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Research article

Development and Physical Characterization of Molded Charcoal Souvenir Products from Rubberwood Charcoal Reinforced with Tea Waste

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Abstract: This research aimed to investigate the physical properties of molded charcoal produced from rubberwood biochar and tea waste, determine the optimal mixing ratio for forming stable products, and evaluate the production cost of the developed souvenir items. Rubberwood charcoal and tea waste were characterized for moisture content, volatile matter, ash content, fixed carbon, iodine adsorption, and moisture adsorption capacity. The rubberwood charcoal exhibited a moisture content of 2.82 ± 0.17%, volatile matter of 85.83 ± 2.07%, ash content of 2.90 ± 0.18%, fixed carbon of 8.45 ± 1.72%, and an iodine adsorption value of 479.94 ± 20.00 mg/g. The tea waste showed a moisture content of 2.75 ± 0.17% and an ash content of 2.83 ± 0.18%. Four formulations with different weight ratios of charcoal powder to tea waste (3:0, 3:1, 1:1, and 1:3) were prepared using tapioca starch as a binder, then formed into pieces using traditional mooncake molds. The 3:1 ratio was found to be the most suitable, providing compact, crack-free specimens with clear surface patterns, no loose powder after drying, and a slightly brown tea color. Moisture adsorption tests over 3 days confirmed that all formulations absorbed moisture, with the 3:1 formulation offering a good balance between structural integrity and functional performance. A preliminary cost analysis indicated that using 1 kg of mixed raw materials yielded 35 molded charcoal pieces at a total cost of 315.84 THB, or 9.02 THB per piece. The results demonstrate the technical feasibility and economic potential of upcycling rubberwood charcoal and tea waste into culturally inspired, environmentally friendly charcoal-based souvenir products with moisture adsorption capability suitable for community-based product development.

Keywords: Rubberwood biochar; tea waste; molded charcoal products; moisture adsorption; circular economy

1. Introduction

Rubberwood is an economically important crop in southern Thailand, where it is extensively cultivated and serves as a primary source of income for many farmers. Rubber cultivation is mainly aimed at natural latex production for industrial applications. After the latex-producing lifespan ends, rubber trees are felled and supplied to rubberwood processing factories, making rubberwood one of the major raw materials in Thailand's wood-processing

industry. However, rubberwood processing generates substantial quantities of substandard wood residues, which are commonly classified as industrial waste. Although a portion of these residues is utilized as fuel, a large amount remains underutilized despite its potential for value addition through environmentally friendly processing approaches [1, 2]. The conversion of rubberwood residues into biochar represents a promising strategy for waste valorization. Biochar is a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions, typically at temperatures between 300 and 700 °C. This process yields a porous structure with high chemical stability and surface functional groups that contribute to adsorption properties for moisture, odors, and various contaminants [3, 4]. Biochar can be produced from a wide range of agricultural and industrial residues, including coconut shells, rice husks, sugarcane bagasse, and rubberwood residues. Its physicochemical properties, such as moisture content, volatile matter, ash content, fixed carbon, and adsorption capacity, are strongly influenced by feedstock characteristics, pyrolysis conditions, and intended applications [5–8].

In recent years, biochar has gained increasing attention as an environmentally friendly material for product development due to its low production cost and multifunctional properties. In addition to its well-documented use in soil amendment and environmental remediation, biochar has demonstrated potential as an odor- and moisture-adsorbing material for household applications. Biochar-based molded charcoal products can be applied in enclosed environments such as wardrobes, refrigerators, vehicles, and storage spaces, providing practical functionality while adding value to agricultural waste materials [9,10]. When developed as souvenir products, such applications may further contribute to community-based economic activities. Although both biochar and activated carbon are porous carbonaceous materials with adsorption capabilities, they differ substantially in production processes and cost structures. Activated carbon requires additional physical or chemical activation to enhance its specific surface area and adsorption efficiency, making it suitable for industrial-scale applications such as water and air treatment. However, these activation processes are energy-intensive and associated with relatively high production costs [11]. In contrast, biochar can be produced without further activation, resulting in lower energy consumption and better alignment with sustainability and resource-efficiency principles. Despite its lower specific surface area, biochar has demonstrated adsorption potential for odor-causing and volatile compounds, supporting its application in low-cost adsorption systems [12, 13].

To enhance the functional performance of rubberwood biochar, the incorporation of secondary biomass residues has attracted growing interest. Tea waste, a by-product generated in large quantities from households and the beverage industry, contains lignocellulosic components and surface functional groups that may contribute to moisture and adsorption-related performance. Previous studies have demonstrated that tea waste exhibits adsorption potential for moisture and volatile compounds, supporting its suitability as a supplementary material in composite charcoal formulations [14, 15]. The use of traditional mooncake molds provides a practical shaping method for molded charcoal products, enabling the formation of decorative patterns and consistent product forms. Incorporating culturally recognizable forms and design elements into souvenir development can enhance product identity, aesthetic value, and differentiation in tourism-related markets [16, 17]. The development of molded charcoal souvenir products from tea-waste-enhanced rubberwood biochar is consistent with sustainable development principles. This approach supports waste reutilization and value addition, aligning with the Sustainable Development Goals, particularly responsible consumption and production and climate action, as well as Thailand's Bio–Circular–Green Economy model, which emphasizes biomass utilization and environmentally friendly product development [18–20]

Therefore, this study focuses on the development of molded charcoal souvenir products from rubberwood biochar enhanced with tea waste using mooncake molds. The objectives of this research are to investigate the physical properties of rubberwood charcoal and tea waste, determine the optimal mixing ratio for producing structurally stable molded products, and evaluate the production costs of the developed souvenir items. Rubberwood charcoal and tea waste were characterized for moisture content, volatile matter, ash content, fixed carbon, iodine adsorption capacity, and moisture adsorption behavior. The findings of this study aim to provide a scientific basis for sustainable material utilization and product development suitable for community-based commercialization.

