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RESEARCH ARTICLE

CONTRIBUTION TO THE IMPROVEMENT OF ENERGY AND TECHNICAL PERFORMANCE OF AN INDIRECT SOLAR DRYER FOR AGRI-FOOD PRODUCTS: STUDY, REALIZATION AND EXPERIMENTAL TESTS

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Nomenclature
Symbols:
S_t-Total area occupied by tomatoes in m^2
S_c- Surface of the racks in m^2
Δm -Mass of water to be extracted in kg
Q_{to} -Quantity of Tomato Heat in kJ
Q_n-Quantity of heat needed to dry the tomato in kJ
$\emptyset_u$ -Useful Total Flow $\emptyset_u$ in kJ
$\emptyset_{pc}$- Flux lost by conduction through the walls in W
$\emptyset_{pv}$- Convection Lost Flux Through the walls in W
$\emptyset_{pt}$ -Total Lost Flow Through the walls in W
$\emptyset_T$-Total flow to be provide in W
S -Sensor surface in m^2

Abstract

According to the Food and Agriculture Organisation of the United Nations, during periods of high production abundance, the losses of agri-food products observed in West Africa amount to 25% for cereals and 50% for fruits and vegetables. Strengthening agri-food preservation techniques through solar drying is a major challenge for African countries with high solar energy resources. This study contributes to the improvement of the energy and technical performance of indirect solar dryers for packaging agri-food products on a small scale. The objective achieved is the design and realization of an indirect solar dryer with forced convection with chimney effect for a better evacuation of the moisture extracted from food products. With a solar collector of 136W of thermal power, the dryer made allows to remove 0.85kg of water from a unit of a kilogram of tomatoes at a temperature not exceeding 60°C for thirteen hours (13 hours) of time. In this way, the nutritional properties of the products are preserved and any microbial proliferation is inhibited. This work includes an experimental part which consists of studying the evolution of the thermo-physical parameters of the drying air (temperature and degree of humidity) in the drying box during characteristic days. The analysis of the data and its interdependencies makes it possible to select the types of agri-food products that can be effectively dried with this device. The study also shows that the air path in the dryer and its temperature are the most important parameters to be optimized for good drying kinetics.

Introduction:-

In the modern world, the demand for energy for food drying is achieved using solar energy, natural gas, and fossil fuels. However, due to the depletion of natural resources, high cost of fuel, and environmental concerns, the use of

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solar energy for food drying is gaining popularity among farmers and industrialists (Kumar et al. 2016; Lucatero et al., 2015). Food drying of agricultural products is mainly carried out using solar dryers and open sun techniques. Direct drying is a common practice in developing countries with its many results such as dust contamination, pollution and damage caused by birds, animals and insects (Wakjira, 2010; Hussain et al. 2020).However, direct solar drying issues can be overcome by a variety of direct, indirect, forced, or hybrid solar dryers. The type of solar dryers relies on the building materials, drying process, and design techniques. Benin's geographical diversity ensures the production of a wide variety of fruits, legumes, cereals and other agricultural products, the preservation of which undoubtedly ensures food security. Food security in Benin for sustainable agricultural development requires, among other things, the efficient conservation of agri-food products. Applied during periods of abundant production, it makes it possible to alleviate food shortages during the less prosperous lean seasons (the dry season, a year of low production, adverse effects of climate change) and even promotes their export to sub-regional and international markets in the form of good quality products. This spares producers from selling off and losing a part of their production. In western countries, several innovative technologies for the preservation of agri-food products are widely developed. Cold preservation (refrigeration, freezing and deep-freezing), preservation by dehydration (solar or oven drying), preservation by adding a preservative, fermentation, coating, smoking and freeze-drying, smoking and canning. However, most of these technologies are struggling to integrate into agricultural practices in Africa, and particularly in Benin. However, Benin, due to its geographical location, is located in West Africa between the Tropic of Cancer and the equator (between the parallels 6°30' and 12°30' north latitude and the meridian 1° and 30°40' east longitude), is a particularly sunny tropical area. Also, the annual averages of sunshine vary from 1643 hours/year in the South to 2190 hours/year in the North. The energy potential is very high. On average, it exceeds 3.9 kWh/m²/day in the South and reaches 6.2 kWh/m²/day in the North [UNDP 2010]. This immense solar energy potential, put to use, could contribute significantly to sustainable development and provide concrete solutions to the socio-economic and technical conservation problems that arise in the agricultural sector. In view of the importance of post-harvest losses of agricultural products, an indirect solar dryer has been developed. Thanks to the tools of functional analysis of needs and products, our study defined the parameters and characteristics expected by a specification that identifies the specifications and intrinsic parameters of the model to be designed. The development and use of solar drying equipment adapted to the realities of the land contributes to the resolution of these problems, among other things. The simulation of the solar dryer was carried out to monitor the air movement and temperature inside the dryer. Then, the solar energy performance of the dryer was evaluated. An experimental drying approach is adopted in view of the large and varied number of agricultural products to be dried.

