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Article

Solar energy utilization and conservation in an industrial solar drying process

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Abstract: Decarbonization in food production systems is one of the greatest challenges today. Solar drying is one of the processes that can help this energy transition and improve food production systems. This research presents the results of the development of a new solar drying technology with applicability in the food production system. A technoeconomic assessment was carried out. The best configuration for an integral drying system for various applications was obtained. The developed solar drying technology is portable, efficient, modular, versatile, continuous processing, with minimal degradation in the dehydrated product. According to the annualized cost method calculations, the cost of drying products with this technology is much lower than when using conventional energies and has a short payback period of 1–2 years. This research is the first part of the ongoing project. Improved equipment and various applications are in progress.

Keywords: modular; decarbonization; portable; versatile; efficient; drying equipment

1. Introduction

Today, decarbonization, the process of reducing carbon emissions, produced by human activity, especially carbon dioxide (CO_2), into the atmosphere is an important issue globally. To achieve decarbonization, an energy transition is necessary to eliminate carbon in energy production and reduce the consumption of conventional energy in production systems based on clean alternative energies [1].

This research is focusing on utilization of solar energy in an industrial process with great demand for thermal energy such as the drying and the conservation of solar energy and usage in a new solar drying technology. These allows for improvement in the food production system, specifically to avoid food waste on farms. These developments contribute to achieving a net zero goal by 2050.

One of the most utilized post-harvest processes in food conservation is the drying. The heat energy consumed during the drying process is about 12%–40% of total industrial energy consumption in the developed countries. This employs 20%–70% of the total cost of production depending on the type of industries. The utilization of solar energy in drying processes minimizes the consumption of non-renewable sources by 27%–80% [2].

Solar drying concept is an emerging technology for drying industries such as food, automobiles, paper, and allied products, including rubber, sugarcane, sewage and industrial waste. The solar dryers equipped with Thermal Energy Storage (TES) systems have helped to decrease the total time required for drying. Solar-based drying technology is a promising area of research. The commercialization of solar dryers is increasing day by day for different drying applications in industries [2]. One example of these applications is the industrial processes involved in food production systems.

For the last 3 years the United Nations (UN) has designated September 29 as the day to highlight the problem of food waste and loss in the world [3]. This year the focus is carried out by "Taking action to transform food systems", proposing to make food systems more resilient and sustainable from the field to the consumer.

According to data from the report by the UN Food and Agriculture Organization [4], it indicates that the food production systems are responsible for 21%–37% of Greenhouse Gas (GHG) emissions globally. Also, if food loss were a country, it would be the third emitter of GHG emissions on the planet. This consumes 30% of the land used for cultivation and consumes 20% of water. If all the food wasted in the world could be used, malnutrition in the world could be ended and 2 billion people fed [5]. Currently 828 million people suffer from hunger, that is, 1 in every 10 inhabitants on the planet [6].

In Mexico, more than 30% of the food produced is wasted, which is equivalent to 12 million tons that could feed 7 million people [7]. The main causes of waste in the crop field are the lack of post-harvest technology, high transportation and cold chain costs, lack of adequate transportation, infrastructure, logistics and consumer market requirements.

There is a high potential of solar energy usage for different industrial drying applications. One of the application areas in this research is the food production system. We developed a portable, efficient, profitable solar drying technology for different uses. In this paper the summary results obtained for the development of a healthy and sustainable food production system are presented.

2. Materials and methods

The technoeconomic assessment was used as a methodology (**Figure 1**). Technoeconomic assessment (TEA), is a widely practiced approach used in both academia and industry for simultaneously evaluating the technical feasibility and the economic viability of a process technology, a product, or a project. A TEA is useful for making a variety of high-level decisions including whether a project should be pursued or terminated, which option best meets a business objective, and where priority should be placed to reduce risk and cost [8].

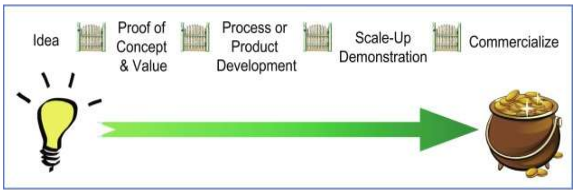

Figure 1. Generic stage-gate process for commercialization of a new idea [8].

A common discipline of successful companies is the use of a formalized Stage-Gate process for assessing technoeconomic factors to help with decision making. A simplified staged process for converting an idea into a commercial success which appears in **Figure 1**. Gate reviews are conducted periodically to determine if a project should advance to the next stage, be redirected to resolve outstanding issues, or be terminated [8].

A commercial technological solution for avoiding food waste on farms using solar energy was the initial idea. This was requested by Mexican farmers. A Proof of Concept (POC) was developed to demonstrate the viability of a product in the market. A Proof of Value (POV) was developed to identify the value of a particular offering to customers. This helps the companies to decide whether the product is worth investing in.

Process and product were developed with a technology assessment and economic evaluation in parallel and iteratively. In this gate, technical feasibility was carried out analyzing and establishing the bases for the implementation and execution of the project establishing recommendations for scale up approaches. Then the final technical, economic and market evaluations were carried out as the final stage.

3. Results and discussion

3.1. Idea

Initially, this project was developed according to the requirements and needs of Mexican farmers. The rest of the main actors of the food supply chain, manufacturer and marketer also were considered as the value proposition and goal of the research is to develop a technological solution to improve the food supply chain. Through a field and market research the main problems and solutions in the food supply chain in México were identified (**Figure 2**).

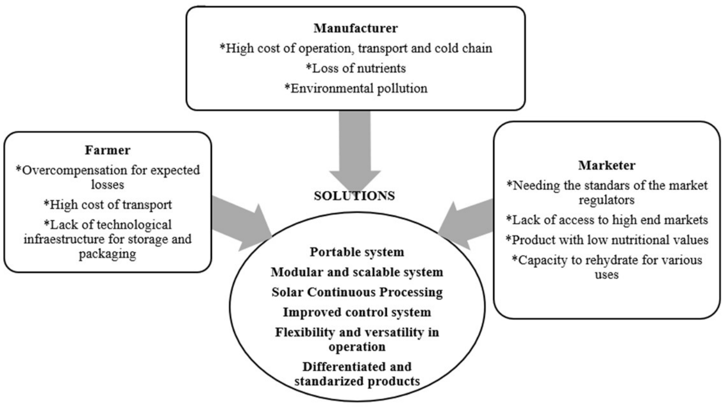

Figure 2. Results of the analysis of the food supply chain, problems and solutions.

