Solar Dryer with Reheating System for Annatto Fruit Pericarp

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Abstract. Annatto fruit is one of the sources of natural food dye coming from its seeds. Aside from this part, the pericarp of the annatto fruit is a candidate for potential source of fuel. It is necessary for the pericarp to undergo drying prior to biomass energy conversion. The pericarp can be dried at least five days in sun drying to remove the seeds. In line with this, the researchers had designed a solar cabinet dryer introducing a reheating system and gravel used as thermal storage to lessen the drying time of the annatto fruit pericarp. The solar cabinet dryer had a multi layered wire mesh inside the drying cabinet that allows hot air from the collector to circulate and evenly dry the pericarp. Using the solar cabinet dryer, the drying time was lessened to seven hours with a drying rate of 4.37 g/min. The experiment compared three modes of drying consists of no reheating, with partial reheating and full reheating. During the drying process, several parameters such as the temperature, humidity and mass of each tray were measured, recorded and analyzed. It is found out that fully opened re heater has the highest moisture removed with 90.38% system efficiency.

1. Introduction

Annatto or Bixa Orellana, also locally known as achuete in the Philippines, is the source of natural dye that can be extracted from its seeds. This can be used as coloring and bleaching agent as well as can be used for medicinal treatment of some health disorders [1]. Aside from its seeds, the pericarp of the annatto fruits is good source of biomass. It was found out to be a potential source of biofuel [2] with an estimated heating value of about 16 MJ/kg [3]. In order to produce this amount of energy, the biomass should be dried prior to combustion [4].

Common drying method is open sun drying since it is practical and cheap however the material is exposed to contaminant and other foreign matter [5]. Also, sun drying is labor intensive and time consuming [6]. Few literatures on other pericarps used different drying methods such controlled heating using automatic convective drier for mangosteen peels [7] and spray drying for Renealmia alpinia (Rottb.) maas fruit [8]. To lessen power input and produce good quality biomass out of the annatto fruit pericarp, it is necessary to further improve the drying process by designing solar dryer. At present, there is lack of literatures that highlights and focus solar drying on annatto fruit pericarp. This study will set benchmark on designing a solar dryer intended for drying annatto fruit pericarp.
2. Methodology

2.1 Solar Dryer
The solar dryer as seen in Figure 1a is made up of mild steel plates for the drying chamber cabinet and copper alloy material for the solar collector. The shape of the solar collector was designed in the form of trapezoid to allow increase of inlet air flow towards the drying chamber as shown in Figure 1b. The insulation used is polyurethane. The cabinet has three trays made up of food grade steel wire mesh. The solar cabinet dryer design utilizes the use of gravel as thermal heat storage, introduction of reheating system and trapezoidal shaped solar collector. Gravel is considered to be cheap and locally available material for thermal energy storage medium [9]. The introduction of reheating system results to higher drying rate and decreases drying time by 23% to 30% less than the conventional solar drying and traditional sun drying [10]. The reheater is also made up of mild steel.

![Figure 1. Solar dryer for Annatto Fruit. (a) With trays (b) Trapezoidal solar collector](image)

2.2 Drying Testing
The drying testing was conducted in Barangay Mapulo, Taysan, Batangas from February 11 -13, 2019. Due to availability of annatto fruit harvested, the study used kilograms of annatto fruit ranging from 0.9kg to 1.4 kg per tray employing three modes of drying such as fully closed reheating, partially open reheating, and fully open reheating. The variations on the relative humidity and temperature in the drying chamber were monitored using sensors. The incident radiation was observed with the use of pyranometer. The moisture content of the annatto fruit was measured using load cell-based weighing scale. The Arduino Uno software was used for data collection and Microsoft Excel for data analysis.

2.3 Drying Analysis
The formulas shown below were patterned from the studies of [3] and [11]. The percent of moisture in wet basis γ removed from the Annatto fruit pericarp was described in (1) where \( m_w \) is wet mass in kilograms and \( m_d \) is dried mass also in kilograms.

\[
\gamma\% = \frac{m_w - m_d}{m_w} \times 100\%
\]  

(1)

On the other hand, the final moisture content of the pericarp \( m_f \) in which \( m_i \) is the initial mass in kilograms as shown in (2)

\[
m_f = \frac{100 - \gamma}{100} \times m_i
\]

(2)
The amount of moisture content removed \( m \) was expressed in (3) in which \( m_i \) is the initial moisture content while \( m_f \) its final moisture content. The average drying rate \( m_{\text{ave}} \) in (4) is the ratio of the amount of moisture removed over time in minutes.

\[
m = \frac{m_w (m_i - m_f)}{100 - m_f} \quad (3)
\]

\[
m_{\text{ave}} = \frac{m}{t} \quad (4)
\]

For the energy analysis in the drying chamber, the heat absorbed by radiation \( Q_{\text{rad,in}_\text{cab}} \) in the drying chamber was described the formula in (5). The essential parameters in the equation were the metal absorptivity \( \alpha \), surface area \( A_d \) of the drying cabinet exposed to sunlight and the incident solar input \( I \).

\[
Q_{\text{rad,in}_\text{cab}} = \alpha A_d I \quad (5)
\]

Heat transfer \( Q_{\text{g,c,in}} \) through the wall of the collector case was shown in (6) where it the ratio of the change in temperature \( \Delta T_{g,c} \), seen in (7), over the heat transfer coefficient \( \Sigma R_{g,c} \) in (8). The change in temperature in (7) is the difference of the temperatures of the collector case and drying cabinet.

