Asian Journal of Water, Environment and Pollution. Vol. 22, No. 6 (2025), pp. 60-72.
doi: 10.36922/AJWEP025240195

ORIGINAL RESEARCH ARTICLE

Optimization of pine sawdust densified biofuel: Effects of process parameters on fuel quality and temperature distribution

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Received: June 13, 2025; 1st revised: July 10, 2025; 2nd revised: July 18, 2025;
Accepted: July 21, 2025; Published online: August 7, 2025

Abstract: The valorization of forestry waste into densified biofuels is critical for sustainable energy development. This study investigates the optimization of the densification process for pine sawdust by examining the effects of key parameters on the final product quality, specifically focusing on the uniformity of the internal temperature field. A four-factor, mixed-level orthogonal experiment was designed, investigating forming pressure, moisture content, binder addition ratio, and heating temperature. The temperature mean square deviation (MSD) was utilized as the primary response variable to quantify thermal distribution uniformity. Analysis of variance (ANOVA) was performed to determine the statistical significance of each factor, and a multivariate regression model was established. Results from ANOVA indicated that the descending order of significance for factors impacting temperature MSD was: moisture content > forming pressure > heating temperature > binder addition ratio. A statistically significant interaction effect was identified between forming pressure and heating temperature. Response surface methodology was employed to optimize these two significant factors. The optimal conditions for minimizing temperature MSD, while maintaining constant moisture content and binder ratio, were determined to be a forming pressure of 10 MPa and a heating temperature of 190°C. By optimizing process parameters to achieve a more uniform temperature field, the quality and stability of the resulting pine sawdust densified fuel were significantly improved. This work provides a quantitative theoretical basis and key technical parameters for the scale-up and industrial application of biomass fuels in boilers and residential heating systems, thereby promoting the development of a low-carbon circular economy.

Keywords: Densified fuel quality; Binders; Fuel quality; Temperature distribution; Mechanical Properties; Forestry waste

1. Introduction

In the face of global resource scarcity, environmental pollution, and intensifying climate change, efficient management and resource utilization of forestry waste have become critical for achieving sustainable development. In China, potential biomass resources from agricultural and forestry waste amount to 850 million and 340 million tons, respectively, with energy crops contributing an additional 740–960 million tons.[1] Depending on development levels, biomass energy potential is estimated at approximately 1.9–41.2 EJ,

equivalent to 0.68–1.4 billion tons of standard coal, representing substantial untapped resources. Pine sawdust, a major forestry waste stream, currently poses significant environmental burdens through conventional disposal methods (e.g., open burning, landfilling), including land occupation and emissions of toxic compounds and greenhouse gases. Densification into densified biofuel offers a viable waste valorization strategy to advance the circular bioeconomy in the forestry sector.[2]

The primary factors influencing biomass densification include forming pressure, moisture content, binder addition ratio, and heating temperature. Among these, forming pressure plays a particularly critical role in determining pellet quality: optimal forming pressure ensures high-quality pellets with minimal energy input, whereas excessive pressure may cause blockages, and insufficient pressure can lead to substandard pellets.[3] Under pressure, sludge particles are extruded into the voids of biomass pellets, where protein denaturation and lignin softening occur, acting as natural binders that facilitate biomass densification.[4]

Moisture content plays an equally critical role; excessive moisture reduces pellet strength, while insufficient moisture increases energy consumption during molding.[5] Although increased moisture content reduces molding energy consumption, the pellet's relaxation coefficient initially decreases before increasing, potentially due to water acting as a lubricant that reduces interparticle friction. The density and durability of municipal solid waste-derived briquettes are significantly affected by both moisture content and particle size distribution.[6] The moisture content significantly affects pellet bonding quality. If it is too low, insufficient lignin plasticization leads to weak bonding; if it is too high, it triggers a steam explosion effect, reducing densified biofuel durability.[7]

Binders, including glycerol or lignin-rich additives, significantly enhance densification performance and pellet durability.[8] The incorporation of 5–20% coal into biomass improves pellet durability while maintaining thermal properties.[9] When sawdust and asphalt are added as binders to sludge, the resulting densified biofuel exhibits increased calorific value, demonstrating potential for coal replacement.[10] Similarly, the NovoGro binder application in densified biofuel production enhances both durability and mechanical strength.[11] These binder applications collectively improve densification efficiency while reducing energy consumption.[12] Adding a binder increases the cost by $0.15 USD per ton for every 1% improvement in durability, making it the preferred choice for cost-sensitive projects.[13] Under high-pressure forming, adding 1–3% sweet potato starch can meet industrial requirements, with 2% achieving a pellet durability of 95.6%.[14]

