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Performance Evaluation of a Natural Convection Solar Dryer for Drying Banana Slices

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Abstract
Solar drying is an environmentally friendly technique for preserving agricultural products by utilizing solar energy as the primary source of thermal energy. The present study investigates the performance of a small-scale natural-convection solar dryer for drying banana slices. A cabinet-type indirect solar dryer consisting of a flat-plate solar air collector (1.00 m²) and an insulated drying chamber was used. Fresh banana slices of approximately 2.05 kg were dried in a single layer on three trays. The experiment was conducted on a clear-sky day from 9:00 AM to 5:00 PM. Ambient temperature, drying-chamber temperature, solar radiation, relative humidity, and sample mass were recorded at one-hour intervals. The initial moisture content of the banana sample was 73.8% on a wet basis (wb). The drying-chamber temperature remained above ambient temperature throughout the experiment and reached a maximum of 55.6°C at 2:00 PM, which was 22.2°C above the ambient temperature. The sample mass decreased from 2.050 kg to 1.053 kg, and the moisture content decreased from 73.8% to 49.0% (wb) at the end of the day. The drying rate reached a maximum of 0.190 kg/h during 10:00-11:00 and thereafter showed a falling-rate behaviour. The average drying efficiency of the dryer was approximately 11.1%. Since the moisture content at the end of the first day was still well above the level required for safe storage, further drying would be needed to complete the process. The study demonstrates the potential of a simple natural-convection solar dryer for low-cost preservation of agricultural products, particularly in regions with adequate solar radiation.
***Keywords**: Solar dryer, banana, drying rate, moisture content, solar radiation, natural convection, drying efficiency.*

1. Introduction

Agricultural products generally contain a considerable quantity of moisture immediately after harvesting. High moisture content promotes microbial activity, enzymatic reactions and deterioration, thereby reducing the storage life and market value of the product. Drying is therefore one of the oldest and most widely used methods of preserving agricultural products.

Traditional open-sun drying is inexpensive and simple, but it has several limitations. Products exposed directly to the environment can be contaminated by dust, insects, animals and microorganisms. Drying is also strongly dependent on weather conditions and may require several days. Solar drying provides an alternative approach in which solar energy is converted into useful thermal energy for removing moisture from agricultural products. Solar dryers can provide higher and more controlled temperatures than open-sun drying while protecting the product from direct environmental contamination.

Several experimental investigations have demonstrated the effectiveness of direct, indirect and forced-convection solar dryers for banana preservation, reporting substantial reductions in banana moisture content [1-5]. Recent work has also investigated the influence of airflow, chamber temperature and tray position on banana drying behaviour [1, 4, 5]. Banana was selected for the present investigation because of its relatively high initial moisture content and its susceptibility to deterioration after harvesting. The main objective of this study is to investigate the drying characteristics and thermal performance of a small-scale natural-convection solar dryer.

Objectives

1. To investigate the performance of a natural-convection solar dryer.
2. To determine the variation of temperature inside the drying chamber.
3. To study the reduction in mass and moisture content of banana slices.
4. To determine the drying rate at different stages of drying.
5. To estimate the drying efficiency of the solar dryer.
6. To assess the potential of solar drying for the preservation of banana slices.

2. Description of the Solar Dryer

The solar dryer considered in this study consists of a flat-plate solar air collector, an insulated drying chamber, transparent glazing, an absorber plate, drying trays, an air inlet, a moist-air outlet and a supporting frame.

The collector absorbs incident solar radiation and converts it into thermal energy. Air entering the collector is heated and rises naturally because of buoyancy. The heated air subsequently enters the drying chamber and passes over the banana slices placed on the drying trays. The system operates without an electrically driven fan; the movement of air is produced by natural convection.

2.1 Dryer Specifications

Table 1. Specifications of the solar dryer

Parameter	Value
Collector length	1.22 m
Collector width	0.82 m
Collector area	1.00 m²
Collector inclination	22°
Drying chamber length	0.82 m
Drying chamber width	0.62 m
Drying chamber height	0.82 m
Number of trays	3
Tray material	Stainless-steel mesh
Glazing	Transparent glass
Air circulation	Natural convection
Initial product load	2.05 kg
Banana slice thickness	5.2 mm

3. Materials and Methodology

3.1 Preparation of Banana Samples

Fresh ripe bananas of approximately uniform size and maturity were selected. The bananas were washed with clean water and peeled manually. The edible portion was sliced into pieces approximately 5.2 mm thick. Approximately 2.05 kg of prepared slices were weighed and distributed uniformly over the drying trays in a single layer to minimize overlapping and to provide maximum exposure to the heated air.

