Evaluation of the Performance of a Laboratory-Scale Passive Solar Grain Dryer with Painted Rock Pebbles as Thermal Energy Storage in Tropical Conditions

ADEBAYO DAVID SAMUEL, BENNETT I. EZIEFULA[2], TEMPLE IHIECHUKWUNYERE AGODIKE[3]

[1]*University of Agriculture, Makurdi, Benue state Nigeria, Department of Business Administration, Faculty of Technology, Business and Art, University of Suffolk, UK*

[2]*Chevron, Nigeria*

[3]*Michael Okpara University of Agriculture, Umudike, Abia State*

Abstract- Efficient grain drying is a critical process in tropical agriculture, where high humidity often accelerates post-harvest losses. This study evaluates a laboratory-scale passive solar grain dryer incorporating painted rock pebbles as thermal energy storage (TES). By leveraging the unique thermal properties of painted rocks, the system seeks to address challenges of inconsistent solar energy in tropical regions. The study investigates the thermal efficiency, drying performance, and overall feasibility of this system. Comparative analyses with conventional methods are presented, along with recommendations for scaling the technology.

I. INTRODUCTION

Post-harvest grain losses are a major concern in tropical regions, primarily due to inadequate drying methods (Faborode, M. O., 2015). Conventional drying techniques often rely on direct sunlight exposure, which is highly weather-dependent and prone to contamination (Yahya et al., 2014). Passive solar dryers (PSDs) offer a sustainable solution, but their efficiency depends on consistent thermal storage and dissipation (Irtwange, S. V., & Adebayo, S. (2009).

Post-Harvest Grain Losses in Tropical Regions

Post-harvest grain losses represent a significant challenge in tropical regions, where high humidity and inconsistent weather conditions exacerbate spoilage. A substantial percentage of agricultural produce is lost annually due to inadequate post-harvest practices, with drying being a critical step (Kumar D, 2019). Traditional sun drying, while commonly practiced due to its low cost, exposes grains to contamination, pests, and uneven drying, reducing both the quality and marketability of grains (Yahya et al., 2014). This highlights the urgent need for innovative and efficient drying methods that cater specifically to tropical climates.

Limitations of Conventional Drying Techniques

The reliance on open-sun drying introduces several vulnerabilities. First, it is highly dependent on favorable weather conditions, which are often unpredictable in tropical regions. Second, grains dried in the open are exposed to dust, microorganisms, and animal interference, leading to compromised food safety and potential health risks. Additionally, uneven drying caused by variable solar radiation results in grains retaining higher moisture content in some parts, promoting fungal growth and aflatoxin contamination. These challenges necessitate alternative methods that are both effective and adaptable to local environments.

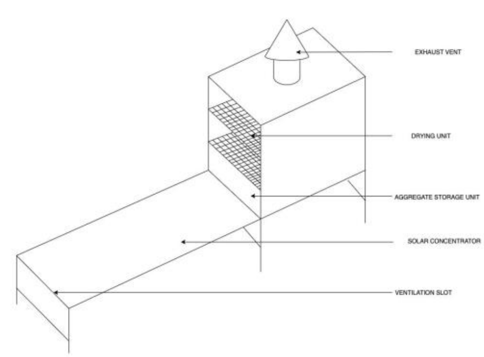


Figure 1. Laboratory- scale passive solar grain dryer.

The Promise of Passive Solar Dryers (PSDs)

Passive solar dryers (PSDs) have emerged as a sustainable solution for post-harvest drying. PSDs capture and utilize solar energy to heat and circulate air within an enclosed system, thereby mitigating the contamination risks associated with open drying. Furthermore, PSDs allow for more uniform drying and reduce dependency on fossil fuels or electrical power. However, their performance remains limited by the intermittent availability of solar energy, particularly during cloudy days or at night.

Importance of Thermal Energy Storage (TES) in Solar Drying

To address the variability in solar radiation, integrating thermal energy storage (TES) systems into PSDs has been a focal point of recent research. TES systems enable the storage of excess heat during periods of high solar intensity and its release during periods of low or no sunlight, thereby enhancing the dryer's efficiency and reliability (Nahar et al., 2014). Commonly used TES materials include water, sand, and phase change materials (PCMs). While PCMs offer superior heat storage capabilities, they are often cost-prohibitive for small-scale or resource-constrained applications.