Heating temperature critically influences pellet quality through lignin softening, which promotes particle bonding and densification.[15] While elevated forming temperatures enhance pellet density and strength, excessively high temperatures may cause surface charring, ultimately compromising durability.[16] Within the 30–110°C range, densified biofuel density and hardness exhibit a parabolic relationship with temperature, peaking at approximately 70°C.[17] Preheating treatment can improve the durability of high-moisture-content particles.[18] Short-term treatment at 200°C can achieve the impact resistance of 99.5%, but it requires a moisture content of ≤12%.[19]

Current research predominantly examines the direct thermal effects, with limited investigations addressing temperature field distribution and its influencing factors. To address this gap, the present study concentrates on pine sawdust densification technology for high-value waste valorization. By systematically evaluating key parameters (forming pressure, heating temperature, binder addition ratio, and moisture content) and their interactive effects on biomass pellet quality, we introduce temperature mean square deviation (MSD) as a novel metric for characterizing temperature field uniformity. This approach elucidates its functional mechanisms in densification processes and regulatory effects on fuel performance. The optimization of process parameters and temperature field distribution aims to improve pine sawdust pellet quality, thereby providing both theoretical foundations and technical solutions for industrial-scale applications (e.g., industrial boilers, residential heating systems). This research contributes to enhanced forestry waste utilization and promotes the development of low-carbon circular economies.

2. Determination of factors influencing densified biofuel and quality evaluation indicators

2.1. Determination of experimental factors and levels

Building upon previous research findings[20-23] while maintaining pine sawdust formability, this study adopted the following experimental parameter ranges: forming pressure (A) within 10–50 MPa, moisture content, (B) within 10–16%, binder addition ratio, (C) within 1–5%, and heating temperature, (D) within 150–190°C. An

L25 (4×5^4) orthogonal experimental design with four factors and mixed levels was adopted.

2.2. Quality evaluation indicators for densified biofuel

For enhanced transportability and storage efficiency of densified biofuel, this study employed three key physical properties as quality evaluation metrics: Relaxed density (H1), relaxation ratio (H2), and impact resistance (H3).

Relaxed density refers to the density of biomass pellets after they reach a stable state following expansion or contraction post-forming.[24] A higher relaxed density indicates a greater density of the densified pellets, which typically corresponds to better forming quality and higher combustion efficiency. The formula is presented in Equation I:

$$\rho = \frac{4m}{\pi d^2 h} \tag{I}$$

Where ρ represents the relaxed density (g/cm^3), m is the pellet weight (g), d is the pellet diameter (cm), and h is the pellet length (cm).

The relaxation ratio of formed pellets is the ratio of the initial relaxation density to the stabilized relaxation density. A high relaxation ratio indicates more internal voids, making the pellets prone to moisture absorption and breakage, while a low relaxation ratio suggests minimal shrinkage after forming, resulting in a compact structure conducive to long-term storage.[25] The lower the relaxation ratio of the pellets, the higher their stability, which is beneficial for subsequent transportation and storage. The formula is presented in Equation II:

$$\lambda = \rho_i / \rho_r \tag{II}$$

Where λ represents the relaxation ratio, ρ_i is the initial density (i.e., the density measured immediately after pellet formation) (g/cm^3), and ρ_r is the relaxed density (g/cm^3).

Impact resistance measures the ability of densified pellets to maintain their original shape after multiple drops and collisions. A higher impact resistance indicates better mechanical strength and higher quality of the pellets. According to the forestry industry standard LY/T 2552-2015, the impact resistance of bamboo-based densified biofuel is considered compliant if it exceeds 90%.[26] Furthermore, the energy standard NB/T 34024-2015 classifies densified biofuels with impact resistance greater than 95% as Grade III densified biofuels.[27] When the impact resistance of densified pellets is ≥95%, the pellets are considered good quality.[28] It demonstrates good performance and market potential in practical applications, meeting the combustion needs of high-temperature equipment such as industrial boilers and kilns, and ensuring that the densified biofuel maintains high combustion efficiency and stability during the burning process.[29] The formula is presented in Equation III:

$$I = M_f / M_b \times 100\% \tag{III}$$

Where I represents the impact resistance of the densified pellets (%), M_f is the weight of the densified pellets before the drop test, without sieving (g), and M_b is the weight of the densified pellets after the drop test, after sieving (g).

2.3. Temperature field and temperature MSD

Temperature represents the thermal energy state of an object's interior or surrounding environment. The spatial distribution of temperature values within a material system constitutes its temperature field.[30]

In biomass densification, the temperature field significantly influences pyrolysis, drying, and compaction processes, consequently affecting key fuel properties including heating value, stability, durability, chemical composition, and energy density. The temperature MSD serves as a critical parameter for characterizing temperature field uniformity, where lower values indicate more homogeneous distributions and higher values reflect greater heterogeneity. The MSD is calculated following Equation IV:[31]

$$Kt = \frac{\sum_{i=1}^{N} \left(T_i - \bar{T}\right)}{N} \tag{IV}$$

where K_t represents the temperature MSD, $\bar{T}$ is the average temperature within the observed region, T_i is the temperature of the i-th pixel in the observed region, and N is the total number of pixels in the observed region.