For the farmers the main problem is overcompensation due to the expected losses because of the market requirements for size, color, appearance in general, the high cost of transport and cold chain and the lack of technology for storage and packaging on the farm. Actually, 30% of the food production on the farm is wasted. Accordingly, there is need to design a portable system, modular and scalable, ready to operate on the farm, lowering the cost of transportation by reducing the weight of the fresh product by 90%. For the manufacturer, the main problems are pollution and loss of nutrients (indicated by the loss of color, flavor and appearance). These problems will be solved by a solar continuous processing and improved control system. For the marketer, the product needs to meet the standards of market regulations. Current products have low nutritional value. Therefore, a technology with flexibility and versatility in operation is needed and the products obtained need to be differentiated and standardized with capacity for rehydration for various uses.

According to the results obtained, there is a need to develop an improved drying process. This increases the profitability of the entire value chain farmer, manufacturer and marketer will be increased. In general, the economic and operational efficiency of the drying process will be maximized.

In this gate, the main characteristics required for the technological solution to be developed were established.

3.2. Proof of Concept (POC)

Effective process and product development require timely and well-informed decisions. A robust, early-stage TEA which addresses the uncertainty of an evolving technology is invaluable in decision making in any technology organization. Use of ranking tools and approaches organizes the consideration of multiple factors and provides a good way of presenting the rationale for the decision to stakeholders [8]. The Political, Economic, Social, Technological, Environmental, Legal (PESTEL) analysis was the tool to decision making process in this gate. This tool allows us to consider the PESTEL factors. The POC was carried out considering the external factors that affect the project in a direct way. A PESTEL analysis was developed for each factor. The results obtained are summarized in **Tables 1–6**. This type of chart was constructed through consensus by an assessment team. This analysis allows to compare a number of options against specific criteria where a plus (+), minus (−), or even (0). where VN = Very negative (–2), N = Negative (–1), Z = Zero (0), P = Positive (1), VP = Very positive (2) score is used to differentiate each option. The sum of scores (T = Total) is tallied in a final row to illuminate the favored option. This result clearly shows how the options ranked relative to each other is a simple tool that clarifies why a specific decision was made.

Table 1. Political factor.

Variable	VN (–2)	N (–1)	Z (0)	P(1)	VP(2)	T	References
Governments can provide great interest and motivation in using solar technologies, which include solar drying systems by applying policies such as renewable portfolio standards (RPS), feed-in-tariff (FIT), and incentives.					X	2	Suresh et al. [9]
Governments of any size can lessen the environmental impact of their regions through a reduction in GHG emissions from carbon usage by increasing their reliance on distributed sources of renewable energy					X	2	Suresh et al. [9]
Most policy goals seek to encourage the diversity of power-generating sources, lessen reliance on fossil fuels by the state, boost the use of renewable energy, cut carbon emissions, or other combinations of these goals					X	2	Suresh et al. [9]

Table 2. Economic factor.

Variable	**VN (–2)**	**N (–1)**	**Z (0)**	**P(1)**	**VP(2)**	**T**	**References**
Each year, an estimated one-third of all food produced, equivalent to 1.3 billion tons worth about $1 billion, ends up rotting in consumer and retail bins, or spoiling due to poor transport and harvest practices.		X				–1	United Nations [10]
Globally, researchers estimate that, in food supply chains, the percentages of food loss in production, postharvest and consumption stages are 24%, 24% and 35%, respectively.		X				–1	Xue et al. [11]
The waste of agricultural crops on farms is mainly related to economic losses due to over production and the rejection of valuable products considered not suitable for consumption or commercialization because of their appearance or size.		X				–1	FAO [12]
Solar drying is an economical, accessible and widely used alternative in various post-harvest processes.					X	2	Salvo and Franco [13]
The global solar dryer market has reached a valuation of US$2.64 billion in 2022. Sales of solar dryers accounted for nearly 8% share of the global dryer market at the end of 2021.					X	2	FACTMR [14]
The Dehydrated Food Market size is estimated at USD 245.39 billion in 2024, and is expected to reach USD 337.18 billion by 2029, growing at a CAGR of 6.56% during the forecast period (2024-2029).					X	2	Mordor 24 [15]

Table 3. Social factor.

Variable	**VN (–2)**	**N (–1)**	**Z (0)**	**P(1)**	**VP(2)**	**T**	**References**
If we could use all the food waste in the world, we could feed more than 2 billion people and solve undernourishment..					X	2	WFP USA [5]
828 million people suffer from hunger, e.i. 1 in every 10 people on the planet.	X					–2	FAO et al. [6]
The agriculture sector is the world’s largest employer and provides livelihoods for 40% of today’s world population. It is the largest source of income and employment for poor rural households.					X	2	United Nations [16]

Table 4. Technological factor.

Variable	**VN (–2)**	**N (–1)**	**Z (0)**	**P(1)**	**VP(2)**	**T**	**References**
The food production stage has been considered one of the “critical points” in value chains. However, access to adequate technology in developing countries allows only 30% of agricultural production to undergo industrial processing.		X				–1	United Nations [17]
The development and application of hybrid energy systems is currently one of the emerging technologies with the greatest prospects for the development of solar drying systems.					X	2	Chayan et al. [18]

Table 4. (*Continued*).

Variable	VN (–2)	N (–1)	Z (0)	P(1)	VP(2)	T	References
The investment cost in solar technology is higher than in technology that uses energy from fossil fuels.		X				–1	Kong et al. [19]
There are industrial applications in Mexico and it is one of the technologies in which research and application development are still ongoing.				X		–1	Chayan et al. [18]
Ensuring the continuity of the process operation due to the intermittency that occurs in the case of renewable energies is one of the greatest challenges in these processes.					X	2	Chanda et al. [20]
Greenhouse effect (GHE) technology appreciably improves the quality of produce and reduces the drying time as compared to the traditional open sun drying method.					X	2	Patil and Gawande [21]
In the case of the solar tunnel dryer, it can be applied in addition to the food industry in sugar production and in the marine industry.					X	2	Lingayat and Balijepalli [22]
For solar tunnels and greenhouse drying the equipment is cheap; the drying temperature is higher than that of sun drying or shade drying. In the drying of some materials, the color can be better guaranteed.					X	2	Deng et al. [23]
The drying efficiency is increased and drying time is decreased due to the storage system in the solar tunnel dryer.					X	2	Vishnuvardhan et al. [24]
A tunnel dryer is the most widely used method for industrial dehydration of fruits and vegetables. The drying time depends on the moisture content of the product, the exposure area, the initial product load, and the meteorological conditions. The tunnel greenhouse drier works continuously, obtaining a daily production.					X	2	Ortiz-Rodriguez et al. [25]
Solar tunnel dryers are mostly used for large scale drying of agricultural goods.					X	2	Lingayat et al. [26]
High costs of materials, installation and control systems used are a disadvantage in its implementation, since it requires a significant initial investment compared to common devices that run on conventional fuels.	X					2	Patil and Gawande [21]

Table 5. Environmental factor.

