Solar Technology in Agribusiness: Impact and Results of the Solar Drying Plant in Zacatecas

Néstor Manuel Ortiz-Rodríguez[1], Efraín Alonso Puerto-Castellanos[2], Jesús Águila-León[3], Octavio GarcíaValladares[1]*

[1] Institute of Renewable Energies, National Autonomous University of Mexico. Privada Xochicalco s/n, Temixco CP. 62580, Morelos, Mexico.

[2] Technical Direction. DIPAC HEAT RECOVERY E.U., Bogotá, Colombia.

[3] Department of Water and Energy Studies, Tonalá University Center, University of Guadalajara, Mexico.

*Corresponding author: nmorr@ier.unam.mx

Abstract

In response to global challenges in agribusiness, this work presents the results of the strengthening of the Solar Drying Plant for Agricultural Products in Zacatecas, Mexico. The plant has implemented solar energy technologies combined with biomass and LP gas backup systems, as well as a heat pump dryer. These advancements have increased the plant's capacity by 300%, enabling the recovery and valorization of over 232 tons of fresh agricultural products between 2022 and 2024, such as garlic, prickly pear, and apples. Additionally, the project has promoted regional development through the creation and strengthening of 16 businesses and enterprises, generating employment and enhancing the agribusiness value chain. More than 50 training and outreach events have been held, along with the formation of over 20 professionals specialized in solar drying. Environmentally, the plant avoided the emission of 58.217 tons of CO_2 by replacing fossil fuel-based energy with solar energy. The experience gained in Zacatecas demonstrates that solar technology is an effective solution to promote sustainability in agribusiness and the energy transition, integrating technological, economic, social, and environmental impacts. This model is replicable in other regions seeking sustainable solutions for food preservation.

Keywords: Solar drying, Solar energy, Food waste, Agribusiness

Introduction

Food Loss and Waste (FLW), particularly of fruits and vegetables, represents a global challenge that affects food security and significantly contributes to the waste of natural resources, resulting in a negative environmental impact [1], [2]. Globally, it is estimated that about one-third of all food produced is lost or wasted, generating approximately 8% of global greenhouse gas emissions [3]. In Mexico, annual FLW is estimated at 20.4 million tons—enough to feed 7.4 million people—and it generates 36 million tons of CO_2 emissions [4]. The food drying process can play a crucial role in mitigating global food waste, but it typically involves high energy consumption, especially in preserving perishable products. In the food industry, drying is energy-intensive, accounting for between 10% and 25% of the sector's energy consumption [5], and is predominantly powered by fossil fuels [6]. From an environmental perspective, FLW reduction solutions must ensure that their negative impacts are outweighed by their benefits [7]. Solar drying has emerged as an effective solution in agribusiness, not only addressing issues such as food insecurity, energy supply sustainability, and environmental degradation [8], but also due to its ability to preserve the nutritional quality of food during dehydration. This technology has been successfully implemented in various regions to preserve high-demand perishable products such as fruits, vegetables, and herbs [9]. In this context, since 2017, a solar thermal drying plant for agricultural products has been built and operated in Zacatecas, Mexico. This study aims to assess the impact of this plant through a comprehensive approach that encompasses technological, economic, social, environmental, scientific, and educational aspects. The results will highlight how the plant has contributed to sustainable development in the region's agribusiness sector, presenting a model that is replicable in other areas with similar conditions.

Plant Description

The agricultural product drying plant is located in the municipality of Morelos, Zacatecas (22°53'N, 102°39'W), at 2,207 meters above sea level. The climate is semi-arid, with an average annual temperature of 14.8°C, rainfall of 407.7 mm concentrated between June and September, and an average wind speed of 4 m/s. With an average annual solar irradiance of 520 W/m², the location is ideal for the use of solar drying technologies [10]. The plant is equipped with three drying systems designed to maximize the use of renewable energy and minimize fossil fuel consumption in the processing of agricultural products (see Figure 1):

1. Hybrid Distributed Solar Drying System (Solar-Biomass-LP Gas):

This system uses forced convection of hot air in a tunnel-type chamber that operates in batch or semicontinuous mode. Air heating is achieved through two solar thermal systems: a direct system consisting of 48 solar air heaters covering an area of 111.1 m², and an indirect system with 40 solar water heaters and a thermal storage capacity of 6 m³. To ensure continuous operation, it includes a backup energy source using an indirect hot air generator powered by biomass pellets and a direct LP gas burner. The drying chamber can operate in three modes:

- Conventional, using LP gas only;
- Solar, using direct or indirect solar energy independently or simultaneously;
- Hybrid, combining solar energy with biomass or LP gas backup

2. Integrated Solar Greenhouse-Type Drying System:

This system consists of a drying chamber with a galvanized steel structure and a 6 mm double-wall polycarbonate alveolar cover. The concrete floor measures 9 m wide by 8 m long, providing an internal area of 72 m². The greenhouse reaches a maximum height of 3.4 m, creating a total volume of 163.2 m³. The dryer can operate in passive mode, using direct solar radiation, or in active mode with forced air circulation.

3. Heat Pump Drying System:

This system uses a U-shaped drying chamber, where convective air is heated by the condenser of a heat pump powered by electricity from an 11 kW photovoltaic system. It is energy-efficient and allows operation at low temperatures (35–50 °C), preserving the quality of agricultural products.

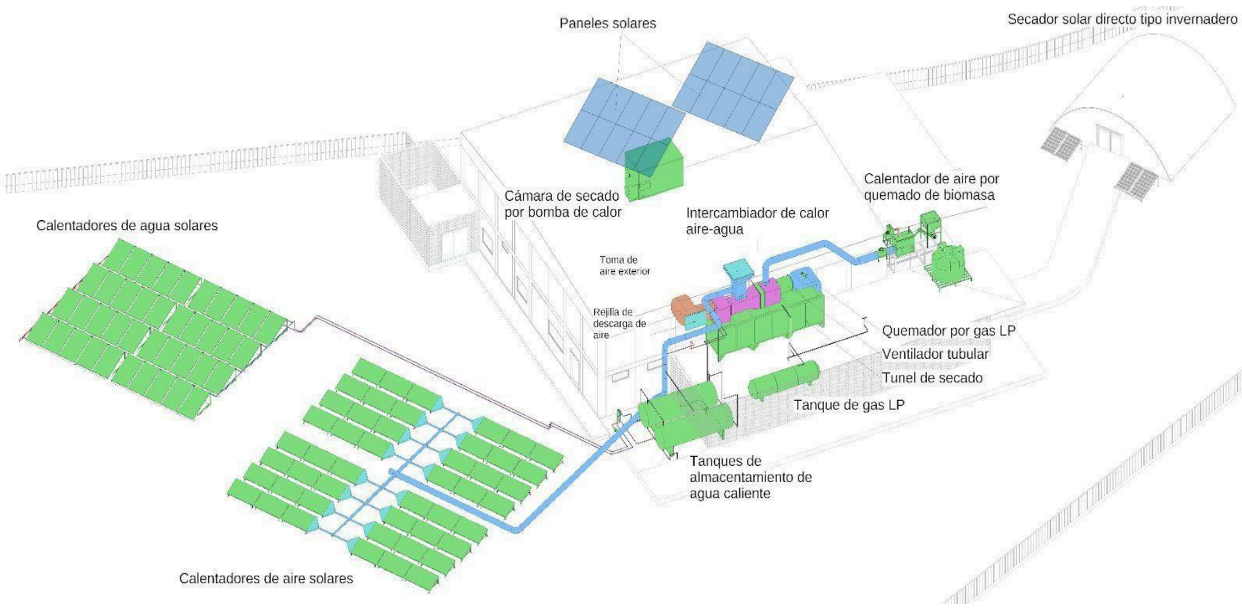


Figure 1. Schematic representation of the layout of the dehydration plant technologies

Table 1 details the operational capacities of the three drying systems implemented at the Zacatecas Solar Thermal Plant. The hybrid Solar-Biomass-LP Gas system stands out for its versatility and its ability

to process large volumes of agricultural products, while also allowing greater control over drying parameters. On the other hand, the greenhouse-type system, although having a lower capacity, is suitable for products that do not require continuous drying and can be exposed to solar radiation without losing their properties, making it an effective option for gradual drying processes. Finally, despite its lower capacity, the heat pump system is notable for its high energy efficiency (COP > 2) and its ability to operate at low temperatures, which is crucial for drying delicate products that require precise and homogeneous conditions, ensuring uniform drying and preserving the final product's quality.

