How to Cite:
Deshmukh, K. M., Deshmukh, S. J., Gumte, K., Deshmukh, S. M., & Samal, K. (2025). Solar drying of bee pollen using polycarbonate-based solar dryer: A technologically and economically viable model for rural development. *International Journal of Economic Perspectives*, *19*(8), 1–22. Retrieved from https://ijeponline.org/index.php/journal/article/view/1121

Solar drying of bee pollen using polycarbonate-based solar dryer: A technologically and economically viable model for rural development

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Submitted: 27 June 2025, Revised: 18 July 2025, Accepted: 05 August 2025

***Abstract*---**In alignment with the objectives of the National Beekeeping and Honey Mission (NBHM) under the Ministry of Agriculture & Farmers Welfare, Government of India, this study explores the techno-economic and social dimensions of bee pollen processing. Bee pollen, a nutrient-rich natural substance secreted by bees, contains a complex mixture of proteins, essential amino acids, B-complex vitamins, minerals, immune-boosting agents and antioxidants. Recognized as a superfood, it is composed of over 250 medicinal and nutraceutical compounds, making it valuable in both health and commercial sectors. This work develops a discounted cash flow model to assess the Net Present Worth (NPW) of bee pollen drying systems from a financial standpoint. The model includes Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), while factoring in the time value of money, capital depreciation and inflation. This allows for a realistic and comprehensive financial analysis of investment returns over time. From a technical perspective, the feasibility of solar drying bee pollen using a polycarbonate-based dryer is evaluated. This analysis is not isolated but integrated with economic and social considerations, as the technology is particularly suited for rural deployment where most beekeepers operate. The solar drying approach is low-cost, energy-efficient and easily adaptable to small-scale use. Importantly, the study emphasizes the role of apiculture as a secondary income source for farmers. By adopting affordable solar drying methods, rural farmers can enhance their earnings and improve product value without significant investment. A sensitivity analysis is also conducted to determine the financial threshold and adaptability of the proposed model under varying economic conditions.

***Keywords*---**Bee Pollen, Solar Drying, Techno-Economic Analysis, Apiculture, Rural Economy

1. Introduction

1.1. The Role of Beekeeping in Sustainable Agriculture

Beekeeping, or apiculture, plays an indispensable role in sustainable agriculture and environmental conservation. It not only supports crop pollination vital for food security and biodiversity, but also provides diverse bee products such as honey, beeswax, propolis, royal jelly, venom and pollen. Among these, bee pollen has emerged as a nutraceutical product of growing commercial interest due to its rich nutritional composition and potential health benefits. With the rise in global demand for organic and health-promoting food products, bee pollen is increasingly positioned as a valuable commodity in local and international markets. Bee pollen is collected by bees during their foraging activity. It is agglomerated with nectar and bee secretions and stored in pollen baskets on their hind legs. Once collected by beekeepers using traps installed at hive entrances, the pollen is often moist and vulnerable to microbial spoilage. Therefore, drying it promptly and efficiently is essential to ensure its quality, safety and shelf-life.

1.2. Significance of Bee Pollen Processing

Fresh bee pollen typically contains 20% to 30% moisture content. If left untreated, this high moisture fosters microbial growth particularly molds and yeasts leading to fermentation, colour degradation and nutrient loss. Proper drying not only minimizes microbial risks but also helps preserve the chemical composition of pollen, especially heat-sensitive vitamins, enzymes and polyphenols. Inadequate or improper drying techniques can significantly deteriorate pollen quality, leading to discoloration, textural changes and reduced bioactivity. Therefore, post-harvest management of bee pollen, particularly the drying phase, is a critical determinant of its market value and consumer acceptability.

1.3. Limitations of Traditional Drying Methods

In many rural and semi-urban beekeeping communities particularly in countries like India sun drying is the most commonly adopted technique. While sun drying is inexpensive and straightforward, it poses serious limitations:

i. **Uncontrolled Drying Conditions:** Ambient temperature and humidity fluctuations lead to non-uniform drying.
ii. **Contamination Risks:** Exposure to dust, insects and airborne pathogens compromises hygiene.
iii. **UV Degradation:** Prolonged exposure to direct sunlight can degrade sensitive compounds such as flavonoids and vitamins.
iv. **Weather Dependency:** Cloud cover, rain, or insufficient sunlight reduces drying efficiency and increases processing time.

On the other hand, hot-air or electric dryers offer improved control but are often unaffordable and impractical in off-grid or rural areas due to cost, power requirements and technical complexity.

1.4. Emergence of Solar Drying Technology

Solar drying offers a sustainable and technically viable solution to bridge the gap between traditional and modern drying systems. It harnesses abundant solar energy, requires minimal operational cost and can be adapted to decentralized, low-resource environments. Solar dryers are broadly categorized as:

i. **Direct Solar Dryers**: The product is exposed directly to sunlight within a closed chamber.
ii. **Indirect Solar Dryers**: Solar radiation heats up air in a separate collector, which is then circulated through the drying chamber.
iii. **Mixed-mode Dryers**: Combine features of both direct and indirect systems.

Indirect dryers are preferred for high-value or sensitive products like bee pollen as they prevent direct sunlight exposure, offer better protection against contamination and can maintain more stable temperature and humidity conditions.

1.5. Technological Promise of Polycarbonate-Based Solar Dryers

The performance and durability of solar dryers significantly depend on the materials used for construction. Polycarbonate sheets, especially twin-wall or multiwall variants, have proven advantageous for solar dryer fabrication due to the following characteristics:

i. **High Impact Resistance:** Compared to glass and acrylic, polycarbonate is highly impact-resistant and less prone to breakage.
ii. **Thermal Insulation:** Multiwall polycarbonate retains heat effectively, maintaining stable internal temperatures.
iii. **UV Protection:** Most commercial polycarbonate sheets include UV-resistant coatings, reducing solar degradation of both the material and the dried product.
iv. **Lightweight and Easy Installation:** Polycarbonate is lightweight and easy to cut, shape and assemble which is ideal for rural construction.