Variable	VN (-2)	N (-1)	Z (0)	P(1)	VP(2)	T	References
If food waste were a country, it would be the third largest emitter of greenhouse gas emissions on the planet at 8%. It would consume 30% of the land used for cultivation. It would also consume 20% of the fresh water.	X					–2	FAO [2]
One of the main emitters of GHG are food systems. Food systems are globally responsible for 21–37% of total greenhouse gas emissions. They cause deforestation for use of crop areas; the loss of associated biodiversity; use of resources like water, and pollution from the use of pesticides. Food loss and waste is a global problem with important implications.					X	2	Crippa et al. [27]
Food loss and waste is an important topic due to its high socioeconomic costs and its relationship to waste management and climate change challenges.					X	2	Chauhan et al. [28]

Table 6. Legal factor.

Variable	VN (–2)	N (–1)	Z (0)	P(1)	VP(2)	T	References
In Mexico there is a law that favors the use of renewable energies and the financing of the energy transition.					X	2	CRE [29]
There are laws that protect technological developments in the area of solar drying, such as patent protection..					X	2	GOB [30]
There are laws and regulations that govern the operation of drying processes and ensure the quality of dried products.					X	2	NOM-044-FITO-1995 [31]

Political factor (**Table 1**). Considering the political factors favor the use of renewable energies and the development of technologies that employ this type of energy were analyzed.

Political factor: Total = 6. This is good opportunity for the energy transition and the promotion of more sustainable alternatives.

Economic factor (**Table 2**). From an economic perspective, negative impacts of food waste and the post-harvest alternative of a solar dryer usage to avoid food loss were analyzed.

Economic factor: Total = 3. The results indicated that this alternative would benefit the economy of farmers, by being able to market products considered outside the standards; adding value to agricultural products that, when processed, can enter a higher market niche than fresh products.

Social factor (**Table 3**). From a social standpoint, supporting small-scale food producers is critical to improving food security, reducing poverty and hunger, the waste of natural resources and deforestation due to agricultural expansion.

Social factor: Total = 2. This result indicates the implementation of technology such as a solar dryer can help produce high-value foods and preserve the nutritional properties of farm products.

Technological factor (**Table 4**). The main variables analyzed were the type of dryer, auxiliary energy system, operational factors, applications, investment cost. The results obtained indicated that tunnel-type dryers are the most commonly used for food processing; the greenhouse effect improves the quality of the products and reduces drying time; hybrid energy systems avoid the inconveniences of intermittent solar energy. tunnel and greenhouse dryers are easier to scale up to an industrial level. Although the investment cost is higher, operating costs are considerably reduced.

Technological factor: Total = 15. It is a high value. Therefore it is highly technologically favorable to develop a tunnel type dryer with a greenhouse effect and a hybrid energy system to ensure continuity in the drying process and optimize its operation, ensuring the quality of the products.

Environmental factor (**Table 5**). From an environmental perspective, the main factor to be analyzed was the negative impact of food waste, as the resources invested in production are lost.

Environmental factor: Total = 2. The proposed dryer could reduce these impacts by taking advantage of products that would not even be marketed by market standards.

In addition, the use of a dryer reduces the use of fossil fuels contributing to the decarbonization process.

Legal factor (**Table 6**). In a new technology to be commercialize the legal perspective is important. Therefore, the main laws and intellectual protection were considered.

Legal factor: Total = 6. This indicates that there are laws that favor the use of renewable energy and the development of innovative solar technology with its respective intellectual protection in the form of patents, in addition to the rules and regulations for the production of dehydrated foods helping to ensure the quality of the processes and products.

The conclusions of this analysis indicated that there is a large area of opportunity for a feasible scientific and technological (Total score 15) development with a great implication in the economic, social and environmental sectors, great favored by the political (Total score 6) and legal sphere (Total score 6) for the development and use of a solar dryer with a hybrid energy system at an industrial level. With the main challenge and risk in the economic factor (Total score 3), like a new technology.

3.3. Proof of value (POV): Evaluation of the conventional dryers and solar dryers

POV was developed considering the offering of solar dryers in the Mexican market. Basic conventional electric dryers, industrial dryers and solar available dryers were evaluated. The main parameters analyzed were operating conditions, and price. It was assumed that the capacity and cost of labor are identical in both equipment (**Figure 3**).

Model Type	Dryer		Capacity		Operating conditions		Price	
	Conventional	Solar	Conventional	Solar	Conventional	Solar	Conventional	Solar
Basic			5 kilograms	5 kilograms	Electric drying of 5-9 hrs. Average drying time 7 hrs. Power 800 W.	Drying time of 24 - 72 hrs. Average drying time 48 hrs	Equipment price $305 USD. Average energy consumption 38 kWh. kWh price $0.057 USD. Energy operating cost per cycle $2.20 USD	Equipment price $262.45 USD. Energy operating cost $0.00 USD
Industrial			500 kilograms	500 kilograms	Electric drying of 2-4 hrs. Average drying time 3 hrs. Power 5000 W.	Drying time of 12 - 36 hrs. Average drying time 24 hrs	Equipment price $30,000 USD. Average energy consumption 15 kWh. kWh price $0.15 USD. Energy operating cost per cycle $2.30 USD	Equipment price $10,712 USD. Energy operating cost $0.00 USD

Figure 3. Analysis of solar dryers available on the market in Mexico 2024.

The results obtained for operation parameters indicated the time of process with electric equipment is almost 6–8 times faster than the solar equipment.

For price parameters, the electrical equipment price is 15%–200% higher than the solar one. Conventional equipment has a higher operating cost, due to the higher cost of fossil energy.

