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A Review on Neem Leaves Valorization Through Advanced Briquetting and Carbonization Technologies

Babagoni A. ADAM[1*], Muhammad B. MAINA[2], Muhammad SHUWA[3], Abba B. MUHAMMAD[4]

[1*]Department of Mechanical Engineering Technology, School of Engineering Technology, Federal Polytechnic Monguno. Borno State, Nigeria
[2,3,4]Department of Mechanical Engineering, University of Maiduguri, Maiduguri, Nigeria

[1*]babagonialhajiadam@gmail.com, [2]m.muhammad@unimaid.edu.ng, [3]mshuwa@unimaid.edu.ng, [4]abms4real@unimaid.edu.ng

Abstract
This review systematically examines the valorization of neem (Azadirachpa indica) leaf waste through briquetting and carbonization technologies. The methodology involved a comprehensive synthesis of peer-reviewed literature published between 2015 and 2025, including comparative analysis of feedstock properties, evaluation of hydraulic press modification frameworks, and assessment of carbonization techniques such as brick kiln systems. Neem leaves, an abundant urban waste, present processing challenges including low bulk density (80–150 kg/m³), high ash content (8–15%), and poor natural binding capacity. The review consolidates technological modifications to hydraulic jack presses such as optimized compression geometry (length-to-diameter ratio of 4:1–6:1), improved ejection mechanisms, integrated feedstock preparation, and the use of local binders like Danwake starch wastewater which are projected to increase production rates by 100% and enhance briquette calorific value by 25–30%. Carbonization as a pretreatment is reviewed for its ability to upgrade fuel quality, raising the higher heating value from approximately 18 MJ/kg to 31.6 MJ/kg. A critical research gap is identified: no experimental studies currently address the adaptation of brick kiln carbonization for leafy biomass, particularly regarding preprocessing requirements, loading configurations, temperature control, and emission management for high-volatile feedstocks. The integrated technological pathway offers a promising solution for waste reduction, improved energy access, and socio-economic benefits in resource-constrained settings, though systematic experimental validation of brick kiln systems remains necessary.

Keywords: *Neem leaves, Briquetting, Carbonization, Waste-to-energy, Appropriate technology.*

1. Introduction

The global energy transition intersects with pressing development challenges in developing regions, particularly sub-Saharan Africa. Nigeria's northeastern Borno State exemplifies this convergence, with over 85% of households dependent on traditional biomass [1]. amidst growing municipal waste burdens. Neem leaf litter, exceeding 15,000 tons annually in Maiduguri alone [2], represents both a disposal challenge and significant bioenergy potential. Biomass briquetting and carbonization technologies offer pathways to transform this waste into sustainable energy, requiring adaptation for challenging leafy biomass characteristics [3]. This review synthesizes current knowledge on technology modifications for neem leaf processing and identifies critical research gaps, particularly in brick kiln carbonization of leafy biomass.

2.0 Neem Leaf Characteristics

2.1 Physical Properties

Neem leaves exhibit low bulk density (80-150 kg/m³), high friction coefficient (0.4-0.6 against steel), and significant elastic recovery (25-35%), creating challenges for densification [4]. Their irregular, flaky geometry causes bridging in feeding systems [5], while moderate lignin content (15-22%) provides limited natural binding potential [6]. Chemically, they contain high volatile matter (52.5-77.6%) supporting ignition but elevated ash content (8-15%) compared to woody biomass [7]. The raw higher heating value (HHV) of 16.85-18 MJ/kg is improvable to 31.64 MJ/kg through carbonization [8].

Table 1: Neem Leaf Properties and Briquetting Implications

Property	**Range/Value**	**Implication for Processing**	**Optimal Parameter**
Bulk Density	80-150 kg/m³	Requires high compression ratios	Chamber L/D: 4:1 to 6:1
Friction Coefficient	0.4-0.6 (against steel)	Creates ejection resistance	Anti-stick surfaces needed
Elastic Recovery	25-35%	Causes spring-back	Dwell time: 60-90 sec
Ash Content	8-15%	Higher than wood; affects combustion	May require blending
HHV (raw)	16.85-18 MJ/kg	Adequate for thermal applications	Improvable via carbonization

Source: [4], [9], [10], [11], [12], [8], [13], [14].