Methods and Materials:-

Literature review on solar drying of agri-food products

In this section, we use the Systematic literature review (SLR) protocol, which consists of defining the scope of study, collecting data, synthesizing and analyzing the results of studies, in this case in the field of drying of agri-food products. We define keywords, understand the scope of the search, search databases, select primary studies, and perform quality assessment, data extraction, and synthesis. These search engines Google, Google scholar, ScienceDirect, and SpringerLink are prioritized among many others. These sources provide important information on the evolution of solar dryer technology. The identification of the documents resulted in about a hundred research articles, scientific reports, and projects. We applied exclusion criteria to filter out relevant studies. I) The abstract or title does not deal with dryers. ii) Dryers are not a goal, are not mentioned in relation to the context of the study. iii) The document does not address the challenges associated with the use of solar dryers. (iv) Duplicates that have already undergone the exclusion process. v) Short and less illustrated versions of documents are excluded and more extensive versions are considered.

Application of functional analysis tools

During the design of the equipment, the solar dryer takes a methodical and rigorous approach using various functional analysis tools. These tools, such as the performance graph, the interaction diagram, the diagram of technical and systematic analysis functions, as well as the diagram of the top-down functional analysis method, were essential to evaluate the viability and performance of our concept. The intelligent combination of data from these different tools fed into the development of the functional specifications.

A digital mock-up was made using SolidWorks 2021 mechanical design software.

Table 1:- Reduced functional specifications.

Type of functions	Functions	Criteria	Level of assessment
Service Function	Enable efficient and fast drying of agricultural products from solar energy	• Capacity • Type of convection • Dryingtime • Drying temperature • Air velocity	• 1 kg • Forced • 12 h • 50°C • 0,5 m/s
Constraintfunction 1	Must be made from local materials	• Materials collection time • Material costs • WorkforceCompetence	• Lessthanthreedays • Average • Local
Constraintfunction 2	Should be less bulky and easy to use	• Removableand arrangeable • NecessaryLevel of Instruction	• YES • Primary + formation
Constraintfunction 3	Must be ecological, resistant and waterproof	• Pollution • Lifespan • Isolation • Hot air leakage	• None • 10 years • Yes • Minimize

Sizing
Design
Table 2:- Summary of some dimensional and drying parameters.

Designation	Formulas	Results	Units
Total area occupied by tomatoes (S_t)	$S_t = \frac{m_t}{\rho_t * e_t}$	0,18	m^2
Surface of the racks (S_c)	$S_c = \frac{S_t}{d}$	0,6	m^2
Mass of water to be extracted (Δm)	$\Delta m = m_{ei} - m_{ef}$	0,85	kg
Quantity of Tomato Heat (Q_{to})	$Q_{to} = C_{pt} * m_t * \Delta\theta$	78,8	kJ
Quantity of heat needed to dry the tomato (Q_n)	$Q_n = \Delta m * C_{pe} * \Delta\theta + \Delta m * LV_e + Q_{to}$	2070,86	kJ
Useful Total Flow ($\emptyset_u$)	$\emptyset_u = \frac{Q_n}{t_S}$	48	W
Flux lost by conduction through the walls ($\emptyset_{pc}$)	$\emptyset_{pc} = \frac{\Delta\theta}{\sum \frac{e}{K * S}}$	32,75	W
Convection Lost Flux Through the walls ($\emptyset_{pv}$)	$\emptyset_{pv} = \Delta\theta * h_{air} * \sum S$	0,7061	W
Total Lost Flow Through the walls($\emptyset_{pt}$)	$\emptyset_{pt} = \emptyset_{pc} + \emptyset_{pv}$	33,46	W
Total flow to be provided ($\emptyset_T$)	$\emptyset_T = \frac{(\emptyset_u + \emptyset_{pt})}{\eta}$	136	W
Sensor surface (S)	$s = \frac{\emptyset_T}{\tau_v + a_\alpha * G}$	0,36	m^2