This is important when scaling up the technology towards an industrial implementation. It is noted that the cost per initial investment increases considerably depending on the scale.

Solar dryers on small scales can be considerably cheaper. However, they have the disadvantage of the time of process being longer, since only solar energy is use.

It is worthwhile to point out that in the last years the approaches to sustainable food drying have been focused on improving the efficiency of the dryer, which may be achieved through insulation, heat recovery, recirculation and altering operating constraints of the systems. Also, the focus has been on reduction of drying time, improving or substituting the system's energy supply by using combined heat and power (CHP), biomass derived fuels and other renewable energy sources, mainly hybrid systems [32]. The recent trends that are reshaping the domain of solar drying venture into the dynamic evolution of materials, innovative designs, and the seamless amalgamation of these advancements with state-of-the-art energy storage solutions. In doing so, also navigation of the complex confluence of technology, innovation, and sustainability, cast light on how solar drying has transcended its conventional practices to become an advanced, eco-conscious discipline [33].

According to the market forecasting analysis, the global solar dryer market was valued at USD 3.5 billion in 2023 and is predicted to increase at a compound annual growth rate of 10.6 % from 2023 to 2031 [34].

Considering the results obtained of the idea assessment, POC and the above information the development, design and operation of a solar dryer with a solar-assisted energy type (hybrid system) for energy source was considered as the best option to respond to the solutions required by the consumer.

With this equipment a more uniform and continuous operation can be obtained by combining various energy sources. The drying process needs to be carried out efficiently, so solar energy must be used as the primary source, taking advantage of the greatest amount of time possible. It is necessary to consider the usage of materials and development of a control system that allow this to be done. They are expensive. However, currently there are adequate tools and materials for solar concentration and microprocessors for the development of interfaces necessary for the control of industrial processes with a focus on efficient use of energy at low cost. In the case of drying of vegetable raw materials, if it is not done under controlled conditions the product is contaminated. Its characteristics are not standardized nor does it comply with food safety regulations. It is therefore lacking real added value for export or high-value markets. For this reason it is necessary to establish scalable parameters for a technological innovation of our own creation with an optimal cost-benefit ratio, with an improvement in product quality and safety, high energy, operational and economic performance, with a versatility of use and load in the process, but with continuous energy availability, using an electronically controlled system for data acquisition and monitoring through self-created software.

This entire system will be used for the drying process of different raw materials, according to the requirements of the process and the product, with an efficient use of energy, reducing the costs of the process and the final product. Since, as it is a self-created technology, the costs of the equipment and consequently of the transformation process would be reduced, ensuring an adequate rate of return. This would grant an important competitive advantage in operation due to the operation and design of the system components.

The POV analysis indicated that the proposed process and equipment are innovative for the food industry carrying out a sustainable modernization in accordance with current sustainability-technological innovation requirements. Therefore, this proposal meant value to the customer and the company, and the development of the next gate for this process was possible.

3.4. Process and product development

The technology assessment and economic evaluation should be done in parallel and iteratively. Assessment of the technology is the first part of a TEA. The concept needs to be rock solid in terms of technical feasibility and the economic target. As a developing technology, it will mean that some significant portion of the process has not been practiced at a commercial scale. The technology will have a higher degree of technical risk which should be managed appropriately [8].

The first question to ask when assessing a new technology is does it violate any laws of thermodynamics or nature. So, the assessment analysis started with the evaluation of the solar drying process in the Yucatan Peninsula as the first step. Then, the operational requirements for solar drying was established with the relationship between solar radiation and temperature. Finally, it was possible to develop a feasible solar dryer design and evaluate the operation.

3.4.1. Evaluation of the solar drying process in the Yucatan Peninsula

In order to determine whether the solar drying process (regardless of its configuration, method and/or technology) was feasible in the Yucatan Peninsula, the solar area potential needs to be known. The following data are documented [35]:

- Average monthly number of hours of sunshine per day: between 6 and 8.5 h.
- Average daily ambient temperature greater than 30 °C from March to October, with a critical period in the months of April, May and June with average maximum temperatures of 37 °C and extreme maximum of 40 °C.
- Availability of solar radiation per hour. With maximum daily integrated solar radiation of 1016 W/m^2; and with a minimum integrated solar radiation of 560 W/m^2.
- As can be seen, there is excellent solar potential in the area, since throughout the year (months such as June and July) up to 8.5 h of sunshine can be used; likewise, having an ambient temperature greater than 30 °C is appropriate, since it will allow maintaining the heat gained by using radiation, which can be said to have adequate levels, ranging between 1.106 and 560 W/m^2. In other words, in the Yucatan Peninsula, there is between 79% and 40% of radiation with respect to the solar constant.

The data above indicated that the solar drying process in the Yucatan Peninsula was viable, since if implemented, this would mean a relatively lower economic cost with respect to conventional dryers and zero operating costs with respect to energy usage.

Although the technical feasibility is positive, it is necessary to know the performance and parameters for the drying process within equipment such as the proposed.

3.4.2. Operacional requirements for solar drying

One of the first parameters to design a drying process is to determine the appropriate drying temperature. The radiation levels in the Yucatan Peninsula were measured to assure that it is a feasible place for the implementation of solar dryers, also if the desired temperatures in a solar dryer will be reached. It is considered that to carry out a good drying process, the air, which serves as a workflow, must have a temperature between 40 °C and 70 °C; likewise, it must contain minimum amounts of humidity (which it has gained outside, prior to entering the system); in addition, its movement must be constant.

For this case, an indirect radiation dryer which is one of the simplest solar dryers was used. If the temperatures are the minimum required for drying agro-food products (and sustained for a suitable period of time) and for drying habanero chili, the feasibility would be proven. For this case, radiation and temperature measurements were taken inside the experimental prototype, this for a period of 800 min, that is, 12.5 h. The habanero chili has been chosen as the base product to be dried, because it has a large amount of water content, on average 90%. The samples were stipulated in sizes of 0.3 and 1.3 cm. A Kipp Zonen pyranometer model CMP10 for radiation measures and LM35 temperature sensors were utilized.

