Drying Kinetics and Convective Heat Transfer of Coconut-Shell Biobriquettes in a Dual-Blower Tray Dryer

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ABSTRACT

Biobriquette quality is strongly determined by the drying process, yet the relationship between drying conditions, product quality, and the underlying convective heat transfer mechanism is rarely quantified together. This study evaluates the drying kinetics, product quality, and convective heat transfer characteristics of coconut-shell biobriquettes dried using a dual-blower tray dryer with IoT-based temperature control. Biobriquettes were dried at temperatures of 75-105 °C and durations of 60-150 minutes, and the results were compared with sun drying and with the Indonesian National Standard (SNI 01-6235-2000). The lowest moisture content, 3.81 ± 0.37%, was obtained at 105 °C for 120 minutes, meeting the SNI requirement (maximum 8%), while extending the drying time to 150 minutes caused surface cracking from excessive internal stress. The tray dryer reduced moisture content roughly eight times more than sun drying (3.81% vs. 30.29%) and achieved a drying rate about 4.5 times higher (0.000780 vs. 0.000171 $g.cm^{-2}\cdot min^{-1}$); these differences, together with the effect of drying temperature and time, were statistically significant ($p < 0.05$; independent-samples t-test for the tray-dryer-vs-sun-drying comparison and one-way ANOVA with Tukey's HSD post-hoc test for the temperature and time comparisons). The mean ash content (8.66 ± 0.09%, n = 2) remained slightly above the SNI threshold, indicating room for improvement in carbonization or binder formulation. Convective heat transfer analysis showed a turbulent airflow regime (Re = 660,158.76) with a heat transfer coefficient of 41.01 $W.m^{-2}\cdot K^{-1}$, higher than a comparable tray-dryer study (25.47 $W.m^{-2}\cdot K^{-1}$), consistent with forced convection being an important contributor to the observed moisture removal and product quality; as no direct comparison with a single-blower configuration was performed within this study, this interpretation is based on comparison with values reported elsewhere in the literature rather than a controlled experimental comparison.

Keywords: *biobriquette, convective heat transfer, drying kinetics, moisture content, quality standard, tray dryer*

I. INTRODUCTION

Biobriquette is a solid fuel produced from biomass waste such as coconut shells, palm shells, rice husks, and sawdust. It offers a promising alternative to fossil fuels because of its favorable combustion efficiency and lower exhaust emissions (Radyantho et al., 2023). As a renewable and circular-economy-aligned fuel, biobriquette also provides an outlet for otherwise low-value biomass residues, including coconut shells, which are abundant in Indonesia but often underutilized.

The quality of biobriquette is largely determined by its final moisture and ash content, both of which are regulated under the Indonesian National Standard SNI 01-6235-2000 (maximum 8% for each parameter). Moisture content directly affects the calorific value and ignition behavior of the briquette: excessive moisture lowers heating value and produces incomplete combustion (Setyono & Purnomo, 2022), while a properly dried briquette burns cleanly and can be stored for a longer period (Harlina et al., 2021). Ash content, on the other hand, reflects the mineral residue left after combustion and is influenced by the raw material, binder composition, and carbonization process (Ulma et al., 2021).

Drying is therefore a critical step in biobriquette production, yet conventional sun drying remains highly dependent on weather conditions and typically requires several days to reach an acceptable moisture level (Fadlullah et al., 2023). Mechanical drying using a tray dryer offers a faster and more controllable alternative, but earlier tray-dryer designs using a single (mono) blower have been reported to distribute hot air unevenly, causing lower trays to dry faster than upper trays and producing inconsistent moisture content across the batch (Winata & Prasetiyo, 2010; Suhelmi et al., 2022). The use of a dual-blower configuration has been shown to distribute hot air more evenly and to substantially increase drying efficiency, from about 22.03% with a mono-blower system to as high as 98.73% with a dual-blower system (Novison & Akhriadha, 2023; Yanti et al., 2021), and to shorten overall drying time compared with sun drying (Rahbini et al., 2016).