Dryer Operating Principle

The system is made up of the following components:

• A hot air production unit: consisting of a single-glazed solar collector, inclined 35° to the horizontal plane and oriented to the south;

• A drying chamber: this is a box with a capacity of 0.08 m3.

• 6 racks, on which the products to be dried are placed. The racks are 10 cm apart from each other; a space large enough for air circulation to take place in the best way;

• A solar chimney consisting of a single-circulation and single-glazed air-cooled solar collector, inclined 35° to the horizontal plane and oriented to the south;
• A solar panel that allows the fans to operate.

It mainly works from solar energy in the following way: the solar collector works using the greenhouse effect. It consists of a black plate specially treated to absorb as much solar radiation as possible in order to heat up. This heat is transmitted to the air trapped between the glass and the black plate by radiation and convection. As a result, this air is heated and becomes less dense, drier and lighter. It then naturally climbs up to the drying chamber above the first rack.

A thermal equilibrium seeks to be established between the drying air and the products stored on the racks. Thus, the heat transfer air gives up its heat to the products, takes on their moisture, becomes heavier and descends to the bottom of the drying chamber at the mouth of the chimney. The latter, warmed by the same principle. The solar collector transmits part of its heat to the humid air at the bottom of the drying chamber, thus creating a draught. This air suction created at the level of the drying chamber and reinforced by two minis vacuum cleaners, ensures the evacuation of humide air from the dryer.This principle is repeated continuously throughout the day, until the products reach their drying limit.

The dryer is placed on the ground at an angle of 35° oriented towards the sun's rays and thus keeps in a horizontal position the racks on which the tomato slices previously cleaned with water are placed. Pre-drying treatments are planned in the future to improve the texture of the finished product.

Tests And Experiments

Data on the raw material, tomatoes

For tomato drying, the following data are measured:

Table 3:- Measured data for tomato drying.

Saved Settings	Value	Units
Initial moisture content	93	%
Final water content	08	%
Drying temperature	50	°C
Ambient temperature measuredoutdoors	30	°C
Selected charge density for convective solar drying	0,3	Kg/m^2
Mass of the product to be dried	1	kg

Photo 1:- Initial product before drying.