2. Materials and Methods

2.1 Materials

Rubberwood biochar powder was used as the primary material in this study. It was obtained from rubberwood residues generated during wood-processing activities in southern Thailand. The residues were carbonized under limited-oxygen conditions to produce biochar, which was then ground and sieved to obtain a uniform particle size suitable for molding and adsorption-related performance. Spent tea leaves collected after beverage brewing were used as a supplementary material. The tea waste was dried and finely ground before use to enhance adsorption performance and add value to the agricultural waste. Tapioca starch was employed as a natural binder to promote adhesion between the rubberwood biochar powder and tea waste, allowing the mixture to be formed into compact shapes with good structural stability. Clean water was used as a solvent to control moisture content and to obtain appropriate consistency for the compression process. The products were molded using mooncake molds with floral patterns, which served as the primary forming molds to produce uniform shapes and decorative surface details. The compression process was performed using manual pressure or a simple compression device to achieve sufficient density and mechanical strength, enabling the molded charcoal products to be removed from the molds without cracking or deformation. The potential susceptibility of the products to microbial or mold growth due to the presence of tapioca starch and tea waste should be noted. To mitigate this risk, all products were thoroughly oven-dried at 85 °C before use and storage. Future investigations should assess the incorporation of natural antifungal agents or the implementation of supplementary heat-treatment protocols to improve the long-term microbial stability and shelf life of the developed products. The compression force applied during molding was not precisely quantified in the present study, which constitutes a limitation affecting process reproducibility. Future studies should employ a calibrated compression device and report the applied pressure in standardized units (N or MPa) to enable reliable replication and comparison across different production contexts.

2.2 Preparation of the molded charcoal souvenir product samples

2.2.1 Preparation of Rubberwood Charcoal

Rubberwood residues were air-dried and subsequently carbonized at 500-800 °C for 4–5 h under controlled oxygen conditions. After completion of the carbonization process, the charcoal was allowed to cool naturally to ambient temperature (Fig. 1a). The resulting rubberwood charcoal was then ground into a fine powder using an electric grinder (OTTO, model CP-390B, 1.8 L capacity). The obtained rubberwood charcoal powder was collected and stored for further experimental investigations (Fig. 1b). It is acknowledged that the reported carbonization temperature range of 500–800 °C represents a wide operational span ($\Delta T = 300$ °C). Biochar physicochemical properties, including surface area, pore structure, volatile matter content, and fixed carbon, are known to vary substantially within this range [5,6]. This range reflects the operational variability of the carbonization equipment used in this study. Future work should target a more precisely controlled pyrolysis temperature to improve batch-to-batch reproducibility and ensure consistency of proximate analysis results.

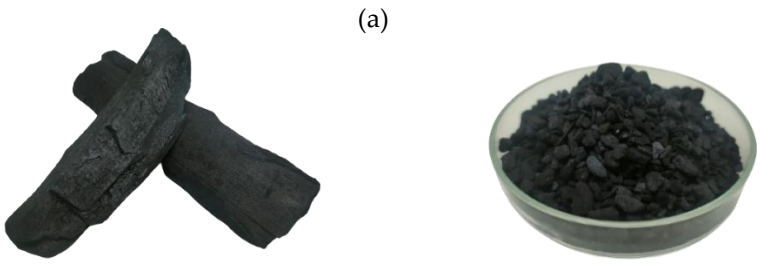


Figure 1. Shows (a) Rubberwood charcoal and (b) ground rubberwood charcoal powder.

2.2.2 Preparation of Tea Waste Powder

Spent tea leaves obtained after beverage brewing were sun-dried and subsequently oven-dried at 85 °C for 24 h to remove residual moisture. The dried tea waste was then ground into a fine powder and stored for further experimental investigation (Figure 2).



Figure 2. Spent tea leaves are collected after the tea brewing process and used to prepare tea powder.

2.2.3 Studying the optimal formula and ratio for molding activated carbon adsorption material fortified with tea waste

Based on investigations into suitable formulations and mixing ratios for molding charcoal products reinforced with tea waste, four formulations were examined by varying the mass ratio (weight ratio) of rubberwood charcoal powder to tea waste powder, as presented in Table 1.

Table 1. Formulations and mass ratios of materials used for molding molded charcoal products

Formulation	Rubberwood charcoal powder (g)	Tea waste powder (g)	Tapioca starch (g)
1	100	0	30
2	75	25	30
3	50	50	30
4	25	75	30

2.2.4 Studying the composition and molding of molded charcoal products reinforced with tea waste using mooncake molds.

Rubberwood charcoal powder, tea waste powder, and tapioca starch were thoroughly mixed according to the different formulations (Formulations 1–4), as summarized in Table 1. Each mixture was portioned into 60 g samples and subsequently molded into charcoal products using a mooncake mold with a peony lotus floral pattern. The molded samples were then oven-dried at 85 °C for 24 h to remove residual moisture. During the molding process, tapioca starch acted as a binding agent, facilitating adhesion between the charcoal powder and tea waste, improving compactness, and enhancing the mechanical strength and shape stability of the molded charcoal products (Figure 3).



