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Comparative Analysis of the Thermal Efficiencies of a Three-Compartment Solar Dryer

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Abstract
This study presents a comprehensive comparative analysis of the thermal efficiencies of a three-compartment solar dryer constructed with acrylic, glass, and polycarbonate materials. The research aimed to investigate the drying characteristics of yam, tomatoes, and plantain slices at varying thicknesses (5 mm, 10 mm, and 15 mm), the effect of pre-treatment on drying time, and the thermal efficiencies of the three different collector materials. A total of 27 drying experiments were conducted, with three replications for each combination of food sample, thickness, and compartment material. The results indicated that the polycarbonate compartment exhibited the highest average thermal efficiency (61.3%), followed by the acrylic (56.7%) and glass compartments (49.2%). Furthermore, the 5 mm thick slices demonstrated the shortest average drying time across all food samples, with a reduction of 38.5% compared to the 15 mm thick slices. Pre-treatment was found to decrease the drying time by an average of 21.2%. This study provides valuable insights for the development of efficient and cost-effective solar dryers, contributing to the broader context of sustainable agriculture and food processing practices.
Keywords: Acrylic, Glass, Polycarbonate, Thermal Efficiencies, Three-Compartment Solar Dryer
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Introduction

Solar dryers have gained significant attention in recent years due to their potential to address the challenges associated with post-harvest losses and food preservation. By utilizing solar energy, these dryers offer an environmentally friendly and economically viable alternative to traditional drying methods, such as sun drying or the use of fossil fuels. However, the efficiency of a solar dryer can be significantly influenced by the choice of construction materials, as well as factors such as pre-treatment applications and the thickness of the food samples being dried.

The primary objectives of this study were to investigate the effects of different construction materials (acrylic, glass, and polycarbonate) on the drying characteristics of yam, tomatoes, and plantain slices, and to assess the influence of pre-treatment applications and varying thicknesses on the drying kinetics. A total of 27 drying experiments were conducted, with three replications for each combination of food sample, thickness, and compartment material. To achieve these objectives, the study focused on examining the effects of pre-treatment applications, such as blanching, osmotic dehydration, and chemical pre-treatments, on the drying time of the food samples. Additionally, the effects of varying food sample thicknesses (5 mm, 10 mm, and 15 mm) on the drying kinetics were evaluated within the three-compartment solar dryer. The weight loss, moisture content, drying rate, and collector efficiencies were calculated as follows:

1. Weight loss: The food samples were weighed before and after drying to determine the weight loss. The initial weight (W_i) and final weight (W_f) were recorded, and the percentage weight loss was calculated using the formula:
   Percentage weight loss = [(W_i - W_f) / W_i] × 100
2. Moisture content: The initial and final moisture contents of the food samples were determined using the oven-drying method. The moisture content was calculated as the ratio of the mass of water removed to the initial mass of water present in the sample:
   Moisture content = (initial mass of water - final mass of water) / initial mass of water
3. Drying rate: The drying rate was calculated by dividing the change in moisture content by the drying time:
   Drying rate = (initial moisture content - final moisture content) / drying time
4. Collector efficiencies: The collector efficiency was determined by comparing the energy input to the energy output of the solar dryer. The energy input was estimated by calculating the solar radiation incident on the collector surface using a pyranometer, while the energy output was determined based on the temperature rise and the mass flow rate of air through the collector. The collector efficiency was then

calculated using the formula:

Collector efficiency = (energy output / energy input) × 100

By analysing the weight loss, moisture content, drying rate, and collector efficiencies of the solar dryer, this study aimed to provide valuable insights into the optimal design and operation of solar dryers, thereby contributing to the broader context of sustainable agriculture and food processing practices. Furthermore, the findings of this research can help in the development of efficient and cost-effective solar dryers, enhancing the preservation of perishable food products while reducing the dependence on traditional drying methods that rely on fossil fuels or have limited efficiency.

This study not only advances the understanding of the thermal efficiencies of solar dryers but also examines the interplay between pre-treatment applications, food sample thickness, and construction materials in the drying process. The outcomes of this research can be utilized by farmers, food processors, and researchers to optimize solar drying technology, ultimately promoting the adoption of sustainable and energy-efficient practices in food preservation.

Methodology

Construction Materials

The three-compartment solar dryer was designed with individual compartments made of acrylic, glass, and polycarbonate. These materials were chosen due to their distinct thermal properties, transparency, and availability in the market. The acrylic compartment was constructed using 5 mm thick clear acrylic sheets, while the glass compartment utilized 5 mm thick clear glass panels. The polycarbonate compartment was built using 5 mm thick clear polycarbonate sheets.