In line with the material advantages highlighted above, as shown in Figure 1a custom-designed polycarbonate-based indirect solar dryer was developed to address the specific drying needs of sensitive bio-products like bee pollen. The model features a polycarbonate sheet chamber that not only allows solar radiation to enter but also traps heat through the greenhouse effect, significantly boosting internal temperatures even on moderately sunny days. The solar air collector attached to the unit ensures pre-heated air is circulated inside the chamber, maintaining a uniform drying temperature between 45°C and 60°C ideal for preserving the bioactive components of bee pollen. This design is particularly beneficial to apiculturists, as it ensures that bee pollen, which is often prone to spoilage or nutrient loss when dried using electric dryers, is preserved with its color, aroma and nutritional integrity intact. Unlike electric dryers that can overheat and degrade the bee pollen, as shown in Figure 2this solar dryer eliminates the risk of nutrient burn, while operating cost-free under sunlight. Additionally, the closed-chamber prevents dust, insects and microbial contamination, enabling hygienic drying.

Figure 1. Solar Dryer made with

Figure 2. Dried Bee Pollen in Drying Chamber of Solar

From an economic standpoint, the dryer is cost-effective, durable and easy to fabricate using locally available tools. Its low maintenance and modular construction make it scalable and accessible to rural apiculturists and SHGs (Self-Help Groups). By deploying this model, beekeepers can enhance product quality, command better market prices (₹1,200–₹1,800 per kg) and reduce operational dependency on electricity a major advantage in off-grid regions.

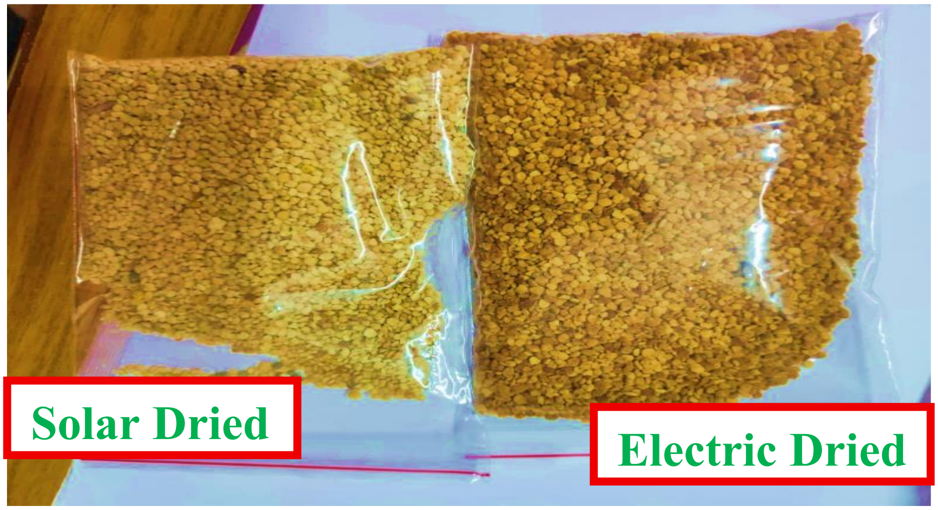

Figure 3Visual Comparison of Solar-Dried and Electric-Dried

The Figure 3shows two samples of bee pollen from the same batch, processed using different drying methods one with a solar dryer and the other with an electric dryer. The distinct difference in color between the two samples highlights the impact of the drying technique on product quality. The brighter, more vibrant hue of the solar-dried pollen indicates better retention of natural pigments and possibly nutrients, while the darker tone of the electrically dried sample suggests greater exposure to heat. This visual contrast underscores how drying methods can influence the appearance and potentially the quality of bee pollen. Farmers and Apiculturists can also use the solar dryer to dry various food materials, ensuring better nutrient and color retention during the drying process. The model thus aligns with India's National Beekeeping and Honey Mission (NBHM), supporting decentralized post-harvest processing and adding value to bee pollen a product often overlooked in rural income generation strategies.

1.6. Linking Renewable Energy with Rural Livelihoods

India’s rural sector, which constitutes nearly 65% of the nation’s population, continues to grapple with several developmental challenges, including unreliable energy access, inadequate infrastructure and limited availability of mechanized tools for post-harvest processing. In this context, the integration of renewable energy technologies such as solar dryers emerges as a powerful solution to bridge these gaps. Solar drying not only offers a clean and sustainable method for preserving agricultural products but also brings multiple socio-economic benefits. By minimizing post-harvest losses and enhancing the quality of products like bee pollen, solar dryers help increase farmers’ income and market competitiveness.

These systems are particularly beneficial for women, as solar drying initiatives are frequently managed by women-led self-help groups (SHGs), thereby fostering local entrepreneurship and contributing to women's empowerment. Moreover, solar dryers facilitate decentralized processing, enabling value addition at the community level and reducing dependence on centralized, resource-intensive processing centres. Importantly, the adoption of solar-based technologies supports India's broader climate and sustainability goals by reducing carbon emissions and promoting energy independence.

1.7. Research Gaps and Need for This Study

Although solar drying has been widely studied and applied for a range of agricultural commodities such as fruits, vegetables and grains, focused research on its application to bee pollen remains sparse. Bee pollen, being a high-value nutraceutical product, requires careful handling and controlled drying conditions to preserve its bioactive compounds. However, most existing solar dryer designs do not adequately cater to the specific temperature and airflow requirements essential for drying bee pollen without compromising its nutritional quality. Additionally, maintaining hygienic conditions during the drying process is critical, yet often overlooked in current models particularly when used in rural or resource-limited settings. Another major gap is the lack of attention to economic feasibility at the level of small-scale or cluster-based beekeepers, for whom cost-effectiveness and ease of use are paramount. Most technological interventions remain confined to experimental prototypes or high-investment models that are not scalable or affordable for grassroots deployment. Furthermore, very few studies have holistically evaluated the techno-economic viability of polycarbonate-based solar dryers in the real-world context of Indian rural environments. This gap underscores the urgent need for a comprehensive study that not only explores the technical efficiency of such dryers but also examines their economic sustainability and replicability among rural stakeholders.

2. Literature Survey

Bee pollen, a nutrient-rich product collected by bees, holds significant techno-economic and social value, particularly in the context of the National Beekeeping and Honey Mission. This mission aims to promote beekeeping as a sustainable agricultural practice, enhance honey production and improve the livelihoods of beekeepers. The integration of bee pollen into this framework offers multiple benefits, including economic empowerment, environmental sustainability and social development.