Table 1. Drying System Capacities

Drying System	**Maximum Drying Area (m^2)**	**Maximum Load Capacity (kg)**
Distributed Hybrid Solar Drying System (SolarBiomass-LPG)	310	1500-2500
Integrated Greenhouse-Type Solar Drying System	72	750-1000
Head Pump Drying System	35	250-650

Table 2 shows the variety of heat generation solutions offered by the plant to maximize energy efficiency based on the drying process requirements and environmental conditions. The solar systems for air and water heating stand out for their efficiency under high solar radiation, with the water heater system being the most suitable for fast and stable drying processes. The heat pump, with its high COP, is ideal for delicate products that require precise temperature control and continuous operation, while the biomass burner provides a reliable backup, ensuring continuous operation during periods of low solar radiation. This combination of technologies enables efficient energy use and ensures flexibility in drying different agricultural products.

Table 2. Operating Parameters of the Thermal Energy Generation Systems

Heat Generation System	**Maximum Temperature (°C)**	**Power (kW)**	**Efficiency**	**Operating Time**
Solar air heater field	71	44.23	41.71%	6.53 h
Solar water heater field	95	41.63	51.12%	6.82 h
Heat pump	75	10.5	COP: 2.05	Continuous
Biomass burner	80	75	70%	Continuous

Methodology

This study covers the analysis of data collected between July 2022 and July 2024 to assess the economic, educational, social, scientific, and environmental impacts derived from the use of the Solar Drying Plant in Zacatecas. The economic evaluation was carried out by quantifying the number of enterprises and businesses that have used the solar plant to add value to their agricultural products through solar drying. Additionally, the number of jobs generated in both productive and commercial activities associated with the plant was estimated. To assess the plant's productivity, production log records were used to quantify the products that have been rescued or revalued through the drying process.

The educational and social impact was measured through participation records in courses and workshops aimed at training and technology transfer to local producers. The number of trained individuals and the topics covered in the workshops were evaluated.

The environmental impact assessment can be approached through three methods:

1. Energy Substitution, which estimates the CO_2 emissions avoided by replacing fossil fuel energy with solar energy.

2. Food Loss and Waste (FLW) Mitigation, which focuses on quantifying the reduction in CO_2 emissions and the savings of natural resources (water, land) by preventing food loss.

3. Life Cycle Assessment (LCA), which evaluates the total environmental impacts of the drying system throughout its life cycle—from manufacturing and operation to equipment disposal or recycling.

In this study, the environmental impact was assessed using the energy substitution approach, which determined the CO_2 emissions avoided by using solar energy instead of LP gas in the drying process. To simplify the analysis, the annual composition of processed products was reduced to four representative products: prickly pear (41.13%), garlic (51.69%), apple (4.16%), and guajillo chili (3.02%). The heat required to evaporate the water content of these products was calculated using the latent heat of vaporization, with a value of 2400 kJ/kg, taking into account the initial and final moisture contents of each product. A loss factor of 1.5 was applied to this required energy to reflect the heat transfer inefficiencies inherent to the drying process. Additionally, the inefficiency of the LP gas burner was considered, assuming an efficiency of 80%. This allowed adjustment of the LP gas consumption that would have occurred in the absence of solar systems. Finally, the amount of avoided emissions was determined by applying an emission factor of 2.94 kg of CO_2 per kilogram of LP gas not consumed. In this way, the CO_2 emissions avoided annually during the study period were quantified.

Results

Productivity and Economic Impacts

Throughout the period from July 2022 to July 2024, the solar thermal plant in Zacatecas has shown remarkable progress in terms of productivity, as illustrated in Figure 2. In 2022, the plant processed 39.05 tons of fresh produce, benefiting 15 different agricultural producers. In 2023, production capacity increased significantly, reaching 137.60 tons and benefiting 13 different producers. Although production in 2024 (up to July) is lower (59.58 tons), this aligns with the harvest cycles of the products most commonly dehydrated—such as prickly pear and garlic—whose peak production occurs between August and October, suggesting an increase toward the end of the current year.

