

THERMOCHEMICAL VALORIZATION AND ENGINEERED DENSIFICATION OF RICE HUSK BIOMASS

A Review of Thermal Pre-Treatment, Binder Chemistry, Densification Mechanics, and Combustion Performance

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Abstract: Rice husk (RH) is an abundant agricultural residue generated during milling, representing an important prospective alternative to wood fuels in developing nations where traditional biomass drives extensive deforestation and greenhouse gas emissions. However, raw rice husk possesses low bulk density (86–150 kg/m³), high volatile content, and an abrasive, refractory inorganic ash fraction (6.5%–22.4 wt.%) dominated by silicon dioxide (SiO₂ > 90%), which resists particle deformation and causes severe die cracking during binder less compression. This review synthesizes processing advancements across thermal pre-treatments, binder formulation chemistry, densification mechanics, and combustion dynamics. Slow pyrolysis between 400–500°C successfully concentrates fixed carbon (35%–49%), producing biochar with higher heating values reaching 18–22 MJ/kg. Under low-pressure densification (≤15 MPa), binder chemistry governs briquette performance. While inorganic clay binders increase bulk density and burn duration, they introduce incombustible ash, lowering calorific value down to 9.5 MJ/kg. Edible starch adhesives deliver high drop durability (>94%) and clean combustion, yet raise serious food security concerns in developing countries. Consequently, non-edible municipal peelings (cassava, matooke, sweet potato), rice dust, and natural tree resins have emerged as high-performance substitutes, achieving shatter resistance exceeding 87% to 100% and flame temperatures up to 828.7°C. Furthermore, integrating central draft holes optimizes air-fuel contact, expediting ignition and minimizing particulate emissions. Overcoming machinery wear from abrasive silica and establishing standardized testing protocols remain vital for industrial scaling.

Keywords:- Rice husk; biochar; briquetting; binder chemistry; biomass densification; agricultural waste valorization; bioenergy

1. INTRODUCTION

Agro-industrial crop residues represent an abundant, carbon-neutral resource for decentralized renewable energy generation. Rice (*Oryza sativa*) serves as the primary dietary staple for over half the global population, generating an annual paddy yield exceeding 750 million metric tons. During milling, detachment of the outer hulls generates an estimated 120 to 150 million metric tons of rice husk (RH) annually, representing 16% to 26% of raw grain mass. In Asia, where more than 90% of global rice is produced and consumed, managing these residues presents severe environmental challenges. In sub-Saharan Africa, commercial paddy production is expanding at over 9% annually, generating over 1.2 million tons of milling residues across Uganda, Tanzania, and Nigeria. In Sri Lanka, paddy cultivation generates sufficient husk residue to satisfy up to 246 days of the nation's total industrial boiler steam demand if fully valorized.

Direct open combustion of loose husk is inefficient and hazardous. Its low bulk density (86–150 kg/m³) causes erratic furnace feeding, high fly-ash entrainment, and low volumetric energy release. Consequently, massive volumes are burned in open heaps or dumped in waterways, emitting respirable particulate matter (PM_{2.5} and PM₁₀), carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). Uncontrolled decomposition in landfills also produces methane (CH₄), a potent greenhouse gas. Meanwhile, over 2.4 to 3.0 billion people across developing regions rely on traditional firewood and lump charcoal for domestic cooking, accelerating forest depletion, topsoil loss, and domestic smoke exposure. Mechanical densification of rice husk into uniform solid fuel briquettes and controlled slow pyrolysis into porous biochar transform this liability into clean, high-density energy carriers.

2. PHYSICOCHEMICAL PROPERTIES AND THERMAL PRETREATMENT

2.1 Raw Feedstock Characteristics and Particle Sizing

Raw rice husk is composed of 32.7%–50.0% cellulose, 24.6%–31.7% hemicellulose, 18.8%–30.0% lignin, and 6.5%–22.4% mineral ash. The volatile matter fraction ranges from 51.9% to 85.9% on a dry basis, and its higher heating value (HHV) ranges from 12.4 to 16.1 MJ/kg.