2.1 Techno-Economic Aspects of Bee Pollen

2.1.1 Nutritional and Industrial Value of Bee Pollen

Bee pollen is a rich source of proteins, vitamins, minerals and antioxidants, making it a highly sought-after product in the natural food market (Barros et al., 2024). Its nutritional profile makes it ideal for use in functional foods, dietary supplements and cosmetic products. The processing of bee pollen involves techniques such as fermentation, enzymatic hydrolysis and ultrasound treatment, which enhance its bioavailability and functional properties (Alcalá-Orozco et al., 2024; Qiao et al., 2024). These advancements in processing technology have opened new avenues for the industrial application of bee pollen, contributing to its economic value.

In addition to being a protein-rich food, bee pollen contains essential amino acids, unsaturated fatty acids (including omega-3 and omega-6), dietary fibres, carotenoids and phenolic compounds, which contribute to its strong antioxidant and anti-inflammatory properties (Komosinska-Vassev et al., 2015). It has been demonstrated that bee pollen can contain up to 35% proteins and a comprehensive spectrum of B-complex vitamins, which supports its classification as a superfood and functional dietary component (Carpes et al., 2007). The antioxidant profile, particularly the flavonoid and phenolic content, is heavily influenced by the floral and geographical origin of the pollen, affecting its nutraceutical efficacy (Rzepecka-Stojko et al., 2015). Due to this diverse chemical composition, bee pollen is increasingly used in pharmaceutical formulations aimed at improving gastrointestinal health, immune modulation and chronic disease prevention (Pascoal et al., 2014). From an industrial standpoint, bee pollen is integrated into a range of commercial products, including fortified energy bars, probiotic yogurts, capsules and topical ointments (ß et al., 2009). Cosmetic industries have exploited its antimicrobial and skin-regenerative properties in the formulation of creams, anti-acne gels and shampoos (Xi et al., 2018). To meet quality standards in these sectors, the pollen must retain its bioactive compounds post-harvest emphasizing the importance of appropriate drying technologies that preserve its nutritional integrity. Furthermore, industrial innovation has expanded the utility of bee pollen through biotechnological interventions. The global market for bee pollen is projected to grow steadily, driven by rising consumer awareness of natural and organic supplements. In this context, improving the efficiency of post-harvest processing especially drying becomes crucial for quality preservation and economic returns. Studies by (Almeida-Muradian et al., 2005) emphasized that temperature-controlled drying is key to maintaining the polyphenolic content and enzymatic activity of bee pollen, which directly impacts its industrial usability. Moreover, export markets, particularly in the EU, Japan and the United States, demand rigorous quality control and traceability, further necessitating standardized processing protocols. The Codex Alimentarius and the International Honey Commission (IHC) have recommended guidelines for the compositional standards of dried bee pollen, including moisture content (<6%), microbiological safety and minimal processing to ensure its natural bioactive properties are preserved (Bogdanov, 2004a).

2.1.2 Economic Empowerment through Bee Pollen Production

The production and sale of bee pollen provide a significant source of income for beekeepers, particularly in rural areas. In countries like Indonesia, the value chain of bee products, including pollen, involves various stakeholders such as beekeepers, intermediate traders and processing industries (Harianja et al., 2023). The economic benefits of bee pollen are further enhanced by its high demand in both domestic and international markets, driven by its perceived health benefits and versatility in applications (Anjum et al., 2024; Barros et al., 2024).In India, the National Beekeeping and Honey Mission (NBHM), under the Ministry of Agriculture and Farmers Welfare, emphasizes the promotion of apiculture for income diversification among small and marginal farmers. Bee pollen, though often overshadowed by honey, has been increasingly recognized for its high market value, especially when dried and packaged hygienically. Studies have shown that the price of bee pollen in urban organic and export markets can range between ₹1,500 to ₹3,000 per kilogram, making it a lucrative alternative product for rural beekeepers (FAO, 2021).Moreover, value-added processing of bee pollen such as capsule filling, granulation and blending with other nutraceuticals has created new avenues for micro-enterprises and rural start-ups. According to research by (Pocol & McDonough, 2015), training rural beekeepers in hygienic collection, drying and packaging significantly enhances the marketability and value of bee pollen, increasing their income by 25 to 40% compared to traditional honey sales alone.

Several international development programs and NGOs have successfully demonstrated that community-based beekeeping initiatives, especially those involving women-led cooperatives, have empowered local communities economically and socially. In East Africa, for example, the African Beekeeping Resource Center reported that integrating pollen harvesting and processing into beekeeping operations led to a 30% increase in household income (African Beekeeping Resource Center (ABRC), 2018). Similar success stories are emerging in the Indian states of Himachal Pradesh, Uttarakhand and Madhya Pradesh, where SHGs and Farmer Producer Organizations (FPOs) are supported through training, solar dryer deployment and market linkage facilitation (ICAR, 2023).