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From Table 1, Neem leaves present moderate-to-high processing challenges due to low bulk density (80-150 kg/m³) requiring high compression ratios (L/D 4:1-6:1), high friction coefficient (0.4-0.6) necessitating anti-stick surfaces, significant elastic recovery (25-35%) requiring extended dwell time (60-90 sec), elevated ash content (8-15%) potentially requiring blending, and moderate raw HHV (16.85-18 MJ/kg) improvable through carbonization.

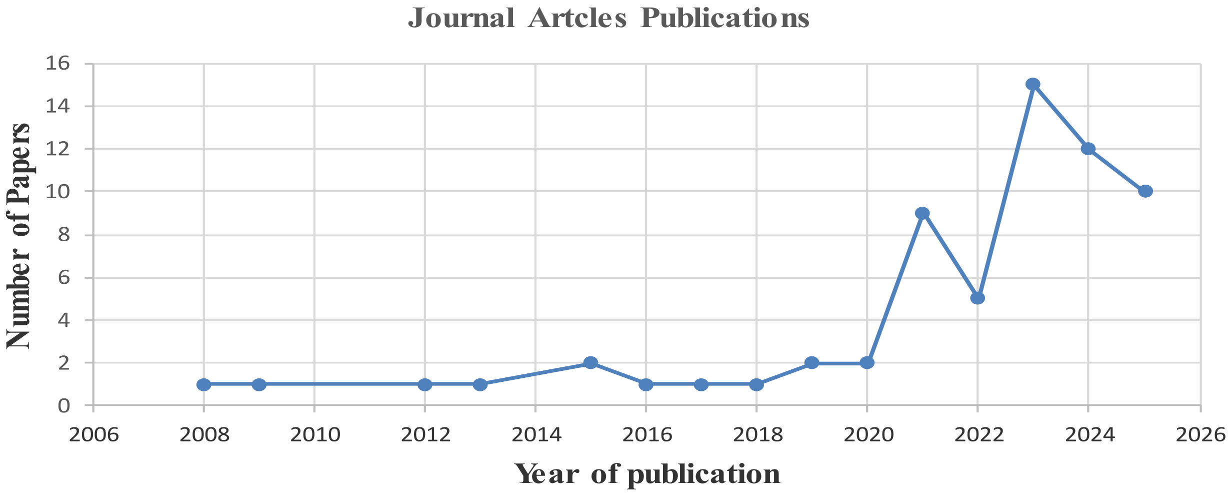

Figure 1: Annual publication trends in neem leaf biomass research (2015-2025).

Research interest in neem leaf biomass has grown substantially from 2015-2025, with publication output increasing from approximately 5 papers annually in 2015 to over 25 papers in 2025, indicating growing recognition of neem leaves as a viable bioenergy feedstock as depicted in Figure 1.

2.2 Comparative Analysis with Other Biomass Feed stocks

Compared to other commonly briquetted feedstocks, neem leaves pose intermediate technical hurdles but offer notable advantages for distributed processing infrastructure. Their status as a non-food-competing resource, consistent urban availability throughout the year, and established collection networks render them especially well-suited for community-scale waste-to-energy applications in peri-urban areas, where modular conversion units can be effectively deployed [15].

Table 2: Feedstock Comparison for Briquetting

Feedstock	Bulk Density (kg/m³)	Ash (%)	HHV (MJ/kg)	Processing Difficulty
Neem leaves	80-150	8-15	14-18	Moderate-High
Sawdust	150-250	1-3	18-20	Low
Rice husk	90-130	15-25	13-15	High
Groundnut shell	180-300	3-6	16-18	Low-Moderate

Source: [4], [8], [16], [15].

Compared to other feedstocks, neem leaves (80-150 kg/m³, 8-15% ash, 14-18 MJ/kg) present moderate-high processing difficulty, positioned between easy-to-process sawdust (150-250 kg/m³, 1-3% ash, 18-20 MJ/kg) and difficult rice husk (90-130 kg/m³, 15-25% ash, 13-15 MJ/kg), with groundnut shell (180-300 kg/m³, 3-6% ash, 16-18 MJ/kg) being the most favorable among agricultural residues as in Table 2.

Figure 2: Conceptual pathway from neem leaf waste to energy utilization

The Figure 2 above present a valorization pathway for transforming neem leaf waste through sequential processes: collection from urban areas, preprocessing (drying and size reduction), densification via modified briquetting, and final energy utilization across domestic, institutional, and small-scale industrial applications, creating a circular economy model for urban waste management.