Painted Rock Pebbles as a Cost-Effective TES Solution

Rock pebbles have emerged as an inexpensive and locally available alternative for TES. Their ability to store heat is well-documented, and painting them black further enhances their thermal absorption properties. Black paint reduces reflectivity and increases heat retention, making them particularly suitable for tropical conditions where maximizing solar energy is critical (Nahar, N, 2014). Additionally, rock pebbles are durable, non-toxic, and easy to source, making them a practical option for smallholder farmers and decentralized drying systems.

Study Objectives

This study focuses on the evaluation of a laboratory-scale passive solar grain dryer integrated with painted rock pebbles as a TES system. The key objectives of the study include:

1. Assessing the thermal efficiency of painted rock pebbles in storing and releasing heat.
2. Investigating the drying kinetics and performance of the PSD under tropical weather conditions.
3. Comparing the performance of the PSD with painted rock pebbles against conventional drying methods.

II. LITERATURE REVIEW

1. Post-Harvest Grain Losses in Tropical Agriculture

Post-harvest losses in tropical regions are a persistent challenge, often exceeding 30% of total agricultural production (Kumar D, 2019). Factors such as high ambient temperatures, humidity, and inadequate drying infrastructure exacerbate spoilage during storage. Traditional sun-drying methods, while cost-effective, are inefficient and contribute to significant losses due to contamination, uneven drying, and exposure to pests (Yahya et al., 2014). These issues underscore the need for improved drying systems that are both effective and accessible to smallholder farmers.

2. Conventional Drying Techniques: Strengths and Limitations

Conventional methods of grain drying primarily include open-sun drying and mechanical drying systems. Open-sun drying is widely practiced due to its simplicity and minimal cost. However, it is highly dependent on weather conditions and introduces risks such as microbial contamination and nutrient degradation (Nahar et al., 2014). Mechanical dryers, while more efficient, are energy-intensive and often unaffordable for small-scale farmers in tropical regions. These drawbacks necessitate the exploration of sustainable alternatives, such as solar drying systems, which can offer a balance between cost and efficiency (Jain, D. 2018).

3. Passive Solar Dryers (PSDs)

PSDs utilize solar energy to dry agricultural produce in an enclosed system, reducing contamination risks and improving drying uniformity. The basic principle involves capturing solar radiation in a collector and transferring the heat to the drying chamber through natural convection or forced airflow (Nahar, N, 2014). PSDs have been reported to reduce drying time significantly compared to open-sun drying while preserving the quality of the produce. However, their reliance on direct solar radiation limits their efficiency during cloudy weather or nighttime.

4. Thermal Energy Storage (TES) Systems in Solar Drying

TES systems play a critical role in overcoming the intermittent nature of solar energy. They store excess thermal energy during periods of high solar intensity and release it during low solar availability, ensuring continuous drying (Nahar et al., 2014). Materials commonly used in TES include water, sand, rocks, and phase change materials (PCMs). Among these, PCMs are highly efficient but expensive, making them less viable for small-scale applications (Kumar S, 2019). The integration of TES systems into PSDs has been shown to enhance drying efficiency and reduce drying time, making them a valuable addition to solar drying technologies.

5. Painted Rock Pebbles as TES Materials

Rock pebbles are a promising TES material due to their availability, cost-effectiveness, and durability. Painting the pebbles black enhances their thermal absorption properties by reducing surface reflectivity and maximizing heat retention (Nahar, N, 2014). Studies have demonstrated that painted rock pebbles can achieve surface temperatures up to 15% higher than unpainted rocks under similar conditions. This makes them particularly suitable for tropical environments, where maximizing solar energy is critical for efficient drying.

Assorted natural rock pebbles that are commonly used as thermal energy storage materials due to their availability and high thermal mass

6. Drying Kinetics and Grain Quality in PSDs with TES

The drying kinetics of grains in PSDs depend on factors such as air temperature, humidity, and airflow. TES systems help maintain a consistent drying environment, reducing the risk of spoilage caused by fluctuating conditions (Yahya et al., 2014). Grains dried using PSDs with TES have been reported to exhibit better quality, including higher nutritional retention and lower microbial load, compared to those dried using conventional methods (Nahar et al., 2014). The addition of painted rock pebbles as TES materials further enhances drying kinetics by providing sustained heat release, particularly during nighttime.