Figure 3. Molding of tea waste–reinforced molded charcoal products using a mooncake mold.

2.3 Characteristic behavior of the samples

2.3.1 Analysis of the physical and chemical properties of rubberwood charcoal.

Moisture Content

The moisture content of the molded charcoal product samples was determined in accordance with the ASTM D2867-95 standard method. Porcelain crucibles with lids were first dried in an oven at 150 °C for 3 h, then cooled to room temperature in a desiccator. Approximately 1.0 g of the charcoal sample was weighed and placed into the pre-dried crucible. The sample was subsequently oven-dried at 150 °C until a constant weight was achieved. After drying, the crucible was cooled in a desiccator before final weighing. The moisture content of the charcoal samples was calculated and expressed as a percentage based on the weight loss during drying, using Equation (1)

$$\text{Moisture content (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

where W_1 is the initial weight of the sample before drying, and W_2 is the weight after drying.

Volatile Matter

The volatile matter content of the molded charcoal product samples was determined according to the ASTM D5832-95 standard method. Porcelain crucibles with lids were first heated to 950 °C for 3 h, then cooled to room temperature in a desiccator. Approximately 1.0 g of the charcoal sample was accurately weighed and placed into the pre-heated crucible. The crucible was immediately covered with a lid and transferred to a muffle furnace, where it was heated at 950 °C for 7 min. After heating, the crucible was promptly removed from the furnace and allowed to cool to ambient temperature for approximately 20 min, then further cooled in a desiccator. The weight of the charcoal sample after heating was recorded. The volatile matter content was calculated and expressed as a percentage based on the weight loss during heating, using Equation (2)

$$\text{Volatile matter (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad (2)$$

where W_1 is the initial weight of the sample before heating, and W_2 is the final weight after heating.

Ash Content

The ash content of the molded charcoal product samples was determined in accordance with the ASTM D2866-94 standard method. Porcelain crucibles with lids were first heated to 650 °C for 3 h, then cooled to room temperature in a desiccator. Approximately 1.0 g of the charcoal sample was accurately weighed and placed into the pre-heated crucible. The crucible was subsequently heated in a muffle furnace at 650 °C with the lid removed until a constant weight was achieved. After combustion, the crucible was cooled in a desiccator before final weighing. The ash content was calculated and expressed as a percentage based on the residual mass after combustion, using Equation (3)

$$\text{Ash Content (\%)} = \frac{W_2}{W_1} \times 100 \quad (3)$$

where W_1 is the initial weight of the charcoal sample before combustion, and W_2 is the weight of the residual ash after combustion.

Fixed Carbon Content

The fixed carbon content of the molded charcoal product samples was determined indirectly from the proximate analysis results. The fixed carbon content was calculated by difference, using the measured moisture, volatile matter, and ash content obtained from the preceding analyses. The percentage of fixed carbon was calculated according to Equation (4)

$$\text{Fixed Carbon (\%)} = 100 - \text{Moisture (\%)} - \text{Volatile matter (\%)} - \text{Ash content (\%)} \quad (4)$$

Iodine Adsorption Analysis (Iodine Number)

The iodine adsorption capacity of the molded charcoal product samples was determined in accordance with the ASTM D4607-94 standard method. Before analysis, the charcoal samples were oven-dried at 120 °C for 3 h and cooled to room temperature in a desiccator. A known mass of the dried charcoal sample was accurately weighed and transferred into a 250 mL Erlenmeyer flask with a stopper. Subsequently, 10.0 mL of 5% (w/v) hydrochloric acid solution was added, and the flask was gently swirled to ensure complete wetting of the charcoal particles. The mixture was then heated at 100 °C for 30 s to remove ash and sulfur impurities. After cooling, 100.0 mL of 0.10 N iodine solution was added to the flask. The flask was immediately stoppered and vigorously shaken for 30 s to allow adsorption equilibrium between the iodine solution and the charcoal sample. The mixture was then filtered through filter paper, and the initial filtrate was discarded until the filter paper became fully saturated. The subsequent filtrate was collected in a 125 mL Erlenmeyer flask. An aliquot of 50.0 mL of the filtrate was pipetted into a 250 mL Erlenmeyer flask and titrated with 0.10 N sodium thiosulfate solution until a pale yellow color was observed. At this point, 2–3 drops of starch indicator were added, producing a blue coloration, and the titration was continued until the solution became colorless. The volume of sodium thiosulfate solution consumed was recorded. The iodine number, expressed as milligrams of iodine adsorbed per gram of charcoal (mg/g), was calculated using Equation (5)

$$X(mg/g) = \frac{M_A - (D_F \times B \times S)}{M} \quad (5)$$

where
A is the amount of iodine corresponding to the iodine solution (mg),
B is the amount of iodine corresponding to the sodium thiosulfate solution (mg),
DF is the dilution factor,
S is the volume of sodium thiosulfate solution used in the titration (mL),
M is the mass of the charcoal sample (g),
N_1 is the normality of the sodium thiosulfate solution, and
N_2 is the normality of the iodine solution.