The formula for the average temperature $\bar{T}$ within the region is presented in Equation V:

$$\bar{T} = \frac{T_i dxdy}{A} \tag{V}$$

Where A represents the area of the region.

The temperature MSD serves as a quantitative metric for assessing temperature field uniformity, reflecting

the dispersion degree of temperature data relative to the mean value. This parameter provides a measurable characterization of both uniformity and dispersion within the temperature field.

3. Materials and methods

3.1. Experimental materials

The experimental materials consisted of pine sawdust (particle size <2.5 mm) containing 34–46% cellulose, 20–35% hemicellulose, and 26–34% lignin.[32] Molasses served as the binder for biomass densification.

Prior to experimentation, the moisture content of the biomass material (pine sawdust) required measurement and adjustment. The moisture content was determined in accordance with the Chinese National Standard GB/T 1927.4-2021, calculated using the following formula in Equation VI:

$$W = \frac{m_1 - m_0}{m_0} \times 100\% \quad \text{(VI)}$$

Where W is the moisture content (%), m is the mass of undried sawdust (g), and m is the mass of oven-dried sawdust (g).

The pine sawdust was heated using a moisture analyzer until a constant mass was achieved. The initial moisture content of the pine sawdust was determined to be 8.3%. Fine water mist spraying was employed to adjust the moisture content to the required experimental range, followed by sealed storage under ambient conditions. The experimental environment was maintained at 15–25℃ with relative humidity ≤80%.

3.2. Experimental equipment

The experimental setup comprised a forming system and measurement instruments. The forming system incorporated a mold with an integrated heating coil and temperature controller, while measurement instruments included a universal testing machine (REGER Model 4050; Shenzhen REGER Instrument Co., Ltd., China) and an infrared thermometer (FLUKE Ti95; FLUKE Test Instruments Co., Ltd., China) with dedicated software.

The heating coil was precisely fitted to the mold's outer circumference, with temperature regulation achieved through the controller. The mold assembly, installed on the universal testing machine, featured a polytetrafluoroethylene insulation plate.

3.3. Experimental steps

This study is divided into three main parts: experimental preparation, biomass densification testing, and data analysis, as shown in Figure 1.

(i) Experimental preparation: Raw material moisture content and binder addition ratio were adjusted to target values, followed by sealed storage.

(ii) Experimental procedure: The forming mold with the temperature controller was mounted on the universal testing machine. Prepared materials were loaded into the die for compression molding under 30-s pressure maintenance, after which samples were extracted and stored at ambient conditions.

(iii) Post-experiment processing: The relaxation ratio, relaxed density, and impact resistance of each test group were calculated and averaged to ensure data reliability. Systematic data processing was performed to evaluate the effects of various parameters on densified biofuel quality and temperature field distribution.

4. Results and discussion

4.1. Experimental results of densified biofuel quality evaluation indicators

Following the experimental steps outlined in Sections 2.1 and 3.3, a total of 25 experimental groups were conducted in this study. Each group was repeated three times, and the average values and standard errors were calculated. The experimental results are shown in Table 1.

Experimental results revealed that the maximum relaxed density of 1.066 g/cm^3 was achieved at 50 MPa forming pressure with 10% moisture content, 2% binder addition ratio, and 160°C heating temperature. The minimum relaxation ratio of 1.009 occurred at 10 MPa forming pressure with 14% moisture content, 4% binder addition ratio, and 190°C heating temperature. Optimal impact resistance (97.939%) was obtained at 40 MPa forming pressure with 10% moisture content, 4% binder addition ratio, and 150°C heating temperature.

With an impact resistance threshold of ≥95% indicating satisfactory densification performance, 92% of the 25 experimental groups produced good-quality densified biofuel. Two exceptions failed to meet the requirement: (i) at 20 MPa forming pressure with 16% moisture content, 2% binder addition ratio, and 150°C temperature, and (ii) at 10 MPa forming pressure with 16% moisture content, 3% binder addition ratio, and 160°C temperature.

