World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Design of a low-cost natural convection solar tunnel dryer to reduce postharvest losses of tomatoes, Maize and Mangoes

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World Journal of Advanced Research and Reviews, 2024, 24(02), 984–989

Publication history: Received on 21 September 2024; revised on 06 November 2024; accepted on 09 November 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.24.2.3328

Abstract

This study presents the design, development, and evaluation of a low-cost natural convection solar tunnel to reduce postharvest losses of tomatoes, maize, and mangoes under the local weather conditions of Abakaliki, southeastern Nigeria. The dryer consisted of key components, including a solar chimney, collector unit, drying unit, and absorber plate made from galvanized iron, covered with a 200 µm polythene sheet and glass to enhance solar radiation absorption and minimize heat loss. Fresh produce from the local market was dried in the solar dryer, with drying temperatures ranging from 25°C to 73°C over two to three days. The dryer's performance was tested during both wet and dry seasons, and key metrics such as solar radiation, temperature, air velocity, and relative humidity were measured. The results demonstrated a 30-50% reduction in drying time compared to traditional sun drying methods while maintaining product quality. The dryer performed better during dry seasons and peak solar radiation hours, and the drying process exhibited an exponential relationship between temperature and drying time. Additionally, solar drying affected the nutritional composition of the dried products, influencing antioxidant activity, flavor, and nutrient content. The solar tunnel dryer offers a promising solution for reducing postharvest losses and preserving the nutritional quality of fruits and vegetables in the region. This innovative technology can contribute to food security and sustainable agricultural practices in developing communities.

Keywords: Solar tunnel dryer; Postharvest losses; Drying efficiency; Food preservation; Abakaliki

1. Introduction

Solar drying is a cost-effective, sustainable technology widely used to preserve agricultural products in tropical regions like Nigeria. By using solar dryers, food is protected from dust, microorganisms, and pests while drying more quickly, reducing spoilage [1, 2 and 3]. Fruits like mangoes, tomatoes, and maize, prone to high postharvest losses, often perish due to poor harvesting methods, lack of processing technologies, and market oversupply during harvest season. Solar drying offers a practical solution to this challenge, as it extends shelf life, reduces waste, and generates income for farmers. Unlike traditional sun drying, which leaves crops exposed to contamination, solar drying provides better control and higher product quality [4, 5]. There are two types of solar dryers: passive (natural convection) and active (forced convection) [6]. Passive systems rely on solar energy alone, making them ideal for small-scale use in developing regions, while active systems, using fans for air circulation, are better suited for larger operations. Both types enhance

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drying efficiency by reducing moisture content in crops through a combination of conduction, convection, and solar radiation [7]. This research focuses on the design and development of a natural convection solar tunnel dryer tailored for drying tomatoes, maize, and mangoes in Abakaliki. The goal is to create a low-cost, efficient, and locally made dryer that uses the region's natural climate. The study investigates the dryer's energy efficiency, drying time, product quality, and economic feasibility, with an emphasis on scalability and cost-effectiveness. Solar drying, especially with improved designs like the tunnel dryer, offers a sustainable way to preserve crops, reduce postharvest losses, and improve farmers' livelihoods, particularly during off-seasons.

2. Materials and Method

The solar dryer was designed using key materials including a solar chimney, collector unit, drying unit, and an absorber plate made from galvanized iron sheet painted black. The dryer was covered with a 200 µm transparent polythene sheet, and wood (Iroko) was chosen for the casing due to its availability, cost, and insulating properties. Glass was used to cover the collector and drying chamber to allow solar radiation in while minimizing heat loss. Other materials like mild steel, aluminum trays, insect netting, nails, and hinges were used for durability and airflow control. The dryer had a 5 cm air gap for ventilation and was positioned facing south with a 15° tilt to maintain stable temperatures. The tomatoes, maize, and mangoes used to test the dryer's performance were purchased from a local market in Abakaliki, southeastern Nigeria. The Fresh mangoes, maize, and tomatoes were prepared, sliced to 5 mm, and loaded into the dryer at 3.0 kg per square meter. The drying temperatures ranged from 25 to 73°C, and the drying process lasted two to three days. After reaching the desired moisture levels, the products were stored in polyethylene bags at -4°C for analysis. The performance of the dryer was evaluated during dry (October to November 2022) and wet (June to July 2022) seasons, with no-load tests (without products) and load tests (with mango, maize, and tomatoes) conducted from 8:00 am to 6:00 pm daily. Key performance metrics such as solar radiation, temperatures at different points, air velocity, and relative humidity were measured every 15 minutes using solar meters, thermocouples, anemometers, and thermohygrometers. These tests provided insights into the dryer's efficiency and drying rates for different products and conditions.