From the readings taken, as it can be seen in **Figure 4**, the radiation levels were variable throughout the day; this may be due to different factors such as cloudiness and time of day. However, the temperatures obtained inside the dryer and their variations did not greatly affect the desired temperatures, since most of the time above 50 °C was obtained (desired temperature for drying habanero peppers) or, failing that, at the limit of 40 °C. An effective range of between 50 °C and 70 °C has practically been stipulated; where it is possible to dry the product and preserve both its color and its own characteristics (Hernández et al. [36]). These results indicated the Yucatan Peninsula had adequate conditions for the solar drying process and a feasible place for the implementation of the solar dryer to be developed.

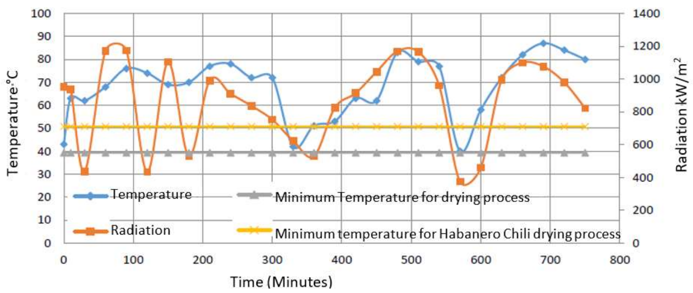

Figure 4. Laboratory-scale radiation temperature measurements in an indirect solar dryer.

3.4.3. Feasible solar dryer design

According to an analysis developed through 100 of the 1675 articles It was found that the energy efficiency of greenhouse-type solar dryers is 11–73 %, and the energy efficiency of solar air collectors and biomass furnaces integrated into them is in the range of 45–81 % and 47–87 %. The lifetime of various greenhouse type solar dryers is between 4–35 years, their price is between $220–$10,659 USD and the payback period is between 0.3–11 years, embodied energy is 136–18,302 kWh, and EPBT is in the range of 1.1–3.63 years [37].

Due to the above information the feasible design selected to be developed was a greenhouse-type solar dryer.

According to the initial requirements of the supply chain identified, the main characteristics of the technology to be developed were:

Portable system: The dehydration process could be located on the farm or in the city, eliminating losing nutrients due to transportation and storage. This was done with a modular and portable greenhouse structure and the usage of affordable and efficient and new materials like recyclable plastic covering and rigid materials. This new system is described in our patent: MX_W_2022_084942.

Processing continuous form. The system operates during the day and night, eliminating the loss of product which would result with intermittent solar energy. There are different alternative auxiliary systems for heating due to the intermittency of solar energy. These systems allow conservation of the solar heat energy for further usage. The results of an art review indicated that the combined power and drying, application of phase change materials and hybrid drying systems with regard to agricultural products are the most auxiliary energy systems utilized [38].Indeed, a new auxiliary system considering phase change materials was developed. This is described in our patent: MX_E_2018_092688.

Improved control system. Minimisation of the thermal degradation is indicated in the colour, flavour, aroma and appearance that remain similar to the fresh product. It is pointed out that this kind of system is expensive [38]. However, we developed an affordable system that allows for controlling the drying system according to the raw material. Python was one of the platforms used. We are improving our wifi system for the control system of the entire drying system.

Differentiated products. The dehydrated foods obtained retain their organoleptic and nutritional properties, without additives and they can be rehydrated. This was obtained due to the improved control system developed.

Modular and scalable system. The processing capacity could be adapted according to the required production. This is done due to the portable structure and the possibility to scale up it according to the needs of the capacity of production required. Several and different types of equipment could be operated at the same time.

Flexibility and versatility in operation. Processing several kinds of food at the same time. This is done due to the modular structure.

Therefore, most of the goals initially proposed at the beginning of the project were achieved. The results of the first stage of this project have been presented.

It is worthwhile to point out that different forms could be obtained with the technology, preserving the colour, taste and aroma of the food’s fresh products. Also, we are developing new applications in other areas like, recycling food waste of industries like beer factories, batteries recycling process among others. Also, we have 2 trademarks CREID BIA and CREIDBI used to promote Mexican regional cuisine especially ethnic products of Mayan origin.

3.4.4. Operation the feasible design of solar dryer

We designed and built a new greenhouse dryer and a new conservation energy system. The goal for these systems is to operate in a continuous form for drying. The operation of these systems is described as follows.

The system is made up of three integrated subsystems: (1) a solar air heating system, (2) an indirect solar dryer or drying chamber, and (3) an auxiliary air heating-dehumidification system to obtain a continuous drying process. During daylight hours, the sun's radiant energy is used for the drying process, and during the absence of solar radiation, a thermal storage system or thermal reservoir or a hybrid energy system is used according to the needs of the process to be carried out, the operating facilities, and the geographic location. To achieve continuous operation, air heating is performed, this allows the drying process to continue at night and when there is a decrease in solar intensity due to intermittence. The equipment used in the system are: filters, axial fans, control equipment developed by our work team, photovoltaic cells, inverters, batteries, temperature sensors, relative humidity sensors, air flow sensors, and radiation measurement sensors. The system operates using solar energy to heat the initial drying air, which upon leaving the drying process is sent to the thermal tank for the purpose of dehumidifying and recirculating it, as there is a negative gradient of approximately 5–10 °C, during solar hours, as indicated in **Figure 5**.

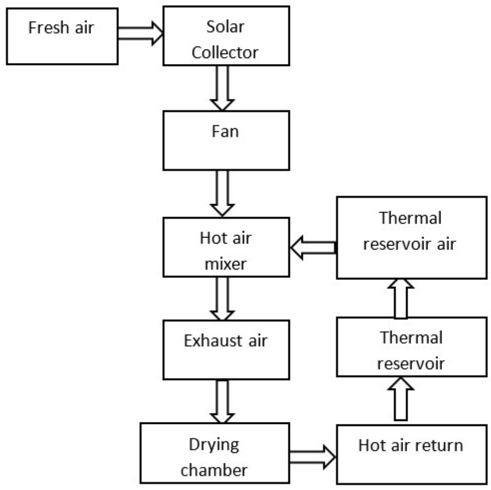

Figure 5. Operation of the drying system with coupled thermal reservoir.