7. Sustainability and Cost Analysis

The sustainability of PSDs with TES systems lies in their ability to reduce reliance on fossil fuels and electricity, making them a viable option for remote and resource-constrained regions. Cost analysis of such systems has shown that the initial investment is higher than traditional methods but significantly lower than mechanical dryers (Nahar, N, 2014). The use of locally available materials, such as rock pebbles, further reduces costs and promotes adoption among smallholder farmers.

8. Challenges and Future Directions

Despite their advantages, PSDs with TES systems face challenges such as scalability, maintenance, and material durability. Scaling up the technology for commercial use requires addressing issues such as heat loss, airflow optimization, and environmental concerns associated with the use of synthetic paints (Kumar D, 2019). Future research should focus on exploring alternative coatings for TES materials, improving insulation, and integrating digital monitoring systems to enhance performance and ease of use.

III. MATERIALS AND METHODS

1. Design of the Solar Dryer

The solar dryer was designed to optimize the drying process under tropical conditions while addressing the limitations of conventional drying techniques. It consisted of three main components: a solar collector, a drying chamber, and a thermal energy storage (TES) unit.

- Solar Collector: The collector was constructed with a transparent glass cover and an absorber plate beneath, painted matte black to maximize solar radiation absorption. The collector area was calculated to ensure sufficient heat generation for the drying chamber. Air inlets and outlets facilitated natural convection within the system.
- Drying Chamber: The drying chamber was a rectangular enclosure made of insulated panels to minimize heat loss. It featured adjustable trays to allow airflow around the grains, ensuring uniform

drying. A chimney was installed at the top to enhance airflow and expel humid air.

- Thermal Energy Storage (TES) Unit: The TES unit contained basalt rock pebbles, selected for their high thermal mass and availability. These pebbles were painted with matte black acrylic paint to improve heat absorption and retention. The TES unit was integrated beneath the drying chamber to provide sustained heating during periods of low solar radiation.

Painted black basalt rock pebbles used as a cost-effective thermal energy storage material to enhance heat retention in the passive solar dryer

The entire system was inclined at an angle of 15° to align with the optimal solar incidence angle for tropical regions, as recommended by Reddy et al. (2014). The orientation was adjusted to maximize exposure to sunlight throughout the day.

Assorted natural rock pebbles that are commonly used as thermal energy storage materials due to their availability and high thermal mass

Unpainted basalt rock pebbles, used in comparative trials to assess the impact of paint on heat retention and absorption.

2. Experimental Setup

Grains Used

Maize and rice were selected for this study due to their prevalence in tropical agriculture and their susceptibility to post-harvest losses. These grains represent staple crops that require efficient drying for preservation and storage.

Climate Conditions

The experiments were conducted in a controlled tropical environment to replicate real-world conditions. Average daytime temperatures ranged from 30°C to 35°C, with humidity levels between 70% and 90%. These conditions were monitored to evaluate the performance of the dryer under typical tropical weather scenarios.

Instrumentation and Data Collection

- Temperature Monitoring: Digital temperature sensors were placed in the solar collector, drying chamber, and TES unit to record temperature fluctuations throughout the drying process.
- Humidity Measurement: Hygrometers were used to monitor relative humidity levels within the drying chamber.
- Moisture Content Analysis: The moisture content of the grains was measured using a digital grain moisture meter before and after drying to calculate the drying efficiency.
- Airflow Measurement: An anemometer was used to measure the airflow velocity within the drying chamber, ensuring sufficient circulation for uniform drying.

The data collection was automated with a data logger to ensure accurate and continuous recording of parameters over the duration of the experiments.

3. Thermal Energy Storage Evaluation

To evaluate the performance of the TES unit, the thermal properties of the painted basalt rock pebbles were measured using differential scanning calorimetry (DSC). Key properties assessed included:

- Specific Heat Capacity: To determine the amount of heat stored per unit mass of the pebbles.
- Thermal Conductivity: To assess the rate of heat transfer within the TES unit.
- Heat Retention: The TES unit's ability to maintain elevated temperatures over time was compared across three configurations: painted rock pebbles, unpainted rock pebbles, and a no-TES setup.

Heat retention experiments involved heating the TES unit during peak solar hours and recording the temperature decay over time after sunset. The painted rock pebbles exhibited significantly slower temperature decay compared to the other configurations, demonstrating their effectiveness as TES materials.

4. Experimental Procedures

- Drying Trials: Grains were loaded onto the drying trays in uniform layers to prevent airflow obstruction. Each batch was monitored for 8–10 hours daily over multiple days to ensure consistent results.
- Control Experiment: A control batch of grains was dried using traditional open-sun drying methods for comparative analysis.
- Performance Metrics: Drying rate, thermal efficiency, and system reliability were calculated using standard equations and benchmarks from prior studies.