The solar dryer efficiency was calculated using the expression

$$n_c = \frac{Q_u}{Acls} \text{ ....1}$$

Where, $Q_u = MC_p \Delta t$, A_c is the collector surface area. The system drying efficiency is the ratio of the energy required to evaporate the moisture of the food material to the heat supplied to the drier. This was evaluated using the relation

$$n_s = \frac{wl}{I_s A_c} \text{ ....2}$$

While the dryer efficiency was evaluated using the relation

$$n_d = \frac{n_s}{n_c} \text{ ....3}$$

Where in equation (2) w is the mass of water evaporated, (l) is the latent heat of evaporation of water at the dryer temperature and A_c is the area of the collector. Tables 1 and 2 show the parameters of the constructed solar dryer.

Table 1 Wooden tray size

S/N	Name	Size
1	Area (m^2)	0.66
2	Thickness	50
3	Density (kg/m^3)	2700

Table 2 Glass material size

S/N	Name	Size
1	Thickness (mm)	4.50
2	Length (m)	0.80
3	Density (kg/m^3)	0.5
4	Specific heat (JKg^{-1} K^{-1})	1.28

3. Results and Discussion

The graphical analysis of the key performance parameters of the designed dryer is presented in Figures 1, 2, 3, 4, 5, 6, 7, and 8.