2.3.2 Calculating the cost of souvenir products made from activated charcoal and tea leaves.

The production costs of molded charcoal souvenir products reinforced with tea waste were calculated to evaluate their economic feasibility. The total production cost consisted of three main components: (1) direct material costs, including rubberwood charcoal, tea waste powder, and tapioca starch; (2) direct labor costs, calculated based on a production rate of 10 molded charcoal products souvenir units per hour; and (3) manufacturing overhead costs, which included expenses for water consumption, electricity usage, adhesive materials, and equipment depreciation. Equipment depreciation was calculated using the straight-line depreciation method. The total product cost was determined as the sum of direct material costs, direct labor costs, and manufacturing overhead costs, as expressed in Equation (6)

$$\text{Product cost} = \text{Direct material cost} + \text{Direct labor cost} + \text{Manufacturing overhead cost} \quad (6)$$

3. Results and Discussion

3.1 Effect of formulation and mixture ratio for molding activated carbon adsorption material fortified with tea waste

Physical Properties and Statistical Analysis

The physical properties of rubberwood charcoal and tea waste were statistically analyzed, and the results are summarized in Table 2. One-way analysis of variance (ANOVA) revealed that there were no statistically significant differences ($p > 0.05$) in moisture content and ash content between rubberwood charcoal and tea waste, as indicated by identical superscript letters. These results suggest that tea waste possesses physical characteristics comparable to those of rubberwood charcoal, supporting its suitability as a supplementary material in the molding process. The low moisture and ash contents are advantageous for maintaining product stability and adsorption performance. Figure 4 illustrates the comparative physical properties of the two raw materials.

Table 2. Physical properties of rubberwood charcoal and tea waste used as raw materials for molded charcoal products production

Physical property	Rubberwood charcoal	Tea waste
Moisture content (%)	2.82 ± 0.17[a]	2.75 ± 0.17[a]
Volatile matter (%)	85.83 ± 2.07	–
Ash content (%)	2.90 ± 0.18[a]	2.83 ± 0.18[a]
Fixed carbon (%)	8.45 ± 1.72	–
Iodine adsorption capacity (mg/g)	479.94 ± 20.00	–

Note: Values are expressed as mean ± SD (n = 3). Values with the same superscript letter within the same row are not significantly different ($p > 0.05$) according to one-way ANOVA. Analyses were conducted following ASTM standard methods. Volatile matter and fixed carbon were not determined for tea waste, as it had not undergone carbonization. Iodine adsorption capacity was not measured for tea waste in the present study; this constitutes a recognized limitation. Future research should include iodine adsorption analysis of tea waste to comprehensively characterize its contribution to adsorption performance in composite formulations.

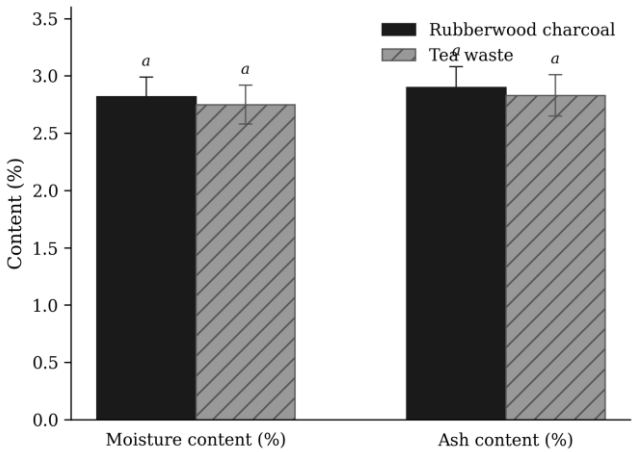


Figure 4. Comparison of the moisture content and ash content between rubberwood charcoal and tea waste

The moisture contents of rubberwood charcoal and tea waste were low. Rubberwood charcoal exhibited a moisture content of 2.82 ± 0.17%, while tea waste showed a moisture content of 2.75 ± 0.17%, with no statistically significant difference between the two materials ($p > 0.05$). These results indicate that both raw materials were sufficiently dry and suitable for the molding and drying processes of molded charcoal products, without causing problems related to shape retention or deterioration of adsorption performance, consistent with previous studies on charcoal-based molded products [21,22]. Rubberwood charcoal showed a volatile matter content of 85.83 ± 2.07%, reflecting the characteristics of charcoal produced under moderate

pyrolysis temperatures, in which some organic components remain within the structure [1]. Volatile matter was not reported for tea waste because it had not undergone carbonization. Nevertheless, an appropriate level of volatile matter can enhance particle adhesion during the molding process, as reported in studies on densified biochar and charcoal briquettes [1, 2]. It should be noted that the reported volatile matter content of 85.83 ± 2.07% is substantially higher than the typical range of 15–35% reported in the literature for rubberwood charcoal and biochar produced at 500–800 °C [5,6]. This elevated value may reflect batch-to-batch variability associated with the wide carbonization temperature range (500–800 °C, ΔT = 300 °C) applied in this study, partial carbonization of some material fractions, or methodological differences in the proximate analysis procedure. The authors acknowledge this discrepancy and recommend re-verification of the proximate analysis raw data and more precise control of pyrolysis temperature in future studies to improve data reliability and consistency with established literature values. (Figure 5)

