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Thermo–Energetic Modelling and Operational Load Limits of a Solar Dryer for Chestnuts

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Abstract. This study presents a thermoenergetic evaluation of a solar drying system for chestnuts, operating with an initial moisture content of 47% and a final moisture content of 20%. The system consists of a 1 m³ drying chamber coupled to a solar collector with a thermal efficiency of 45%, evaluated with an average solar irradiance of 656 W/m² and an ambient temperature of 26 °C.

The processed mass was varied between 2 and 40 kg to analyze energy performance and thermal stability. The specific energy consumption (SEC) decreased from 3.63 to 2.69 kWh/kg as the load increased, indicating better energy utilization at higher processing capacities. These values are within the ranges reported for solar drying of agricultural products, confirming the system's energy suitability.

However, the internal temperature analysis showed a progressive decrease with increasing mass. For loads exceeding approximately 40 kg, the calculated temperature at a critical internal point decreased significantly, indicating an energy deficit under the fixed geometric configuration. This result reveals a thermal operating limit imposed by the chamber volume rather than the collector efficiency, highlighting the need to balance load, geometry, and available thermal energy in the design of a scalable solar dryer.

Key words. Solar drying, specific energy consumption (SEC), thermal stability, system scalability

1. Introduction

Solar drying is widely recognized as a sustainable and cost-effective method for preserving agricultural products while reducing post-harvest losses. Compared to conventional fossil-fuel-based drying systems, solar dryers offer lower operational costs and reduced environmental impact. However, their performance strongly depends on system configuration, climatic conditions, and the thermodynamic balance between heat supply and moisture removal demand.

One of the key performance indicators in solar drying systems is the specific energy consumption (SEC), which quantifies the energy required per unit mass of dried product. Lower SEC values indicate improved energetic efficiency and are frequently used to compare different dryer designs. Nevertheless, SEC alone does not fully describe the thermal feasibility or operational limits of a system, particularly when scaling the processed mass.

Several studies have shown that overloading a drying system can decrease its efficiency. An excessive load can compromise the internal temperature and drying kinetics if the available thermal power and chamber geometry are not properly matched to the evaporation demand [14].

In this context, the present study evaluates the thermo–energetic performance of a solar dryer for chestnuts operating with a collector efficiency of 45% and a chamber volume of 1 m³. The analysis considers processed masses between 2 and 40 kg, integrating both SEC evaluation and internal temperature behaviour. Special attention is given to identifying thermal stability limits and geometric scalability constraints.

By combining global energy indicators with localized thermal analysis, this work aims to provide design-oriented criteria for determining optimal loading conditions and for guiding capacity expansion strategies in solar drying systems.

2. Methodology

A thermo–energetic evaluation of a solar drying system for Chestnut drying was carried out using a coupled energy balance approach. The system consisted of a flat-plate solar collector with a fixed thermal efficiency of 45%, connected to a 1 m³ drying chamber. The processed mass ranged from 2 to 40 kg, and drying was performed from an initial moisture content of 47% to a final moisture content of 20%.

The useful thermal energy supplied by the collector was calculated from the irradiance conditions and the collector efficiency, incorporating heat losses into the total energy requirement. The specific energy consumption (SEC) was determined as the ratio between the total energy supplied and the mass of the dried product. Additionally, an internal energy balance of the drying chamber was implemented to calculate the air temperature at a critical control point under each load condition.

Thermal viability was assessed by identifying the conditions under which the calculated internal temperature decreased critically, indicating an energy deficit between the heat supplied and the evaporation demand. This approach made it possible to determine the operating load limit and evaluate the scalability of the system under fixed geometric and climatic conditions.

A. Geographical location

The Tambopata National Reserve (RNTAMB) is located in the south-eastern of the Madre de Dios department, within the districts of Tambopata and Inambari, in the province of Tambopata. It borders the province of Tambopata in the Madre de Dios region to the north, Bolivia to the east, the Bahuaja Sonene National Park to the south, and the Kotsimba Native Community to the west. Its geographical coordinates are 12°36′S, 69°12′W [2].