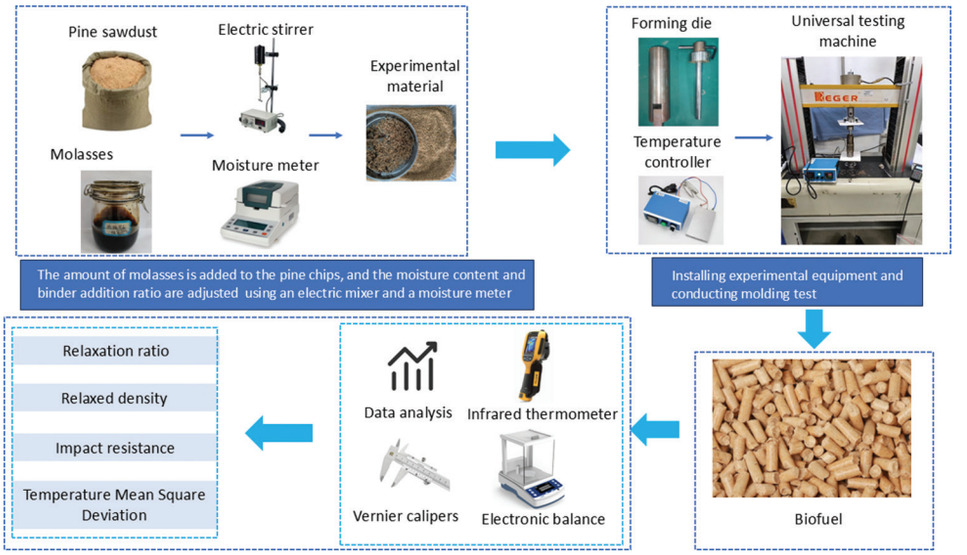

Figure 1. Experimental flowchart

Note: The universal testing machine has a force measurement accuracy of ±1%, and the infrared thermometer has a measurement accuracy of ±2°C or 2% of the reading, whichever is greater.

For systematic analysis of experimental factors' effects on densified biofuel quality, the Design-Expert software (version 12.0) was employed to perform data fitting, yielding a multiple regression equation. Subsequent variance and response surface analyses were conducted. The two-factor interaction model was applied to examine interaction effects between parameters, expressed as Equation VII:

$$Y=k+k1A+k2B+k3C+k4D+k5AB+k6AC+k7AD+k8BC+k9BD+k10CD \quad \text{(VII)}$$

where Y represents the dependent variable, A, B, C, and D are the independent variables, and ki (i=0~10) are the model parameters, representing the degree of influence of each independent variable on the dependent variable Y. AB, AC, AD, BC, BD, and CD represent the interaction effects between the independent variables.

Based on the variance analysis results, the linear regression equations for relaxed density, relaxation ratio, and impact resistance with respect to the experimental factors are shown in Table 2.

In the statistical analysis, R represents the multiple correlation coefficient, with R^2 indicating the proportion of dependent variable variance explained by the regression model. An R^2 value approaching 1 denotes a stronger predictive capacity of the independent variables.

This multiple regression model enables the prediction of relaxed density, relaxation ratio, and impact resistance from given independent variables, while quantifying the magnitude and direction of factor interactions on these parameters.

Variance analysis employs significance levels (p-values) to evaluate factor impacts: $p<0.01$ indicates extremely significant effects, $0.01\leq p<0.05$ shows significant effects, and $p>0.05$ suggests no significant influence.[31,33]

The degree of influence of various experimental factors on the evaluation indicators of densified biofuel quality is shown in Table 3. In the table, only interactions with significant effects are displayed.

Table 3 demonstrates that forming pressure (A), moisture content (B), heating temperature (D), and their BD interaction exert extremely significant effects ($p<0.01$) on relaxed density. For the relaxation ratio, heating temperature (D) and AD interaction show highly significant influences ($p<0.01$). Impact resistance is markedly affected by forming pressure (A), moisture content (B), and BD interaction at extremely significant levels.

To validate the reliability of the multiple linear regression models, residual analysis was conducted. As shown in Figure 2, the residuals versus fitted plots, Q–Q plots, and histogram of residuals confirm that the models for relaxed density, relaxation ratio, and impact resistance meet the assumptions of random distribution, homoscedasticity, and normality, supporting their robustness.

Table 1. Orthogonal test results

Group	Forming pressure (MPa)	Moisture content (%)	Binder addition ratio (%)	Heating temperature (°C)	Relaxed density (g/cm^3)	Relaxation ratio	Impact resistance (%)
1	20	16	2	150	0.653	1.202	87.594
2	10	10	1	150	0.932	1.301	96.346
3	30	12	3	150	0.889	1.101	96.245
4	40	10	4	150	0.99	1.071	97.939
5	50	14	5	150	0.923	1.032	97.322
6	40	14	1	160	0.856	1.013	96.690
7	10	16	3	160	0.694	1.041	91.685
8	30	10	5	160	0.993	1.063	97.368
9	20	12	4	160	0.932	1.120	96.850
10	50	10	2	160	1.066	1.010	97.214
11	40	10	3	170	1.056	1.059	97.891
12	10	12	5	170	0.889	1.042	96.384
13	50	16	4	170	0.838	1.018	96.497
14	20	10	1	170	1.004	1.063	96.694
15	30	14	2	170	0.914	1.012	96.254
16	30	10	4	180	1.054	1.010	97.272
17	20	14	3	180	0.905	1.040	95.870
18	50	12	1	180	0.962	1.014	95.815
19	40	16	5	180	0.900	1.054	95.445
20	10	10	2	180	0.926	1.032	95.567
21	40	12	2	190	1.012	1.021	96.805
22	30	16	1	190	0.891	1.044	96.008
23	20	10	5	190	0.994	1.025	96.528
24	10	14	4	190	0.883	1.009	95.896
25	50	10	3	190	0.989	1.026	96.798