Experimental Results And Interpretation

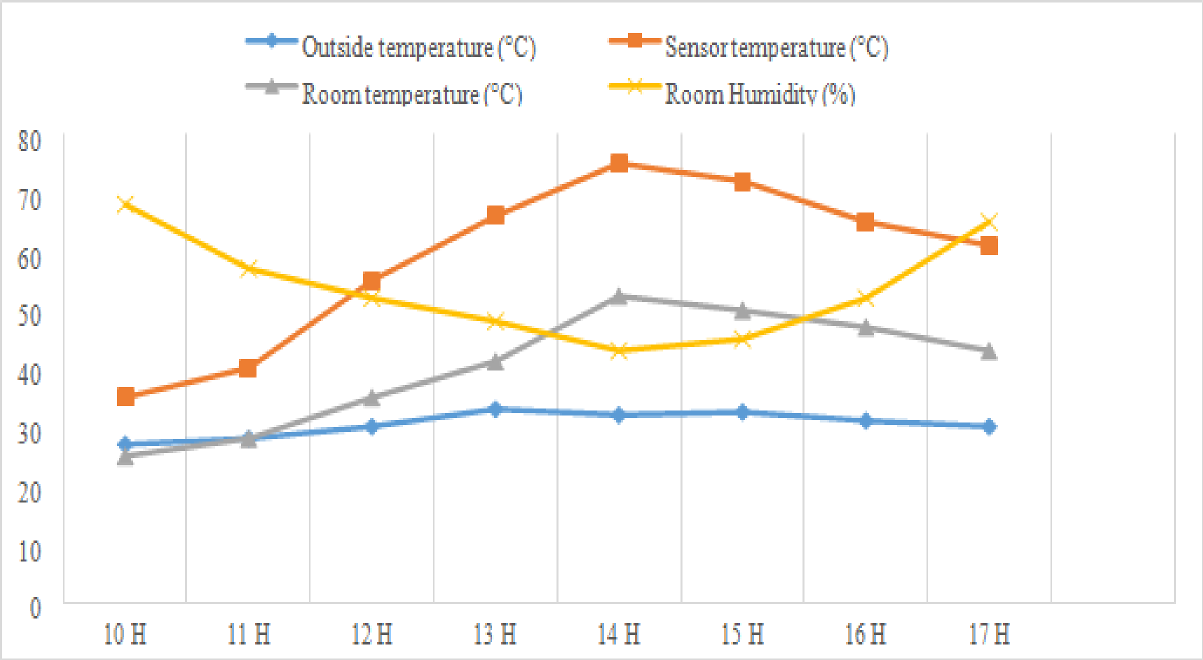
Results:-

The Graph 4 shows the evolution of the relative humidity in the 3 racks containing the laurel leaves during the experiment, and we have noted that the evolution of the water content on the 3 racks decreases with time, the difference in humidity between the air at the inlet and the air at the outlet of the drying chamber decreases, which explains why the mass of water extracted from the product decreases over time and becomes almost negligible at the end of drying (due to the drying speed which decreases over time).

Photo 2:- Indirect solar dryer made.

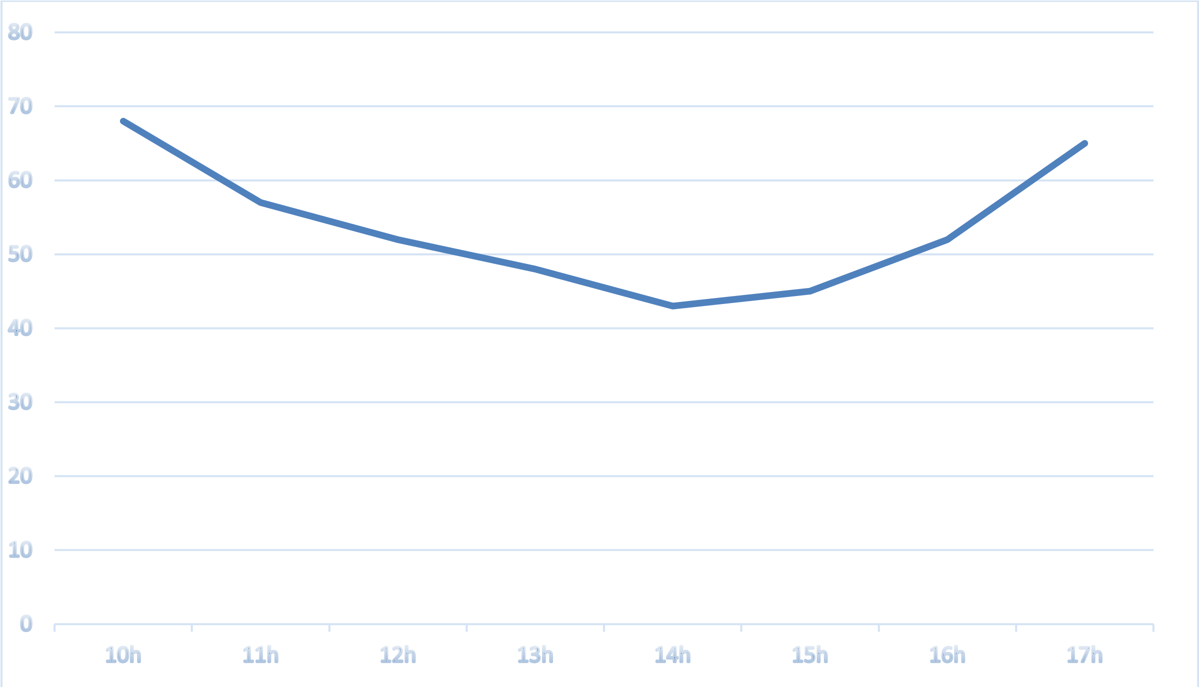
We spent 6 days conducting experimental studies and evaluating the influence of air circulation from the upper part of the solar collector on the drying kinetics, first when empty and then when loaded with the product to be dried. As a result, we recorded the air temperatures at various locations in the drying chamber as well as the temperatures at the inlet and outlet of the solar collectors during the test period for the heat circulation mode.