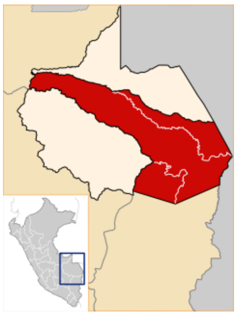

Fig. 1. Geographical location of Madre de Dios in Perú.

B. Current Status of Chestnut Production in Tambopata

The Amazonian chestnut (Bertholletia excelsa) represents one of the most important non-timber forest products in the Madre de Dios region. In Tambopata, harvesting activities are conducted seasonally between December and March and constitute a primary source of income for local communities.

Post-harvest handling typically involves temporary storage of unshelled chestnuts under high ambient humidity conditions, frequently exceeding 80%. These environmental conditions promote fungal growth and increase the risk of product rejection in export markets due to strict sanitary standards.

Local producers have reported that a significant portion of the harvested chestnuts can be affected by contamination during storage and transport prior to industrial processing (approximately 12% losses according to a report by a local company). This problem not only generates economic losses but also increases energy demand during the subsequent stages of industrial drying, where biomass-fuelled rotary dryers are commonly used.

Improving moisture control at the storage stage through decentralized solar-assisted drying could enhance product quality, reduce post-harvest losses, and lower the energy intensity of later processing steps.

C. *Design Conditions*

The solar dryer will be located in the Brazil nut storage area, close to the harvesting zone. Its purpose is to ensure that the nuts reach a final moisture content of 20% before being stored in payoles (storage sheds).

Figure 2 presents the results obtained using climatic/meteorological data extracted from the NASA POWER Data Access Viewer database. Hourly data on temperature, humidity, and irradiance were collected and processed for the months of December through April over the past 11 years (2014–2025) [4].

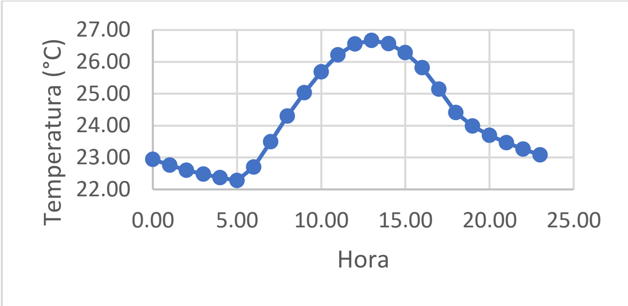

Fig. 2. Recorded Temperatures in Tambopata (2014-2025)

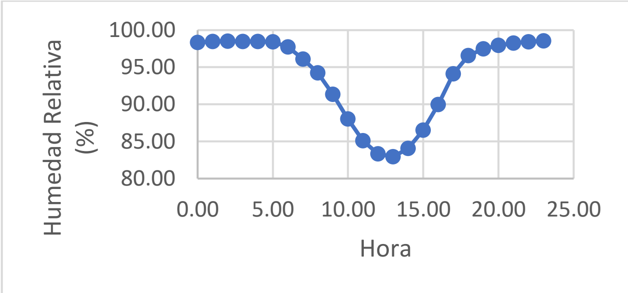

Fig. 3. Recorded Relative Humidity in Tambopata (2014-2025)

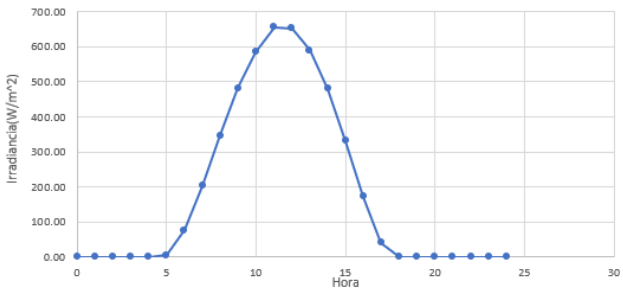

Fig. 4. Recorded Irradiance in Tambopata (2014-2025)

D. Mathematical model used

1. *Thermal Energy Requirement for Chestnut Dehydration*

The total thermal power required for chestnut dehydration consists of:

-Sensible heat to increase chestnut temperature

-Latent heat to evaporate the contained moisture

The sensible heating rate is expressed as:

$$Q_{ph} = \frac{m_{chestnuts} * Cp_{chestnuts} * (T_2 - T_1)}{t_{dry}} \quad (1)$$

The latent heat of vaporization is temperature dependent. The mean chestnut temperature is estimated as [5]:

$$t_{chestnuts} = 0.25 * (3 * T_2 + T_1) \quad (2)$$

$$h_{fg} = 4186 * (597 - 0.56 * t_{chestnuts}) \quad (3)$$

The mass of water to be removed is [6]:

$$m_w = \frac{m_{chestnut} * (M_{iw} - M_{fw})}{1 - M_{fw}} \quad (4)$$

The evaporation heat rate becomes:

$$Q_e = \frac{m_w * h_{fg}}{t_{dry}} \quad (5)$$

$$Q_{lc} = m_{air} * Cp_{air} * (T_2 - T_1) * \eta_{col} \quad (6)$$

Heat losses in the collector were neglected, as the available thermal energy remains sufficient to meet the heat required for the dehydration of 2 kg of chestnuts.

Thus, the total required drying power is:

$$Q_d = Q_{ph} + Q_e \quad (7)$$

2. Solar Collector Design

2.1 Approximation of the temperature at the collector's outlet

The air temperature increase across the collector is estimated by [6]:

$$\Delta T = 2 * \beta * (T_b - T_C) * \frac{I_{sun}}{I_0} \quad (8)$$

2.2 Energy necessary to heat the air

The air enthalpy is approximated as:

$$h_x = Cp_{air} * T_x + w_x * (2501 + 1.86 * T_x) \quad (9)$$

The thermal power collected is [7]:

$$E = \dot{m}_{air} * (h_2 - h_1) \quad (10)$$

2.3 Collector's dimensions

The collector area is determined from the required drying power [7]:

$$A_{col} = \frac{Q_d}{n_{col} * I_{sun}} * 1.2 \quad (11)$$

Where the factor 1.2 accounts for thermal losses.

Where the factor 1.2 accounts for thermal losses [8]:

$$L_{col} = \frac{A}{B_{col}} \quad (12)$$

2.4 Amount of heat lost by the process

Collector thermal losses are [8]:

$$Q_{L=I_{sun}} * A_{col} * (\tau * \alpha) - E \quad (13)$$

3.Calculation of thermodynamic parameters in the drying chamber

3.1 Water activity

It's calculated by [7]:

$$a_w = 1 - e^{[-e^{(0.914+0.5639*ln\,(M_{fd}))}]} \quad (14)$$

Limit humidity:

$$HR = a_w * 100 \quad (15)$$

3.2 Humidity at the entrance of the drying chamber

Vapor pressure:

$$\boldsymbol{P_{v1}} = 10^{[8.07131-1730.63/(233.46+T_1)]} ** 133.22 * HR_1 \quad (16)$$

$$P_{v1} = P_{v2} \quad (17)$$

Saturation pressure at outlet:

$$P_{sat2} = 610.78 * e^{[17.27*\boldsymbol{T_2}/(\boldsymbol{T_2}+237.3)]} \quad (18)$$

$$HR_2 = \frac{P_{V2}}{P_{sat2}} \quad (19)$$

3.2 Humidity at the exit of the drying chamber

The drying rate will be determined according [9]:

$$DR = \frac{m_w}{t_{drying}} \quad (20)$$

Air mass flow rate [7]:

$$\dot{m}_{air} = \frac{DR}{\omega_3 - \omega_1} \quad (21)$$

Air volumetric flow:

$$V_{air} = \frac{\dot{m}_{air}}{\rho_{air}} \quad (22)$$

Humidity evolution:

$$HR_3 = HR_2 + (HR_2 - HR_f)(1 - e^{[-k*V_{air}]}) \quad (23)$$

k : 0.2-0.5 ambient air
0.5-1 forced air

3.4 Air speed at the entrance of the collector

$$V_{inlet-air} = \frac{V°_{air}}{A_{inlet-air}} \quad (24)$$

$$A_{inlet-air} = B_{air} * H_{air} \quad (25)$$

4. Drying chamber design

Porosity of chestnuts in percentage [10]:

$$\vartheta = 0.441 * M_{iw} + 42.01 \quad (26)$$

4.1Volume of chestnuts

$$V_{1\_chestnut} = A * B * C \quad (27)$$

$$V_{total\_chestnut} = 143 * V_{1chestnut} * m_{chestnut} \quad (28)$$

4.2Required area to dry

Vacuum fraction of the drying chamber:

$$\varepsilon_v = \frac{V_{vac}}{V_{chamber}} \quad (29)$$

Apparent density of the chestnuts [10]:

$$\rho_{app\_chestnuts} = -3.357 * M_{iw} + 723.60 \quad (30)$$

Necessary area to dry [10]:

$$A_d = \frac{m_w}{\rho_{app_{chestnuts}} * e_{tray} * \vartheta * (1 - \varepsilon_v)} \quad (31)$$

4.3 *Tray design*

Drying tray surface area [11]:

$$A_{tray} = \frac{A_d}{\#trays} \quad (32)$$

$$L_{tray} = \frac{A_{tray}}{B_{tray}} \quad (33)$$

4.5 *Pressure drop at the outlet of the solar collector*

To characterize additional thermodynamic properties within the solar dryer system, the air pressure at the solar collector outlet (Point 2) will be calculated using the following equation:

$$\Delta P = 0.00308 * g * (T_3 - T_2) * H_{chamber} \quad (34)$$

4.6 *Efficiency of the solar dryer*

Total heat received by the solar collector:

$$Q_{sun} = I_{sun} * A_{col} \quad (35)$$

$$\eta = \frac{Q_d}{Q_{sun}} \quad (36)$$

4.7. Glossary

Table 1 has the glossary of terms.

Table 1. Glossary of terms

Symbol	Description	Unit
m_chestnuts	Mass of chestnuts loaded into the drying chamber	kg
Cp_chestnuts	Specific heat capacity of chestnuts	J/kg·K
T1	Initial temperature of chestnuts	°C
T2	Air temperature at collector outlet	°C
T3	Air temperature inside drying chamber (control point)	°C
t_dry	Drying time	s or h
h_fg	Latent heat of vaporization of water	J/kg
m_w	Mass of water removed during drying	kg
m_dot_air	Mass flow rate of air	kg/s
V_air	Volumetric airflow rate	m³/s
rho_air	Air density	kg/m³
I_sun	Solar irradiance	W/m²
A_c	Solar collector area	m²
η	Thermal efficiency of solar collector	-
E	Thermal power supplied by collector	W
Q_ph	Sensible heat required to warm chestnuts	W
Q_e	Latent heat required for water evaporation	W
Q_lc	Heat loss by convection in the drying chamber	
Q_total	Total thermal power required for drying	W
SEC	Specific Energy Consumption	kWh/kg
ε	Porosity of chestnut bed	-
P_atm	Atmospheric pressure	Pa
RH	Relative humidity	%
P_v	Water vapor pressure	Pa
P_sat	Saturation pressure	Pa
k	Drying constant (empirical coefficient)	-

3. Results

A sample of 2 kg of chestnuts with an initial moisture content of 47% was used. The thermodynamic parameters obtained confirm that the system operates under moderate temperature conditions, reaching 45.9 °C at the collector outlet and 38.2 °C inside the drying chamber under nominal load.

The total thermal power required for chestnut dehydration was 121 W, with a water removal of 0.675 kg during the 4-hour drying period. These results confirm that the system operates within moderate temperature ranges, suitable for controlled moisture reduction under Amazonian conditions (Table 2) .