Table 2. Multivariate fitting models of each dependent variable

Dependent variables	R^2	Multiple regression fitting model
H1	0.9213	Y=0.9064+0.0492A−0.974B+0.0079C+0.0491D+0.0048AB+0.0038AC−0.0215AD+0.0064BC+0.0446BD−0.0030CD
H2	0.8093	Y=1.06−0.0252A−0.0058B−0.007C−0.0372D+0.0082AB+0.0386AC−0.0586AD−0.0157BC+0.0222BD+0.0294CD
H3	0.8133	Y=0.9575+0.0115A−0.0147B+0.0047C+0.0072D+0.0099AB−0.0048AC−0.0063AD+0.0017BC+0.0147BD−0.0043CD

These phenomena occur because optimal moisture and temperature conditions minimize elastic deformation and stress relaxation in densified biofuel, thereby enhancing relaxed density. Conversely, excessive moisture content traps steam during extrusion, inducing substantial elastic deformation and densified biofuel expansion that ultimately reduces relaxed density.

The interaction between forming pressure and heating temperature affects the stability of the densified biofuel. Appropriate molding pressure and heating temperature increase the density of the densified biofuel while causing the binder and lignin in the biomass material to melt, resulting in higher stability and lower relaxation ratio.

Table 3. Influence the degree of each test factor on each evaluation index of densified biofuel quality

Dependent variables	Forming pressure	Moisture content	Binder addition ratio	Heating temperature	Interaction effect
Relaxed density	0.0008	<0.0001	0.5005	0.0008	BD−0.0063
Relaxation ratio	0.0568	0.5667	0.5723	0.0082	AD−0.0037
Impact resistance	0.0096	0.0003	0.2375	0.0806	BD−0.0064

Note: A is forming pressure, B is moisture content, and D is heating temperature.

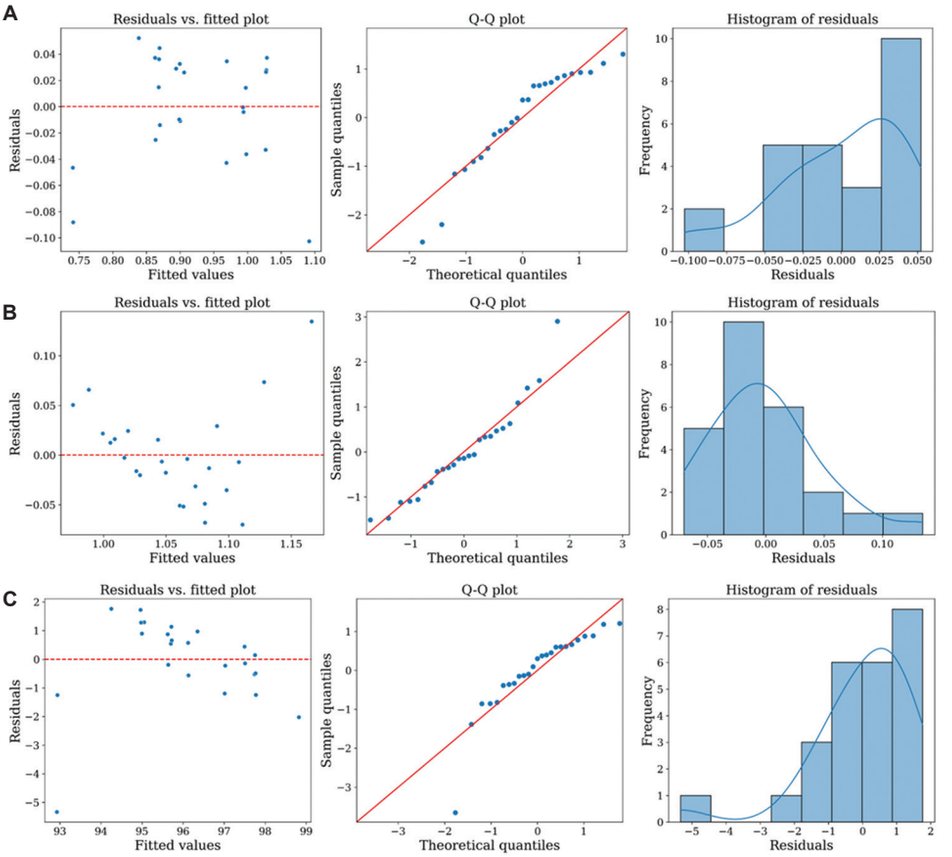

Figure 2. Residual analysis plots. (A) Relaxed density, (B) Relaxation ratio, and (C) Impact resistance