The ash contents of rubberwood charcoal and tea waste were comparable, at 2.90 ± 0.18% and 2.83 ± 0.18%, respectively, and no statistically significant difference was observed ($p > 0.05$). The low ash content indicates a low level of inorganic impurities, a desirable property for adsorption materials, as excessive ash can block pores and reduce adsorption efficiency [4,11]. Rubberwood charcoal had a fixed carbon content of 8.45 ± 1.72%, representing the fraction of carbon remaining after the removal of moisture, volatile matter, and ash. This value reflects the potential of rubberwood charcoal to function as the primary adsorbent material in molded charcoal products. The fixed carbon content of tea waste was not reported because it had not been carbonized. Similar fixed carbon ranges have been reported for biomass-derived charcoals produced at moderate pyrolysis temperatures [4, 19]. The iodine adsorption capacity of rubberwood charcoal was 479.94 ± 20.00 mg/g, indicating an appropriate level of microporosity for the adsorption of odors and small volatile compounds. This moderate-to-relatively high iodine number supports the suitability of rubberwood charcoal for the development of molded charcoal products, particularly in community-based production contexts that emphasize simple processing methods and low production costs [8, 22, 23]

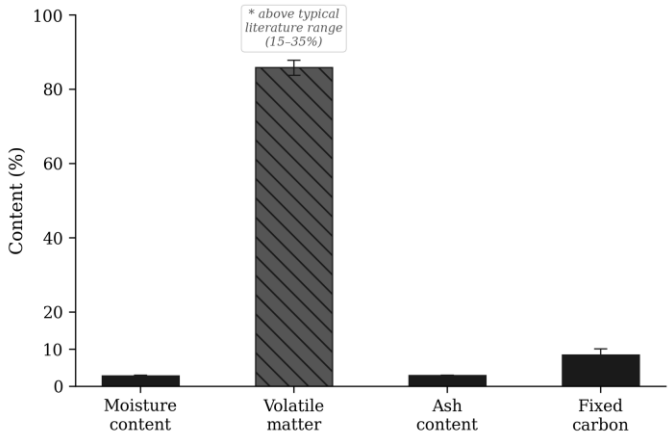


Figure 5. Proximate Analysis Results of Rubberwood Charcoal

3.2 Effect of composition and molding of activated charcoal adsorption material fortified with tea residue using mooncake molds.

The effects of composition on the moldability and structural characteristics of molded charcoal products reinforced with tea waste were investigated using four formulations with different mass ratios of rubberwood biochar powder to tea waste, as summarized in Table 3. When the mixtures were compressed using mooncake molds, clear differences in physical appearance, surface pattern definition, inter-particle cohesion, and shape retention were observed among the formulations, indicating a strong influence of mixture composition on molding behavior. Formulation 1 exhibited strong inter-particle cohesion between rubberwood biochar powder and tea waste, resulting in good moldability and clearly defined surface patterns transferred from the mold. After drying, no loose particles were observed upon manual handling, suggesting adequate particle packing and effective binding interactions between the constituent materials. Formulation 2 demonstrated

molding behavior comparable to, and in some aspects superior to, that of Formulation 1. The charcoal powder and tea waste adhered uniformly, resulting in sharp, well-defined floral patterns on the molded surface. The products retained their shape effectively in both wet and dry conditions, and no particle detachment was detected during handling. These characteristics indicate that formulation 2 possesses optimal material compatibility and consolidation behavior, making it highly suitable for practical application in the production of charcoal products. In contrast, Formulation 3 exhibited the weakest inter-particle adhesion among the tested formulations. The molded products exhibited unclear surface patterns, a friable, powdery texture, and substantial particle detachment upon handling. Poor shape retention after drying was also observed, indicating insufficient consolidation and mechanical integrity. Consequently, this formulation was deemed unsuitable for applications in molded charcoal products.

Formulation 4 showed moderate adhesion between rubberwood biochar powder and tea waste, allowing mold patterns to form to some extent. However, the surface details were less distinct than those observed in Formulations 1 and 2. Although the molded products retained their overall shape after drying, slight particle detachment and reduced surface quality were evident, reflecting inferior mechanical integrity compared with the optimal formulations. Based on these observations, Formulation 2 was selected as the most suitable formulation for molding charcoal products reinforced with tea waste. This formulation provided superior shape retention, clear, well-defined mold patterns, a smooth surface texture, and minimal particle detachment, thereby fulfilling the functional and aesthetic requirements for molded charcoal souvenir products, as summarized in Table 3. It is noted that the present evaluation of moldability was conducted qualitatively. Quantitative mechanical testing, such as compressive strength measurement or drop-test evaluation, was not performed in this study. Future work should incorporate standardized mechanical characterization (e.g., compressive strength in MPa and fracture energy) to provide a more robust, reproducible scientific basis for optimal formulation selection, particularly for souvenir products intended for commercial handling and transport [2, 3].

Overall, the results of the composition and molding study demonstrate that the rubberwood biochar–tea waste ratio plays a critical role in governing moldability, surface pattern definition, particle cohesion, and shape retention of charcoal products produced using mooncake molds. These findings are consistent with previous studies on densified biochar and charcoal-based products, which report that inter-particle adhesion and consolidation behavior are strongly dependent on mixture composition and particle interactions [22–24]. Formulations with balanced proportions of rubberwood biochar and tea waste (Formulations 1 and 2) exhibited strong cohesion, effective particle packing, and stable shape retention after drying, with negligible particle detachment during handling. Such characteristics are essential for achieving sufficient mechanical integrity and aesthetic quality in molded charcoal products [22–24]. In particular, Formulation 2 demonstrated the most favorable overall performance, maintaining structural stability in both wet and dry states while preserving sharp surface details from the mold. Conversely, formulations containing higher proportions of tea waste (Formulation 3) showed poor inter-particle adhesion, friable texture, and inadequate shape retention after drying. This behavior is consistent with reports indicating that excessive incorporation of lignocellulosic or fibrous residues can disrupt particle packing and weaken consolidated carbon structures [24, 25]. Formulation 4 exhibited intermediate behavior, with acceptable overall shape retention but reduced surface definition and slight particle detachment, a trend also reported in composite charcoal and briquette studies employing suboptimal mixture ratios [23, 24, 26] (Table 3).