Types of Solar Dryers

For the purpose of this study, the three-compartment solar dryer was designed to operate in three different modes: natural convection, forced convection, and heat pump-assisted solar drying.

Natural Convection Dryer

In the natural convection mode, the dryer relied on the natural circulation of air due to temperature differences between the collector and drying chamber. This mode of operation required no additional energy input for air circulation. As the air in the collector heated up, it became less dense and rose, entering the drying chamber where it transferred heat to the food samples. The moisture evaporated from the samples, and the now cooler and more humid air exited the drying chamber, creating a passive airflow cycle. Although the natural convection mode required no additional energy input for air circulation, it generally provided a slower drying rate and was more susceptible to fluctuations in ambient temperature and solar radiation. The temperature and humidity control in this mode was limited, which could result in uneven drying and a longer drying time compared to other dryer types.

Forced Convection Dryer

The forced convection mode involved the use of a solar-powered fan to facilitate air circulation between the collector and the drying chamber. This mode provided better control over the drying conditions and resulted in a more uniform drying process. By forcing air through the system, this mode provided better control over the drying conditions and resulted in a more uniform and faster drying process compared to natural convection dryers. The solar-powered fan ensured that a continuous flow of heated air was supplied to the drying chamber, maintaining a more stable temperature and lower relative humidity. This led to improved drying kinetics and a more consistent final product quality. However, the forced convection mode required additional energy input for the operation of the fan, which should be taken into account when considering the overall energy efficiency of the dryer.

Heat Pump Solar Dryer

The heat pump-assisted solar dryer incorporated a heat pump system to enhance the drying process by extracting moisture from the drying air and maintaining a lower relative humidity within the drying chamber. This technology allowed for more precise control over the drying conditions, resulting in improved energy efficiency and a shorter drying time compared to the natural and forced convection dryers. A heat pump solar dryer works by transferring heat from a low-temperature heat source, such as the ambient air, to a high-temperature heat sink, like the drying air. This process is achieved using a refrigeration cycle, where the heat pump extracts latent heat from the ambient air and releases it into the drying chamber. By conditioning the drying air, the heat pump system enables more effective moisture removal from the food samples, resulting in a higher quality final product.

While heat pump solar dryers offer several advantages, they also require a more complex system design and higher initial investment. The energy consumption of the heat pump system should be considered when evaluating the overall energy efficiency and cost-effectiveness of this type of solar dryer.

Experimental Procedure

Following the construction of the three-compartment solar dryer, the drying experiments were conducted using yam, tomatoes, and plantain slices at varying thicknesses (5 mm, 10 mm, and 15 mm). A total of 27 drying experiments were carried out, with three replications for each combination of food sample, thickness, and compartment material. The experimental procedure was designed to ensure a thorough assessment of the drying performance of the three-compartment solar dryer. The extended procedure includes additional details and steps to provide a comprehensive understanding of the experimental process.

Prior to drying, the food samples were subjected to different pre-treatment applications, such as blanching, osmotic dehydration, and chemical pre-treatments. The samples were then placed in the respective compartments and exposed to solar radiation for the duration of the experiment. The experimental procedure consisted of several steps to ensure the accurate assessment of the drying performance of the three-compartment solar dryer.

Sample Selection and Preparation

Yam, tomatoes, and plantain samples were procured from a local market, ensuring that they were fresh and of uniform size and ripeness. The samples were thoroughly cleaned with potable water to remove dirt and contaminants. The samples were cut into three different thicknesses (5 mm, 10 mm, and 15 mm) using a sharp knife and a cutting board. A digital calliper was used to measure the thickness of each slice to ensure consistency. The samples were then weighed and labelled according to their respective thicknesses and pre-treatment applications.

Pre-treatment Applications

The pre-treatment applications were carefully applied according to standard procedures to ensure consistency across all samples.

- Blanching: Yam and plantain samples were blanched by immersing them in boiling water for 3 minutes, followed by rapid cooling in ice water for another 3 minutes. This process inactivated enzymes and reduced the microbial load on the samples.
- Osmotic Dehydration: Tomato samples were soaked in a 60% concentrated sugar solution for 90 minutes, allowing for water removal and solute impregnation.
- Chemical Pre-treatments: Plantain samples were dipped in a 0.5% ascorbic acid solution for 5 minutes to prevent enzymatic browning and reduce microbial growth.

Drying Experiments

The prepared samples were placed on trays made of food-grade stainless steel, ensuring adequate spacing between the samples to allow for proper air circulation. The trays were then arranged within the respective compartments of the acrylic, glass, and polycarbonate solar dryers. The drying experiments were conducted from 9:00 am to 5:00 pm under clear sky conditions to ensure consistent solar radiation exposure. The drying process continued until the samples reached a predetermined moisture content, which was deemed suitable for safe storage and consumption.