Particle sizing directly governs bulk packing density and the strength of mechanical interlocking:

- Unground raw husks exceed 2.0 mm, exhibiting poor bulk densities of 100–130 kg/m³.
- Hammer-milling to <5.0 mm or below 2.0 mm increases bulk density to 367–370 kg/m³ without excessive fines generation.
- Grinding to fine powders (<150 μ m) incurs significant processing losses (up to 60% rejected material), establishing 0.5–2.0 mm as the most energy-effective sizing regime for densification.

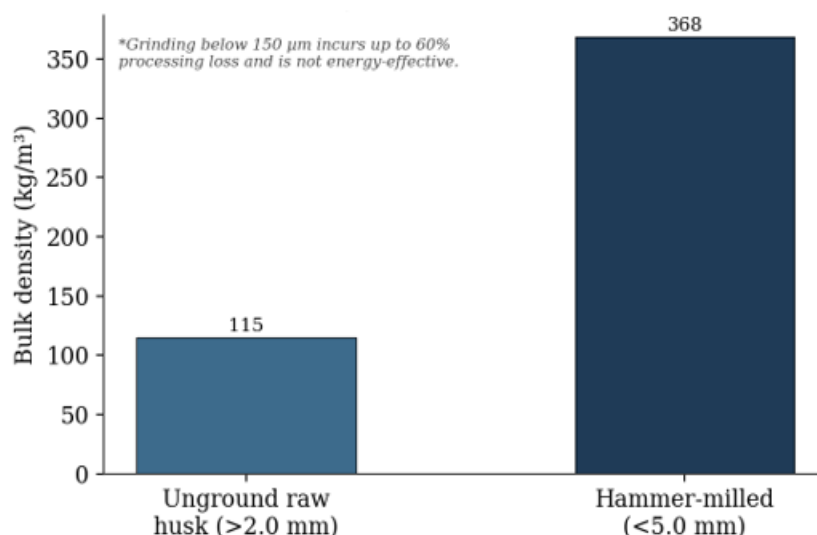


Figure 1. Particle-size reduction increases packing density ahead of densification.

2.2 Pyrolysis and Carbonization Dynamics

Converting raw husk into biochar concentrates fixed carbon while removing smoky volatile matter. Thermal decomposition follows four distinct intervals:

- Moisture Desorption (25–174°C): Cleavage of surface-bound physical water (6.56%–7.12% mass loss).
- Hemicellulose Devolatilization (150–350°C): Depolymerization of amorphous heteropolysaccharide chains (24.98%–26.58% mass loss).
- Cellulose Thermal Cracking (275–400°C): Cleavage of crystalline D-glucopyranose units, liberating combustible syngas (CO, CH₄, H₂) and bio-oil vapors.
- Lignin Cleavage & Char Condensation (300–900°C): Slow scission of complex aromatic ether bonds, consolidating the fixed carbon matrix and crystallizing biogenic silica.

Thermal stability during pre-treatment governs the final char quality. Isothermal carbonization at 260.8°C achieved 62.05% mass loss, concentrating fixed carbon to 35.88% with an HHV of 13.08 MJ/kg (3,126 Cal/g). Non-isothermal carbonization with thermal fluctuations (average 264.6°C, peaking at 350.5°C) yielded only 45.90% mass loss, 33.45% fixed carbon, and 12.67 MJ/kg (3,028 Cal/g) due to incomplete devolatilization. In an auto-thermal continuous downdraft reactor operating at 460–475°C with 650 L/min forced aeration, conversion efficiency reached 48.57% and thermal efficiency reached 42.42%, yielding 36.97 wt.% biochar with 48.89 wt.% fixed carbon, 36.13 wt.% ash, 12.75 wt.% volatile matter, and an HHV of 19.86 MJ/kg. Raising the pyrolysis temperature from 300°C to 700°C expanded the BET surface area from 78.4 to 377.7 m²/g and micropore volume from 0.009 to 0.032 cm³/g, while char yield dropped from 50.67 wt.% at 350°C to 23.32 wt.% at 700°C as minerals concentrated into ash (up to 76.2 wt.%).