Table 3. Morphology of molded charcoal products prepared with different biochar–tea waste ratios.

Formulation	Visual appearance	Observed characteristics
1		The charcoal powder exhibited strong cohesion, resulting in good moldability. The molded product retained its shape well, with clearly defined surface patterns. After drying, no loose charcoal particles were observed upon manual handling.
2		Both charcoal powder and tea waste adhered firmly, yielding well-shaped products with sharp, distinct mold patterns. After drying, no particle detachment was observed when touched. Slight brown coloration from tea waste was visible after drying.
3		Poor adhesion between charcoal powder and tea waste was observed. The molded product exhibited unclear surface patterns, a friable and powdery texture, and noticeable particle detachment upon handling. After drying, shape retention was inadequate, and the surface appeared dark brown.
4		Moderate adhesion between charcoal powder and tea waste was observed. The molded product retained its shape to some extent; however, the surface patterns were not well defined. After drying, slight particle detachment was detected upon handling, and the product exhibited a distinct brown coloration.

3.3 Moisture Adsorption Behavior of Molded Deodorizing Charcoal Formulations

The moisture adsorption behavior of molded charcoal products reinforced with tea waste is summarized in Table 4 and illustrated in Figure 6. Moisture uptake increased progressively with exposure time for all formulations. One-way analysis of variance (ANOVA) revealed that the formulation composition significantly influenced moisture adsorption, particularly at longer exposure times ($p < 0.05$). At day 3, Formulation 4 exhibited significantly higher moisture adsorption than Formulation 1, while no significant difference was observed between Formulations 2 and 3 ($p > 0.05$).

Table 4. Moisture adsorption (%) of molded charcoal products reinforced with tea waste at different exposure times

Time (day)	Formulation 1	Formulation 2	Formulation 3	Formulation 4
0	2.34 ± 0.16^{a}	2.52 ± 0.37^{a}	2.75 ± 0.55^{a}	1.67 ± 0.67^{a}
1	5.52 ± 0.13^{a}	5.65 ± 0.53^{a}	5.93 ± 0.48^{a}	6.12 ± 0.19^{a}
2	7.23 ± 0.17^{a}	7.36 ± 0.32^{a}	7.68 ± 0.61^{ab}	8.25 ± 0.19^{b}
3	7.94 ± 0.14^{a}	8.37 ± 0.50^{ab}	8.64 ± 0.75^{ab}	9.18 ± 0.20^{b}

Note: Values are expressed as mean ± SD (n = 3). Different superscript letters within the same row indicate significant differences at $p < 0.05$ according to one-way ANOVA

At the initial stage (day 0), the moisture adsorption values of all molded charcoal product formulations were low. Formulation 3 exhibited the highest value (2.75 ± 0.55%), followed by Formulation 2 (2.52 ± 0.37%) and Formulation 1 (2.34 ± 0.16%), while Formulation 4 showed the lowest moisture adsorption (1.67 ± 0.67%). Statistical analysis indicated no significant differences among the formulations ($p > 0.05$). These low initial values are consistent with previous studies reporting minimal moisture uptake in freshly dried charcoal and biochar materials before prolonged exposure to humidity [3, 5]. After 1 day of moisture exposure, the moisture adsorption of all formulations increased markedly. This behavior reflects the initial penetration of water molecules into accessible pores and surface functional groups, as commonly reported for charcoal-

based and biochar-based adsorbents under humid conditions [19, 21]. After 3 days of moisture exposure, Formulation 4 continued to exhibit the highest moisture adsorption and showed a statistically significant difference compared with Formulation 1 and Formulation 2 ($p < 0.05$). The increased moisture uptake at longer exposure times is associated with capillary condensation and enhanced interaction between water molecules and oxygen-containing surface functional groups [11, 21]. The enhanced moisture adsorption at longer exposure times may be associated with interconnected pore structures and water-retention behavior, as reported for coconut waste biochar [8].

Overall, the moisture adsorption of all molded charcoal product formulations increased progressively with increasing exposure time. Formulation 4 demonstrated the highest moisture adsorption capacity, reflecting the influence of a higher tea waste content on the increased hydrophilic surface characteristics and the availability of adsorption sites for water molecules [21, 22]. In contrast, Formulations 1 and 2 exhibited moderate, more stable moisture adsorption behavior, indicating their suitability for molded charcoal products that require a balance between adsorption performance and structural integrity, as illustrated in Figure 6. Similar trends have been reported in studies on mixed biomass charcoal-biochar composites designed for humidity and odor control applications [11,24]. Biochar with high porosity (approximately 56.5%) and water holding capacity (approximately 54%) significantly enhances adsorption-related performance. The porous structure and water-retention capacity of biomass-derived biochar facilitate moisture adsorption. In the present study, the moisture adsorption observed in rubberwood charcoal–tea waste composites may be attributed to the inherent porous structure of rubberwood biochar, together with the lignocellulosic composition of tea waste, which enhances surface roughness, pore accessibility, and the presence of hydrophilic functional groups. These findings highlight the importance of biomass composition in determining the physical properties and moisture adsorption capacity of molded charcoal materials. [8]