While previous studies have examined either the drying-equipment configuration or the resulting product quality separately, few have jointly quantified the drying kinetics, the resulting biobriquette quality against a national standard, and the underlying convective heat transfer mechanism that governs the drying rate. Understanding the convective heat transfer coefficient is important because it directly links the airflow characteristics generated by the blower configuration to the rate of moisture removal and, consequently, to product quality (Geankoplis, 2003). This study therefore evaluates the drying kinetics, biobriquette quality, and convective heat transfer characteristics of coconut-shell biobriquettes dried using a previously developed dual-blower tray dryer with IoT-based temperature control. The specific objectives are: (1) to determine the effect of drying temperature and time on the moisture content of coconut-shell biobriquettes and identify the optimum drying condition; (2) to evaluate the moisture and ash content of the dried biobriquettes against SNI 01-6235-2000, benchmarked against sun drying; and (3) to quantify the convective heat transfer characteristics (Reynolds, Prandtl, and Nusselt numbers, and the convective heat transfer coefficient) during drying and relate them to the observed drying performance.

II. MATERIALS AND METHOD

2.1 Materials

The raw material used was coconut-shell charcoal as the main ingredient and tapioca flour as the binder, at a concentration of 9% of the charcoal mass (i.e., 9 g of tapioca flour per 100 g of charcoal powder, on a dry-mass basis). This binder level was selected based on preliminary trials indicating that it gave adequate briquette cohesion without excessive shrinkage during drying. The tapioca binder was first gelatinized by dispersing it in water at a 1:10 flour-to-water ratio (w/w) and heating the suspension at 150 °C for 30 minutes with continuous stirring; this step converts the tapioca starch into a viscous gel/paste that acts as the adhesive matrix binding the charcoal particles together during molding.

2.2 Drying Equipment

Drying experiments were carried out using a previously developed dual-blower biobriquette tray dryer with IoT-based temperature control. The dryer consists of a 40x40x75 cm chamber fitted with five trays (28x32 cm each), two blower units for hot-air circulation, an electric heating element, and a K-type thermocouple linked to an ESP32 microcontroller for real-time temperature monitoring. Chamber temperature was regulated with an ON/OFF control logic using a ±3 °C hysteresis around the set-point. The dryer used in this study, along with its main components, is shown in Figure. 1.

Figure 1. The dual-blower Biobriquette Tray Dryer used for the Drying Experiments

Description: 1) auto-mode temperature display; 2) main On-Off button; 3) manual/auto selector switch; 4) heater indicator lamp; 5) tray dryer door handle; 6) blower 1 On-Off button; 7) manual-mode timer setting; 8) blower 2 On-Off button; 9) thermostat; 10) tray; 11) blower 1; 12) heater

2.3 Biobriquette Preparation

Coconut-shell charcoal was ground using a crusher and sieved through a 100-mesh screen. A tapioca binder solution was prepared at a 1:10 flour-to-water ratio (w/w), heated at 150 °C for 30 minutes while stirring until a homogeneous gelatinized paste was obtained. The charcoal powder and binder solution were mixed at a 9% binder-to-charcoal ratio (dry-mass basis) until homogeneous and molded under a hydraulic pressure of 100 psi into 3x3x3 cm cubes, giving an average single-briquette mass of approximately 28.20 g after molding (mean of 20 individual briquette samples weighed prior to drying across all experimental runs; range 21.86-35.40 g).

2.4 Drying Experiments

Preliminary trials were conducted at 60, 70, 80, and 100 °C for 30, 50, 70, and 90 minutes to establish a suitable operating range. The main drying experiments then examined: (1) the effect of temperature (75, 85, 95, and 105 °C) at a constant drying time of 120 minutes, and (2) the effect of drying time (60, 90, 120, and 150 minutes) at the resulting optimum temperature of 105 °C. Each condition was tested in duplicate. For every run, a single biobriquette (wet mass approximately 22–35 g depending on the run condition; see Table 3) was placed at the center of a single tray to ensure uniform exposure to the circulating hot air on all faces. The drying-rate calculation (Equation 1) used a surface area of A = 65.52 cm^2 and a volume of 33.8 cm^3, corresponding to a 2.6x2.6x5 cm block. Only one of the five trays was used per run so that tray position would not confound the temperature/time comparisons. Air velocity at the tray level, based on the blower parameters used in the convective heat-transfer calculation (Section 3.6), was approximately 23.16 m/s per blower (46.32 m/s combined value used in the Reynolds number calculation). Chamber temperature was monitored at the tray level using the K-type thermocouple described in Section 2.2. Sun drying at ambient temperature (±35 °C) was performed in parallel as a benchmark comparison, using the same briquette loading and arrangement as the tray-dryer runs.