4.2. Analysis of cross-sectional temperature field distribution of densified biofuel

4.2.1. Temperature distribution and results of cross-sectional densified biofuel

Infrared thermography captured cross-sectional temperature profiles of densified biofuel, with subsequent data processing and pixel-level temperature extraction performed using THE SmartView Classic 4.4 software. Equation IV was applied to calculate the temperature MSD for each experimental group's pellet cross-section.

Figure 3 displays experimental groups and heating temperatures on the x-axis, whereas the y-axis presents temperature MSD, moisture content, and binder addition ratio. Bar heights quantitatively measure temperature MSD (Kt).

Figure 3 reveals that experimental group 13 (50 MPa forming pressure, 16% moisture content, 4% binder addition ratio, 170°C) exhibited the maximum temperature MSD of 14.0294. Corresponding infrared thermography in Figure 4A demonstrates pronounced temperature variation within the densified biofuel cross-section (white outline), confirming significant temperature field heterogeneity, which aligns with experimental measurements.

Conversely, group 14 (20 MPa, 10% moisture, 1% binder, 170°C) achieved the minimum MSD (0.3677). Figure 4B displays near-uniform thermal coloration in

the cross-section, indicating homogeneous temperature distribution.

Comparative analysis revealed that non-uniform temperature distributions correlated with surface cracking and rough cross-sections with material fragmentation (Figure 4), whereas uniform distributions produced smooth surfaces and shell-like structural integrity, enhancing transport stability.

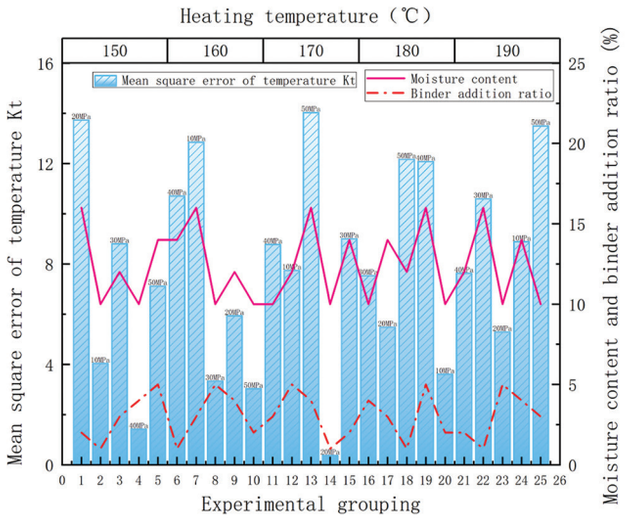

Figure 3. The temperature mean square deviation for each experimental group

Notes: The x-axis (top) represents the heating temperature, the y-axis (right) represents the moisture content and binder addition ratio, the y-axis (left) represents the temperature standard deviation, the bar chart shows the values of the temperature standard deviation, and the forming pressure is indicated directly above the bar chart.

Other researchers have employed different approaches to evaluate temperature field uniformity in their studies. Vanherck *et al.*[34] used the difference between maximum and minimum temperatures as an indicator of temperature uniformity. Bai *et al.*[35] analyzed temperature gradient variations by simulating temperature field distributions at different time points, comparing pavement damage under various temperature field conditions to indirectly assess uniformity impacts. Huang *et al.*[36] defined temperature uniformity as the temperature differences between measurement points inside a drying shed, with computational fluid dynamics simulations revealing higher temperatures in the bottom area compared to the top, whereas water vapor was concentrated in the top and outlet areas.

4.2.2. Effects of experimental factors on temperature field distribution

Using the Design-Expert software, variance analysis was performed with the two-factor interaction model to evaluate the effects of experimental factors (A, B, C, D) on the temperature MSD (Kt). The regression equation relating temperature MSD to the experimental factors is presented in Equation VIII:

$$Kt=8.61+1.61A+3.52B+0.4184C+0.4589D-0.227AB-AC+2.87AD-0.239BC-1.69BD+0.9081CD \quad (VIII)$$

The coefficient of determination for the regression equation, $R^2 = 0.8377$, indicates that the selected factors can explain 83.77% of the variation in the temperature MSD (Kt).