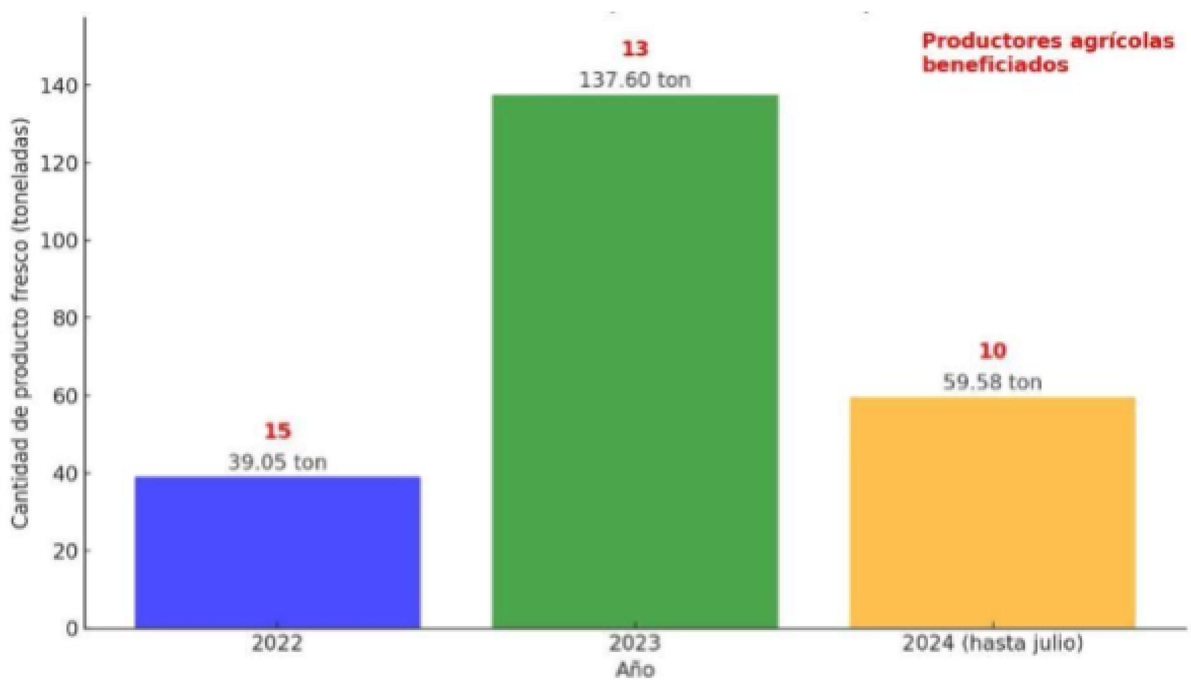


Figure 2. Total production of the solar thermal plant by year and number of agricultural producers benefited (2022–2024)

The processed products vary widely, with garlic and prickly pear (nopal) dominating in volume. As shown in Figure 3A, these products account for more than 85% of the total processed products over the three years evaluated. The upward trend in prickly pear dehydration reflects both a greater availability of this product and the producers' efforts to find new markets. On the other hand, products such as guajillo chili, apple, and other agricultural products diversify the plant's operations, albeit in smaller volumes. Furthermore, the distribution of "Other agricultural products" in Figure 3B reveals that the plant has the capacity to process a wide range of products, including pineapple, tomato, and beetroot, highlighting its versatility. This flexibility is partly due to the fact that some users of the solar thermal plant are entrepreneurs who have chosen to experiment with different products in an effort to diversify their offerings and access new markets. This not only expands the plant's potential uses but also promotes innovation in the regional agroindustry.