Table 2. Initial Conditions

Initial conditions	Unit	Value
Atmospheric Pressure	Pa	101325
Ambient Temperature	°C	26.56
Relative humidity, point 1	%	85
Drying time	hr	4
Specific Heat of Air	J/kg.K	1030
Initial Moisture Content of the Chestnut	%	47
Porosity of chestnuts	%	42.3
Average Irradiance	W/m²	656.23

Most important heat and thermodynamic values obtained during the calculations (Table 3) :

Table 3. Heat and thermodynamic results

Thermodynamic values	Unit	Value
Temperature variation in the Collector	°C	19.2
Amount of water to be evaporated from the Chestnuts (m_w)	kg	0.675
Water activity (a_w)	-	0.681
Relative humidity, point 2 (HR2)	%	29.6
Relative humidity, point 3 (HR3)	%	37.2
Mass Airflow ($m°_{aire}$)	kg/s	0.003
Drying ratio	kg/s	4.7x10^(-5)
Temperature at point 2 (T2)	°C	45.9
Temperature at point 3 (T3)	°C	38.2
Energy in the Collector (E)	W	51
Air speed at the entrance of the collector	m/s	0.26
Volume of Chestnuts	m³	0.018
Heat to preheat the chestnuts (Q_e)	W	8.3
Heat to Evaporate the Water Removed from the Chestnuts (Q_d)	W	112.7
Thermal Energy for Chestnut Dehydration	W	121
Total heat reaching the solar collector (Q_{sun})	W	113.4
Heat lost in the drying chamber	W	50

Total efficiency of the solar collector (η)	%	45

Table 4 presents the results obtained regarding the dimensions and other important values to consider for the design of the solar dryer:

Table 4. Dimensions of the solar dryer

Sizing Values	Unit	Value
Collector efficiency	%	45
Collector width	m	0.8
Collector length	m	0.72
Tray thickness	m	0.01
Chamber width	m	1
Chamber length	m	1
Chamber height	m	1
Number of trays	-	3
Trays width	m	0.4
Trays length	m	0.34

The table 5 shows the components of the solar dryer.

Table 5. Components of the solar dryer

Component	Quantity
Solar collector	1
Drying chamber	1
Trays	6

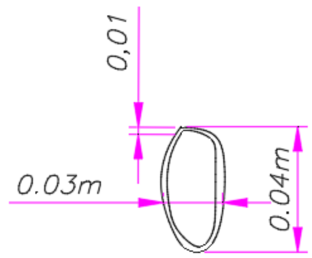

Fig. 5. Dimensions used to determine the volume of one chestnut.

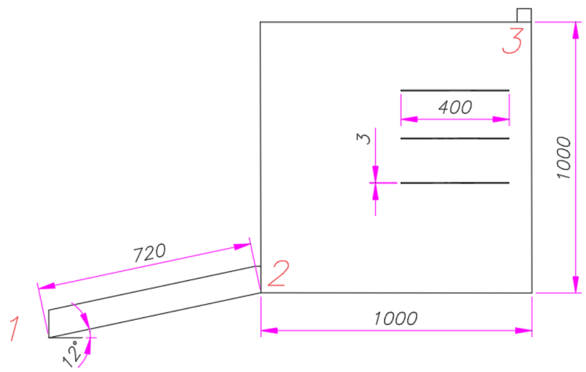

Fig. 6. Solar Dryer Schematic with trays.

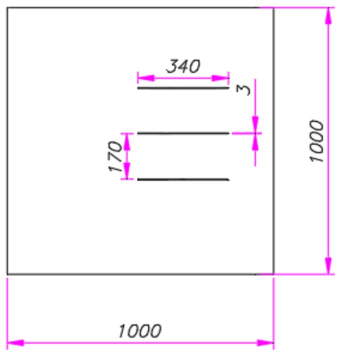

Fig. 7. Chamber Schematic with trays.

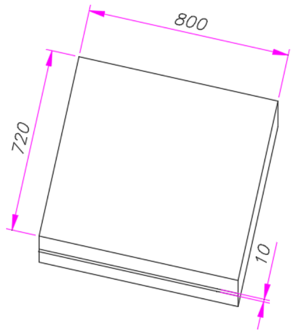

Fig. 8. Solar collector Schematic.

4. Discussion

The specific energy consumption (SEC) shows that the solar thermal efficiency decreases progressively as the chestnut load increases from 2 to 40 kg (3.63–2.69 kWh/kg). This behaviour is consistent with findings published in the literature on forced and natural convection solar dryers, where increased load improves energy efficiency by distributing heat losses over a larger processed mass. The values obtained are within the typical range for solar drying of agricultural products with a final moisture content close to 20%, thus validating the prototype's energy performance.