2.1.3 Challenges in Bee Pollen Production and Marketing

Despite its economic potential, bee pollen production faces challenges such as high labour costs, limited technical knowledge and market competition. For instance, in Malaysia, the high capital expenditure on hive investments and labour costs are significant concerns for stingless bee farming (Abdurofi, 2018a). Additionally, the lack of standardization in pollen processing and marketing hampers its commercialization (Alcalá-Orozco et al., 2024). Addressing these challenges is crucial to maximizing the economic benefits of bee pollen production. The technical knowledge gaps among rural beekeepers in India significantly constrain effective bee pollen production. While beekeeping initiatives like the National Beekeeping and Honey Mission have been promoted, the focus has predominantly been on honey production, leaving pollen production underemphasized. This lack of training in essential techniques such as pollen trap installation, hygienic handling and low-temperature drying affects the quality and marketability of bee pollen, a high-value co-product. Addressing these gaps through targeted training programs could enhance the economic viability of beekeeping by diversifying income sources and improving product quality. Many beekeepers lack training in installing pollen traps, which are essential for collecting pollen efficiently. These traps are designed to separate pollen from bees as they enter the hive (Lee, 2017) Hygienic handling of pollen is critical to maintaining its quality. Improper handling can lead to contamination and spoilage, reducing its market value (Bogdanov, 2004b) Low-temperature drying techniques, such as freeze-drying and microwave-assisted drying, are crucial for preserving the nutritional and sensory properties of bee pollen. These methods help retain polyphenols, flavonoids and amino acids, which are vital for the pollen's health benefits (Castagna et al., 2020). Studies indicate a significant need for training in pollen production techniques among beekeepers. In regions like Rashidiya, Baghdad and Haryana, beekeepers have expressed a need for training in various aspects of beekeeping, including pollen production (Shawkat et al., 2015; N. Singh et al., 2011). Training programs should focus on scientific beekeeping practices, including the installation and maintenance of pollen traps, hygienic handling and advanced drying techniques (Anu et al., 2025). Providing accessible financial support and improving marketing infrastructure for bee products can further bolster the adoption of pollen production (Anu et al., 2025). While addressing technical knowledge gaps is crucial, other challenges also impact bee pollen production. Socio-economic constraints, such as limited financial resources and lack of managerial capabilities, can hinder the establishment of beekeeping enterprises (Anu et al., 2025). Additionally, environmental factors like the scarcity of bee flora during the off-season pose challenges to consistent pollen production (Anu et al., 2025) Addressing these broader issues through comprehensive support systems, including financial aid and resource management, can enhance the sustainability and profitability of beekeeping as a whole.

2.2 Social Aspects of Bee Pollen

2.2.1 Role in Rural Livelihoods

Bee pollen production plays a vital role in the livelihoods of rural communities. In regions like Chiapas, Mexico, beekeeping is integrated into agro-ecological farming systems, providing additional income sources for smallholder farmers (Anderzén et al., 2024). Similarly, in Kenya, beekeeping is promoted as an alternative livelihood in arid and semi-arid lands, contributing to food security and economic empowerment (Huho et al., 2024). The social impact of bee pollen production extends beyond economic benefits, fostering community development and resilience. In India, similar outcomes have been observed in tribal and forest-fringe communities in states such as Jharkhand, Odisha and Chhattisgarh. Under schemes like the National Beekeeping and Honey Mission (NBHM), rural self-help groups (SHGs) and women's cooperatives are increasingly being trained in apiculture practices, including pollen collection. These initiatives have helped women engage in income-generating activities without requiring large landholdings or capital investment (Ministry of Agriculture, 2021). Bee pollen, in particular, is viewed as a high-value product with export potential, making it an attractive option for micro-entrepreneurs in rural India. The social impact of bee pollen production goes beyond economic empowerment. It fosters collective action, skill development and organizational strengthening through cooperatives and SHGs. When communities engage in shared apiculture activities, they develop institutional capacities around product quality control, fair pricing and market negotiation. In Ethiopia, the BEE-LIEVE project co-funded by the European Union has empowered over 2,000 smallholder beekeepers, with a strong emphasis on supporting women and youth through training, equipment access and cooperative development (EU International Partnerships, 2022). The project documented increased household income, stronger entrepreneurial skills among women and a notable shift in community perceptions about gender roles, thereby contributing to greater social inclusion and rural transformation. These findings underscore the potential of beekeeping, including bee pollen production, to serve not only as an economic driver but also as a catalyst for broader social change, especially in rural and resource-constrained settings.

2.2.2 Cultural and Traditional Practices

Beekeeping and the use of bee pollen are deeply rooted in cultural and traditional practices in many regions. In Manipur, India, traditional bamboo hives are used for stingless beekeeping, reflecting a culturally significant and sustainable approach to beekeeping (T. B. Singh & Singh, 2024). Similarly, in Kenya, beekeeping is often practiced using indigenous knowledge and traditional methods, highlighting the importance of preserving cultural heritage in beekeeping practices (Huho et al., 2024).

2.2.3 Educational and Training Needs

The social benefits of bee pollen production can be further enhanced through education and training programs. Many studies emphasize the need for beekeepers to acquire modern beekeeping techniques, pest management strategies and marketing skills to improve the quality and profitability of their products (Huho et al., 2024; Iswara et al., 2024). Educational initiatives can empower beekeepers, particularly women and youth, to participate more effectively in the bee pollen value chain.

2.3 Environmental Aspects of Bee Pollen

2.3.1 Ecological Sustainability

Bee pollen production contributes to ecological sustainability by promoting pollination services and biodiversity conservation. Bees play a crucial role in pollinating flowering plants, including many food crops, thereby enhancing agricultural productivity (KAYA et al., 2023; Köse, 2024). The conservation of natural habitats for bees is essential for maintaining the ecological balance and ensuring the sustainability of bee pollen production.

2.3.2 Environmental Threats and Mitigation

Despite its environmental benefits, beekeeping faces threats such as habitat loss, climate change and pesticide use. These factors can negatively impact bee health and pollen production (KAYA et al., 2023; T. B. Singh & Singh, 2024). Sustainable beekeeping practices, such as organic beekeeping and the use of integrated pest management strategies, can mitigate these threats and ensure the long-term sustainability of bee pollen production (Köse, 2024; Selma et al., 2024).

2.3.3 Policy and Regulatory Frameworks

The environmental and economic sustainability of bee pollen production is also influenced by policy and regulatory frameworks. In Indonesia, for instance, the development of policies to manage the relationships among stakeholders in the honey production value chain is crucial for achieving sustainable livelihoods (Harianja et al., 2023). Similarly, government support through subsidies, training programs and market interventions can enhance the competitiveness of bee pollen products in both domestic and international markets (Abdurofi, 2018b).
The techno-economic and social aspects of bee pollen are intricately linked to the goals of the National Beekeeping and Honey Mission. By leveraging the nutritional and industrial value of bee pollen, promoting sustainable beekeeping practices

and addressing the challenges in production and marketing, the mission can contribute to economic empowerment, social development and environmental sustainability. The integration of modern technologies, education and policy support will be key to unlocking the full potential of bee pollen in achieving the mission's objectives.

3. Methodology

From a financial perspective the bee pollen can be termed as product which has good amount of demand in the market due to its medical benefits, hence in the methodology section, the concept of financial model of discounted cash flow is used with depreciation and inflation i.e. time value of money.

