International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 7 [July 2025] PP: 70-74

Enhancing Solar Drying Efficiency through Fresnel Lens Concentration: Design, Performance, and Prospects.

Aniket V. Deshmukh[1]*, Sanjay M. Kherde[2]
[1]Department of Mechanical Engineering, Sipna College of Engineering & Technology, Amravati, India.
**Corresponding author: aniket.deshmukh11292@gmail.com , https://orcid.org/0000-0001-7980-667X*

Abstract
Post-harvest losses due to inefficient drying remain a major challenge in agriculture, particularly in energy-deficient regions. This study explores the integration of Fresnel lenses into solar drying systems to enhance thermal performance, reduce drying time, and improve product quality. The paper reviews the optical principles of Fresnel lenses, their material and manufacturing characteristics, and their application in direct, indirect, and hybrid solar dryers. Experimental and simulation-based analyses demonstrate significant gains in drying efficiency (up to 65%) and temperature (up to 120 °C) over conventional methods. Design considerations, such as tracking and thermal storage, are discussed alongside implementation challenges. The study concludes that Fresnel lens-assisted dryers, especially when coupled with thermal storage, present a scalable and sustainable solution for modernizing agricultural drying technologies.
Keywords: *Fresnel lens concentrator, Solar drying systems, Post-harvest technology, Thermal energy efficiency, Agricultural product drying, Thermal storage integration*

Date of Submission: 06-07-2025 Date of acceptance: 17-07-2025

I. Introduction

Post-harvest management is a critical concern in developing regions, where inefficiencies in drying technologies contribute significantly to food losses. Solar drying, as a low-cost and environmentally friendly method, offers a promising solution for smallholder farmers and micro-enterprises[1]. It plays a key role in extending shelf life and improving the quality of fruits, vegetables, herbs, and spices. However, conventional solar drying systems are limited by their dependence on ambient conditions, resulting in low temperatures (35–55°C), prolonged drying durations (>12 hours), and non-uniform drying—all of which affect product quality and safety[2].

To address these shortcomings, concentrated solar energy technologies have been explored to enhance heat intensity and system efficiency. Among these, Fresnel lenses present a particularly attractive option. Their lightweight and flat design allows easy integration into dryer systems, while their capability to achieve moderate to high solar concentration (10×–200×) can significantly raise drying chamber temperatures (up to 120°C)[3,4]. This results in faster moisture removal, improved microbial safety, and better preservation of color, flavor, and nutrients.

Compared to flat-plate or conventional solar dryers, Fresnel-assisted systems offer higher thermal performance, reduced drying times (2–6 hours), and improved drying uniformity—without relying on fossil fuels[5]. They are also more cost-effective than parabolic or CPC-based concentrators due to simpler fabrication from polymers like PMMA.

This article reviews the current state of solar drying systems that integrate Fresnel lens technology. It details the underlying optical principles, system configurations (direct, indirect, hybrid), material and design considerations, and evaluates experimental studies demonstrating their effectiveness. Furthermore, it highlights future research directions and commercialization prospects. Overall, the paper positions Fresnel-based solar dryers as a transformative solution for energy-efficient and high-quality drying, particularly suited to regions where energy access, food preservation, and affordability are pressing concerns.

II. Literature Review

2.1. Optical Principles

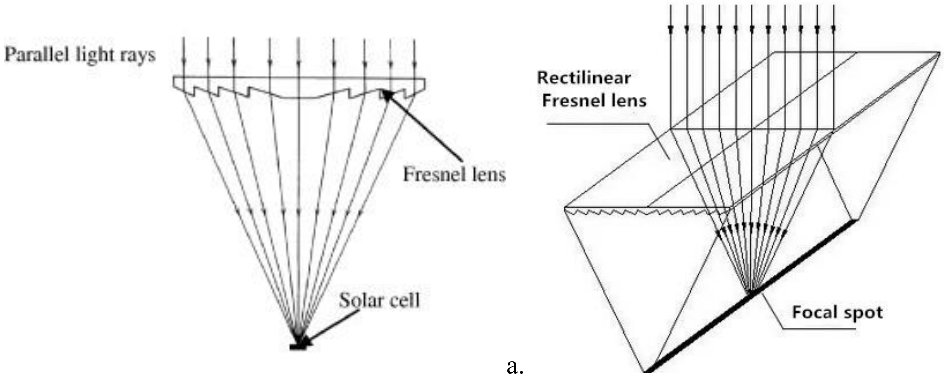
Fresnel lenses are planar optical elements engineered to concentrate light through a series of concentric, prismatic sections. Their fundamental advantage lies in their ability to mimic the focusing effect of a traditional curved lens while significantly reducing weight and material usage.