In conditions of intermittent solar energy and absence of solar energy, access to ambient air is closed, so the cover of the drying chamber, i.e., the air heating system is used as an insulator to avoid nocturnal heat losses, thus, only air from the thermal tank is recirculated to the drying tunnel or plenum. In this mode, the temperature inside the thermal tank tunnel is kept constant and with a positive gradient of approximately 10–30 °C with respect to the environment. Likewise, a thermal equilibrium is achieved between both equipment (thermal tank and drying tunnel), with positive gradients of the system of approximately 10–20 °C with respect to the environment during night hours, allowing the drying process to be carried out, obtaining a temperature of approximately 30–45 °C maximum, allowing slow but continuous drying, avoiding rehydration of the product in process during night hours or intermittent solar energy, since the same mode is applied when there are decreases in radiation during solar hours. The above mentioned allows continuity of the drying process, since the system operates in batches with loads from 250 to 500 kg, in a total drying time range from 8 h to 30 h considering the presentations of the cut and whole product according to the characteristics of the material to be dried.

3.5. Scale up demonstration

According to the test developed before. The main equipment was built and the auxiliary equipment fitted. Then operational tests were carried out on habanero chili as a base product and subsequently on various products simultaneously, from aromatic herbs, fruits, vegetables and a variety of chili peppers. Four points were monitored: the air temperature sensor at the thermal reservoir inlet (Dr), air temperature sensor at the thermal reservoir exit (Tr), air environmental temperature sensor (Am) and air temperature sensor at the drying chamber (Tu). DHT Humidity and temperature sensor model 22 and LM35 temperature sensor were utilized in the test. In the **Figure 6**, the location of these sensors is indicated.

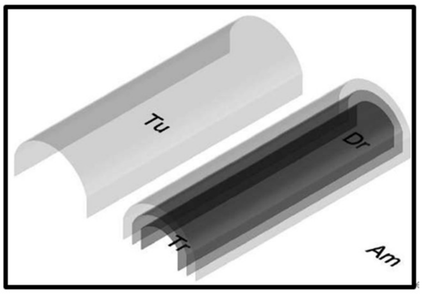

Figure 6. Location of sensors inside the drying tunnel and thermal storage.

Drying tests with Habanero Chili

Initially, the processing time was 90 h without thermal storage. With the coupling tests, the time was reduced to 27 h, that is, 70% less. The tests were carried out in environmental conditions with excellent solar radiation for certain periods and with intermittent periods and therefore a decrease in temperature.

The results showed that there was a thermal equilibrium in the system that allows obtaining storage temperatures (Dr. Tr, Tu) and a decrease in humidity in periods of high humidity in the environment (Am = 100%), as observed in **Figures 7** and **8** respectively.

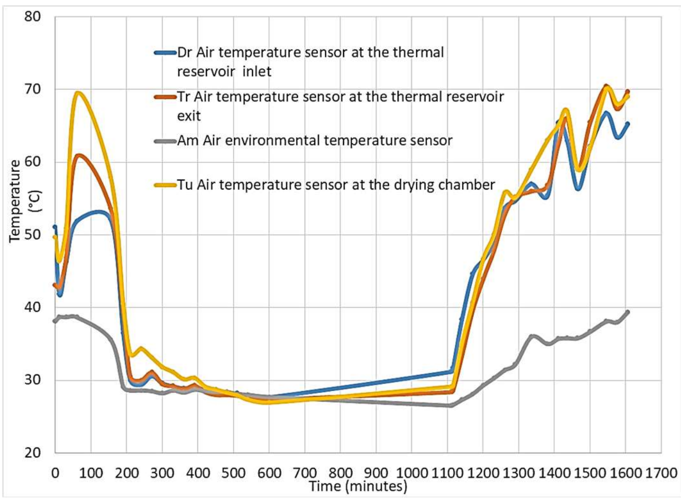

Figure 7. Temperature variation vs. time in the drying kinetics of habanero chili with the reservoir thermal-drying chamber system.

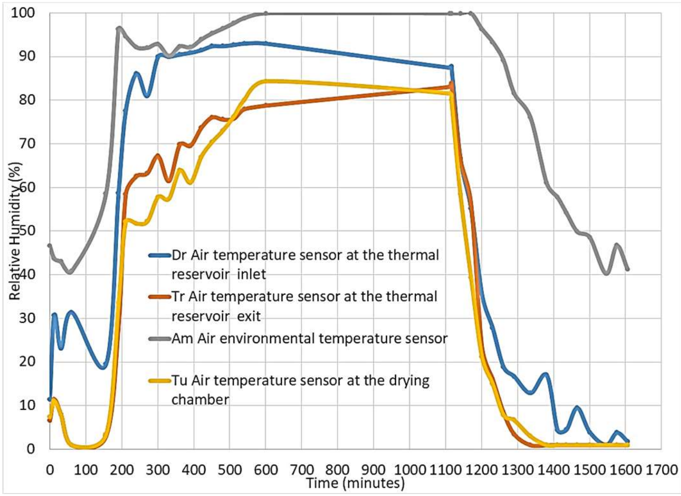

Figure 8. Humidity variation vs. time in the drying kinetics of habanero chili with the reservoir thermal-drying chamber system.

Therefore, the use of the thermal storage tunnel system allowed obtaining reductions in drying time of chopped habanero chili of the order of 30 to 50% of the initial tests according to the current environmental conditions. For whole habanero chili, drying times of 36 to 48 h were obtained in periods of low and high solar intermittence. It is worth pointing out that the normal time for a sky open solar drying is on average 72 and 120 h for chopped and whole habanero chilli.

It is noted that the green, yellow, orange and red colors were obtained and maintained as close to the fresh product as shown in **Figure 9**, it is indicated in circles. It should be noted that the different colors of habanero chili are associated with the degree of maturity of the fresh product, in an increasing manner, that is, green at the lowest degree of maturity and red at the highest degree of maturity.

Figure 9. (a) habanero chili dried orange; **(b)** habanero chili dried red; **(c)** habanero chili and chopped green; **(d)** habanero chili and chopped yellow.

The results of the humidity and volume reduction of the dried products of whole habanero chili indicate that on average the whole chilies shrink in the drying process by 50 to 30% of their initial volume (**Table 7**). The official procedures described by Horwitz and Latimer [39] were used for the analyses shown in **Table 7**.

Table 7. Humidity and shrinkage results of drying whole habanero chili.

Maturity level	Humidity (%)	Shrinkage (%)
Red	9.64	49.44
Orange	10.56	32.39
Yellow	11.54	39.17

3.6. Commercialize: Tests in the drying plant

Field tests were carried out coupling other drying equipment and thermal storage (**Figure 10**) with various products. The goal was to analyze and test various air flow arrangements, by operating the system in parallel and with counterflow of the humidified air. This air was dehumidified as it passed through the thermal storage tunnels and heated in turn to be sent back to the drying tunnels. Also, the controls were tested and monitoring points along the system.