3.4 Production Cost Analysis of Deodorizing Charcoal Souvenir Products Reinforced with Tea Waste

Based on the material characterization and performance evaluation, Formulation 2 was selected for cost analysis due to its balanced physical properties, moisture adsorption behavior, and morphological stability. Selecting a formulation with stable structural integrity and moderate adsorption performance is essential to ensure both functional reliability and economic feasibility in molded charcoal products, as reported in previous studies on densified biochar and charcoal-based materials [3,5]. A cost per unit and cost–benefit analysis was conducted to evaluate the economic feasibility of producing molded charcoal products and souvenir products reinforced with tea waste at the community level. Cost analysis is an important component of community-based product development, as it reflects production scalability, affordability, and potential income generation for local producers [19, 21]. Using a total raw material input of 1 kg, the production process yielded 35 molded charcoal pieces. The total production cost was 315.84 THB, corresponding to an average unit cost of 9.024 THB per piece. This cost structure reflects small-scale, community-based production conditions and includes direct materials, direct labor, and manufacturing overhead. Similar cost structures and unit-cost ranges have been reported for molded charcoal and biochar-based household or souvenir products produced under small-scale or community enterprise settings, where low capital investment and simple processing techniques are emphasized [11–15].

Table 5. Production cost per unit of molded charcoal products, souvenir products, reinforced with tea waste

Cost component	Cost per hour (THB)	Cost per unit (THB)
Direct materials	12.50	1.25
Direct labor	42.50	4.25
Manufacturing overhead	35.24	3.52
Total	90.24	9.024

Note: One hour of production yields approximately 10 units of molded charcoal. Unit cost was calculated by allocating hourly production costs to individual products.

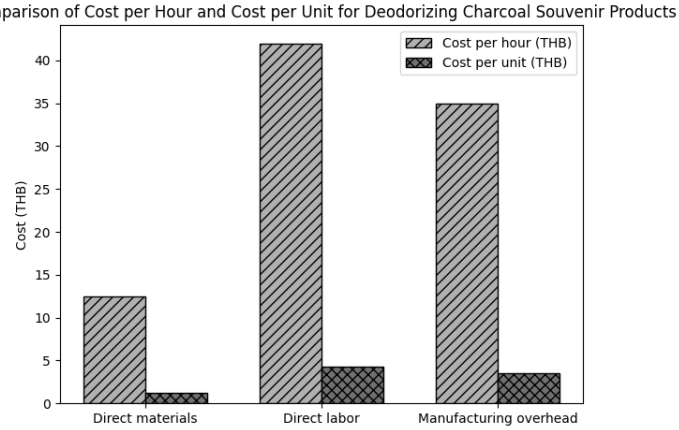


Figure 6. Unit production cost breakdown of molded charcoal products, souvenir products, reinforced with tea waste

Figure 6 compares the production cost per hour and the allocated cost per unit for each cost component. Direct labor exhibits the highest cost in both hourly (42.50 THB/hour) and unit-based (4.25 THB/unit) calculations, indicating that labor intensity is the primary contributor to overall production cost. Manufacturing overhead also accounts for a substantial portion of the cost, reflecting energy consumption, utilities, and equipment depreciation associated with the molding process. In contrast, direct material costs remain relatively low in both representations, highlighting the economic advantage of using rubberwood charcoal residues and tea waste as raw materials. The proportional consistency between hourly and unit costs confirms the appropriateness of allocating production costs based on a standardized output rate of approximately 10 units per hour.

3.5 Cost–Benefit Implications for Community-Based Production

From a cost–benefit perspective, the estimated unit production cost of 9.024 THB indicates that the molded charcoal products can be competitively positioned in local and tourist markets. Comparable handmade or eco-friendly molded charcoal products typically retail for 25-50 THB per piece, depending on packaging, branding, and point of sale. At a conservative selling price of 30 THB per unit, the gross margin would be approximately 20.98 THB per piece, representing a value addition of more than three times the unit production cost. Such value multiplication is consistent with previous reports on small-scale charcoal and biochar-based products developed for community enterprises and souvenir markets [11, 21]. It should be noted that the conservative selling price of 30 THB per unit was estimated based on general market knowledge of comparable eco-friendly and handmade deodorizing products and was not derived from a formal market survey. Future studies should conduct a structured market survey or cite comparable product pricing data from established retail channels or community enterprise reports to provide a stronger empirical basis for the cost–benefit analysis. The use of rubberwood charcoal residues and tea waste further enhances economic efficiency by reducing raw material expenses while simultaneously adding value to agricultural and industrial by-products. This strategy is widely recognized as an effective approach to improving profitability while minimizing waste generation, in accordance with circular-economy and biomass valorization principles [3, 4, 23]. Overall, the cost–performance balance achieved by Formulation 2 demonstrates its suitability for commercialization as a souvenir product. The relatively low production cost, combined with acceptable functional performance and aesthetic quality, supports its potential for sustainable adoption by community enterprises and small-scale producers, which is consistent with prior studies emphasizing low-capital, community-based manufacturing of biochar and charcoal products [11, 21, 24].

