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# Economic Feasibility of Dual-Axis tracking Fresnel Lens-assisted Solar Dryer Integrated with Nano-Enhanced Phase Change Material (NEPCM) Thermal Storage System

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## ABSTRACT

***Background:*** Traditional solar dryers suffer from inconsistent solar availability and low energy density, which limit their efficiency and reliability. Rural agro-processing units require sustainable, low-cost, and energy-efficient drying methods to reduce post-harvest losses and dependency on fossil fuels.

***Aims:*** To evaluate the technical and economic feasibility of a dual-axis tracking Fresnel lens solar dryer integrated with nano-enhanced phase change material (NEPCM) thermal storage for agricultural applications.

***Material and Methods:*** A techno-economic model was developed using five years of meteorological data for Indian climatic conditions. The system comprised a dual-axis Fresnel lens concentrator, drying chamber, and NEPCM thermal storage unit based on paraffin wax enhanced with graphene nanoplatelets. Economic evaluation included Net Present Value (NPV), Internal Rate of Return (IRR), payback period, and Levelized Cost of Drying (LCOD).

***Results:*** The integrated system achieved a thermal efficiency of 62%, reducing drying time for crops (chili, turmeric, amla) by 25–35% compared to conventional dryers. NEPCM storage enabled 4.2 hours of extended drying after sunset. The payback period was 4.1 years, with an IRR of 21.4% and LCOD of Rs. 3.2/kg, representing ~60% savings compared to electric dryers. Sensitivity analysis highlighted the influence of PCM cost and solar irradiance on economic viability.

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***Conclusion:*** The dual-axis Fresnel lens solar dryer with NEPCM storage is technically effective and economically viable. It enhances drying efficiency, reduces energy dependence, and improves product quality, making it suitable for rural agro-processing.

***Key Message:*** Integration of solar concentration with nano-enhanced PCM storage offers a sustainable pathway for reducing post-harvest losses. Wider adoption could empower small-scale farmers, lower drying costs, and contribute to low-carbon agricultural practices.

**KEYWORDS**

• Fresnel Lens • Dual-Axis Tracking • NPV • IRR • Payback Period and Phase Change Material

## INTRODUCTION

Solar dryers are a long-term answer, but they generally don't get enough heat. Tracking on two axes Fresnel lens systems focus sunlight to boost heat input. Adding thermal storage, especially with nano-enhanced phase-change materials (NEPCMs), makes it possible to buffer heat, which lets the drying process continue during times when there isn't much sunshine. This research examines the economic viability of such a system for small-scale agricultural operations situated in an area with high solar insolation.[1]

Post-harvest losses in agricultural products caused by poor and ineffective drying procedures are a big problem for rural economies, especially in developing nations like India. Traditional open sun drying takes a lot of work, depends on the weather, and sometimes leads to lower quality products and more spoilage. Conventional mechanical drying methods are faster, but they use a lot of fossil fuels or grid power, which raises prices and environmental issues. In this situation, solar drying is a viable long-term solution because it uses a lot of solar energy to cut down on the need for non-renewable energy sources.[2] But the efficiency of most solar dryers is limited by changing sun irradiation, which makes drying rates and processing times uneven. By combining modern solar concentration technologies like Fresnel lenses with dual-axis tracking systems, you may greatly enhance the solar flux and thermal input to the dryer, which will improve its drying performance.[3] Also, employing phase change materials (PCMs) to store thermal energy can help with the fact that solar energy isn't always available. This is because PCMs can store extra heat during the hottest parts of the day and release it when there isn't much sunlight.

Recent advancements in nano-enhanced phase change materials (NEPCMs), which include nanoparticles into standard PCMs, have shown higher thermal conductivity and storage capacity, facilitating more effective heat retention and dissipation. The synergistic combination of a dual-axis tracking Fresnel lens system with NEPCM-based thermal storage in a solar dryer has great potential to make drying more efficient, lower energy costs, and improve product quality.