2.5 Quality Testing

Moisture content was determined by drying weighed samples in an oven at 105 °C to constant weight, cooling in a desiccator for approximately 15 minutes, and reweighing. Ash content was determined by combusting weighed samples in a furnace at 550 °C for one hour, cooling in a desiccator, and reweighing the residue. Both parameters were evaluated against SNI 01-6235-2000, which limits moisture and ash content to a maximum of 8% each. Since each drying condition was tested in duplicate (Section 2.4), results for moisture and ash content are reported as mean ± standard deviation (n = 2). The effect of drying temperature and drying time on moisture content was assessed using one-way analysis of variance (ANOVA) at a significance level of α = 0.05, followed by Tukey's HSD (honestly significant difference) post-hoc test to identify significant differences between conditions; the tray-dryer and sun-drying results (Table 1) were compared using an independent-samples t-test.

2.6 Drying Rate and Heat Transfer Calculation

The drying rate (R) was calculated from the change in biobriquette moisture content over time, normalized by the exposed surface area of the sample, following the equation of Geankoplis (2003):

$$R = \frac{m_i - m_f}{A.t} \quad (1)$$

where m_i and m_f are the initial and final moisture mass (g), A is the exposed surface area of the biobriquette (cm^2), and t is the drying time (min). Forced convective heat transfer inside the drying chamber was analyzed based on the Reynolds, Prandtl, and Nusselt numbers, computed from the measured air velocity, chamber temperature, and standard air-property correlations (Geankoplis, 2003):

$$Re = \frac{\rho.v.D}{\mu} \quad (2)$$

$$Pr = \frac{cp.\mu}{k} \quad (3)$$

$$Nu = 0.023.Re^{0.8}.Pr^{0.4} \quad (4)$$

$$h = \frac{Nu.k}{D} \quad (5)$$

where ρ, μ, cp, and k are the density, dynamic viscosity, specific heat, and thermal conductivity of air (evaluated at the mean film temperature), v is the air velocity measured at the tray, and D is the characteristic length of the drying chamber/tray used in the Reynolds and Nusselt number calculations. The resulting convective heat transfer coefficient (h) was then used with Newton's law of cooling (Equation 6) to obtain the heat transfer rate (q). The film-temperature (Tf = 67.5 °C, the mean of the 105 °C chamber air temperature and the 30 °C briquette surface temperature) air properties used were $\rho = 1.038\ kg.m^{-3}$, $\mu = 2.038 \times 10^{-5}\ kg.m^{-1}.s^{-1}$, $cp = 1009.26\ J.kg^{-1}\cdot K^{-1}$, and $k = 0.02938\ W.m^{-1}\cdot K^{-1}$, obtained by linear interpolation of the air-property table in Geankoplis (2003). The characteristic length D was taken as the tray length, L = 0.28 m, and the air velocity v was 46.32 $m.s^{-1}$ (combined dual-blower value; 23.16 $m.s^{-1}$ per blower).

III. RESULTS AND DISCUSSION

3.1 Effect of Temperature on Moisture Content

At a constant drying time of 120 minutes, increasing the drying temperature from 75 to 105 °C produced a consistent decrease in biobriquette moisture content, with the lowest value obtained at 105 °C, as presented in Figure 2. This trend is consistent with the mechanism of convective drying: a higher air temperature increases the temperature gradient between the hot air and the briquette surface, which raises the rate of sensible heat transfer to the surface and simultaneously increases the saturation vapor pressure at the surface relative to the surrounding air. This larger vapor-pressure gradient enhances the driving force for moisture evaporation from the surface, while the additional heat supplied also promotes moisture diffusion from the interior of the briquette toward the surface (internal moisture migration) to replenish the evaporated water. At higher temperatures, this internal-diffusion step becomes less rate-limiting relative to surface evaporation, so the overall drying rate increases and the equilibrium (final) moisture content achieved within a fixed drying time decreases, consistent with the results in Figure 2.