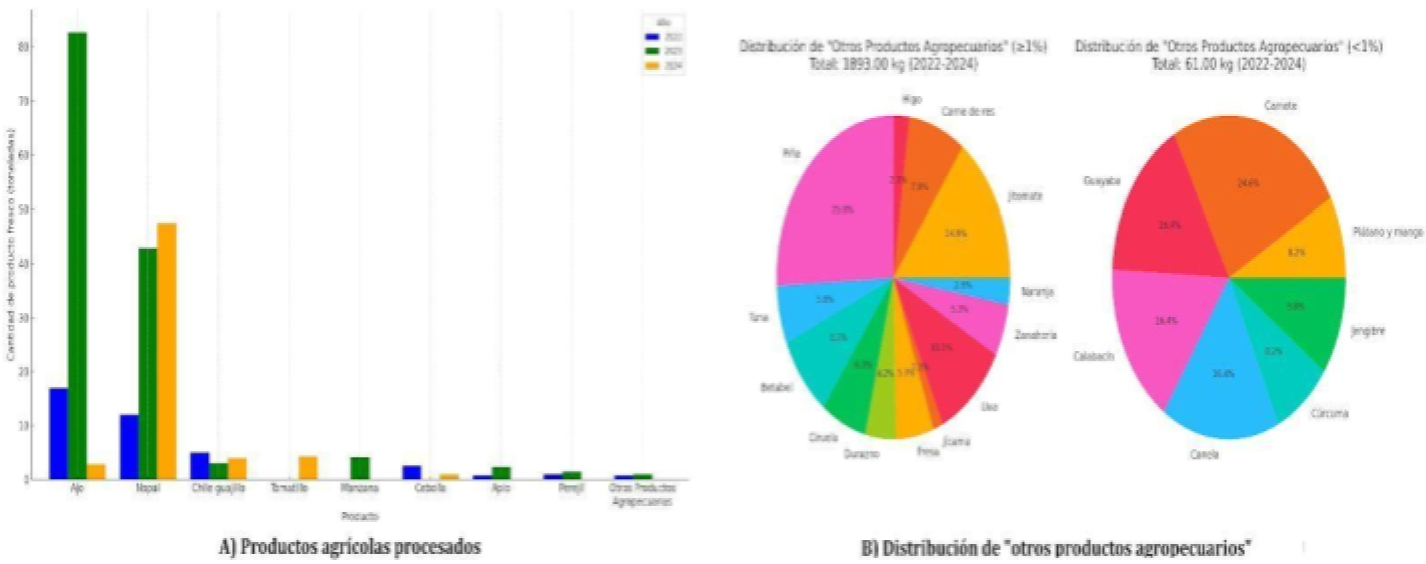


Figure 3. Distribution of dried agricultural products processed at the solar thermal plant (2022–2024)

According to the results shown regarding the plant's productivity, the infrastructure improvements implemented have successfully increased production capacity, while also demonstrating great flexibility in processing a variety of regional products. The changes made to enhance the solar thermal plant not only boosted its capacity and adaptability, but also positioned it as a driving force to promote and diversify the local agroindustry, with positive effects throughout the value chain. In economic terms, the Solar Thermal Plant has helped foster collaboration with 16 companies and ventures, generating more than 250 direct jobs in the Zacatecas region. The products processed by these businesses range from traditional market options such as chili and garlic, to less common items like beetroot, pineapple spiced with chili, and even powdered nopal, opening opportunities for product innovation and access to new national and international markets. Through this ecosystem, the plant has strengthened the business fabric in the municipalities of Fresnillo, Calera, and Guadalupe by implementing a versatile and sustainable business model in the region.

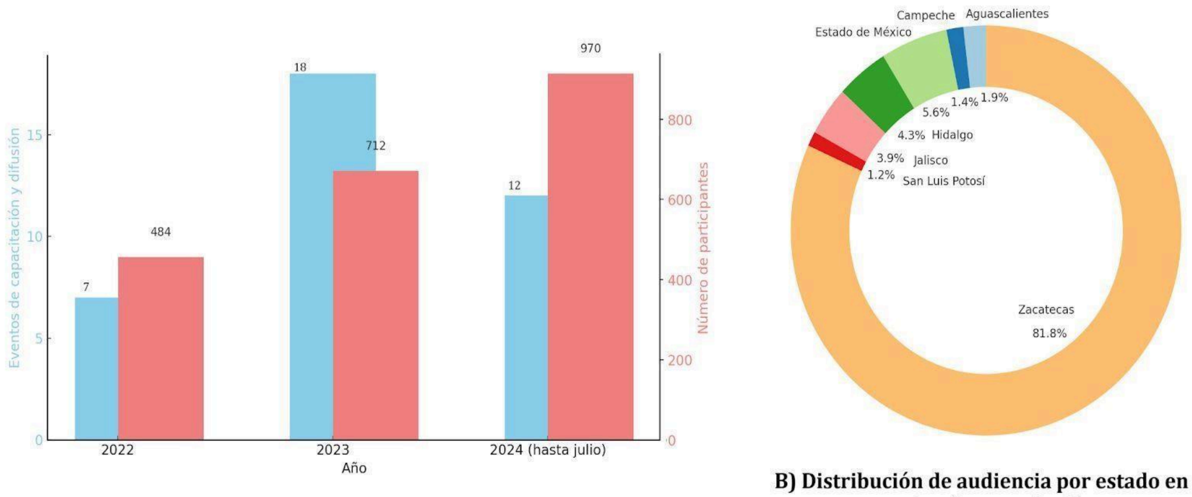
Figure 4 shows the logos of the companies and brands that make up this entrepreneurial ecosystem. The fact that producers are using the solar thermal plant promotes continuous exchange, where each actor contributes their expertise and plays an active role in the growth of the Zacatecan agroindustry and that of other Mexican states. A clear example of collaboration and alliances among the plant's users is the formation of the SOLDEZAC association, which focuses on the marketing of solar-dried products, promoting the integration of small and medium-sized producers into more competitive and diversified markets.