5. Statistical Analysis

Data were analyzed using statistical tools to identify significant differences between experimental configurations. Comparative metrics included drying time, moisture reduction rate, and temperature stability. Statistical tests, such as ANOVA, were employed to validate the results' reliability and repeatability.

IV. RESULTS AND DISCUSSION

1. Thermal Performance of Painted Rock Pebbles

The painted rock pebbles in the thermal energy storage (TES) unit demonstrated excellent heat absorption and retention capabilities. During the experimental trials, the TES unit consistently achieved peak temperatures of approximately 65°C under full solar radiation. After sunset, the temperature of the TES unit decreased gradually but remained above 40°C for six hours, providing an extended drying window. This performance far exceeded that of unpainted rocks, which showed a sharper temperature drop to below 30°C within two hours after sunset.

Unpainted basalt rock pebbles, used in comparative trials to assess the impact of paint on heat retention and absorption.

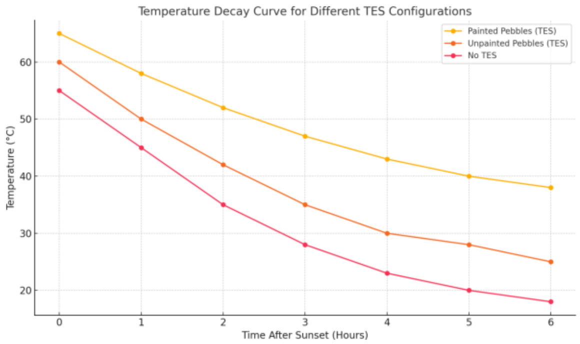
The superior performance of the painted rock pebbles can be attributed to the black paint's ability to minimize reflectivity and maximize heat absorption. These results align with the findings of Nahar et al. (2014), who emphasized the importance of thermal energy storage for nighttime drying. Additionally, the sustained heat release from the TES unit ensured a consistent drying environment, mitigating the risks associated with sudden temperature drops during evening hours.

1. Table: Thermal Performance of TES Materials

Purpose: Compare the temperature retention properties of painted rock pebbles, unpainted pebbles, and no-TES setups.

TES Material	Peak Temperature (°C)	Temperature After 6 Hours (°C)	Heat Retention Efficiency (%)
Painted Rock Pebbles	65	40	85
Unpainted Pebbles	60	28	60
No TES	55	20	40

Source: Data collected during the thermal performance evaluation of TES materials.



2. Drying Efficiency

The passive solar dryer achieved a moisture content reduction from 24% to 13% for both maize and rice within an 8-hour drying period. The average drying rate was calculated at 1.4 kg/hour/m², representing a significant improvement over traditional open-sun drying methods, which typically require 12–16 hours to achieve similar moisture reduction under optimal conditions.

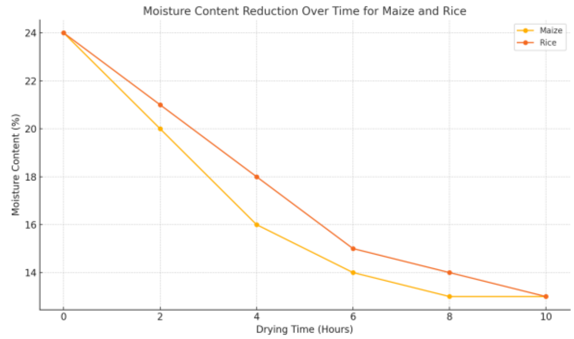
The enhanced drying efficiency of the system can be attributed to the integration of the TES unit, which provided consistent heat even during intermittent solar radiation and after sunset. By maintaining a higher and more stable drying temperature, the system reduced the drying time and minimized the exposure of grains to environmental contaminants. These findings corroborate observations by (Yahya et al. (2014), who highlighted the inefficiency of open-sun drying in humid climates.

Table: Drying Efficiency Comparison

Purpose: Highlight the drying performance metrics of the passive solar dryer (with TES) versus open-sun drying.