Fresnel lenses are categorized based on their focusing geometry:

- Linear focus lenses concentrate sunlight along a focal line, suitable for trough-type collectors or channel air heaters[6].
- Point focus lenses, in contrast, focus solar irradiance to a single spot, often used for applications requiring higher thermal intensity, such as solar cookers or high-temperature dryers[6,7].

Additionally, Fresnel lenses are classified into imaging and non-imaging types. *Imaging lenses* are designed to form a real image of the sun, necessitating precise tracking and alignment[8]. *Non-imaging Fresnel lenses*, on the other hand, focus light without forming a sharp image, allowing for larger acceptance angles and shorter focal lengths—attributes beneficial for solar drying applications where uniform heating is preferred[9].

The acceptance angle is a critical design parameter, defining the maximum angular deviation from the optical axis at which the lens still maintains acceptable performance. Focal length and f-number (ratio of focal length to aperture diameter) dictate the concentration ratio and spot size. Transmittance, typically ranging from 85–92% for high-grade PMMA[10], directly affects the thermal efficiency. The concentration ratio (geometric or optical) quantifies the lens's ability to intensify solar irradiance, with values ranging from 10× to over 500× depending on design (see Table 1).



a. b.

Fig 1: Cross-sectional schematic of a. point-focus and b. linear Fresnel lenses

Table 1: Key optical characteristics of typical Fresnel lenses for solar applications[11]

Parameter	Linear Fresnel Lens	Point-Focus Fresnel Lens
Focus Type	Line	Point
Focal Length (mm)	100–300	200–800
Acceptance Angle (°)	3–10	0.5–2
Optical Efficiency (%)	65–75	70–85
Typical CR (×)	10–50	50–400

2.2. Materials and Manufacturing

Fresnel lenses were initially fabricated from glass, offering superior thermal and UV stability. However, modern systems predominantly use polymethylmethacrylate (PMMA) due to its lower weight, moldability, and high optical transmittance (~90%)[11]. PMMA's refractive index (~1.49) aligns closely with that of glass, enabling efficient light bending with thinner profiles.

Manufacturing techniques include:

- Injection molding, used for mass-producing lenses with fine prism structures and high repeatability.
- Extrusion, suitable for linear lenses, especially in continuous formats.

Durability under outdoor conditions depends on environmental resistance. PMMA lenses are generally UV-stabilized but may suffer from yellowing over extended exposure without proper coatings. Therefore, surface treatments or UV-resistant additives are often employed to maintain optical clarity and prolong service life[12].

These optical and material characteristics position Fresnel lenses as ideal candidates for compact, high-performance solar dryers, especially in resource-constrained or off-grid applications.

III. Fresnel Solar Dryer Efficiency and Applications

3.1 Solar Drying Principles and Challenges

Solar drying is a thermally driven moisture removal process involving simultaneous heat and mass transfer phenomena. The process relies on the application of solar thermal energy to increase the temperature of the product and surrounding air, thereby enhancing the vapor pressure gradient that facilitates moisture diffusion from the product's interior to its surface, and eventually to the ambient environment via convection[13].

3.1.1. Heat and Mass Transfer

In solar drying, heat transfer occurs through radiation (from the sun and absorber surfaces), conduction (within the drying material), and convection (from heated air to the product surface). Mass transfer primarily involves the migration of bound and unbound water from within the material to its surface, followed by evaporation into the airstream. The rate of moisture removal is significantly influenced by the temperature of drying air, relative humidity, and air velocity across the product.

Fresnel lenses, with their capacity to concentrate solar radiation, can elevate air or surface temperatures rapidly, enabling higher drying rates compared to conventional solar dryers. However, the localized intensity must be managed to avoid thermal degradation or case hardening of biological materials[14].