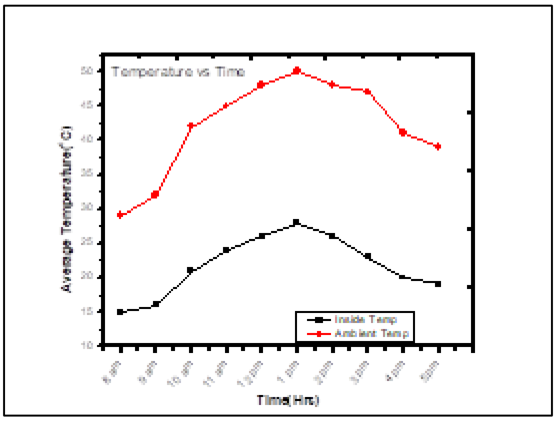

Figure 1 Inside and ambient Temperature profile

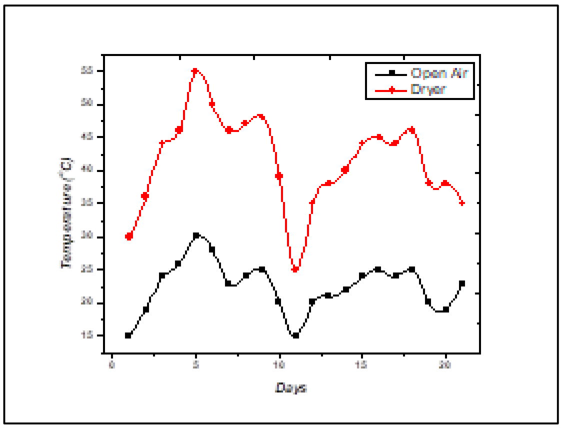

Figure 2 Solar dryer and open air Temperature profile

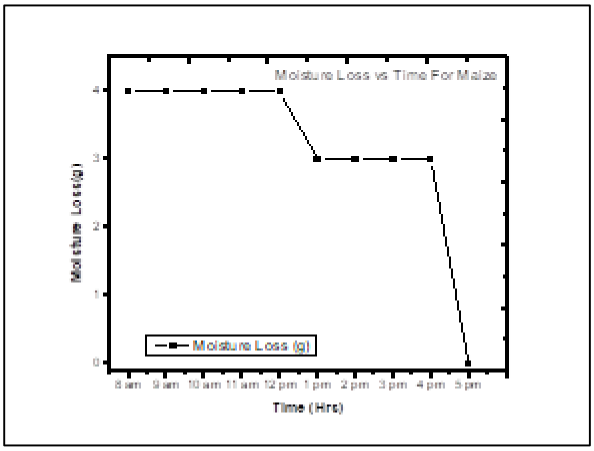

Figure 3A Moisture loss during wet and dry season

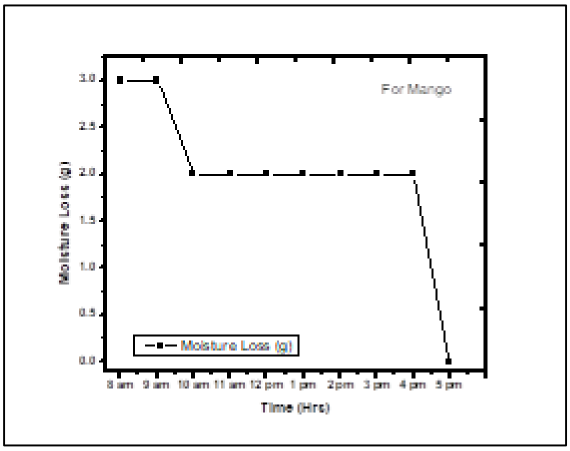

Figure 3B Moisture loss during wet and dry season

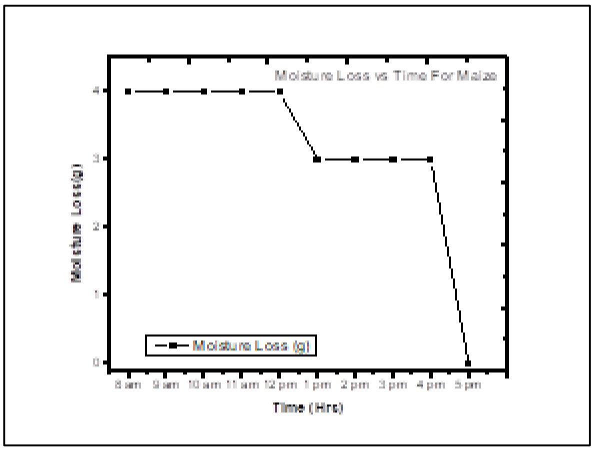

Figure 3C Moisture Loss profile during dry and wet seasons

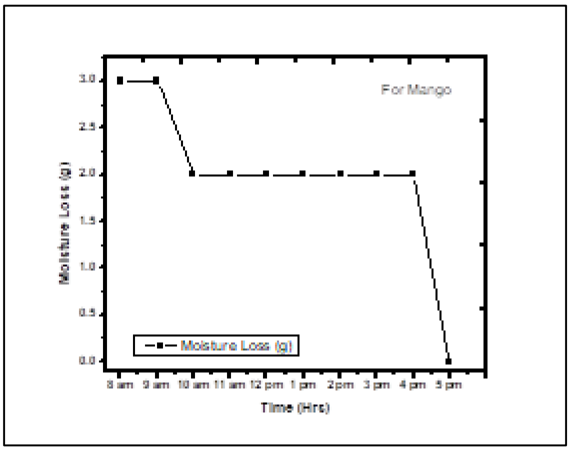

Figure 4 Relative Humidity profile during dry and wet seasons

Figure 1 illustrates the variation in ambient and inside temperature profiles of the designed dryer over the course of the day during solar drying. The results indicate that the temperature fluctuates in response to changes in solar radiation intensity, with maximum ambient and inside temperatures recorded at 47.5°C and 27.5°C, respectively, at 1:00 pm. The dryer demonstrates effective cooling of the air inside, improving drying efficiency during peak solar hours and reducing the risk of overheating.