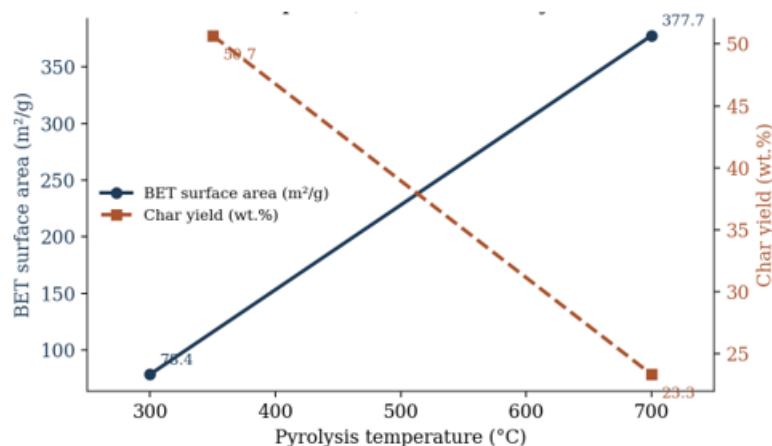


Figure 2. Trade-off between pyrolysis severity, porosity development, and char mass yield.

3. DENSIFICATION TECHNOLOGIES, TOOLING, AND AERATION GEOMETRIES

3.1 High-Pressure Binder less Compaction vs. Low-Pressure Systems

High-Pressure Compaction (>50 to 830 MPa): At elevated pressures, frictional heating exceeds the lignin glass transition temperature (100–140°C), allowing native biopolymers to flow and form solid bridges. In coal-rice husk blends, compaction at 830 MPa produced binder less briquettes with a compressive strength of 860 MPa and a shatter index of 2,600. Increasing pressure to 1,110 MPa provided no significant mechanical gains. However, pure rice husk fails under binder less compression. At 230 MPa, abrasive silica and low flowable lignin content cause die seizure and circumferential laminar cracking.

Low-to-Medium Pressure Systems (≤ 15 MPa): Decentralized facilities utilize manual, hydraulic, or screw presses operating between 2.5 and 10 MPa. Because compression remains below the plastic deformation limit of rice husk, mechanical integrity depends on external binding agents to bridge void spaces and resist elastic spring-back.

3.2 Die Geometries and Central Core Aeration

Extrusion tooling geometry significantly influences airflow and combustion completeness. Incorporating an axial mandrel pin to form hollow, cylindrical “doughnut” briquettes (outer diameter 45–70 mm with a 9–16.5 mm core hole) induces an internal chimney draft. This channel supplies convective air to the inner fuel boundary, accelerating ignition, reducing smoldering, and lowering cold-start emissions.

4. BINDER CHEMISTRY AND INTERFACIAL BONDING

4.1 Inorganic Binders (Clays and Minerals)

Bentonite, kaolin, and local clays disperse in water, enveloping fuel particles through ionic interactions and plate-like silicate slip. Clay binders increase bulk density (>800 kg/m³), improve structural hardness, and resist ambient moisture absorption. In burning duration trials, clay-bonded composite briquettes sustained combustion for up to 51.0 minutes (compared to 28.3 minutes for molasses-bonded briquettes). However, clay adds incombustible mass, which lowers calorific values (9.5–13.8 MJ/kg in rice husk chars) and increases ash content up to 50.5–60.6 wt.%, leading to increased slagging and extended water boiling times (up to 74 minutes for 5 L).