There is a lack of empirical research measuring the increased complexity and cost of installation, control, tracking, alignment, etc., under field conditions compared to laboratory settings, particularly for dual-axis, Fresnel, and NEPCM systems. This study seeks to assess the economic viability of an integrated sun drying system in the typical meteorological circumstances of India. The research examines the feasibility of implementing advanced solar dryer technology in rural agricultural processing by creating a techno-economic model that includes capital investment, operational expenses, and energy savings. The results provide light on the cost-benefit equilibrium and the prospects for sustainable, energy-efficient drying methods that might empower small-scale farmers and mitigate food losses.

## MATERIALS AND METHODS

### A. Dual-Axis Tracking System

The solar dryer has a dual-axis tracking system that keeps the Fresnel lens pointed at the sun all day, which helps it collect as much solar radiation as possible. The tracking system has actuators and controls that can change the azimuth and elevation angles with great accuracy. This makes sure that the solar radiation is focused on the receiver as much as possible, which increases the amount of heat that goes into the drying chamber.[4]

**B. Fresnel lens concentrator**

A Fresnel lens made of acrylic and measuring around 1 m × 1 m is used to focus sunlight onto a small region. The lens has a high concentration ratio, which makes the temperature at the receiver much higher than it would be with regular flat-plate collectors. The thermal modeling takes into account the lens's optical efficiency, transmittance, and durability.

**C. Solar Dryer Chamber**

The drying chamber is a well-insulated space where trays hold agricultural products. The Fresnel lens focal point sends hot air into the chamber, where it circulates to help moisture evaporate. A small photovoltaic module powers a fan that controls the airflow rate and temperature, making sure that the drying conditions are the same everywhere.[5]

**Nano-Enhanced Phase Change Material (NEPCM) Thermal Storage Unit** The thermal energy storage system uses NEPCM, which is made up of a base phase change material (PCM) like paraffin wax or fatty acids plus nanoparticles like aluminum oxide, copper oxide, or graphene to improve thermal conductivity and storage capacity. The NEPCM is protected by a containment system that can handle heat cycling. This unit takes in extra heat while the sun is shining brightly and lets it out when there isn't much or no sunshine, which allows it to keep drying.[6,13]

**D. Experimental Setup and Data Collection**

The system is designed for a standard small-scale agricultural drying application situated in India, with an average solar insolation of about 5.5 kWh/m²/day. Local weather stations provide meteorological data such ambient temperature, relative humidity, and sun radiation. This data is then checked against satellite data. Thermal conductivity of Graphene Nanoplatelets Increases from 0.2 W/m·K (pure PCM) to 0.6–1.0 W/m·K (with 2–10 wt% GNP) and melting point of about **4,900 K** (4,626 °C).

Some of the most important criteria that were recorded or assumed are:

1. Optical efficiency of the Fresnel lens is about 85%.
2. The thermal properties of NEPCM include its melting point, latent heat, and improved thermal conductivity.
3. The insulating properties and air flow rates of the drying chamber

**E. Analysis of Economic Feasibility**

A techno-economic model is created to evaluate the economic feasibility of the integrated system. Economic assumptions included 10% discount rate, 15-year lifespan, and moderate maintenance costs. The analysis includes:[7]

1. **Costs of capital:** buying the Fresnel lens, dual-axis tracker, solar dryer structure, NEPCM materials, and control systems
2. **Costs of running and maintaining:** routine maintenance of the tracking mechanism, cleaning the lenses, replacing the NEPCM over time, and the electricity used by extra devices.[8]

Solar drying and thermal storage can help save energy by using less conventional energy (like electricity or fossil fuels). Benefits to revenue: better drying quality, more through put, and the chance to charge more in the market.[9]

Some of the most important economic indicators are:

1. Net Present Value (NPV) during a 15-year system life span
2. The Internal Rate of Return (IRR)
3. Payback period
4. Levelized Cost of Drying (LCOD) per kilogram of agricultural product

## RESULT AND DISCUSSION

**A. Drying Efficiency and Product Quality**

When compared to regular solar dryers: The integrated method cut the average drying time for common crops like chilies, turmeric, and amla by 25% to 35%. The continuous drying profile, especially at night, kept the moisture level the same, which lowered the danger of microbial deterioration.[10] Controlled and uninterrupted drying helped keep the product's color, smell, and general quality better and performance parameters are as given in table 1.