“Figure 4: Companies and ventures associated with the Thermosolar Plant, grouped under the ‘SOLDEZAC’ association and their geographical distribution in Mexico.”

Social and Educational Impact

In the social realm, the thermosolar plant has had a significant social impact by supporting more than 40 local producers and entrepreneurs in Zacatecas. The ecosystem of producers that the thermosolar plant has consolidated has not only allowed different companies to use the same space but has also integrated them into a community of producers with a significant social and environmental sustainability impact.

Since 2022, as part of the strengthening strategies of the Thermosolar Plant, a training, dissemination, and technology transfer program has been implemented, with a total of 37 events held until July 2024, involving 2,100 people. As shown in Figure 5, in 2023, the highest number of events was organized, with 18 training sessions and a total of 712 participants. During the first half of 2024, participation exceeded 970 attendees through 12 events, demonstrating the effectiveness and positive impact of the promotion strategies and the adoption of solar drying technologies by the community. The courses and workshops offered address topics such as solar drying technologies, technology transfer, and agroindustry applications, with the goal of training students and producers from the region. In addition to workshops and courses, dissemination events have played a key role in promoting technology transfer and the adoption of renewable energy in the agricultural sector, positively impacting the educational field and strengthening and repairing the social and productive fabric of the region.



A) Eventos de capacitación y número de participantes por año

B) Distribución de audiencia por estado en eventos de capacitación

Figure 5: Growth of training events and geographical distribution of the audience during the 2022–2024 period

Likewise, since 2022, the project has actively contributed to the training of specialized human resources.More than 30 students from various institutions—mainly the Autonomous University of Zacatecas (UAZ), the Technological University of the State of Zacatecas (UTZAC), and the University of Guadalajara (UdeG)—have participated. These students have been involved in activities such as social service, professional internships, research projects, and industrial visits related to solar drying technologies. This approach has allowed students to develop both specific and transversal competencies in chemical and mechanical engineering, as well as in renewable energies, thereby contributing to their academic training and the development of innovative solutions for the agroindustrial sector in Zacatecas.

Environmental Impact

The environmental impact of the Thermosolar Plant has been significant. During the evaluation period, the plant has prevented a total of 58,217.14 kg of CO_2 emissions, representing a substantial contribution to the reduction of greenhouse gases. This calculation is based on the substitution of LP gas with solar energy for the drying process, achieving a notable decrease in emissions. However, a comprehensive environmental impact assessment should not only quantify the reduction in emissions due to fossil fuel replacement, but also consider other aspects such as the consumption of natural resources like water and land use, as well as food waste reduction. These aspects are typically evaluated through Food Loss and Waste mitigation (FLW) approaches and Life Cycle Assessment (LCA). Nonetheless, a full analysis is beyond the scope of this work and is proposed for future research.

Conclusions

This work presented the results regarding the productivity, economic, social, educational, and environmental impacts that the Thermosolar Drying Plant in Zacatecas has had in the region. In terms of productivity and economy, the plant has increased production capacity and promoted the diversification of processed products, forming an active ecosystem of producers. In the social and educational dimension, the impact has been closely tied to this producer ecosystem, with strategies implemented such as workshops and courses for users of the plant to promote the use of ecotechnologies in agroindustry, along with collaboration with universities such as UAZ, UTZAC, and UdeG. Students have been hosted for social service, internships, research, and industrial visits. Regarding environmental impact, although a more comprehensive analysis is still needed—including not only the reduction of greenhouse gas emissions but also aspects such as water and land use, food loss and waste (FLW), and life cycle analysis (LCA)—the plant has already prevented the emission of over 58 tons of CO_2. The integration of hybrid technologies—combining solar energy with biomass and LP gas backup—as well as the implementation of a heat pump system, has allowed the plant to operate flexibly and efficiently, adapting to the needs of various agricultural products. For future work, it is important to continue optimizing the solar drying process and expand the adoption of these technologies to other regions to maximize their impact on both environmental sustainability and rural economies.

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