Figure 10. CREID BI SAFE® Drying system with a coupled reservoir thermal.

The energy consumption of the developed process was analyzed considering conventional technologies based on electricity and natural gas as energy sources (**Table 8**). The financial results obtained have been promising not only with respect to the annual energy use, but also in the annual investment, which places the developed continuous solar process as the best option over the processes and equipment that use conventional energies.

Table 8. Comparison of energy–cost of the developed process vs. conventional drying processes for a fixed annual production.

Energy source	Anual energy (USD)	Annual investment (USD)
Natural gas	15,255.16	21,129.40
Electricity	11,258.40	32,119.100
Developed process	521.30	1490.90

The financial projection was carried out from the perspective of the producer who acquired the technology. The preliminary results show the viability of acquiring the technology and a payback time of approximately 2 years and 2 months. These indicators may vary depending on the crop to be processed, on which the yield and processing time depend. Without the project, the raw material would not be processed, which would mean an economic loss for the producer and under the scheme that said raw material is the loss of the crop, the differential is high. From a total loss of 10% to 20% of production to a total use of it.

Likewise, if the financial projection is carried out considering the perspective of the manufacturer who acquires the technology, the break-even point will be reached with 35.34% of sales and a payback time of 1 year and 11 months.

According to these indicators, the drying plant project is viable and economically profitable.

In **Figure 11**, it can be observed that the colors and appearance of the dry products are similar to the fresh products.

Figure 11. Some dried products **(a)** epazote; **(b)** sweet chili, Xcatic, habanero; **(c)** orange; **(d)** chaya; **(e)** poblano chili, jalapeño, bell pepper; **(f)** tomato; **(g)** pineapple; **(h)** red onion; **(i)** white onion; **(j)** lemon.

At this stage, the initial characteristics proposed for the equipment referring to portable system, modular and scalable system, solar continuous processing, improved control system, flexibility and versatility in operation and the production of differentiated and standardized food products are obtained.

Therefore, a new solar drying technology has been developed. CREID BI SAFE® will be an intelligent solution advancing food processing efficiency.

4. Discussion

At this point in the development, the monitoring and control system has shown various failures in the sensors when the scale is up. The development of an improved monitoring system and a wireless system with more robust monitoring are being worked on.

Likewise, the possibility of creating a more robust air heating system is being considered. The use of technologies such as parabolic solar collectors or heliostats, among others, are under development.

The use of biodiversity and carbon footprint indicators specifically coupled to the production system and the crop field are developing.

With this technology and process new applications are being developed like waste recovery from a beer factory, a battery recycling production among others.

Sinergy and alliance with small farms and new food products are developing.

A line of healthy and sustainable products have been developed according to the needs of the market to articulate the food supply chain in a sustainable way, avoiding food waste in the crop field.

5. Conclusion

The results of the development of a new solar drying technology with applicability in the food production system were presented. The best configuration for an integral drying system for various applications was obtained. Therefore, the solar drying technology developed was portable, efficient, modular, versatile, continuous processing, with minimal degradation in the dehydrated product. According to the annualized cost method calculations, the cost of drying products with this technology was much lower than when using conventional energies and had a short payback period of 1–2 years. This research is the first part of the ongoing project. Improved equipment and various applications are in progress.

Today for the technology, we have 2 patents MX_W_2022_084942 and MX_E_2018_092688 in Mexico and 1 trademark CREID BI SAFE. We have 2 trademarks CREID BIA and CREIDBI used to promote Mexican regional cuisine especially ethnic products of Mayan origin.

Author contributions: Conceptualization, CRE and RMCA; methodology, CRE and RMCA; design of equipment and software, CRE and RMCA; validation, CRE and RMCA; formal analysis, CRE and RMCA; investigation, CRE and RMCA; resources, CRE and RMCA; data curation, CRE and RMCA; writing—original draft preparation, CRE and RMCA; writing—review and editing, CRE and RMCA; visualization, CRE and RMCA; supervision, CRE and RMCA; project administration, CRE and RMCA; funding acquisition, CRE and RMCA. All authors have read and agreed to the published version of the manuscript.