Figure 2 shows that both the dryer and open air temperatures follow a similar pattern, increasing from Day 1 to Day 5, decreasing until Day 10, and fluctuating until Day 20. The highest temperature recorded was 55°C for the dryer and 29°C for the open air, with variations attributed to changing weather conditions such as sunlight, wind, and humidity.

The moisture loss profile in a solar dryer typically shows an initial rapid decrease in moisture content, followed by a slower rate as drying progresses, resulting in a curve that flattens over time. Temperature and humidity play crucial roles in drying efficiency, with solar dryers generating higher temperatures and lower humidity to enhance moisture removal [8]. Figures 3A, 3B, and 3C indicate that the highest moisture reduction occurred between 4-5pm, highlighting optimal drying conditions during this time, consistent with findings by [9, 10]. Additionally, the elevated temperatures achieved in solar drying help prevent insect and microbial infestation [11], making it a more effective alternative to natural and mechanical drying methods commonly used in developing countries.

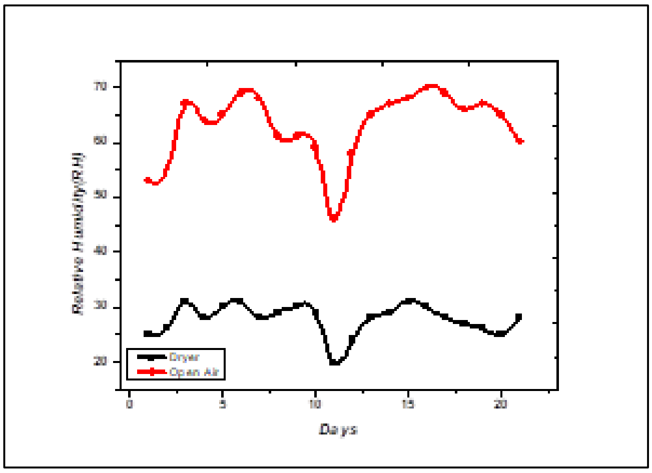

Figure 5 Relative Humidity Variation in days in the open and the solar dryer profile during dry and wet seasons

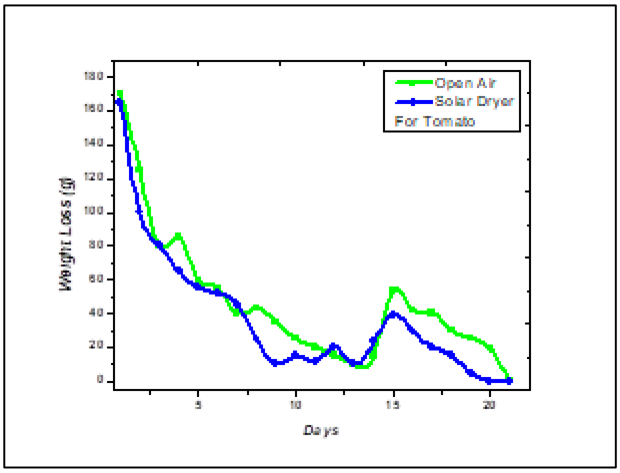

Figure 6 Tomato weight loss in days

Figure 4 shows that relative humidity at the dryer's collector entry decreased significantly from 10:00 h to 01:00 h, with the wet and dry seasons following similar trends. The drop in relative humidity, more pronounced in the dry season, is attributed to decreased temperature at night, reducing the air's moisture-holding capacity. The daily variation of relative humidity for both solar dryers and open air is influenced by temperature changes, with higher moisture-holding capacity during the day and lower at night. Figure 5 show that the relative humidity followed the same trend for both the dryer and open air, with the highest on Day 15 and the lowest on Day 11.