Table 4 displays the analysis of variance results for experimental factors affecting temperature field

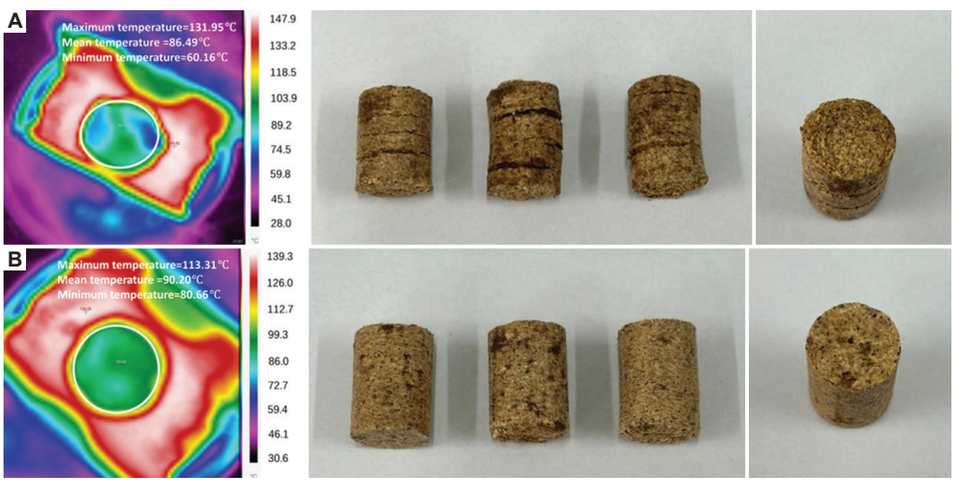

Figure 4. Temperature field distribution and appearance of densified biofuel. (A) The 13th experimental group and (B) The 14th experimental group

Table 4. Variance analysis results of the effects of various experimental factors on temperature field uniformity

Source of variation	Sum of squares	Degrees of freedom	Mean square	*F*-value	*p*-value
Model	315.16	10	31.52	7.23	0.0005**
A (Forming pressure)	25.28	1	25.28	5.80	0.0304*
B (Moisture content)	183.74	1	183.74	42.12	<0.0001**
C (Binder addition ratio)	1.74	1	1.74	0.3990	0.5378
D (Heating temperature)	2.07	1	2.07	0.4749	0.5020
AB	0.2826	1	0.2826	0.0648	0.8028
AC	3.68	1	3.68	0.8430	0.3741
AD	41.77	1	41.77	9.57	0.0079**
BC	0.3075	1	0.3075	0.0705	0.7945
BD	19.33	1	19.33	4.43	0.0538
CD	3.79	1	3.79	0.8697	0.3668
Residual	61.07	14	4.36		
Total	376.23	24			

Note: Statistical significance determined at *$0.01 \leq p < 0.05$ and **$p<0.01$.

uniformity, as computed by the Design-Expert software. The analysis reveals that moisture content (B) and the pressure-temperature interaction (AD) exhibited highly significant effects on temperature MSD ($p<0.01$), while molding pressure (A) showed significant influence ($p<0.05$). *F*-value comparisons established the factor importance ranking as B (moisture content) > A (pressure) > D (temperature) > C (binder addition ratio), with moisture content emerging as the dominant factor. This predominance stems from moisture's capacity to form insulating layers that impair interlayer bonding and cause irregular heat transfer. The moisture content is a critical parameter in biomass densification, significantly influencing both the process and final product quality.[37] It directly impacts key metrics such as density and mechanical strength, with research showing that an optimal moisture range is crucial for superior pellet properties. The relationship is complex; exceeding the optimum can decrease pellet durability,[38] while in some cases, quality increases with moisture up to a certain point.[39] This behavior is partly linked to moisture's effect on interparticle forces, which can impact energy consumption and molding quality.[40] Crucially, moisture content is closely interlinked with processing temperature, and both must be co-optimized to achieve the best results.[41] The presence of moisture significantly improves the thermal conduction efficiency of biomass.[42] Uneven distribution of moisture can lead to spatial differences in the temperature field. The moisture content affects the temperature difference between the center and the outer surface of particles.[43] It reduces the glass transition temperature of lignin through hydrogen bonding, and lignin's glass transition temperature decreases linearly with increasing moisture content.[44] In addition, moisture acts as a natural lubricant, but in excess, it increases viscous resistance, which in turn raises energy consumption and amplifies temperature fluctuations.[45] Therefore, precise moisture control is a foundational strategy for regulating temperature distribution during compaction and enhancing final densified biofuel quality, which corroborates the findings presented in our study. Consequently, the moisture content's impact on temperature MSD should be prioritized in future temperature field uniformity investigations.