However, although the SEC improves with increasing load, the temperature analysis at point 3 reveals a progressive decrease as the processed mass increases. When the load exceeds approximately 40 kg within a 1 m³ chamber, the calculated temperature becomes progressively lower. Physically, this represents an energy deficit: the available usable energy is insufficient to simultaneously compensate for moisture evaporation and the system's heat losses. This result should not be interpreted as an actual temperature, but rather as a mathematical indicator of thermal infeasibility under the given geometric configuration. Therefore, the limiting factor of the system is not the collector itself, but the chamber's capacity to maintain a stable thermal regime under increased evaporation demands.

Consequently, although from a global energy perspective (SEC) the system appears to benefit from higher loads, the thermal analysis demonstrates the existence of an operational limit imposed by the chamber volume. This highlights the need to incorporate geometric scalability criteria in the design of solar dryers, where the processed mass, chamber volume, and available thermal power must be kept in dynamic equilibrium.

Table 6. Comparison of results

Parameter	Value	This study	Reference
Solar collector area	16.8m^2	0.58m^2	[7]
Drying Time	10 h	4h	[7]
Average drying rate	3.97	0.17	[7]
Total energy required	201.56MJ	1.7MJ	[7]
Mass of water evaporated	79.33kg	0.68kg	[7]
Collector efficiency	28.4%	45%	[12]
Solar collector dimensions	1.5x1.5m	0.8x0.72m	[13]
Temperature at the drying chamber	52°C	45.9	[13]

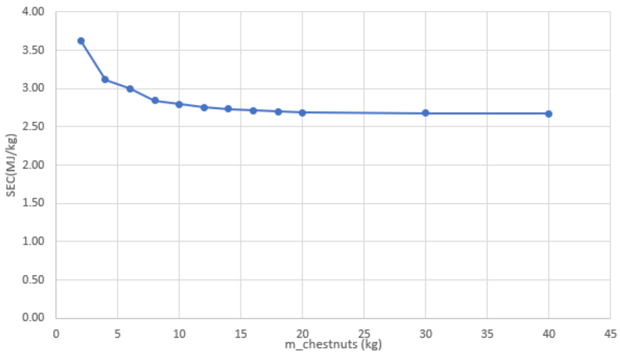

Fig. 10. Specific Energy Consumption vs mass of chestnuts

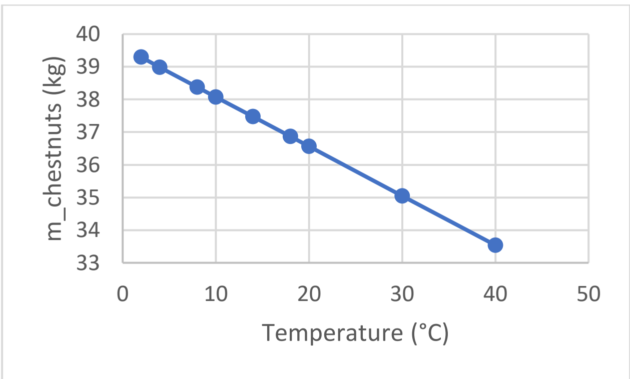

Fig. 11. Temperature at point 3 vs mass of chestnuts

5.Conclusions

The system's SEC decreases as the processed mass increases, reaching values between 3.63 and 2.69 kWh/kg, which fall within the range reported in the literature for solar drying of agricultural products. This validates the energetic performance of the prototype.

The progressive reduction in internal temperature and the appearance of negative values for loads above approximately 40 kg reveal an energy deficit associated with the fixed chamber volume of 1 m³.

The system presents a thermal operational limit close to 40 kg under the current configuration. Capacity expansion would necessarily require: increasing the chamber volume, improving thermal insulation, or increasing the effective solar collection area.

Optimal solar dryer design should not rely solely on global energy indicators such as SEC, but must also incorporate local thermal analysis and thermal stability criteria to ensure physical feasibility and technological scalability.

Acknowledgement

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