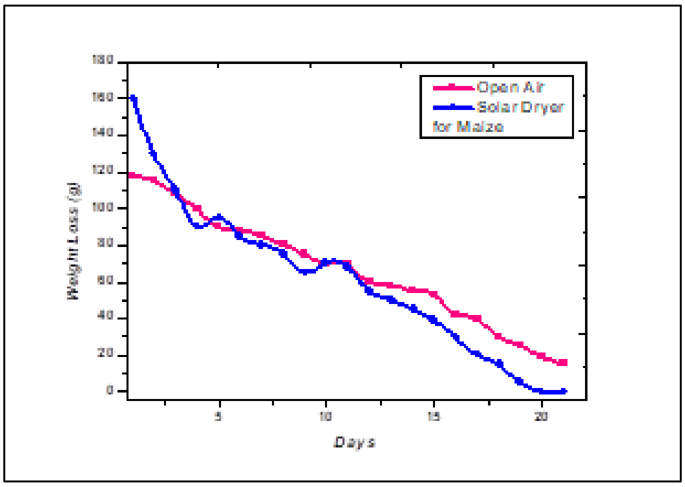

Figure 7 Maize weight loss in days

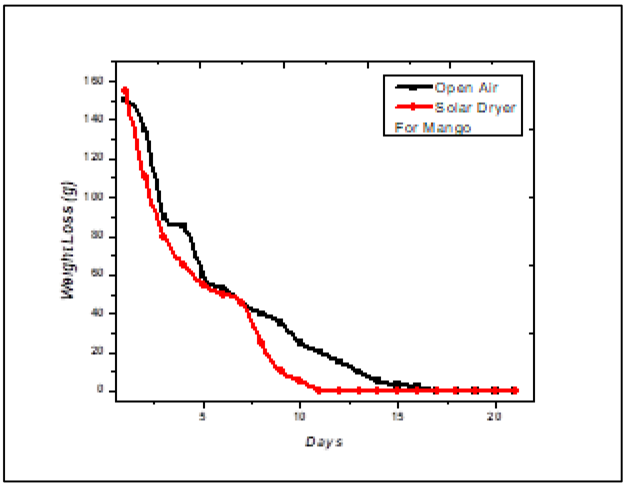

Figure 8 Mango weight loss in days

Figure 6 shows that the drying rate for tomato slices increased during the first 12 days, with the most rapid moisture removal occurring between days 1 and 5, and then slowed significantly after day 16. The solar dryer exhibited a higher average moisture removal rate of 10.52g/day compared to 7.28g/day in the open dryer, due to its ability to harness solar energy to heat the air and increase evaporation; this is in agreement with [12]. In contrast, the open dryer depended solely on ambient conditions, resulting in a slower drying process.

Figure 7 shows that maize seeds lost more weight as the number of drying days increased, with higher weight loss in the solar dryer (160g) compared to the open air (120g). This indicates that solar drying is more efficient at reducing moisture content than open air drying. As the drying progresses and moisture content decreases, the rate of evaporation slows, causing the drying curves for both methods to eventually merge. Figure 8 indicates that mango fruit experiences a rapid weight loss during the initial days of drying, with weight loss decreasing exponentially from day 1 to day 16 in open air and from day 1 to day 11 in the solar dryer, after which it stabilizes until day 21. This suggests that mango dries more quickly when exposed to open air compared to the solar dryer. Ultimately, the drying process reaches a point where the mango will not lose any more weight, indicating that open-air sun drying is more effective for mangoes than using a solar dryer [13].

4. Conclusion

This study successfully designed and evaluated a low-cost natural convection solar tunnel dryer tailored to the local weather conditions of Abakaliki, demonstrating its efficacy in reducing postharvest losses of tomatoes, maize, and mangoes. The findings indicate a significant reduction in drying time—between 30-50% compared to traditional sun drying—while improving the quality of the dried products. The performance of the solar dryer was notably better during dry seasons and peak solar radiation hours, emphasizing the impact of weather conditions on drying efficiency. Furthermore, the analysis revealed an exponential relationship between temperature and drying time, highlighting the intricate nature of the drying process. Solar drying not only accelerated the drying rate but also impacted the nutritional composition of the food materials, affecting antioxidant activity, flavor profiles, and nutrient content. Overall, the solar tunnel dryer offers a promising solution to reduce postharvest losses in the region, potentially extending the shelf life of dried fruits and vegetables for several months. This innovative approach can significantly contribute to food security and sustainable agricultural practices in developing communities.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflicts of interest.

Data Availability Statement

The data used in this study are available upon reasonable request from the corresponding author.

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