3.1.2. Drying Rate Phases

The drying process is conventionally divided into two principal phases:

1. **Constant Rate Period**: Initially, the surface of the product is saturated with moisture, and evaporation proceeds at a nearly constant rate, governed by external conditions (temperature, air velocity, relative humidity)[15]. This phase is often limited by energy supply and is most affected by solar irradiance.
2. **Falling Rate Period**: As drying progresses, surface moisture is depleted, and internal diffusion of moisture becomes the rate-limiting step. This phase is governed by the material's properties (e.g., porosity, diffusivity) and is less influenced by external air parameters[16].

Accurate temperature control, enabled by optical concentration from Fresnel lenses, is crucial to optimize these phases and avoid product damage.

3.1.3. Key Parameters and Performance Metrics

The effectiveness of a solar drying system is influenced by several critical environmental and system parameters:

- Temperature of drying air or absorber surface
- Relative humidity of incoming and exiting air
- Air flow rate and velocity
- Solar irradiance and its temporal variation

Performance evaluation typically employs the following metrics.

Drying time (hrs): Time to reduce initial to final moisture content. Specific Moisture Extraction Rate (SMER, kg/kWh): Moisture removed per unit of energy input. Thermal efficiency (%): Ratio of useful energy used for evaporation to total incident solar energy[16]. Product quality indices (e.g., retention of color, nutrients, and texture)

$$\text{SMER} = \frac{\text{Total Energy Input (kWh)}}{\text{Moisture Removed (kg)}} \qquad (1)$$

Incorporating Fresnel lenses can substantially improve energy efficiency by providing higher temperature gradients and shorter drying times, though care must be taken to homogenize temperature distribution and prevent hot spots.

3.4. Integration of Fresnel Lenses in Solar Drying Systems

3.4.1. Types of Dryers Enhanced with Fresnel Lenses

Fresnel lenses can be effectively integrated into various solar drying configurations to improve thermal performance. Direct-type dryers with Fresnel focus use point- or line-focus lenses to directly irradiate the drying chamber or product surface. While capable of achieving high temperatures (80–120 °C), such systems require optical shielding to avoid overheating or localized burning[15,17].

Indirect solar dryers with Fresnel-driven air heating leverage concentrated sunlight to heat an air stream, which is then circulated through the drying chamber. This configuration ensures more uniform drying conditions and improved product quality. solar-electric dryers combine Fresnel-based solar input with auxiliary electrical heating to enable drying under intermittent or low-irradiance conditions, ensuring operational continuity[9].

3.4.2. Design Strategies

Design optimization involves several critical decisions. Fixed vs. tracking concentrators. Fixed systems are simpler and cheaper but suffer from sub-optimal alignment throughout the day. Single- or dual-axis tracking improves concentration efficiency, especially in point-focus systems. Thermal storage integration using phase change materials (PCM) or rock beds enables energy buffering for extended drying cycles and night-time operation. Heat exchanger coupling allows better control of air temperature and humidity, reducing product degradation due to thermal shocks[18].

3.4.3. Experimental Case Studies

Experimental studies have demonstrated the efficacy of Fresnel lens-enhanced dryers. Reported systems have achieved drying temperatures up to 110 °C, reducing drying time by 40–60% compared to conventional solar dryers. Fuel savings of 30–50% have been noted in hybrid configurations. Enhanced retention of color, ascorbic acid, and volatile compounds has been reported in dried fruits and vegetables, underscoring the benefit of controlled, high-temperature drying enabled by Fresnel concentration[12].

3.5. Modeling and Simulation Approaches

Numerical modeling and simulation are indispensable tools for designing and optimizing Fresnel lens-enhanced solar drying systems. Given the high flux densities and temperature gradients involved, accurate modeling of both optical concentration and thermal behavior is essential[8].

Optical ray tracing methods, using software such as Zemax, TracePro, or OptisWorks, allow simulation of solar radiation pathways through Fresnel lenses. These simulations predict focal intensity distributions, concentration ratios, and acceptance angles, informing lens geometry and placement. Parameters such as groove pitch, lens curvature, and incidence angle can be optimized for maximum transmittance and uniformity of radiation on the absorber or air heater[11].