Vacuum test



Graph 3:- Evolution of temperature in function of time (Hours).

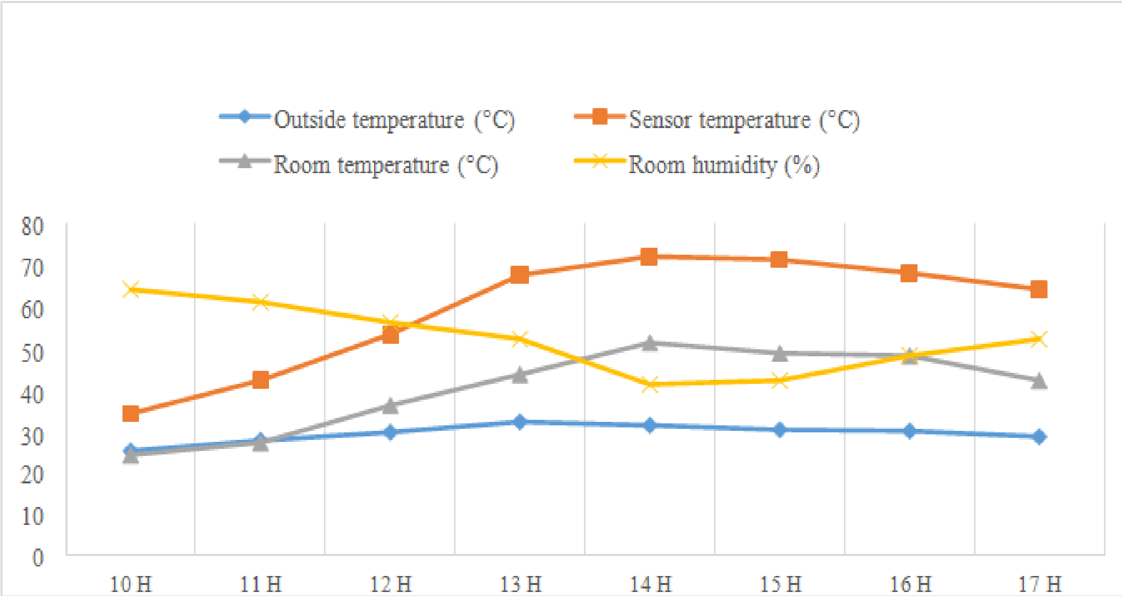
The evolution of the humidity inside the dryer is unstable. It is high in the morning to reach the maximum around 10 hours, then it decreases continuously to reach the minimum around 14 hours and then rises again and reaches the maximum around 17 hours.



Graph 4:- Evolution of humidity in function of time during the no-load test.