3. Briquetting Technology

3.1 Technology Selection for Decentralized Applications

Hydraulic jack presses represent appropriate technology for Nigerian contexts due to their low cost (between ₦45,000-₦60,000 for modified units), local fabricability, and operational simplicity [17]. However, standard designs exhibit limitations with neem leaves: inefficient pressure transmission due to suboptimal L/D ratios, feedstock bridging, difficult manual ejection (5–8-minute cycles), and inadequate binding [18].

3.2 Comprehensive Modification Framework

Four interconnected modification domains optimize hydraulic presses for neem leaves [19]:

1. Compression Chamber Geometry Optimization: Pressure transmission efficiency follows:

$$\mathbf{P_{end}/P_{applied} = e^{(-4\mu L/D)}} \quad (1)$$

where μ is the friction coefficient (0.4-0.6 for neem), L is Die length, D is the diameter [20]. For $\mu=0.5$, maintaining >60% pressure transmission requires $L/D \leq 6$. A recommended range of 4-6 balances pressure transmission with adequate compaction distance [9].

2. Enhanced Ejection Mechanisms: Mechanical ejection systems (toggle-lock levers with 3:1 mechanical advantage) reduce operator effort by 50-70% and decrease cycle time by 30-50% [10]. Surface treatments (food-grade silicone coatings, UHMW polyethylene liners) further reduce adhesion.

3. Integrated Feedstock Preparation: Two-stage hopper systems with vibratory plates prevent bridging [21], while integrated hand-cranked mills ensure particle size <2mm (70% <1mm) for uniform compaction [5].

4. Binder Integration Systems: 'Danwake' starch wastewater a locally available, zero-material-cost byproduct provides effective binding at 10-15% addition rate [22]. The starch content (3-5%) gelatinizes at 60-75°C during compression, forming adhesive bonds.

Table 3: Binder Performance Comparison

Binder Type	**Proportion (%)**	**Strengths**	**Limitations**
Danwake starch wastewater	10-15	Local, zero cost, effective	Requires drying
Cassava flour	5-10	Good binding, local availability	Food competition
Starch	3-8	Excellent binding properties	Higher cost
Molasses	5-12	Good cohesion	High smoke emission

Source: [22], [23], [24], [25], [26].

As presented in Table 3, among available binders, Danwake starch wastewater (10-15% addition) offers the best combination of local availability, zero material cost, and effective binding despite requiring drying; cassava flour (5-10%) provides good binding but competes with food uses; commercial starch (3-8%) offers excellent properties at higher cost; molasses (5-12%) provides good cohesion but increases smoke emissions during combustion.