4.2 Edible Starch Binders

Commercial cassava, wheat, and tapioca starches are applied at 5%–15% mass ratios. When cooked in water at 68–75°C, amylose and amylopectin granules swell and gelatinize. Upon cooling, retrogradation forms continuous solid polymeric networks that bridge particle voids. Starch-bonded briquettes ignite rapidly (21–44 seconds), burn with clean blue flames, and attain drop strengths exceeding 94%. However, utilizing edible starches competes directly with human food supplies in developing nations, highlighting the need for non-food alternatives.

4.3 Non-Edible Agro-Industrial and Municipal Wastes

Municipal Solid Waste (MSW) Fruit Peels, gelatinized peel powders from cassava, sweet potato, and cooking bananas (“matooke”) serve as effective non-food binders. Incorporating 15% matooke peel binder into rice husk biochar yielded an HHV of 21.75 MJ/kg, an attainable flame temperature of 828.7°C, and a drop strength of 87.1%. Cassava peel binders produced particle

densities of 427.1 kg/m³ and drop strengths of 84.4%. Industrial Milling Residues, rice dust produced higher compressive strengths (2.54 kN) and durability (91.9%) than cassava starch wastewater (1.60 kN and 91.8%). Wastepaper pulp forms strong cellulose fiber networks, yielding shatter resistance indices of >90%. Natural Tree Resins, dummala resin (*Shorea oblongifolia*), melted with vegetable oil at 200°C, acts as a hydrophobic bio-binder. At a 1:7 ratio with rice husk (<5 mm), it achieved a density of 834.0 kg/m³, a compression ratio of 7.13, and 100% shatter resistance. Polymeric Formulations, combining amylopectin-rich glutinous rice flour with polyvinyl acetate glue at 5 wt.% produced cohesive briquettes that reached core combustion temperatures of 427.1°C with a 27.46-minute burn time.

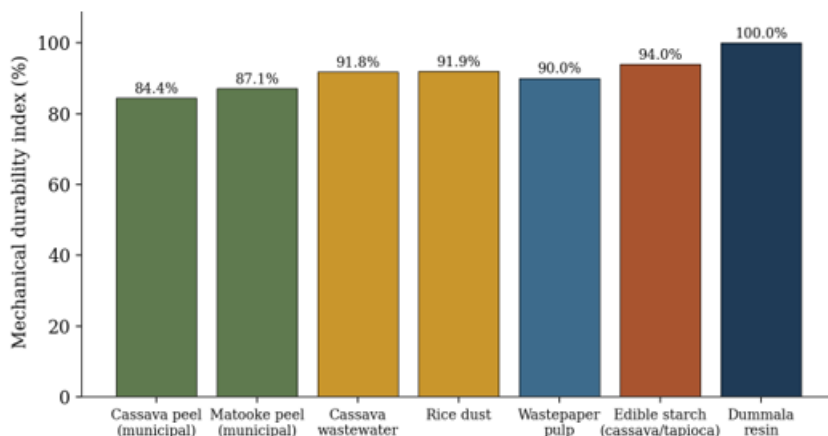


Figure 3. Mechanical durability of rice husk briquettes by binder class.

5. SYSTEMATIC PERFORMANCE METRICS OF RICE HUSK BRIQUETTES

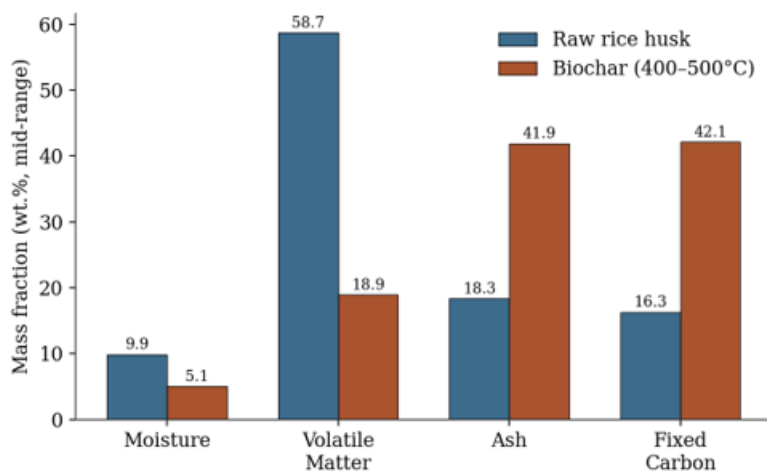


Figure 4. Proximate composition shift upon pyrolysis (mid-range values).