Table 6. Cost–Benefit Analysis of Deodorizing Charcoal Product

Item	Value (THB per unit)
Unit production cost	9.024
Selling price (conservative scenario)	30.00
Gross margin per unit	20.98
Value addition (times of production cost)	≈ 3.32 times

The analysis indicates that the product has a relatively low unit production cost compared with its market selling price, resulting in a high gross margin per unit and generating value addition of more than three times the production cost. This finding reflects the strong commercial potential of the molded charcoal products as eco-friendly souvenirs.

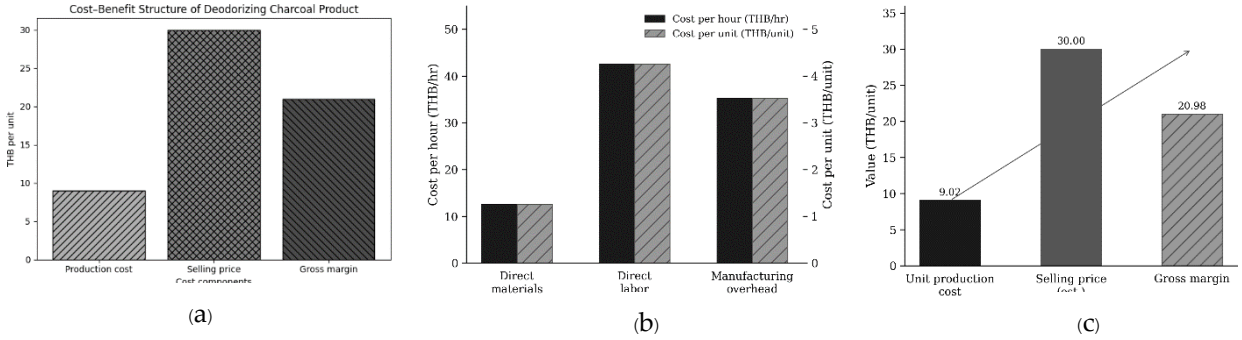


Figure 7. Economic analysis of molded charcoal products: (a) Cost–benefit structure of molded charcoal products souvenir products, (b) Production cost breakdown of molded charcoal products souvenir products, (c) Cost–benefit analysis of molded charcoal products souvenir products.

The graph clearly illustrates the differences among the unit production cost, selling price, and gross margin. The selling price is significantly higher than the production cost, resulting in a high gross margin per unit. This outcome is consistent with the principles of the circular economy and value addition of waste materials derived from rubberwood charcoal and tea waste.

4. Conclusions

This study demonstrates the technical and economic feasibility of producing molded charcoal souvenirs from rubberwood charcoal reinforced with tea waste, through optimized formulation and molding processes. Rubberwood charcoal exhibited suitable physical and adsorption-related properties, including a moderate iodine adsorption capacity indicative of appropriate microporosity for adsorption applications. These characteristics support its potential suitability as the primary adsorbent material for molded charcoal applications. It must be explicitly acknowledged that direct adsorption-related performance testing (e.g., using target gases such as ammonia, hydrogen sulfide, or standardized VOC adsorption experiments) was not conducted in this study. The odor-adsorbing potential of the developed products is therefore inferred from indirect performance indicators, namely iodine adsorption capacity and moisture adsorption behavior. The iodine number serves as a proxy for microporosity and is generally accepted as indicative of adsorption potential, but it does not directly measure adsorption-related performance. Future studies must incorporate quantitative measurements of odor or VOC adsorption to substantiate the molded charcoal claims stated in the title, abstract, and throughout the manuscript. Tea waste showed moisture and ash contents comparable to those of rubberwood charcoal, with no statistically significant differences, indicating good material compatibility. This compatibility enabled tea waste to be incorporated as a supplementary component without adversely affecting molding behavior, drying efficiency, or baseline adsorption performance, while contributing to waste valorization and sustainability. The rubberwood charcoal–tea waste ratio was identified as a critical parameter governing moldability, particle cohesion, surface definition, and shape retention.

Among the evaluated formulations, Formulation 2 provided the most favorable balance between mechanical integrity and functional performance, exhibiting clear mold patterns, stable shape retention, smooth surface texture, and minimal particle detachment. Formulations with excessive tea waste content showed enhanced moisture adsorption but suffered from reduced structural stability, highlighting the trade-off between adsorption capacity and mechanical performance. Moisture adsorption increased progressively with exposure time for all formulations, reflecting the hygroscopic nature of the composite materials. The synergistic interaction between the porous carbon matrix of rubberwood charcoal and the hydrophilic functional groups of tea waste enhanced adsorption performance in optimized formulations. From an economic perspective, the low unit production cost and high gross margin confirm strong commercial potential. Overall, the rubberwood charcoal–tea waste composite, particularly Formulation 2, represents a structurally sound, functionally effective, and economically viable material system for community-based production of molded charcoal products and souvenir products aligned with circular economy principles. It is acknowledged that direct adsorption-related performance testing was not performed in this study, and the molded charcoal claims are supported only by indirect indicators (iodine adsorption capacity and moisture adsorption behavior). Recommended directions for future research include: (1) quantitative odor or VOC adsorption experiments using target gases such as ammonia (NH_3), hydrogen sulfide (H_2S), or acetic acid; (2) standardized mechanical testing including compressive strength and fracture resistance measurements; (3) sensory evaluation and consumer preference studies relevant to souvenir market positioning; (4) long-term microbial stability and antifungal efficacy assessment; (5) more precisely controlled carbonization temperature conditions to improve batch reproducibility and proximate analysis reliability; and (6) a formal market survey to validate commercial viability assumptions.

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