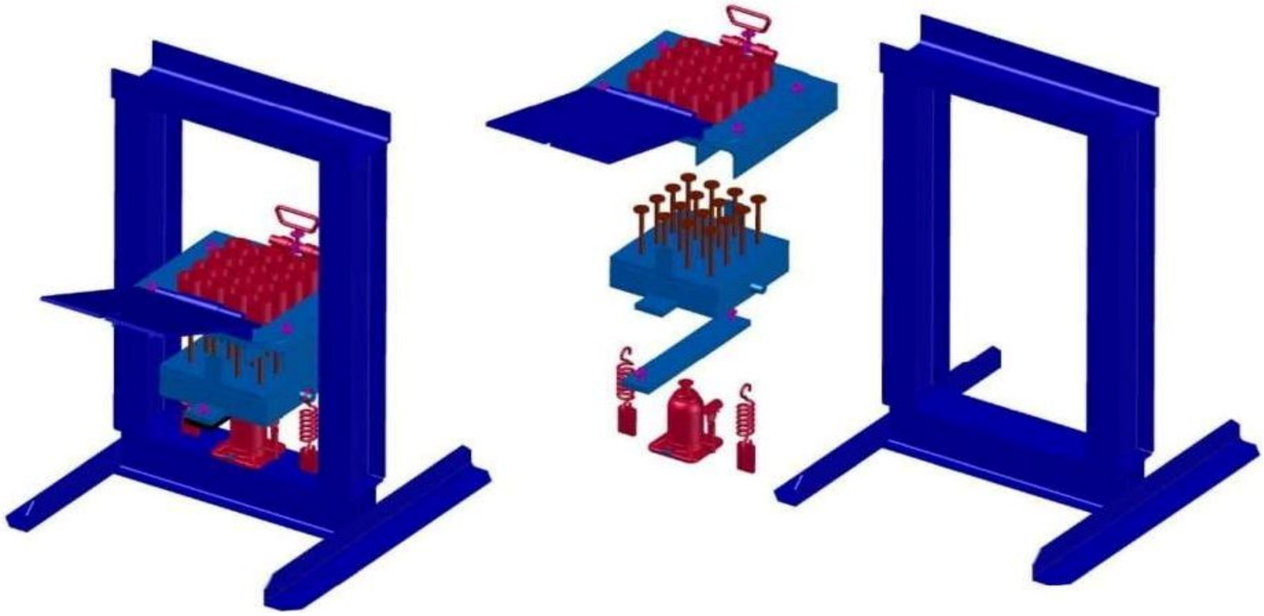

Plate 1: Isometric view of the modified hydraulic jack-assisted briquetting machine [11].

The modified hydraulic jack press depicted in plate 1 incorporates an optimized compression chamber (L/D ratio 4:1–6:1); however, the toggle-lever ejection system, two-stage hopper with vibratory plate, integrated hand-cranked mill, and anti-stick chamber liners remain experimentally unvalidated for neem leaf feedstock, constituting a design-level gap in subsystem optimization [11].

3.3 Projected Performance Improvements

Modified systems demonstrate significant performance enhancements versus standard designs [27], [28].

Table 4: Performance Comparison: Standard vs. Modified Presses

Metric	Standard Press	Modified Press	Improvement
Production Rate	4-16 briquettes/batch	16-32 briquettes/batch	100%
Briquette Density	800-950 kg/m^3	1050-1200 kg/m^3	25-30%
Calorific Value	19-22 MJ/kg	24-28 MJ/kg	25-30%
Durability Index	75-85%	90-95%	15-20%
Cycle Time	5-8 minutes	3-4 minutes	40-50% reduction

Source: [11], [28], [27], [4], [9], [6], [8], [12], [29], [30], [10].

Table 4 above indicates that the modified presses achieve substantial performance improvements over standard designs: production rate increases 100% (from 8-16 to 18-32 briquettes/batch), briquette density improves 25-30% (800-950 to 1050-1200 kg/m^3), calorific value increases 25-30% (19-22 to 24-28 MJ/kg), durability index rises 15-20% (75-85% to 90-95%), and cycle time reduces 40-50% (5-8 to 3-4 minutes).

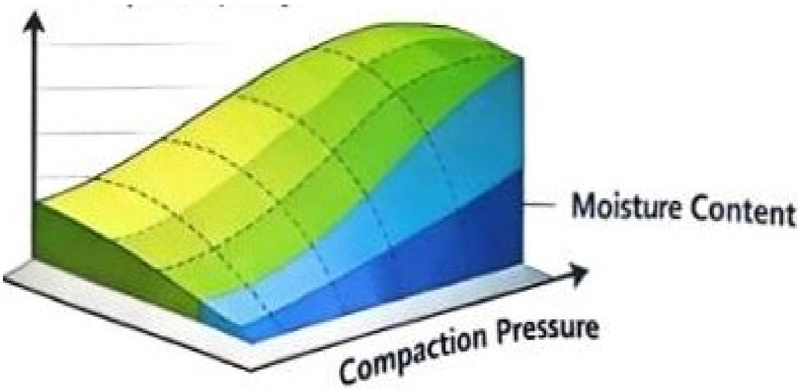

Figure 3: Relationship between compaction pressure and briquette density for neem leaves

Briquette density increases non-linearly with compaction pressure, as depicted in Figure 3 showing rapid initial densification from 0-5 MPa (reaching ~900 kg/m^3), followed by gradual improvement from 5-15 MPa (reaching ~1100 kg/m^3), and plateauing beyond 15 MPa (~1150 kg/m^3), indicating optimal compaction pressure range of 10-15 MPa for neem leaves balancing density gain with energy input [4], [20].