Thermal modeling of drying chambers can be conducted using transient heat transfer equations that consider solar gain, convective losses, thermal mass, and airflow rates. Models can be solved analytically for simplified systems or numerically using finite difference or finite element methods[14].

More detailed Computational Fluid Dynamics (CFD) simulations, using tools like ANSYS Fluent or COMSOL Multiphysics, provide insights into airflow dynamics, temperature distribution, and moisture removal patterns inside the drying chamber. These models help avoid hot spots and identify optimal airflow configurations for homogeneous drying[6].

Energy efficiency can be evaluated using energy balance equations, accounting for:

$$Q_{useful} = m_{water} \cdot h_{fg} \qquad (2)$$

$$\eta = Q_{incident} \cdot Q_{useful} \qquad (3)$$

where, m_{water} is the mass of moisture removed, h_{fg} is the latent heat of vaporization, and $Q_{incident}$ is the total solar input.

3.6. Comparative Analysis

Fresnel-based dryers offer substantial performance improvements over conventional drying technologies. Table 2 provides a comparative overview based on typical experimental and field-reported data.

Technology	Max Temp (°C)	Drying Time (hrs)	Energy Efficiency (%)	Product Quality
Conventional solar dryer	45–60	10–14	~25–30%	Moderate
Flat-plate collector dryer	60–70	8–10	~35–45%	Good
Fresnel-based system	80–120	3–6	~50–65%	High

Fresnel lenses provide higher operational temperatures, which reduce the drying time by up to 60%, especially for high-moisture crops such as fruits and vegetables. Additionally, the higher concentration ratio enables smaller collector areas or lower material costs for achieving the same drying throughput[15].

The improved product quality is attributed to faster drying in the falling rate phase, which limits enzymatic degradation, microbial growth, and nutrient loss. Fresnel systems also outperform fossil-fuel-based dryers in terms of operational cost and environmental impact, though the latter still dominate in high-capacity commercial setups due to weather independence.

3.7. Challenges and Opportunities

3.7.1. Challenges

Despite the advantages, Fresnel-based drying systems face several technical and economic challenges. High local temperatures near the focal spot can lead to thermal degradation of sensitive materials or structural components, requiring robust thermal control or diffusers. Accurate solar tracking is critical for maintaining focus, especially for point-focus systems. Passive tracking is often insufficient, necessitating active dual-axis mechanisms that increase complexity and cost**.** Non-uniform heating across the drying chamber can result in inconsistent drying, especially in direct-type systems. This demands careful airflow management and chamber design. Material degradation, particularly in PMMA lenses, can occur under prolonged UV exposure, leading to reduced transmittance. High initial costs for lens fabrication, tracking systems, and control hardware may hinder adoption in low-income or smallholder contexts.

3.7.2. Opportunities

Conversely, several opportunities exist to scale and improve Fresnel-enhanced dryers. Modular scalable designs allow adaptation to various processing capacities, making them suitable for small and medium enterprises (SMEs) in decentralized settings. Systems can be adapted for combined drying of food and non-food agricultural products, such as medicinal herbs or biomass, enhancing year-round utility. Integration with thermal energy storage systems, such as phase change materials (PCM) or rock beds, enables continuous or nighttime drying, overcoming the intermittency of solar availability. IoT-enabled monitoring and control systems can track internal chamber temperature, humidity, and air velocity in real-time, enabling precision drying and quality assurance, while also allowing remote diagnostics.

IV. Conclusion

Fresnel lens-based solar dryers offer a promising solution for efficient, high-quality, and sustainable drying of agricultural products. Their ability to concentrate solar radiation enables higher temperatures (up to 120 °C), faster drying times, and better product preservation compared to conventional and flat-plate systems. Modeling and experimental studies confirm their enhanced energy efficiency and suitability for decentralized use. While challenges such as temperature control, material durability, and tracking remain, these can be mitigated through smart design and hybrid integration. Looking forward, coupling Fresnel lenses with thermal storage technologies like phase change materials can enable continuous, weather-independent drying. This integration positions Fresnel-enhanced dryers as transformative tools for post-harvest management, especially in off-grid and resource-limited settings.