Table 1. Physicochemical and Proximate Profiles of Raw Rice Husk and Derived Biochar

Property	Raw Rice Husk	Biochar (400–500°C)	Impact on Performance
Moisture Content (%)	5.56–14.18	2.23–7.90	Low moisture in biochar avoids energy loss to water vaporization.
Volatile Matter (%)	51.96–65.40	9.60–28.20	High volatiles in raw husk accelerate ignition but raise smoke/PM _{2.5} .
Ash Content (%)	14.68–22.00	36.13–47.60	High SiO ₂ ash forms diffusion barriers, increases tool abrasion.
Fixed Carbon (%)	14.20–18.39	35.28–48.89	Concentration of fixed carbon raises net heating value.

SiO ₂ in ash (%)	94.38	up to 95.00	Abrasive phase prevents binder less high-pressure consolidation.
HHV (MJ/kg)	13.39–16.08	18.41–21.75	Carbonization strips volatiles, enhancing energy density.
Bulk Density (kg/m ³)	86–150	150–250	Volume reduction improves transport, storage, handleability.

Table 2. Comparative Evaluation of Briquette Binder Classes

Binder Category	Agents	Proportion	Advantages	Limitations
Inorganic	Bentonite, clay, wood ash	10–25%	Bulk density >800 kg/m ³ ; prolongs burn duration	Dilutes HHV to 9.5 MJ/kg; slagging
Edible Starch	Cassava, tapioca, wheat starch	5–15%	Drop durability >94%; rapid ignition (21–44 s); sootless flame	Competes with food supply; swelling if rehydrated
Agro By-Products	Cassava wastewater, rice dust	10–15%	Compressive 2.54 kN; durability 91.9%; uses industrial effluent	Slower dehydration; needs pre-heating
Municipal Peelings	Cassava, matooke, sweet potato peels	10–15%	HHV to 21.75 MJ/kg; flame 828.7°C; diverts waste	Needs oven-drying and pulverization <500 µm
Resins & Mucilages	Dummala resin, gum arabic, okra gum	5–20%	Shatter resistance 100%; water resistant; density 834 kg/m ³	Requires thermal melting at 200°C

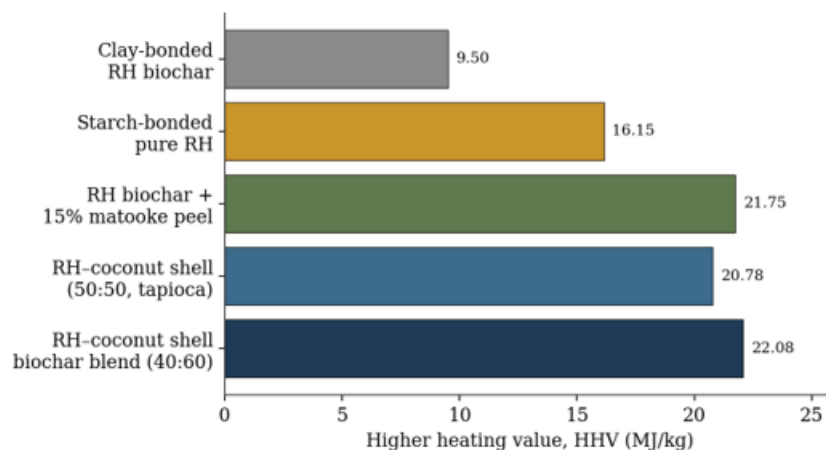


Figure 5. Calorific value across representative binder and co-briquetting formulations.