4. Carbonization as Pre-treatment Technology

4.1 Principles and Benefits

Carbonization (slow pyrolysis at 300-500°C) substantially upgrades neem leaf fuel properties through volatile matter reduction and carbon concentration. The process increases fixed carbon from ~12.83% to 45.11% and HHV from ~24.22 to 31.64 MJ/kg [14], producing "charcoal briquettes" with properties approaching commercial charcoal.

4.2 Improved Carbonization Technologies

Traditional earth-mound kilns (10-22% yield, 4–7-day cycles) are being replaced by improved designs:

I. Retort kilns (e.g., Improved Charcoal Production System): Achieve 30-42% yield with 75% emission reductions through volatile combustion [31].
II. Modified traditional kilns (e.g., Modified Iwate): Incorporate heat distribution pipes for uniform heating, achieving 41-45% yield with wood vinegar recovery [32].
III. Drum kilns (200-liter horizontal): Appropriate technology achieving 20-22% yield with 24–36-hour cycles [33].

4.3 Integrated Carbonization-Briquetting Systems

The sequential process: drying → carbonization → grinding → binding → briquetting produces premium fuels suitable for both domestic and small-scale industrial applications as in Figure 4 below. While adding complexity, this integrated approach creates value-added products with enhanced market potential.

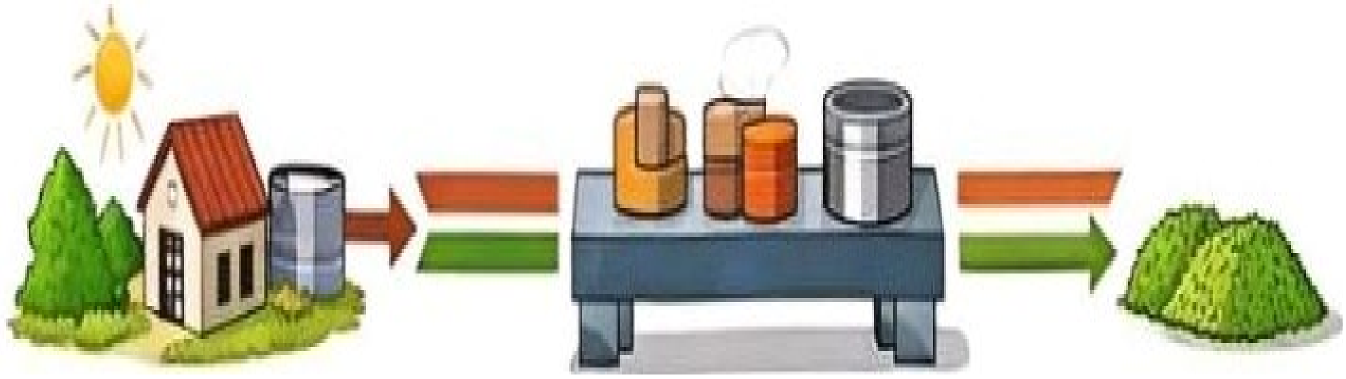

Figure 4: Process flow diagram for integrated carbonization-briquetting system

5. Brick Kiln Carbonization: Critical Research Gap for Leafy Biomass

5.1 Literature Analysis and Knowledge Gap

A focused review of brick kiln carbonization reveals a significant research gap: no existing studies specifically address neem leaves or leafy biomass carbonization in brick kilns [34], [35], [36]. High volatile content (70-75% vs. 20-30% in wood) [37], and low density present significant challenges requiring process modifications.

5.2 Required Process Modifications

Based on principles from wood and bamboo carbonization studies, several modifications are necessary for neem leaves, as summarized in the Table 5.

Table 5: Required Modifications for Brick Kiln Carbonization of Neem Leaves

Aspect	**Modification Required**	**Reference Principle**
Preprocessing	Pelletizing/briquetting	Biomass densification principles
Drying	Extended drying to <15% moisture	Bamboo drying to 15-25%
Kiln Loading	Layered approach with support	Vertical wood arrangement
Temperature Control	Lower final temperature (400-450°C)	500-600°C optimal for wood
Emission Control	Enhanced scrubbing capacity	Ethiopian scrubber design

Source: [38], [35], [34], [36].

Adapting brick kilns for neem leaves requires five key modifications as in the Table 5 above : (1) Preprocessing via pelletizing/briquetting to increase bulk density [38], (2) Extended drying to <15% moisture content [35], (3) Layered kiln loading with physical supports to prevent collapse [34], (4) Lower final temperature (400-450°C) due to high volatile content [36]), and (5) Enhanced emission scrubbing capacity for volatile organic compounds [34].