3.2 Experimental Procedure

Before loading the product, the solar dryer was exposed to solar radiation for approximately 30 minutes so that the collector and drying chamber could reach stable operating conditions. The banana slices were then placed on the trays, and measurements were taken at approximately one-hour intervals. The following parameters were monitored: ambient temperature, drying-chamber temperature, solar radiation, relative humidity and product mass. The experiment was carried out on a clear-sky day from 9:00 AM to 5:00 PM.

4. Experimental Observations

Table 2. Meteorological and dryer conditions

Time	Ambient temp (°C)	Chamber temp (°C)	Solar radiation (W/m²)	Relative humidity (%)
09:00	27.5	35.1	510	65
10:00	28.3	38.8	630	59
11:00	29.8	44.2	725	56
12:00	31.6	50.1	795	48
13:00	32.2	53.8	860	47
14:00	33.4	55.6	868	43
15:00	32.4	54.2	825	45
16:00	31.1	50.9	712	52
17:00	29.5	45	558	54

The maximum drying-chamber temperature was 55.6°C at 2:00 PM, while the maximum solar radiation was 868 W/m². The chamber temperature remained higher than the ambient temperature throughout the experiment.

5. Mass Reduction During Drying

Table 3. Variation of banana sample mass

Time	Sample mass (kg)	Mass loss from initial mass (kg)
09:00	2.050	0.000
10:00	1.865	0.185
11:00	1.675	0.375
12:00	1.500	0.550
13:00	1.352	0.698
14:00	1.234	0.816
15:00	1.146	0.904
16:00	1.088	0.962
17:00	1.053	0.997

The sample lost 0.997 kg of mass during the experimental period, i.e. approximately 48.6% of the initial mass, which was removed in the form of water.

6. Determination of Moisture Content

The moisture content on a wet basis at any time is calculated as $MC(wb) = (m - m_d)/m \times 100$, where m is the sample mass at that time and m_d is the mass of dry matter, which remains constant during drying. The initial moisture content of the sample was 73.8% (wb). The dry matter in the initial 2.05 kg sample is therefore $m_d = 2.05 \times (1 - 0.738) = 0.537$ kg. The moisture content on a dry basis is $M = (m - m_d)/m_d$.

Table 4. Calculated moisture content

Time	Sample mass (kg)	Moisture content (% wb)	Moisture content (kg/kg db)
09:00	2.050	73.8	2.817
10:00	1.865	71.2	2.472
11:00	1.675	67.9	2.119
12:00	1.500	64.2	1.793
13:00	1.352	60.3	1.517
14:00	1.234	56.5	1.298
15:00	1.146	53.1	1.134
16:00	1.088	50.6	1.026
17:00	1.053	49.0	0.961

The moisture content remaining after one day of drying (49.0% wb) is still high, indicating that banana slices would require further drying to reach the lower moisture level suitable for long-term storage.

7. Drying Rate

Table 5. Drying rate

Period	Mass loss (kg)	Drying rate (kg/h)
09-10	0.185	0.185
10-11	0.190	0.190
11-12	0.175	0.175
12-13	0.148	0.148
13-14	0.118	0.118
14-15	0.088	0.088
15-16	0.058	0.058
16-17	0.035	0.035

The drying rate increased slightly during the first two hours as the dryer warmed up, reached a maximum of 0.190 kg/h during 10:00-11:00, and then decreased steadily to 0.035 kg/h by the end of the experiment. This behaviour is characteristic of agricultural products: easily available surface moisture is removed first, followed by increasingly difficult internal moisture migration [2, 4].

8. Moisture Ratio

The moisture ratio was calculated on a dry basis as MR = (M − M_e)/(M_0 − M_e), where M is the moisture content at time t, M_0 is the initial moisture content and M_e is the equilibrium moisture content. An equilibrium moisture content of 10% (wb), equivalent to 0.111 kg/kg (db), was assumed for the present calculation; this value was not measured, and the moisture ratio is sensitive to it.

Table 6. Moisture ratio

Time	Moisture content (kg/kg db)	Moisture ratio
09:00	2.817	1.000
10:00	2.472	0.873
11:00	2.119	0.742
12:00	1.793	0.622
13:00	1.517	0.520
14:00	1.298	0.438
15:00	1.134	0.378
16:00	1.026	0.338
17:00	0.961	0.314

The continuous decrease in moisture ratio indicates progressive removal of moisture from the banana slices.

9. Temperature Characteristics

The drying-chamber temperature increased with increasing solar radiation during the morning. At 9:00 AM the chamber temperature was 35.1°C compared with an ambient temperature of 27.5°C. It reached a maximum of 55.6°C at 2:00 PM, after which both solar radiation and chamber temperature decreased. The maximum temperature difference between the drying chamber and the ambient air occurred at 2:00 PM (22.2°C). This temperature elevation demonstrates the ability of the solar collector to provide heated air for drying.