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References

1. Iberdrola. Decarbonization (Spanish). Available online: https://www.iberdrola.com/conocenos/descarbonizacion-economia-principios-acciones-regulacion (accessed on 6 November 2024).
2. Lingayat A, Balijepalli R, Chandramohan VP. Applications of solar energy based drying technologies in various industries – A review. Solar Energy. 2021; 229: 52-68. doi: 10.1016/j.solener.2021.05.058
3. European Commission. International day of awareness of food loss and waste. Available online: https://food.ec.europa.eu/safety/food-waste/international-day-awareness-food-loss-and-waste_en (accessed on 1 June 2024).
4. Food and Agriculture Organization. Food wastage footprint: Impacts on natural resources. Available online: https://www.fao.org/4/i3347e/i3347e.pdf. (accessed on 20 July 2024).
5. World Food Program USA. How food waste affects world hunger. Available online: https://www.wfpusa.org/articles/how-food-waste-affects-world-hunger/ (accessed on 20 July 2024).
6. Food and Agriculture Organization. The state of food security and nutrition in the world 2022. Available online: https://openknowledge.fao.org/server/api/core/bitstreams/67b1e9c7-1a7f-4dc6-a19e-f6472a4ea83a/content (accessed on 20 July 2024).
7. Gobierno de México. More than ten thousand tons of food are wasted every year in Mexico (Spanish). Available online: https://www.gob.mx/bienestar/prensa/se-desperdician-mas-de-diez-mil-toneladas-de-alimentos-cada-ano-en-mexico. (accessed on 20 July 2024).
8. Leng R, Anderson J. Techno-economic analyses. In: Perlmutter BA (editor). Integration and Optimization of Unit Operations. Elsevier; 2022. pp. 373-412. doi: 10.1016/b978-0-12-823502-7.00023-2
9. Suresh BV, Shireesha Y, Kishore TS, et al. Natural energy materials and storage systems for solar dryers: State of the art. Solar Energy Materials and Solar Cells. 2023; 255: 112276. doi: 10.1016/j.solmat.2023.112276
10. United Nations. Responsible consumption and production. Available online: https://unric.org/en/sdg-12/ (accessed on 20 July 2024).
11. Xue L, Liu G, Parfitt J, et al. Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data. Environmental Science & Technology. 2017; 51(12): 6618-6633. doi: 10.1021/acs.est.7b00401
12. Food and Agriculture Organization. Global Food Losses and Food Waste: Extent Causes and Prevention. Available online: https://www.fao.org/4/mb060e/mb060e00.pdf (accessed on 20 July 2024).
13. Aien S, Judith F. Update on the state of the art of solar food drying: A review from Latin American literature (Spanish). Revista Iberoamericana de Tecnología Postcosecha. 2022. 23(2): 101.
14. FACT.MR. Solar dryer market. Available online: https://www.factmr.com/report/solar-dryer-market (accessed on 30 July 2024).
15. Mordor Intelligence. Dehydrated Food Market Size & Share Analysis - Growth Trends & Forecasts (2024-2029). Available online: https://www.mordorintelligence.com/industry-reports/dehydrated-food-market (accessed on 30 July 2024).
16. United Nations. Sustainable Development Goals. Available online: https://sustainabledevelopment.un.org/content/documents/8326Factsheet_SummitPress_Kit__final.pdf (accessed on 20 July 2024).
17. United Nations. Industry, innovation and infrastructure: Why it matters. Available online: https://www.un.org/sustainabledevelopment/wp-content/uploads/2018/09/Goal-9.pdf (accessed on 20 July 2024).
18. Saha CK, Roy NK, Khatun J, et al. Solar hybrid dryers for fruits, vegetables, and fish: A comprehensive review on constructional features and techno-economic-environmental analysis. Sustainable Energy Technologies and Assessments. 2024; 68: 103878. doi: 10.1016/j.seta.2024.103878
19. Kong D, Wang Y, Li M, et al. A comprehensive review of hybrid solar dryers integrated with auxiliary energy and units for agricultural products. Energy. 2024; 293: 130640. doi: 10.1016/j.energy.2024.130640
20. Chanda PR, Podder B, Biswas A, et al. Advancements in solar assisted drying technologies: A comprehensive review post 2017. Journal of Stored Products Research. 2023; 104: 102190. doi: 10.1016/j.jspr.2023.102190
21. Patil R, Gawande R. A review on solar tunnel greenhouse drying system. Renewable and Sustainable Energy Reviews. 2016; 56: 196-214. doi: 10.1016/j.rser.2015.11.057
22. Lingayat A, Balijepalli R, Chandramohan VP. Applications of solar energy based drying technologies in various industries – A review. Solar Energy. 2021; 229: 52-68. doi: 10.1016/j.solener.2021.05.058

23. Deng Z, Li M, Xing T, et al. A literature research on the drying quality of agricultural products with using solar drying technologies. Solar Energy. 2021; 229: 69-83. doi: 10.1016/j.solener.2021.07.041
24. Mugi VR, Das P, Balijepalli R, et al. A review of natural energy storage materials used in solar dryers for food drying applications. Journal of Energy Storage. 2022; 49: 104198. doi: 10.1016/j.est.2022.104198
25. Ortiz-Rodríguez NM, Condorí M, Durán G, et al. Solar drying Technologies: A review and future research directions with a focus on agroindustrial applications in medium and large scale. Applied Thermal Engineering. 2022; 215: 118993. doi: 10.1016/j.applthermaleng.2022.118993
26. Lingayat A, Zachariah R, Modi A. Current status and prospect of integrating solar air heating systems for drying in various sectors and industries. Sustainable Energy Technologies and Assessments. 2022; 52: 102274. doi: 10.1016/j.seta.2022.102274
27. Crippa M, Solazzo E, Guizzardi D, et al. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food. 2021; 2(3): 198-209. doi: 10.1038/s43016-021-00225-9
28. Chauhan C, Dhir A, Akram MU, et al. Food loss and waste in food supply chains. A systematic literature review and framework development approach. Journal of Cleaner Production. 2021; 295: 126438. doi: 10.1016/j.jclepro.2021.126438
29. CRE. Law for the use of renewable energies and the financing of the energy transition (Spanish). Available online: https://www.cre.gob.mx/documento/3870.pdf (accessed on 30 July 2024).
30. GOB. Manual on the enforcement of intellectual property rights (Spanish). Available online: https://www.gob.mx/cms/uploads/attachment/file/94515/MANUAL_PROPIEDAD_INTELECTUAL_OBSERVANCIA.pdf (accessed on 30 July 2024).
31. Mexican Official Standard NOM-044-FITO-1995, which establishes the phytosanitary requirements and specifications for the importation of nuts, processed and dehydrated vegetable products and by-products (Spanish). Available online: https://dof.gob.mx/nota_detalle.php?codigo=4950461&fecha=21/06/1999#gsc.tab=0 (accessed on 30 July 2024).
32. Pandey S, Kumar A, Sharma A. Sustainable solar drying: Recent advances in materials, innovative designs, mathematical modeling, and energy storage solutions. Energy. 2024; 308: 132725. doi: 10.1016/j.energy.2024.132725
33. Lamidi RasaqO, Jiang L, Pathare PB, et al. Recent advances in sustainable drying of agricultural produce: A review. Applied Energy. 2019; 233-234: 367-385. doi: 10.1016/j.apenergy.2018.10.044
34. Saini RK, Saini DK, Gupta R, et al. Technological development in solar dryers from 2016 to 2021-A review. Renewable and Sustainable Energy Reviews. 2023; 188: 113855. doi: 10.1016/j.rser.2023.113855
35. Autonomous University of Yucatan. FIQUADY. Available online: https://www.ingenieria.uady.mx/meteorologica/estacion/datosmeteorologico2.htm (accessed on 30 July 2024).
36. Hernández J, Martínez O, Quinto P, et al. Drying habanero chili with solar energy (Spanish). Revista Iberoamericana de Tecnología Postcosecha. 2010; 10(2): 120-127.
37. Amonovich KB, Salimovich MM, A'zamovich SK. A systematic review on greenhouse type solar dryers. Solar Energy. 2024; 283: 113021. doi: 10.1016/j.solener.2024.113021
38. Nukulwar MR, Tungikar VB. A review on performance evaluation of solar dryer and its material for drying agricultural products. Materials Today: Proceedings. 2021; 46: 345-349. doi: 10.1016/j.matpr.2020.08.354
39. Horwitz W, Latimer GW (editors). Official Methods of Analysis of AOAC International, 18th ed. AOAC International; 2005.