$NPW=\sum_t \frac{1}{(1+\alpha)^{N-1}}((EAR_t - OPEX_t - DEPR)\times(1-\Psi_p)+DEPR)-\sum_t \frac{1}{(1+\alpha)^{N-1}} \times CPEX_t$……………Eqn.1

$EAR_t = Dmd_{p,t} \times Sp_{p,t}$……………………………………………………………………………Eqn.2

$OPEX_t = RaMC_t + MaintC_t + EleC_t + LabC_t$ ……………………………………………………… Eqn.3

$CPEX_t = MachC_t$…………………………………………………………………………………… Eqn. 4

$DEPR = \sum_t \frac{int}{((1+int)^N - 1)}(CPEX_t - 0.2 \times CPEX_t)$……………………………………………………Eqn. 5

Eqn.1 shows the NPW equation, which takes into account the time value of money along with depreciation (DEPR), earning (EAR), operating (OPEX) and capital expenditure (CPEX). The major sources of earning, is by retail selling of product (SP) as per the market demand (Dmd) Eqn.2.The variable costs are calculated in terms of operating expenditures i.e., raw material cost, maintenance cost, electricity cost and labour cost (Eqn.3). The fixed cost includes capital expenditure (Eqn.4) calculated in terms of one-time infrastructure cost (INFC) during the considerable time horizon. The project depreciation is estimated using straight-line depreciation methodology (Eqn.5).

Further the raw material cost is estimated using unitary method where the product demand is multiplied with number of units demanded, where the production is done as the market demand (Eqn.6). Similar equations follow for maintenance cost (Eqn.7), electricity cost (Eqn.8), infrastructure cost (Eqn.9) and Labor Cost (Eqn.10).

$RaMC_t = Dmd_t * URaMC_t$…………………………………………………………………Eqn.6

$MaintC_t = Dmd_t * UMaintC_t$……………………………………………………………Eqn.7

$EleC_t = Dmd_t * UEleC_t$………………………………………………………………………Eqn.8

$INFC_t = MachC_t$………………………………………………………………………………Eqn.9

$LabC_t = Dmd_t * ULabC_t$………………………………………………………………………Eqn.10

4. Data Collection

In this study, we focus on the modeling and economic evaluation of a **30 kg capacity polycarbonate solar dryer**. For the purpose of financial analysis, it is assumed that the manufacturing facility will produce **eight units per month**. Each unit is intended to be sold at a price of **₹90,000**, reflecting its optimized design, material cost and functionality. The **capital expenditure (CAPEX)** includes investments required for machinery, tools and initial workspace setup. In contrast, the **operational expenditure (OPEX)** covers recurring costs such as labor, electricity, raw material procurement and administrative overheads. Revenue is calculated based on the number of units sold multiplied by the selling price per unit. To evaluate the long-term financial feasibility, the **Net Present Worth (NPW)** is computed over a **5-year period**, applying a **discount rate of 10%** to reflect the time value of money. The data collection outlined in this chapter serves as the foundation for assessing the profitability and sustainability of the solar dryer manufacturing model. The following Table 1is the data of expenses for the manufacturing of a single unit polycarbonate solar dryer.

Table 1Cost Parameters for Solar Dryer Manufacturing

Component	**Symbol**	**Value**	**Remarks**
Time Period	t	5 years	Evaluation horizon
Discount Rate	α	10%	Standard for micro enterprises
Units Manufactured	Q	8/month (96/year)	Manual + semi-mechanized
Selling Price	SP	₹90,000/unit	Market avg for compact solar dryers
Material Cost/unit	MCU	₹53,585/unit	Polycarbonate, GI, tray, frame
Labor (Welder +Fitter+ Helper)	LAB	₹7,800/3 day (As 1 unit of solar dryer takes 3 days to fabricate)	3-person team
Electricity	ELEC	₹1600/month ₹200/unit	Cutting, welding, blower tests
Maintenance	MAINT	₹1,000/month	Tools, blades, welding rods
Marketing & Misc.	MISC	₹1,000/month	Local promotions
CAPEX	CPEX	₹34,000	One-time setup for tools, jig, space (including equipment)
Infra Cost	INFC	₹2,00,000	Fabrication table, layout, shed (except land cost)
Depreciation	DEPR	₹30,000/year	Straight-line on CAPEX

Table 2 6-Year Cost Projection: Solar Dryer Manufacturing Unit (2025–2030)

Year	Units/ Year	SP/unit (₹)	MCU/unit (₹)	Labour Cost (₹)	Electricity (₹)	Maintenance + Misc (₹)
2025	96	90000	53585	957	250	24000
2026	106	94500	56264	1005	238	25200
2027	116	99225	59077	1055	228	26460
2028	126	104186	62031	1108	220	27780
2029	136	109396	65133	1163	214	29170
2030	146	114865	68390	1221	210	30629

Table 3 Category wise growth assumption for next 5 years

Category	Growth Assumption
Selling Price (SP)	+5% annually
Material Cost (MCU)	+5% annually
Labor Cost (LAB)	+5% annually
Electricity (ELEC)	Fixed (or +3%/yr)
Maintenance & Misc.	Fixed or marginal
Units Produced/Year (Q)	Start: 96 → grow +10 units/year
CAPEX	One-time in 2025
Depreciation (DEPR)	₹30,000 fixed (straight-line)

5. Results & Discussion

The model is coded into GAMS software using 10 blocks of equations, 10 block of variables and 105 non-zero elements to be executed in 0.344 CPU seconds using Linear Programming Optimization for maximizing the profit NPV. Here CPLEX solver is used.

The NPV value obtained is found to be INR or Rs 1.6084E+7 and is positive. For economic feasibility the NPV value must be above zero. Hence condition for economic feasibility is satisfied for the time horizon 2025 to 2030. The overall depreciation obtained is considerable over the years and is found to be Rs. 20737.181. The time period considered is 2025 as t1 to 2030 as t6 respectively.