Reference

[1]. E. A. Krasina, E. V. Tver'yanovich, and A. V. Romankevich, "Optical efficiency of solar engineering Fresnel lenses," *Appl. Solar Energy*, vol. 12, no. 6, pp. 6–10, 1989. [English translation of *Geliotekhnika*].

[2]. M. Collares-Pereira, A. Rabl, and R. Winston, "Lens–mirror combinations with maximal concentration," *Appl. Opt.*, vol. 16, no. 10, pp. 2677–2683, 1977.

[3]. F. Erismann, "Design of a plastic aspheric Fresnel lens with a spherical shape," *Opt. Eng.*, vol. 36, no. 4, pp. 988–991, 1997.

[4]. I. Oshida, "Step lenses and step prisms for utilization of solar energy," in *Proc. New Sources of Energy Conf.*, Rome, 1961, pp. 598–603.

[5]. S. Harmon, "Solar-optical analyses of a mass-produced plastic circular Fresnel lens," *Solar Energy*, vol. 19, no. 1, pp. 105–108, 1977.

[6]. R. L. Donovan, H. C. Hunter, J. T. Smith, R. L. Jones, and S. Boardbent, "Ten kilowatt photovoltaic concentrating array," in *Proc. 13th IEEE Photovoltaic Specialists Conf.*, Washington, D.C., 1978, pp. 1125–1130.

[7]. L. W. James and J. K. Williams, "Fresnel optics for solar concentration on photovoltaic cells," in *Proc. 13th IEEE Photovoltaic Specialists Conf.*, Washington, D.C., 1978, pp. 673–679.

[8]. M. J. O'Neil, "Solar concentrator and energy collection system," U.S. Patent 4,069,812, Jan. 1978.

[9]. M. J. O'Neil, "Bi-focused solar energy concentrator," U.S. Patent 4,545,366, Oct. 1985.

[10]. Y. Nakata, N. Shibuya, T. Kobe, K. Okamoto, A. Suzuki, and T. Tsuji, "Performance of circular Fresnel lens photovoltaic concentrator," *Jpn. J. Appl. Phys.*, vol. 19, Suppl. 19–2, pp. 75–78, 1980.

[11]. N. F. Shepard and T. S. Chan, "The design and performance of a point-focus concentrator module," in *Proc. 15th IEEE Photovoltaic Specialists Conf.*, Orlando, FL, 1981, pp. 336–341.

[12]. A. L. Moffat and R. S. Scharlack, "The design and development of a high concentration and high efficiency photovoltaic concentrator utilizing a curved Fresnel lens," in *Proc. 16th IEEE Photovoltaic Specialists Conf.*, San Diego, CA, 1982, pp. 601–606.

[13]. M. Mijatovic, D. Dimitrovski, and V. Veselinovic, "Fresnel lens-absorber system with uniform concentration and normal incoming rays to the absorber," *J. Opt. (Paris)*, vol. 18, no. 5–6, pp. 261–264, 1987.

[14]. R. W. Jebens, "Fresnel lens concentrator," U.S. Patent 4,799,778, Jan. 1989.

[15]. K. Akhmedov, R. A. Zakhidov, and S. I. Klychev, "Optical and energy characteristics of round Fresnel lenses with flat bands," *Appl. Solar Energy*, vol. 27, no. 1, pp. 43–46, 1991. [English translation of *Geliotekhnika*].

[16]. A. A. Soluyanov and V. A. Grilikhes, "A method for designing Fresnel lenses as solar radiation concentrators," *Appl. Solar Energy*, vol. 29, no. 5, pp. 57–62, 1993. [English translation of *Geliotekhnika*].

[17]. S. R. Kurtz, D. J. Friedman, and J. M. Olson, "The effect of chromatic aberrations on two-junction, two-terminal devices in a concentrator system," in *Proc. 1994 IEEE 1st World Conf. Photovoltaic Energy Conversion & 24th IEEE Photovoltaic Specialists Conf.*, Waikoloa, HI, 1994, pp. 1791–1794.

[18]. V. A. Grilikhes, V. D. Rumyantsev, and M. Z. Shvarts, "Indoor and outdoor testing of space concentrator AlGaAs/GaAs photovoltaic modules with Fresnel lenses," in *Proc. 25th IEEE Photovoltaic Specialists Conf.*, Washington, D.C., 1996, pp. 345–348.