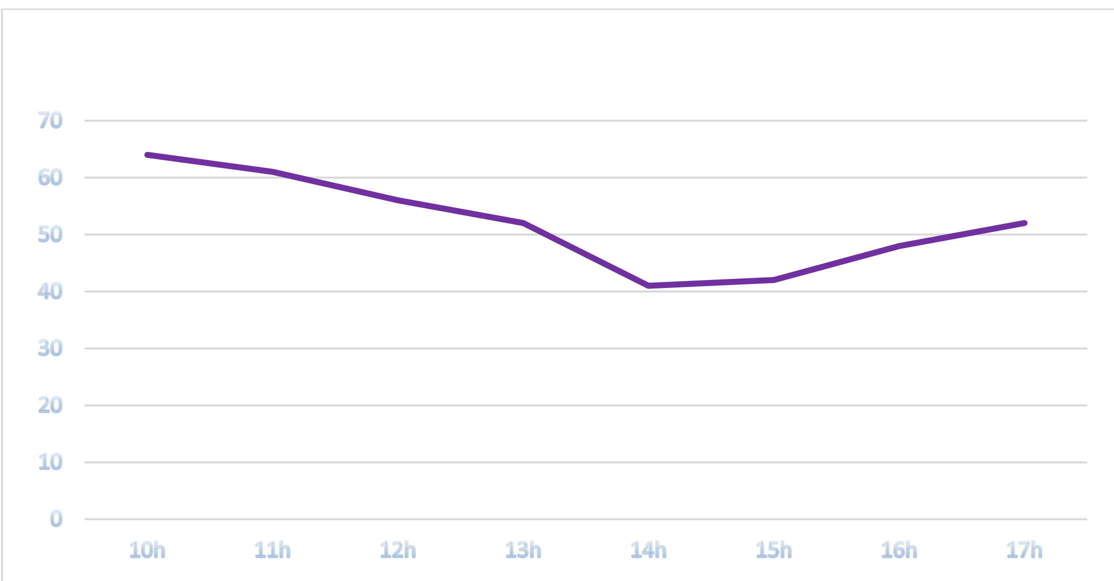
Load test with the product to be dried

Graph 4:- Evolution of the Temperature in function of time during (Hours) the load test.



Interpretation and Discussion:-

The previous graphs show curves reflecting the evolution of ambient temperatures, on the surface of the sensor, in the drying chamber and the evolution of the humidity of the air in the drying chamber, for seven hours of experimentation per day from 10 hours to 17 hours, we notice that the temperature peaks are obtained at 14 hours with a decrease in the humidity level of the drying air during the two different tests. Thus, at no load, the maximum temperature inside the drying chamber is 52.3°C for a temperature of 73°C at the absorber, and during drying, the maximum temperatures obtained are 51.1°C and 72.3°C respectively in the drying chamber and at the sensor level. As for the humidity of the drying air, a moisture loss of up to 30% between the outlet and the inlet of the sensor is observed. The tomato was dried in thirteen hours. These results are very satisfactory and testify to the relevance and importance of the system in agricultural development. The image below shows the dried tomato obtained at the end of the operation.



Graph 5:- Evolution of humidity in function of time (Hours).

Photo 3:- Final product on a rack after drying.

Envisaged Benefits

The solar dryer has significant benefits for Benin and middle-income countries.

• Construction is based on local resources that enhance the value of the region's wood, thus promoting sustainable management of forest resources.

• Local labour is required throughout the manufacture and use of the dryer.

• Job creation, thus strengthening the local economic fabric.

• Post-harvest losses are reduced through efficient drying,

• Increased financial incomes for farmers, thus playing a critical role in the country's economic stability and food security.

• Easy operation and maintenance.

Conclusion:-

Republic of Benin has an immense solar energy potential which, when used in food preservation techniques, can contribute significantly to sustainable development and provide concrete solutions to the problems of food insecurity and famine. Taking into account the real needs of users, the characteristics of the products to be dried and the environment in the design of dryers to improve drying activities, The functional analysis method, makes it possible to develop functional specifications that clearly highlight the technical solutions for each constraint related to its operation and efficiency. The indirect solar forced convection dryer with solar chimney ensures better evacuation of humid air from the dryer. Similarly, it makes it possible to remove 0.85 kg of water from a unit of a kilogram of fresh tomato during the drying period of about twelve (12) hours at a temperature of 51°C during good sunlight. It makes it possible to identify the influence of several aerothermal parameters at the same time. These are the drying time, the drying temperature (51°C), the better quality of the dried product, the negligible water content of the product and the relatively low cost price.

In perspective, to evaluate the effectiveness of this equipment on several agri-food products and better adapt it to climatic conditions and operate in the absence of the sun with the addition of another energy boost.

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