Given the highly significant interaction effect between forming pressure (A) and heating temperature (D) on temperature MSD (Kt), their response surface was analyzed while maintaining moisture content (B) and binder addition ratio (C) at central levels (Figure 5).

The response surface exhibited pronounced curvature variations with changing pressure and temperature. Notably, lower forming pressures (10 MPa) combined with elevated temperatures (190°C) significantly reduce K_t, indicating improved temperature field uniformity.

Thus, optimal process conditions for temperature field homogeneity involve: (i) 10 MPa forming pressure, (ii) 190°C heating temperature, and (iii) stable moisture/binder levels. This configuration minimizes K_t while maintaining other quality parameters.

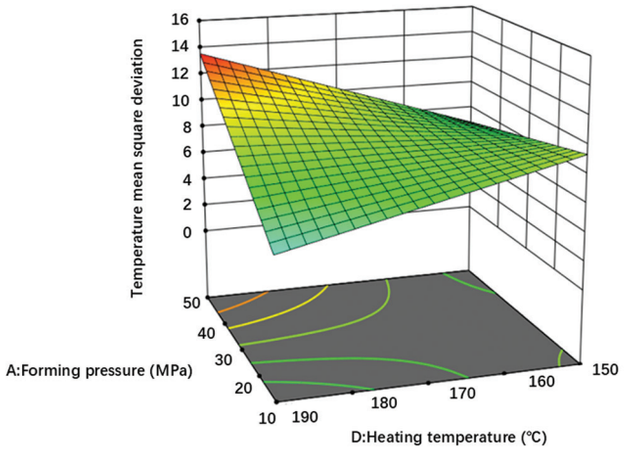

Figure 5. Response surface plot for forming pressure and heating temperature

To verify the reliability of the conclusions drawn from the response surface analysis and to assess the influence of temperature field uniformity on densified biofuel quality, a multiobjective optimization was performed using the Design-Expert 13.0 software on the experimental data from Table 1. The optimal parameter combination was predicted as follows: forming pressure = 10.0003 MPa, moisture content = 10%, binder addition ratio = 3.16532%, and heating temperature = 190℃, which aligns with the response surface plots.

Validation experiments confirmed that under these optimal conditions, the pellets exhibited a relaxed density of 0.964 g/cm^3, a relaxation ratio of 1.076, and an impact resistance of 98.78%. This parameter combination ensures that the pellets achieve maximized relaxed density and impact resistance while minimizing relaxation ratio and specific energy consumption, allowing for low-pressure compaction of biomass feedstock while maintaining high pellet quality.

4.2.3. The effect of temperature field uniformity on densified biofuel quality

To investigate the relationship between temperature field uniformity and biomass densification quality, Spearman correlation analysis was conducted using the Statistical Package for the Social Sciences software (version 2022 to assess associations between temperature MSD and both impact resistance and relaxed density. This nonparametric method was selected due to the nonnormal distribution of MSD data.

The correlation analysis revealed a significant negative correlation ($\rho = -0.633$, $p<0.001$) between temperature MSD and relaxed density, indicating that increased temperature heterogeneity (higher MSD) corresponds to reduced relaxed density. This phenomenon likely resulted from insufficient lignin softening and bonding under non-uniform temperature conditions.

A moderately negative correlation ($\rho = -0.500$, $p=0.011$) exists between MSD and impact resistance, attributable to structural inhomogeneity caused by uneven heat distribution. However, the non-significant relationship with relaxation ratio ($\rho = -0.199$, $p=0.339$) suggests minimal MSD influence, implying dominant effects from other factors.

Temperature field uniformity critically affects densified biofuel quality. Uniform heating (low MSD) promotes homogeneous lignin activation, enhancing interparticle bonding and consequently improving both relaxed density and impact resistance.

5. Conclusion

This study developed an innovative pine sawdust densification methodology based on temperature field optimization, providing an effective solution for forestry waste valorization. The investigation demonstrated that forming pressure, moisture content, and heating temperature critically influence pellet quality. Statistical analysis revealed that forming pressure, moisture content, heating temperature, and their interactions exhibited extremely significant effects ($p<0.01$) on both relaxed density and impact resistance, whereas heating temperature and its interaction with pressure significantly affected the relaxation ratio. The relative importance of factors affecting temperature MSD follows the hierarchy: moisture content (most influential) > forming pressure > heating temperature > binder addition ratio (least influential). Process optimization suggests that reduced moisture content combined with elevated temperature effectively minimizes temperature variation. Importantly, strong negative correlations exist between temperature MSD and both relaxed density and impact resistance, confirming that precise temperature field control substantially improves densified biofuel quality.

Acknowledgments

None.

Funding

This study was funded by the Beijing Forestry University (Award Number: 31500478, Grant Recipient: Zhongjia Chen).

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Availability of data

All data analyzed have been presented in the paper.

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