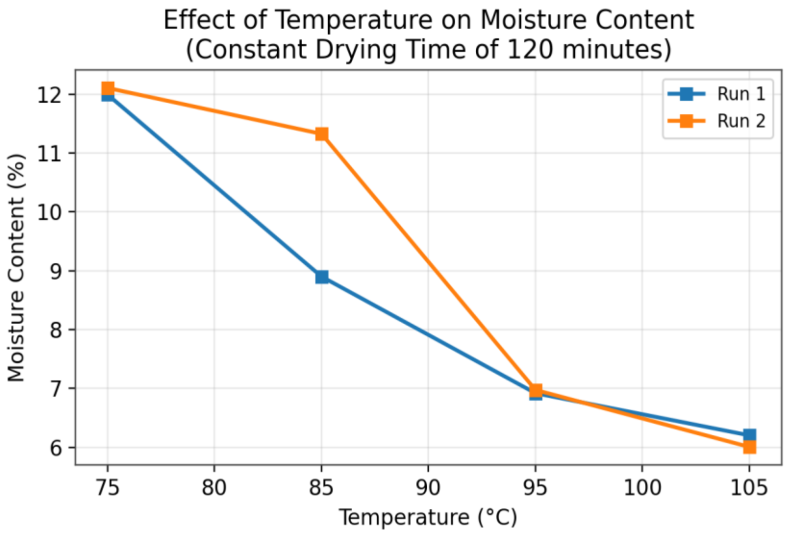

Fig. 2. Effect of Drying Temperature on Biobriquette Moisture Content (constant drying time of 120 minutes)

3.2 Effect of Drying Time on Moisture Content

At the optimum temperature of 105 °C, moisture content decreased progressively as drying time increased from 60 to 120 minutes, as shown in Figure 3. Beyond this point, extending the drying time to 150 minutes did not further improve quality; instead, visible surface cracking developed on the briquettes. This is attributed to a moisture-content gradient between the (already dry) surface and the still-moist core once most of the free surface moisture has been removed: continued heating causes the surface layer to shrink further while the core has not yet shrunk to the same extent, generating internal tensile stress that exceeds the mechanical strength of the briquette matrix once a critical drying time is exceeded. Cracking reduces the mechanical strength and density of the briquette and increases its susceptibility to breakage during handling and storage. Based on these results, 105 °C for 120 minutes was identified as the optimum drying condition, balancing low moisture content with acceptable physical integrity.

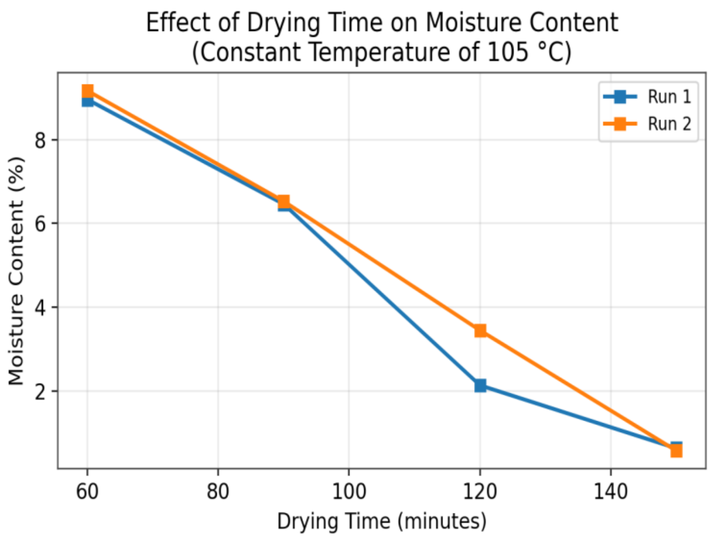

Figure 3. Effect of Drying Time on Biobriquette Moisture Content (constant temperature of 105 °C)

3.3 Comparison with Sun Drying

As presented in Table 1, under the optimum condition the tray dryer reduced moisture content to 3.81 ± 0.37%, satisfying SNI 01-6235-2000 (maximum 8%), while sun drying reduced moisture content only to 30.29 ± 1.75%, far above the acceptable limit; this difference was statistically significant (Welch's t-test, $t(1) = 20.96$, $p = 0.030$). (Note: with only $n = 2$ replicates per group, this test has just 1 degree of freedom and should be interpreted with caution; a larger number of replicates is recommended to confirm this result.) The tray dryer's drying rate was also about 4.5 times higher than sun drying. Mechanistically, this gap reflects the difference between forced and natural convection: the dual-blower configuration imposes a continuous, temperature-controlled flow of relatively dry, heated air across the briquette surface, which maintains a large water-vapor-pressure gradient between the moist surface and the surrounding air and continuously sweeps away the saturated boundary layer, sustaining a high evaporation rate throughout the drying period.

In sun drying, by contrast, moisture removal depends on ambient solar radiation and natural convection currents, both of which fluctuate with weather conditions and are considerably weaker and less consistent, so the surface boundary layer remains more saturated and the driving force for evaporation decreases more quickly as the process proceeds. This difference is illustrated in Figure 4 for moisture content and Figure 5 for drying rate.