\[
Q_{\text{g,c,in}} = \frac{\Delta T_{g,c}}{\Sigma R_{g,c}} \quad (6)
\]

\[
\Delta T_{g,c} = T_{\text{collector case}} - T_{\text{drying cabinet}} \quad (7)
\]

\[
\Sigma R_{g,c} = \frac{1}{h_{g,c} A_{g,c}} + \frac{x}{k A_{g,c}} \quad (9)
\]

The amount of heat radiated \( Q_{\text{rad,out}} \) by the cabinet to the environment was illustrated in (10). This can be calculated using the metal emissivity \( \varepsilon_m \), Stefan-Boltzmann constant \( \sigma \) and surface area \( A_d \) of the cabinet where heat is exchanged with the environment.

\[
Q_{\text{rad,out}} = \varepsilon_m \sigma A_d (T_d^4 - T_a^4) \quad (10)
\]

On the other hand, the heat transfer \( Q_{\text{vc}} \) from the cabinet through the side wall was expressed in (11) and it is the ratio of change in temperature of the drying cabinet and ambient in (12) with the heat transfer coefficient \( \Sigma R_{\text{vc}} \) in the inside of the cabinet as seen in (13)

\[
Q_{\text{vc}} = \frac{\Delta T_{d,a}}{\Sigma R_{\text{vc}}} \quad (11)
\]

\[
\Delta T_{d,a} = T_{\text{drying cabinet}} - T_{\text{ambient}} \quad (12)
\]

\[
\Sigma R_{\text{vc}} = \frac{1}{h_{\text{vc} A_{\text{vc}}}} + \frac{x}{k A_{\text{vc}}} \quad (13)
\]

The equation in (14) expresses the heat transfer from the cabinet through its top cover. It the quotient of (12) and heat transfer coefficient in the lower side of the top of the cabinet \( \Sigma R_{\text{tc}} \) as seen in (15)

\[
Q_{\text{tc}} = \frac{\Delta T_{d,a}}{\Sigma R_{\text{tc}}} \quad (14)
\]

\[
\Sigma R_{\text{tc}} = \frac{1}{h_{\text{tc} A_{\text{tc}}}} + \frac{x}{k A_{\text{tc}}} \quad (15)
\]

The amount of heat removed \( m \) was expressed in (3) in which \( m_i \) is the initial moisture content while \( m_f \) its final moisture content. The average drying rate \( m_{\text{ave}} \) in (4) is the ratio of the amount of moisture removed over time in minutes.
The total heat loss through the cabinet walls $Q_{\text{loss}}$ and useful heat in the cabinet $Q_{u_{\text{cab}}}$ were shown in (16) and (17)

$$Q_{\text{loss}} = Q_{v_c} + Q_{t_c} + Q_{b_c} + Q_{\text{rad, out}} \quad (16)$$

$$Q_{u_{\text{cab}}} = Q_{\text{rad, in}} + Q_{g_c, \text{in}} - Q_{\text{loss}} \quad (17)$$

Finally, the dryer system efficiency $\eta_s$ can be obtained using the (18)

$$\eta_s = \frac{Q_{u_{\text{cab}}}}{Q_{\text{rad, in}_{\text{cab}}} + Q_{g_c, \text{in}}} \times 100\% \quad (18)$$

3. Results and Discussion

3.1 Temperature and Relative Humidity

The temperature inside the drying chamber was monitored and the trends for each drying configuration were shown in Figure 2. The average temperature recorded in fully closed reheating as shown in Figure 2a was 38.47°C while for the half-opened reheating was 47.46°C as seen in Figure 2b. The highest average temperature observed occurred in the fully open reheating system at 48.46°C as shown in Figure 2c due to small opening in the exhaust that restricts air flow to go out easily from the drying chamber hence trapping less dense air at the top.

![Figure 2](image)

**Figure 2.** Temperature trends of bottom (1), middle (2) and top (3) trays for a) Full closed reheating b) Half open reheating and c) Full open reheating

The highest average relative humidity was 57.60% in fully closed reheating followed by half-opened reheating at 37.34%, both seen in Figure 3a and 3b. The lowest average relative humidity was recorded...
also at fully open reheating with 34.73% as shown in Figure 3c. The reason behind this is that the reheating enhanced further drying in the system.

![Figure 3](image)

**Figure 3.** Relative humidity trends of bottom (1), middle (2) and top (3) trays for a) Full closed reheating b) Half open reheating and c) Full open reheating

### 3.2 Mass and moisture content reduction

Figure 4 represents that the mass reduction of annatto fruit pericarp per drying configuration. It is found out that at fully open reheating as seen in Figure 4c, the moisture reduction was greatest at 50.96% with the least drying time of 7.05 hours and highest drying rate of 4.37 g/min. This corresponds to 90.38% system efficiency for moisture removal. On the hand the fully closed reheating showed the lowest moisture reduction of 35.68%, longest drying time of 9.12 hours and lowest drying rate of 2.87 g/min. This concludes that the effective drying can be achieved through introduction of fully open reheating in the solar dryer.

![Figure 4](image)
Figure 4. Mass reduction of bottom (1), middle (2) and top (3) trays for a) Full closed reheating b) Half open reheating and c) Full open reheating

4. Conclusion
The researchers were able to design an effective solar dryer with a reheating system and a thermal storage. Using the data gathered from the three drying configurations. It can be observed that the fully closed re-heater has the lowest moisture content removed from the annatto pericarp. The fully open reheating configuration has the highest drying rate of 4.37 grams per minute (g/min) and a system efficiency of 90.38% with highest average temperature inside the cabinet of 48.46°C. The total capacity of the system, it can dry up to 5 kilograms of annatto fruit pericarp equally divided in each tray.

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