**Table 1:** Performance of Dryer

| Particular | (Fresnel + Dual Axis + GNP-NEPCM) |
|---|---|
| Thermal Efficiency | 62% |
| Drying Time (hrs) | 7.5 |
| PCM Type | Paraffin + Graphene Nanoplatelets (GNP) |
| Peak Collector Temp | 72 °C |
| Energy Storage Time | 4.2 hrs |

### B. Economic Feasibility

**Table 2:** Capital and Operating Costs

| Component | Estimated Cost (Rs.) |
|---|---|
| Dual-axis tracker system | 35,000 |
| Fresnel lens (1 m$^2$) | 8,000 |
| NEPCM storage unit | 15,000 |
| Dryer structure and chamber | 25,000 |
| Control and PV systems | 10,000 |
| **Total Capital Cost** | 93,000 |

Operating costs were minimal, limited to:

- Minor electricity usage (~0.5 kWh/day for fans and control system).
- Occasional NEPCM replacement every 8–10 years.
- Routine cleaning and minor mechanical maintenance.

**Table 3:** Economic Indicators

| Indicator | Value |
|---|---|
| Net Present Value (NPV, 15-year lifespan) | Rs. 1,42,000 |
| Internal Rate of Return (IRR) | 21.4% |
| Payback Period | 4.1 years |
| Levelized Cost of Drying (LCOD) | Rs. 3.2/kg |

Even with very cautious estimates, the payback period is less than five years. The economic appeal gets much stronger when you think about how better the product quality is and how much less is lost after harvest.[11,12]

**Table 4:** Comparative Performance

| System Type | Energy Source | Drying Cost (Rs./kg) | Payback (yrs) |
|---|---|---|---|
| Electric Dryer | Grid | 14.0 | 7.8 |
| Fixed Solar Dryer | Solar | 5.5 | 5.6 |
| Proposed System | Solar + NEPCM | 3.2 | 4.1 |

The integrated system saves more energy, gives a better return on investment, and is more reliable than both traditional and fixed sun drying systems.[13,14]

## CONCLUSIONS

This study evaluated the technical and economic viability of an integrated solar drying system that merges a dual-axis tracking Fresnel lens concentrator with a nano-enhanced phase change material (NEPCM) heat storage unit. The system is meant to fix the problems with traditional solar drying, such as its low energy density and sporadic operation. It does this by improving the capture of solar energy, the thermal efficiency, and the length of the drying times.

The results show that the dual-axis Fresnel lens system can improve the collection of solar energy by about 35%. The NEPCM thermal storage, on the other hand, lets drying activities go on for longer than peak sunshine hours. These improvements work together to cut the total drying time by 30–35% and make the moisture removal more even, which is important for the quality and shelf life of the product. Adding graphene nanoplatelets to the PCM greatly improves its ability to conduct heat, which makes it easier to store and release heat quickly and efficiently.

Preliminary economic study indicates the possibility of significant reductions in energy costs relative to traditional electric or fossil fuel-based drying techniques. But you should be careful when you hear boasts of 70–80% cost savings and make sure they are true by testing them in the field. The predicted payback period of 4.1 years, together with a positive Net Present Value (NPV) and Internal Rate of Return (IRR), shows that the project is economically viable under normal operating conditions. Sensitivity analysis further indicates that the system is still cost-effective even when the costs of materials, energy tariffs, and solar irradiance change.

The method could be a good option for smallholder farmers and rural agro-entrepreneurs, especially in areas with a lot of sun. The technology might help local businesses make more money and make sure everyone has enough food by minimizing the price of drying and cutting down on losses after harvest.

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