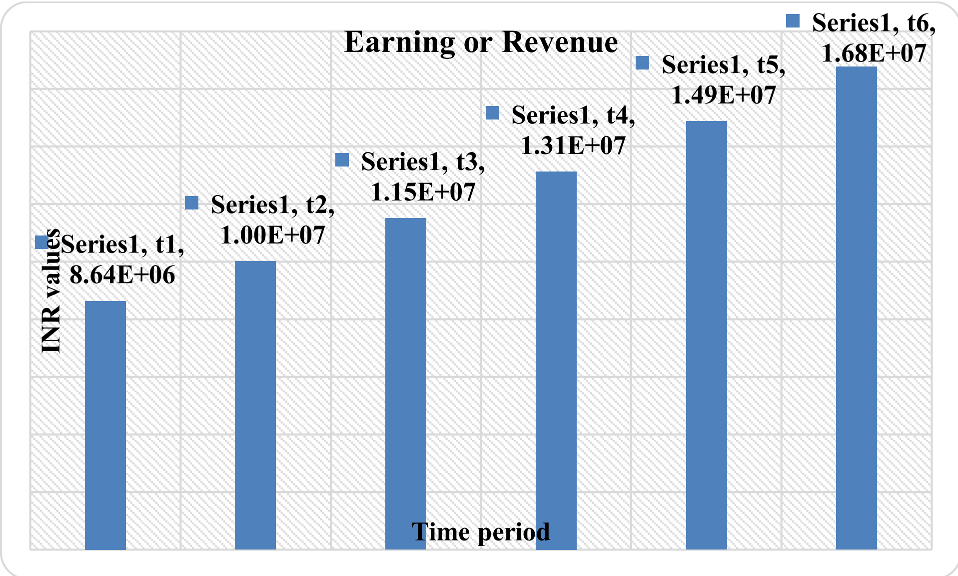

Figure 4. The earning values shown across the time horizon.

As from Figure 4, it is observed that the revenue or earning increased with increase in time period. The reason being the selling price of the product starting at time period t1 equals Rs. 90,000/unit and increases over the time at 5% annually due to the inflation effect. Similar trend can be found across raw material cost Figure 5, maintenance cost Figure 6, electricity charges Figure 7and labor charges Figure 8.