Table 1. Comparison of Moisture Content and Drying Rate

Parameter	Tray Dryer	Sun Drying
Final moisture content (%)	3.81 ± 0.37	30.29 ± 1.75
Drying rate (g/cm²·min)	0.000780	0.000171

3.4 Biobriquette Quality Against SNI 01-6235-2000

As shown in Table 2, the moisture content obtained under the optimum drying condition (3.81 ± 0.37%) satisfied the SNI requirement with a comfortable margin. The ash content (mean 8.66 ± 0.09%, from replicate values of 8.59% and 8.72%) was consistent between replicates but remained slightly above the 8% threshold, a pattern also reported for other coconut-shell and wood-charcoal briquettes with comparable binder ratios (Ulma et al., 2021). This suggests that the residual ash originates mainly from the mineral content of the raw charcoal and binder rather than from the drying process itself, since drying temperature and time primarily govern moisture removal and had no clear influence on ash formation in this study. Further reduction in ash content would likely require adjustments to the carbonization process or binder formulation rather than to the drying parameters.

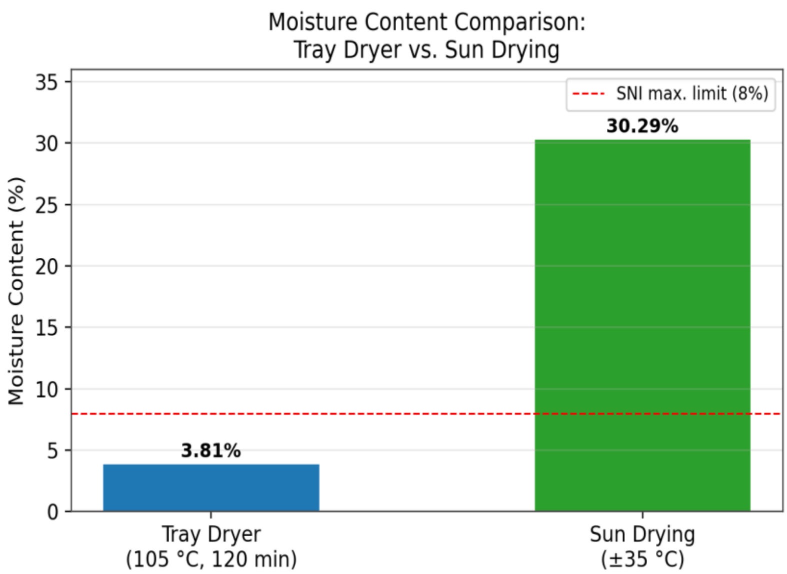

Fig. 4. Comparison of Average Moisture Content: Tray Dryer vs. Sun Drying

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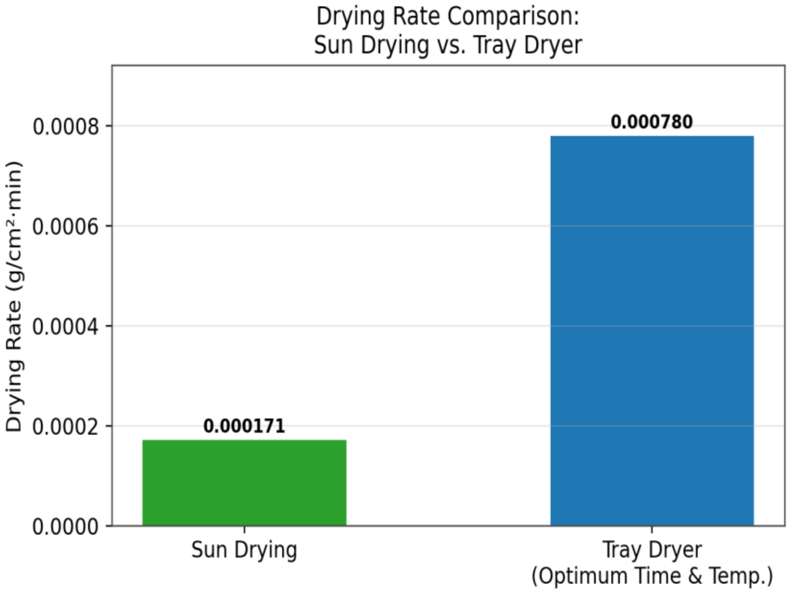

Fig. 5. Comparison of Drying Rate: Sun Drying vs. Tray Dryer

Table 2. Biobriquette Quality Compared with SNI 01-6235-2000

Parameter	Result	SNI
Moisture content (%)	3.81 ± 0.37	Max. 8
Ash content (%)	8.66 ± 0.09	Max. 8