10. Drying Efficiency

The drying efficiency was calculated as the ratio of the energy used to evaporate moisture to the solar energy incident on the collector during the drying period. For the present experiment:

- Mass of moisture removed = 0.997 kg
- Latent heat of vaporization ≈ 2380 kJ/kg
- Mean solar radiation = 720.3 W/m² (mean of the nine hourly readings)
- Collector area = 1.00 m²
- Drying time = 8 h

The energy used for moisture evaporation is 0.997 × 2380 = 2372.9 kJ. The incident solar energy was obtained by integrating the hourly radiation readings over the 8 h period using the trapezoidal rule, which gives 21416 kJ for a collector area of 1.00 m². The drying efficiency of the dryer for the considered operating period is therefore 2372.9/21416 ≈ 11.1%. (Using the simple mean radiation of 720.3 W/m² × 8 h gives 20745 kJ and about 11.4%, a difference of less than 0.4 percentage points.)

11. Discussion

The analysis indicates that the solar dryer provided a substantially higher drying-air temperature than the surrounding atmosphere. The increase resulted primarily from absorption of solar radiation by the collector. The chamber temperature followed the trend of solar radiation, which increased during the morning, peaked in the early afternoon and then decreased.

The product mass decreased continuously during drying. The largest mass reductions occurred in the earlier stages, while the rate of mass loss decreased gradually later. This suggests that moisture movement from the interior of the slices toward the surface became the limiting process in the later stage, although the present data alone cannot confirm the controlling mechanism. The falling-rate behaviour agrees qualitatively with published solar-drying studies on banana [1, 2, 4].

The enclosed dryer also protects the product from dust, insects and other contaminants, which is an advantage over open-sun drying. Previous experimental studies have reported shorter drying times and improved product quality for solar drying compared with open-sun drying [1, 5]; however, no open-sun control was run in the present work, so no such comparison is made here.

12. Comparison with Published Studies

Table 7. Comparison with published studies

Study	Product	Dryer type	Reported result
Present investigation	Banana	Natural-convection indirect	Maximum chamber temperature ≈ 55.6°C
Mawire et al. (2024) [1]	Banana	Indirect, forced convection	Chamber temperature ≈ 48-50°C
Nabnean and Nimnuan (2020) [3]	Banana	Direct, forced convection	Drying temperature 35-60°C

The values in Table 7 are given for reference only and are not directly comparable, because dryer configuration, airflow, weather conditions, product loading and collector design differ between the studies and can substantially affect drying performance.

13. Advantages of the Solar Dryer

1. Solar energy is freely available and renewable.
2. No conventional fuel is required.
3. Natural convection eliminates the electrical power requirement for a fan.
4. The product is protected from direct environmental contamination.
5. The dryer can be constructed from relatively simple materials.
6. The drying temperature is higher than the ambient temperature.
7. The system is suitable for small-scale agricultural applications.
8. It can potentially reduce post-harvest losses.

14. Limitations

The performance of the dryer depends strongly on weather conditions. The present investigation covers a single drying day and therefore does not represent the performance of the dryer in different seasons; the experiment was not repeated. Drying was not continued to the final storage moisture level, and no open-sun control was run in parallel. The equilibrium moisture content used for the moisture ratio was assumed rather than measured. The chamber temperature may also be non-uniform when several trays are used; tray position has been reported to influence drying behaviour and moisture-ratio distribution [5]. Performance could be improved by incorporating thermal energy storage, better insulation or controlled airflow.

15. Future Scope

- Comparison between natural and forced convection.
- Comparison with open-sun drying.
- Drying of other agricultural products.
- Effect of slice thickness and loading density.
- Mathematical drying models (Page, Henderson-Pabis, Midilli), which have been reported to describe banana drying kinetics well.
- Energy and exergy analysis.
- Thermal energy storage and a photovoltaic-powered fan.
- Optimization of collector inclination.
- Product quality and nutritional characteristics.

16. Conclusion

A small-scale natural-convection solar dryer was investigated for drying banana slices. The drying-chamber temperature increased from 35.1°C in the morning to a maximum of 55.6°C in the afternoon, while solar radiation reached 868 W/m². The sample mass decreased from 2.050 kg to 1.053 kg and the moisture content from 73.8% to 49.0% (wb) in one day of drying.

The drying rate was highest (0.190 kg/h) in the early stage and decreased progressively thereafter, which suggests that the later stage of drying was limited mainly by internal moisture movement. The estimated drying efficiency was approximately 11.1%. The results indicate that a simple natural-convection solar dryer can provide a useful low-cost approach to agricultural-product preservation in regions with good solar availability.

Further investigations involving multi-day drying to the safe storage moisture level, different products, loading conditions, airflow rates and dryer geometries are recommended to optimize the system.

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