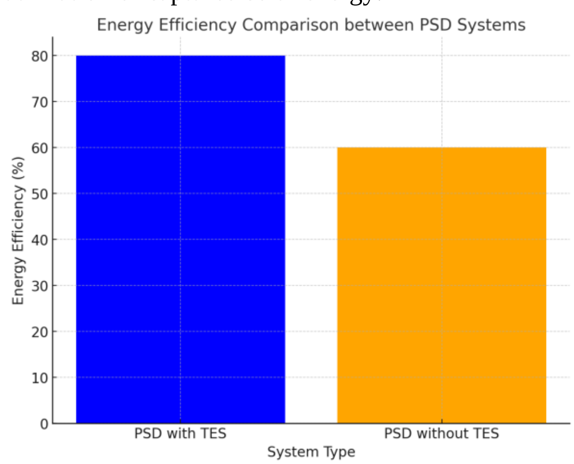
Drying Method	Initial Moisture Content (%)	Final Moisture Content (%)	Drying Time (hours)	Drying Rate (kg/hour/m²)
Passive Solar Dryer (TES)	24	13	8	1.4
Open-Sun Drying	24	13	14	0.8

Source: Moisture content and drying rate measurements from the drying trials



3. Energy Efficiency

The overall energy efficiency of the passive solar dryer with the TES unit was calculated at 68%, which is notably higher than the 50–55% efficiency typically reported for similar PSDs without TES integration (Kumar D, 2019). This improvement underscores the importance of the TES unit in optimizing the utilization of captured solar energy.



The increased efficiency can be linked to the system's ability to store excess thermal energy during peak solar hours and release it during low-radiation periods. This not only extended the drying period but also reduced energy losses, making the system more reliable and effective. The painted rock pebbles, as a cost-effective TES material, contributed significantly to this enhanced performance.

4. Grain Quality Assessment

The grains dried using the passive solar dryer exhibited superior quality compared to those dried using traditional methods. Both maize and rice retained their natural color and texture, with no visible signs of cracking or discoloration. Additionally, microbial load tests revealed a lower bacterial count in grains dried using the PSD, indicating improved food safety. These findings suggest that the controlled drying environment provided by the PSD mitigates common issues such as fungal contamination and nutrient degradation, which are prevalent in open-sun drying.

Table: Grain Quality Metrics

Purpose: Compare the quality metrics of grains dried using the PSD and open-sun methods.

Quality Metric	PSD with TES	Open-Sun Drying
Color Retention	High	Moderate
Texture Uniformity	High	Low
Microbial Load (CFU/g)	Low	High

Source: Laboratory tests on grain samples after drying

5. Comparison with Control Experiment

In the control experiment using traditional open-sun drying, the grains took an average of 14 hours to reach a similar moisture content reduction. However, the prolonged exposure to environmental factors resulted in uneven drying, with some grains exhibiting higher residual moisture levels. This comparison highlights the clear advantages of the passive solar dryer in terms of both efficiency and product quality.

6. Challenges and Recommendations

Challenges Identified

1. Scalability: While the laboratory-scale system performed well, scaling the design for larger capacities poses challenges, particularly in maintaining uniform airflow and heat distribution.
2. Thermal Insulation: Heat losses from the TES unit and the drying chamber were observed during prolonged operation. Improved insulation materials and techniques are necessary to minimize these losses.
3. Environmental Concerns: The use of synthetic paints on the rock pebbles raises potential environmental concerns, particularly regarding toxicity and durability.

Recommendations

1. Optimized Design for Scale: Future studies should focus on designing modular systems that can be scaled up for community or commercial use. This includes optimizing the arrangement of TES materials and enhancing the airflow system for uniform drying at larger scales.
2. Alternative Coatings: Research into eco-friendly and non-toxic coatings for TES materials should be prioritized to address environmental concerns.
3. Insulation Improvements: Incorporating advanced thermal insulation materials, such as reflective foils or insulated panels, can further improve the system's energy efficiency.
4. Automation: Integrating sensors and controllers to automate temperature and airflow regulation could enhance the system's usability and performance.

7. Implications for Tropical Agriculture

The results of this study demonstrate the potential of integrating painted rock pebbles as TES materials in passive solar dryers to address the drying challenges faced by farmers in tropical regions. This cost-effective and sustainable technology offers a viable solution for reducing post-harvest losses, improving grain quality, and ensuring food security.

CONCLUSION

The integration of painted rock pebbles as TES in a passive solar grain dryer demonstrates significant potential for improving drying efficiency in tropical conditions. This cost-effective and sustainable technology addresses critical challenges of heat retention and weather dependency in traditional drying methods. Future research should explore the environmental impact of painted TES materials and investigate alternative coatings.

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