Table 3. Impact of Densification Method and Mold Geometry

Processing Regime	Tooling / Pressure	Effects	Challenges
High-Pressure Binder less	280–1,110 MPa	Densifies coal-husk blends without binders	Pure RH fails from silica abrasion, low lignin flow
Low-to-Medium Pressure	2.5–15.0 MPa	Stable briquettes with 5–15% organic binders	Needs binders, water, 1–3 weeks sun drying
Solid Cylindrical Die	30–50 mm	Simple manufacture, uniform loading	Restricted O ₂ diffusion, longer ignition/smoldering
Hollow “Doughnut” Die	9.0–16.5 mm core	Chimney draft; faster ignition, lower CO/PM _{2.5}	Needs specialized extractor to avoid core cracking

Table 4. Consolidated Performance Metrics of Evaluated Co-Briquette Formulations

Blend Formulation	System / Pressure	Density	Durability	HHV (MJ/kg)	Ref.
Carbonized RH + coffee husks (1:1)	Manual, ≤ 7 MPa	14.4–17.5 kg/m ³	Compressive 1.62–12.25 kN/m ²	17.14–18.67	[1]
Carbonized RH + bagasse + charcoal (1:3:6)	Hydraulic, 5.0 MPa	0.54–0.70 g/cm ³	Minimal expansion	11.3–26.8	[2]
Raw RH + lignite coal (2–20% RH)	Hydraulic, 280–1,110 MPa	n/r	Compressive 250–860 MPa	8.2–13.8	[3]
Raw uncarbonized RH	Hydraulic, 2.5 MPa	491–623 kg/m ³	29.3%–93.0%	n/e	[4]
Carbonized RH biochar	Hydraulic, 98.1 MPa	0.86 g/cm ³	Compressive 2.02 kg/cm ²	13.08	[5]
Continuous pyrolysis RH	Continuous gasifier	n/r	Cohesive particulate char	19.86	[9]
Carbonized RH biochar + peelings	Hydraulic, ≤ 7 MPa	415–427 kg/m ³	Drop strength 68.0%–87.1%	16.8–21.75	[17]
Raw RH sized fractions (<5 mm) + resin	Hand press	504–834 kg/m ³	Shatter 40%–100%	14.18–15.45	[18]
Raw milled RH + rice bran	Manual lever, 4.2 MPa	382–471 kg/m ³	Durability up to 91.9%; 2.54 kN	16.01–16.45	[19]
Carbonized RH + coconut shell	Hydraulic, 93.6 MPa	0.68–0.84 g/cm ³	Handling intactness	17.17–20.78	[20]

Co-briquetting carbonized rice husk with coconut shell (CS) and palm kernel shell (PKS) biochar overcomes the low energy density of single-feedstock rice husk briquettes. CS and PKS chars contain high fixed carbon (73.2%–79.7 wt.%) and low ash content (2.0%–5.5 wt.%). A blend of 40% RH biochar and 60% CS biochar with 25% starch binder achieved an HHV of 22.08 MJ/kg (5,277 kcal/kg), representing a 37% gain over starch-bonded pure rice husk briquettes (16.15 MJ/kg) and a 116% gain over clay-bonded pure rice husk briquettes (10.21 MJ/kg). Fixed carbon reached 55% while ash content dropped to 20%. Similarly, a 50:50 carbonized rice husk-coconut shell blend with 6% tapioca starch achieved an HHV of 20.78 MJ/kg (4,966 cal/g), an ash content of 20.21%, and a fixed carbon value of 49.04%.

