pump dryers, and biomass dryers. These innovations enhanced energy efficiency and sustainability in cardamom drying (Table 1). Recently, modern dryers such as hybrid dryers, freeze dryers, microwave dryers, and automated dryers have revolutionized the industry. Looking ahead, future directions for cardamom drying technologies include developing energy-efficient dryers like gasifiers, sustainable drying solutions, advanced automation and monitoring systems, and integrating artificial intelligence and IoT. By embracing these innovations, the cardamom industry can enhance quality, productivity, and profitability.

## 4. CONCLUSIONS

The comprehensive analysis of various cardamom drying technologies revealed significant variations in drying time, capacity, energy consumption, quality, cost, and space requirements. The study demonstrated that solar and heat pump dryers offered the shortest drying time (6-12 hours), while traditional *bhattis* required the longest time (24-48 hours). In terms of energy consumption, solar dryers showed zero energy consumption, while LPG fired and electric dryers consumed significant amounts. Heat pump and solar dryers retained excellent color and moisture content (10-12%). Solar dryer for large cardamom achieved

(40.02%) collector efficiency and (35.8%) daily energy efficiency. ICRI Improved Bhatti showed (5-15%) thermal efficiency, while hot air convective drying and Abraham Low Pressure Cardamom Drying Chamber demonstrated high efficiency in drying time and energy consumption. The cost analysis revealed that solar dryers offered the lowest cost per kg (Rs. 0.3-2.10), while traditional *bhattis* incurred high costs due to firewood consumption. To optimize cardamom drying, adopting solar and heat pump drying technologies is recommended. Additionally, promoting biomass dryers as a sustainable alternative to traditional *bhattis* and developing cost- effective and scalable dryer designs are crucial. Future research should focus on investigating hybrid drying technologies, developing energy-efficient and cost-effective dryer designs for small-scale cardamom producers, and studying the impact of drying methods on cardamom's nutritional and medicinal properties. The future research may be diverted towards establishing gasifier-based dryers owing to its potential use in regions where electricity and adequate sunlight is not available. By adopting efficient and sustainable drying technologies, the cardamom industry can enhance product quality, reduce energy consumption, and contribute to a more environmentally friendly future.

## ACKNOWLEDGEMENT

The authors would like to acknowledge National Innovation Foundation-India for sharing the details of grassroots technology titled “Abraham Low Pressure Cardamom Drying Chamber” which was deemed useful from comparative perspective.

## CONFLICT OF INTEREST

The Authors declare no conflict of interest.

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