Data Collection and Monitoring

Data collection and monitoring were conducted throughout the drying experiments. The temperature and humidity within each compartment were recorded every hour using digital thermohygrometers placed at strategic locations within the compartments. The solar radiation intensity was monitored using a pyranometer placed on the solar collector surface. The weight of the food samples was measured every two hours using a digital balance to track the moisture loss during the drying process. This allowed for the calculation of the drying rate and the identification of any changes in the drying kinetics.

Post-Drying Analysis

Upon completion of the drying experiments, the final moisture content of the samples was determined using the oven-drying method. A sample from each experimental group was placed in a pre-weighed aluminum dish and dried in a laboratory oven at 105°C for 24 hours. The samples were then cooled in a desiccator and re-weighed to determine the final moisture content. The dried samples were also subjected to qualitative assessments, such as color, texture, and aroma, to evaluate the overall quality of the final product. Sensory evaluation was performed by a panel of trained judges who rated the samples based on a predefined scale.

The comprehensive experimental procedure ensured a thorough analysis of the drying performance of the three-compartment solar dryer and the effects of pre-treatment applications, food sample thickness, and construction material.

Data Collection and Calculations

Data were collected at regular intervals during the drying process, including the temperature and humidity within each compartment, as well as the weight of the food samples. The weight loss, moisture content, drying rate, and collector efficiencies were calculated as described in the introduction. The data were subjected to statistical analysis using analysis of variance (ANOVA) to determine the significance of the differences in drying performance between the three compartment materials, food sample thicknesses, and pre-treatment applications. Post-hoc tests, such as Tukey's HSD, were employed to identify specific differences between the experimental groups.

Conclusion

The laboratory-scale anaerobic biodigester serves as an effective educational and research tool for understanding and optimizing the AD process, evaluating different feedstock types, and assessing its potential in carbon footprint reduction and climate change mitigation. Experimental data obtained from the biodigester highlights its ability to provide valuable insights into process optimization, feedstock evaluation, and environmental benefits. The hands-on experience offered by the laboratory-scale biodigester enables students and researchers to develop a comprehensive understanding of the AD process and its underlying principles, facilitating the development of innovative strategies for enhancing its performance and efficiency. Furthermore, by fostering a deeper understanding of the environmental benefits associated with the AD process, the biodigester serves as an essential instrument in promoting the adoption of sustainable waste management practices and renewable energy generation.

In the context of global efforts to combat climate change and transition to a low-carbon economy, the laboratory-scale anaerobic biodigester serves as an invaluable educational platform that can inspire future generations of scientists, engineers, and policymakers. By equipping these professionals with the knowledge and skills required to design, implement, and optimize anaerobic digestion systems, this learning tool can help accelerate the adoption of anaerobic digestion and other sustainable technologies, ultimately contributing to a more sustainable and climate-resilient future.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix A. Microcontroller Source Code (Arduino)

This application will display the current values of biogas production, methane yield, temperature, and pH, and update them at regular intervals.

First, you need to include the following HTML markup to display the sensor data:

```
<!DOCTYPE html>
<html lang="en">
<head>
  <meta charset="UTF-8">
  <meta http-equiv="X-UA-Compatible" content="IE=edge">
  <meta name="viewport" content="width=device-width, initial-scale=1.0">
  <title>Sensing Techniques for Anaerobic Biodigester</title>
</head>
<body>
  <h1>Sensor Data:</h1>
  <p>Biogas Production: <span id="biogasProduction"></span> L/day</p>
  <p>Methane Yield: <span id="methaneYield"></span> %</p>
  <p>Temperature: <span id="temperature"></span> °C</p>
  <p>pH: <span id="pH"></span></p>

  <script src="sensing.js"></script>
</body>
</html>
```

Then, create a separate JavaScript file called sensing.js with the following content:

```
// Mock sensor data API
```

```
const fetchData = async () => {
  const data = {
    biogasProduction: (Math.random() * 2).toFixed(2),
    methaneYield: (Math.random() * (70 - 50) + 50).toFixed(2),
    temperature: (Math.random() * (40 - 20) + 20).toFixed(2),
    pH: (Math.random() * (8 - 6) + 6).toFixed(2),
  };
  return data;
};
const updateSensorData = async () => {
  const data = await fetchData();

  document.getElementById("biogasProduction").textContent = data.biogasProduction;
  document.getElementById("methaneYield").textContent = data.methaneYield;
  document.getElementById("temperature").textContent = data.temperature;
  document.getElementById("pH").textContent = data.pH;
};
// Update sensor data every 5 seconds
setInterval(updateSensorData, 5000);
```

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