For agricultural waste blends, hot-compressed mixtures of cabbage leaves and raw rice husk (600 kg/cm² at 250–270°C) initially yielded modest calorific values (15.5–16.2 MJ/kg). Subsequent slow pyrolysis at 500°C increased the calorific value by ~24.7%, reaching 21.03 MJ/kg (5,026.7 cal/g) for a 60:40 RH-to-cabbage formulation, satisfying the Thai Community Product Standard (TCPS $\geq 5,000$ cal/g). Response Surface Methodology (RSM) optimization of mahogany sawdust-rice husk briquettes identified optimal parameters of 28% rice husk, 57% sawdust, 15% starch binder, and 9.3 MPa compaction pressure, achieving an energy content of 23.05 MJ/kg (5.51 kcal/g), a water boiling time of 17.2 minutes, and a cooking thermal efficiency of 46.7%.

6. ENVIRONMENTAL LIFE CYCLE ASSESSMENT AND COMBUSTION EMISSIONS

6.1 Life Cycle Assessment (LCA)

Life cycle assessment indicates that rice husk briquettes are net carbon-mitigating fuels because combustion carbon emissions balance photosynthetic carbon uptake during crop growth. Replacing 100,000 tons of industrial coal with biomass briquettes avoids an estimated 335,679 tons of CO₂ eq emissions, while displacing 63,558 tons of coal eliminates 5,460 tons of SO₂ and 1,012 tons of PM₁₀. Cradle-to-gate LCA for 1 kg of pyrolyzed rice husk-cabbage charcoal identified an impact value of 3.42 kg CO₂ eq. The pyrolysis stage accounted for 63.24% of global warming potential, 81.95% of ozone depletion, 87.53% of human toxicity, and 79.80% of acidification, driven by auxiliary energy use and uncaptured flue gas release. This highlights the need for continuous auto-thermal gasifiers that burn syngas internally, eliminating external fossil fuel inputs and cutting net life cycle emissions.

6.2 Flue Gas Emissions and Ash Slagging Kinetics

Rice husk contains low elemental sulfur (0.019–0.16 wt.%) and nitrogen (0.41–0.45 wt.%), keeping combustion emissions of SO₂ and NO_x low compared to coal. In co-combustion trials, NO concentrations remained between 1.6 and 23.6 ppm, while CO ranged from 2,080 to 2,821 ppm. In domestic water boiling tests, carbonized biochar briquettes cut cold-start CO emissions compared to raw husk briquettes, while simmering phases produced minimal PM_{2.5}.

The primary thermal limitation of rice husk remains its high ash content. Biogenic silica (SiO₂) forms physical diffusion barriers that retard reaction kinetics and increase unburnt carbon in bottom ash. Furthermore, when biomass rich in alkali metals (potassium, sodium) is co-combusted with silica-rich rice husk, low-melting alkali silicates form (<750°C), coating grate surfaces and causing boiler slagging and clinkering. Adding phosphorus-based additives captures volatile potassium into high-melting potassium calcium phosphates, mitigating ash agglomeration.

8. CONCLUSION

Rice husk represents an abundant, renewable biomass resource capable of offsetting wood fuel dependency and abating open-field burning hazards. However, its high ash content and abrasive silica make binder less densification unfeasible under standard industrial conditions. Controlled slow carbonization (400–500°C) upgrades rice husk into biochar, increasing fixed carbon and calorific output (18–22 MJ/kg) while reducing combustion smoke.

At low-to-medium compaction pressures (≤10 MPa), binder selection governs final fuel quality. Inorganic clay binders increase structural hardness but dilute calorific value and increase ash clinkering. Gelatinized starches provide superior drop durability (>90%) and clean burning, though using edible crops raises food security concerns. Waste-derived organic binders—including fruit peelings, rice dust, and natural tree resins—match the binding strength of commercial starches without competing with food supplies. Integrating hollow cylindrical geometries further enhances draft airflow, cuts ignition delay, and lowers emissions. Scaling this technology requires standardized testing methodologies, wear-resistant processing machinery, and sustainable, decentralized waste valorization networks.

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