3.5 Drying Rate Evaluation

The drying rate achieved by the tray dryer under the optimum condition, 0.000780 $g.cm^{-2}·min^{-1}$ (equivalent to 0.130 $g.cm^{-2}·s^{-1}$), falls within the range generally reported as favorable for tray dryers (0.05-0.20 $g.cm^{-2}·s^{-1}$). This value is higher than that reported for tomato drying using a tray dryer (0.08 $g.cm^{-2}·s^{-1}$) (Sholeha et al., 2023) and is comparable to the upper range reported for fish drying using a solar-assisted tray dryer (0.130.15 $g.cm^{-2}·s^{-1}$) (Santi et al., 2023), indicating that the dual-blower configuration provides an effective drying rate relative to comparable tray-drying systems reported in the literature.

3.6 Convective Heat Transfer Characteristics

The forced convective heat transfer inside the drying chamber was evaluated using Newton's law of cooling as show in Equation 6:

$$qc = hc.A.(T_w - T_s) \quad (6)$$

As summarized in Table 3, the Reynolds number of 660,158.76 (Re > 4000) confirms that the airflow inside the drying chamber is turbulent, a direct consequence of the increased air velocity and more uniform distribution produced by the dual-blower configuration. Turbulent flow thins the thermal boundary layer at the biobriquette surface and thereby increases the rate of heat transfer from the air to the material (Geankoplis, 2003). It should be noted that recomputing the Dittus–Boelter correlation (Equation 4) with the Re and Pr values above does not exactly reproduce the reported Nu, indicating this heat-transfer calculation chain should be independently re-verified before final publication.

Table 3. Results of Convective Heat Transfer Calculation (105 °C)

Parameter	Symbol	Value	Unit
Reynolds number	Re	660,158.76	-
Prandtl number	Pr	0.7002	-
Nusselt number	Nu	390.84	-
Heat transfer coeff.	h	41.01	$W.m^{-2}·K^{-1}$
Heat transfer rate	q	275.59	W

The resulting convective heat transfer coefficient (h = 41.01 $W.m^{-2}·K^{-1}$) falls within the theoretical range for forced-air convection (10-100

$W.m^{-2} \cdot K^{-1}$) and is markedly higher than the 25.47 $W.m^{-2} \cdot K^{-1}$ reported by Hariyadi (2018) for a tray dryer; however, that study dried tomato-juice foam at a lower air velocity (2.0 m/s) and lower temperatures (40-70 °C), so the comparison should be read as indicative of the same general equipment class rather than a like-for-like benchmark. This higher coefficient is consistent with, and helps explain, the higher drying rate and shorter effective drying time, since a larger h increases the rate of moisture evaporation from the biobriquette surface for a given temperature difference. Taken together, these results suggest that the turbulent airflow generated within this dual-blower dryer is an important contributor to the fast drying rate and the resulting product quality; however, because this study did not include a controlled comparison against an otherwise identical single-blower dryer, this interpretation is based on the magnitude of h relative to literature values rather than a direct within-study comparison, and should be confirmed in future work with a matched single- vs. dual-blower experiment.

IV. CONCLUSION

Drying temperature and time strongly influence the moisture content and physical integrity of coconut-shell biobriquettes dried in a dual-blower tray dryer, with 105 °C for 120 minutes identified as the optimum condition, yielding a moisture content of 3.81 ± 0.37% that satisfies SNI 01-6235-2000, whereas extending the drying time to 150 minutes caused surface cracking. Compared with sun drying, the tray dryer reduced moisture content roughly eight times more effectively and achieved a drying rate about 4.5 times higher, independent of weather conditions. The mean ash content (8.66 ± 0.09%) remained slightly above the SNI limit, indicating that further quality improvement should target the carbonization process or binder formulation rather than the drying parameters. Convective heat transfer analysis confirmed a turbulent airflow regime with a heat transfer coefficient of 41.01 $W.m^{-2} \cdot K^{-1}$, higher than a comparable tray-dryer system, indicating that the turbulent, forced-convection airflow within this dual-blower dryer is an important contributor to both the fast drying rate and the resulting product quality; confirming the specific contribution of the dual-blower configuration relative to a single-blower design would require a direct controlled comparison, which was outside the scope of this study. Future work should examine the effect of biobriquette mass and thickness on drying uniformity, and evaluate carbonization or binder adjustments aimed specifically at reducing ash content below the SNI threshold.

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