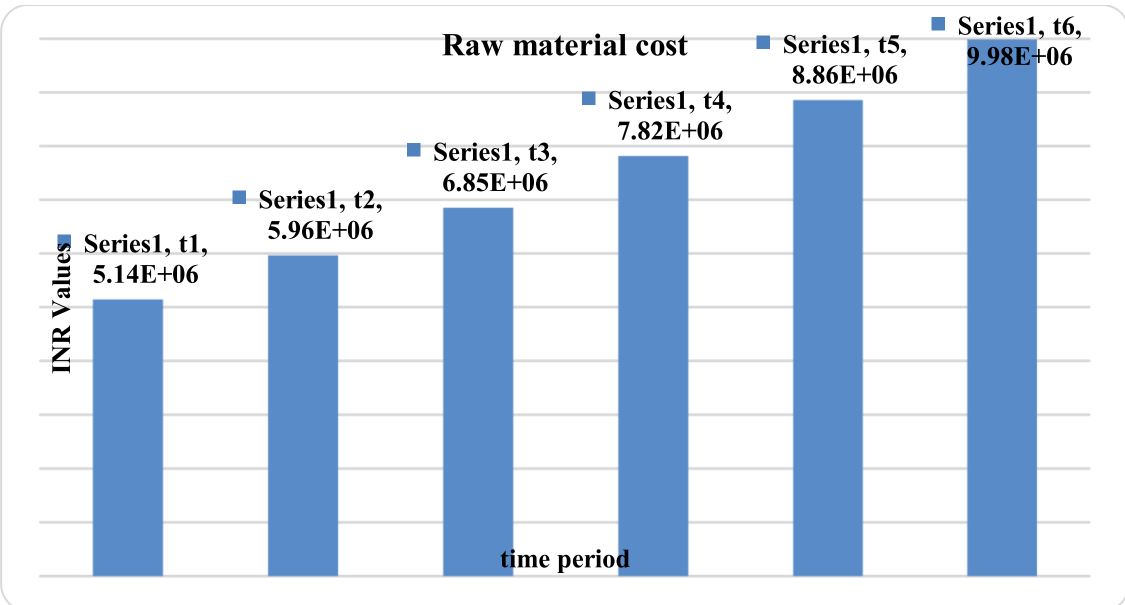

Figure 5. The raw material cost values shown across the time horizon

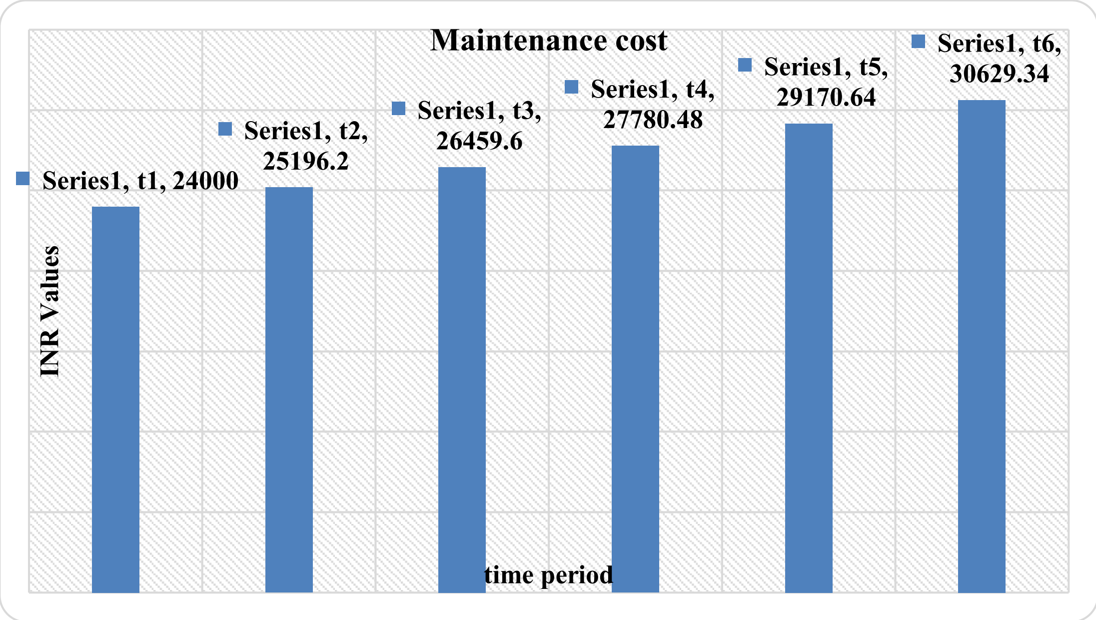

Figure 6. The maintenance cost values shown across the time horizon

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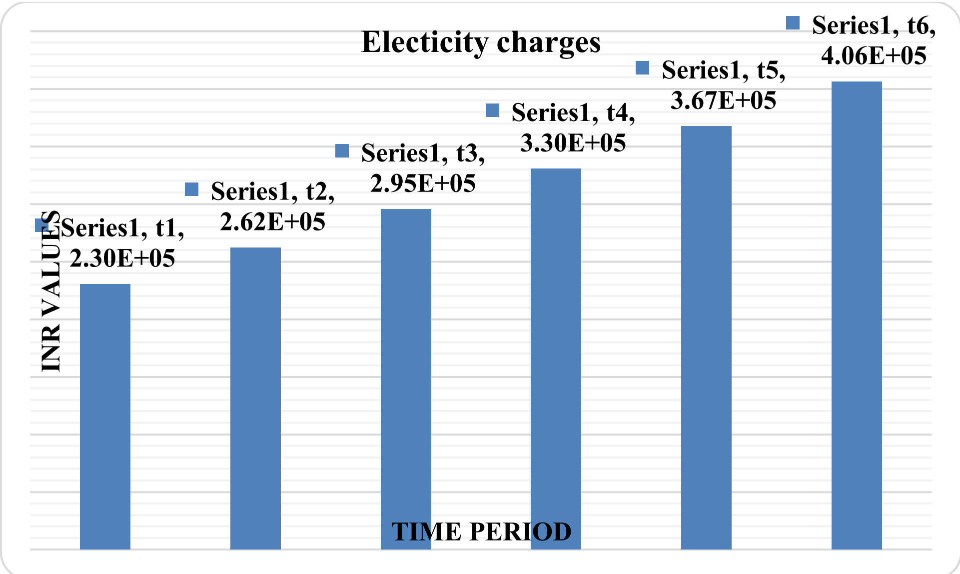

Figure 7. The electricity charge values shown across the time horizon

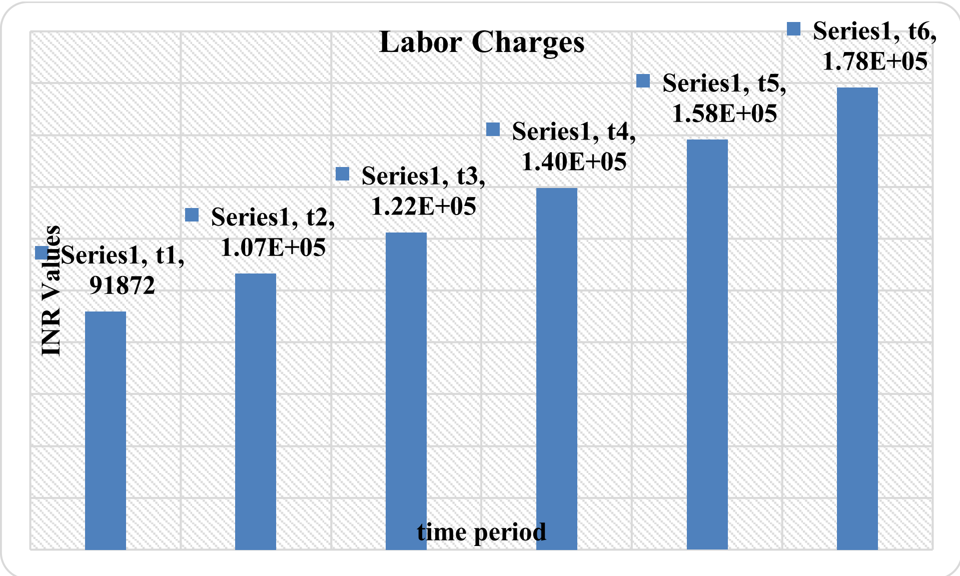

Figure 8. The labor charges values shown across the time horizon

Further, the infrastructure cost obtained is in form of machine cost of Rs. 2.0000E+5 and is one time cost at the start of time horizon. The total cost obtained from Opex is found to be Rs. 4.75E+07 and CapexFigure 9. shows the cost distribution with Opex bearing 99.6% of the cost. This also shows that while doing the manufacturing of the product. The variable cost is dominant.

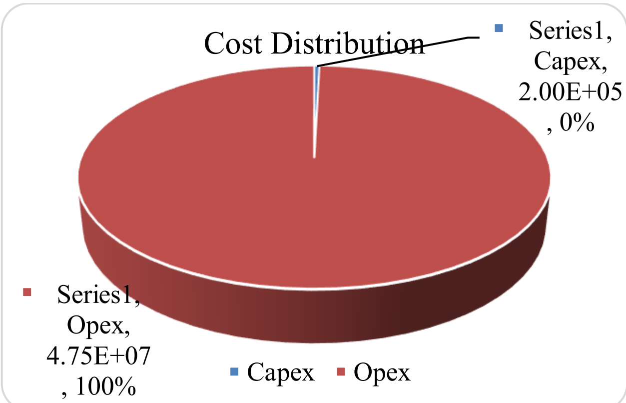

Figure 9. Cost distribution of total expenditure

Further, analysis of variable cost suggests thatFigure 10,the raw material cost account for major chunk of expenditure around 84% followed by minor contribution from electricity charges 4%, Labor cost around 2% and minimum maintenance cost 0.1%.

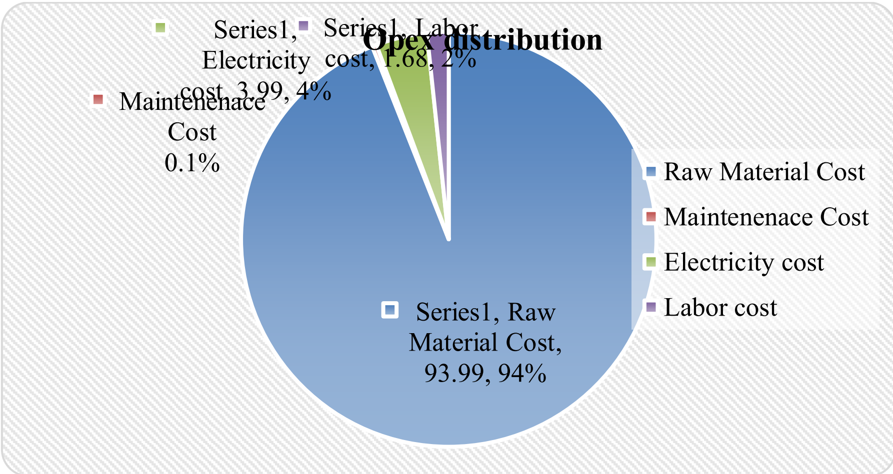

Figure 10. Opex cost distribution showing raw material as major component

Technically the manufacturing process is sound and feasible where (explain the manufacturing process in steps or inform of a flow chart) The entire process's major accountability that comes on the raw material around is 94% which is a bottleneck of the process. Hence, more focus is needed in their part.

6. Implications

6.1 Theoretical Implications

This study contributes to the academic discourse by presenting a comprehensive techno-economic-social model for evaluating solar drying technologies using polycarbonate-based dryers, specifically tailored for high-value apicultural products like bee pollen. By integrating technical parameters (temperature control, material performance), financial modeling (NPW, depreciation, inflation-adjusted returns) and rural development indicators (livelihood improvement, gender empowerment), the research bridges a critical gap in interdisciplinary sustainability studies. The inclusion of a discounted cash flow model with sensitivity analysis provides a replicable framework that future studies can adopt for similar Agri-tech innovations.

6.2 Managerial and Practical Implications

For rural entrepreneurs, farmer-producer organizations (FPOs) and self-help groups (SHGs), the findings offer actionable insights into the viability of decentralized bee pollen processing. The demonstrated model empowers small-scale beekeepers by reducing post-harvest losses, ensuring hygienic drying and increasing value addition through quality enhancement. From a management standpoint, the model aids decision-makers in justifying capital investment by demonstrating positive NPW and scalable production potential over a five-year period.

Policymakers and government agencies such as the Ministry of Agriculture and Farmers Welfare, Ministry of Rural Development and NABARD can leverage these findings to frame subsidy schemes, capacity-building modules and local manufacturing incentives. The alignment with the National Beekeeping and Honey Mission (NBHM) strengthens the case for its inclusion in rural employment schemes like MGNREGA or start-up incubation for rural youth.

7. Conclusion, Limitations & Future Work

7.1. Conclusion

The study successfully demonstrates the technological, economic and social feasibility of adopting polycarbonate-based solar dryers for bee pollen processing in rural India. The design effectively addresses technical limitations of traditional drying methods, ensures retention of bioactive components and meets hygienic standards critical for high-value nutraceutical products. The economic model, evaluated using discounted cash flow analysis, confirms profitability with a positive NPW (₹1.6084 crore) over a 6-year period. Additionally, the study underscores the potential of such technology to promote decentralized income generation, women’s empowerment and eco-friendly entrepreneurship in alignment with India's rural development goals.

7.2. Limitations

While the model provides a robust framework, certain limitations persist:

i. The financial model assumes linear growth and fixed depreciation, which may not fully capture real-world volatility such as raw material price fluctuations or market saturation.
ii. The study does not incorporate lifecycle environmental assessment or carbon footprint of materials like polycarbonate.
iii. Behavioral and cultural barriers to technology adoption among rural users are not evaluated in detail.
iv. Nutritional testing of the dried pollen post-process was assumed based on literature but not experimentally verified in this work.

7.3. Future Work

Future research should focus on:

i. Experimental validation of bioactivity retention in bee pollen processed through polycarbonate-based dryers.
ii. Integration of AI/ML tools for real-time monitoring and optimization of drying parameters.
iii. Development of modular, mobile versions of solar dryers for remote locations.
iv. Assessment of lifecycle sustainability, including environmental impact of dryer materials.
v. Incorporating feedback from rural end-users to improve user-friendliness and adoption.
vi. Expansion of the model to other high-value perishable agro-products (e.g., medicinal herbs, mushrooms).

8. Acknowledgement

The authors gratefully acknowledge the following institutes:

- Mahatma Gandhi Institute for Rural Industrialization (MGIRI), Wardha. (The National Institute under the Ministry of MSME, Govt. of India)for their valuable technical and developmental support.
- Council of Scientific and Industrial Research (CSIR) for their financial and economic modelling support under Project Number HCP/54/02.

Appendix

Acronyms/Nomenclature

Sets, subsets, subscripts, superscripts, indices

t	Time period

Scalars

α	Discount factor
N	Number of years or total time period of project
int	The annual interest rate for depreciation
Ψ_p	Goods and service tax for the bee pollen product p (%)

Parameters

$Dmd_{p,t}$	Demand of product for that time period
$Sp_{p,t}$	Selling price of product for that time period
$MachC_t$	Machine cost (₹) for that time period
$URaMC_t$	Unit raw material cost (₹) for that time period
$UMaintC_t$	Unit maintenance cost (₹) for that time period
$UEleC_t$	Unit electricity cost (₹) for that time period
$ULabC_t$	Unit labor cost (₹) for that time period

Decision Variables

NPW	Net present worth or value
EAR_t	Earnings or revenue generation (₹) for that time period
$OPEX_t$	Operating expenditures (₹) for that time period
DEPR	Depreciation of project assets on annual basis
$CPEX_t$	Capital expenditures (₹) for that time period
$PRODC_t$	Production cost (₹) for that time period
$INVTC_t$	Inventory or storage cost (₹) for that time period
$RaMC_t$	Raw material cost (₹) for that time period
$MaintC_t$	Maintenance cost (₹) for that time period
$EleC_t$	Electricity cost or charges (₹) for that time period
$INFC_t$	Infrastructure cost (₹) for that time period
$MachC_t$	Machine cost (₹) for that time period

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