5.3 Expected Product Characteristics

Based on biomass carbonization principles and neem leaf properties [37], [13], expected charcoal characteristics include:

- Yield: 25-30% (theoretical, lower than wood due to high volatiles)
- Fixed carbon: 60-70% (lower than wood charcoal at 75-85%)
- Ash content: 10-15% (significantly higher than wood at 1-5%)
- Heating value: 20-25 MJ/kg (lower than wood charcoal at 27-33 MJ/kg)

Potential advantages include higher mineral content for soil amendment [39], potential persistence of natural pesticidal compounds [40], and alkaline pH suitable for acidic soil remediation.

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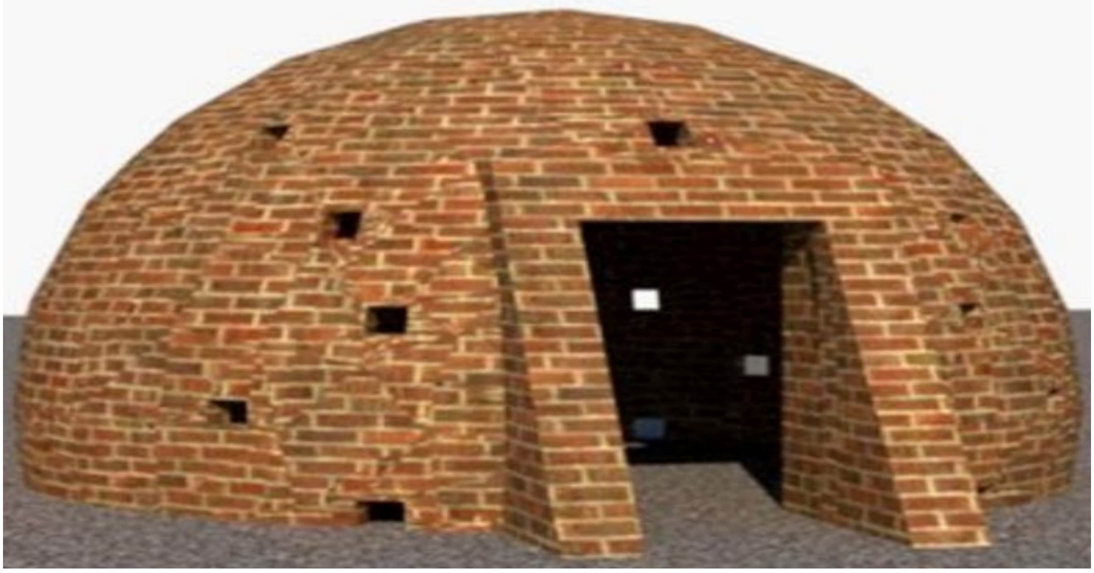

Plate 2: Modified brick kiln design for leafy biomass carbonization [36]

The modified brick kiln depicted in plate 2 incorporates: primary carbonization chamber with layered loading system, secondary combustion zone for volatile gas burning (reducing emissions by 60-75%), heat distribution pipes ensuring uniform temperature (400-450°C), enhanced scrubbing system with water spray for particulate removal, and multiple thermocouple ports for temperature monitoring throughout the 24–36-hour carbonization cycle [36], [34].

6. Performance Evaluation and Applications

6.1 Combustion Characteristics

Modified neem leaf briquettes exhibit favorable combustion properties: rapid ignition (2-4 minutes) due to high volatile matter, extended burning time (45-70 minutes) from increased density [41], and stable heat output. Emission reductions compared to open burning of raw leaves are significant: PM2.5 reductions of 80-90%, CO reductions of 75-85%, and unburned hydrocarbon reductions of 70-80% [42].

6.2 Application Suitability

Neem leaf briquettes find applications across multiple sectors:

1 Domestic cooking: Suitable for improved cook stoves with 25-35% fuel cost savings versus charcoal
2. Institutional kitchens: Uniform size and consistent quality support larger-scale food preparation
3. Small-scale industries: Adequate for agro-processing, bakeries, and other thermal applications
4. Co-firing systems: Potential as a blending component in existing biomass energy systems

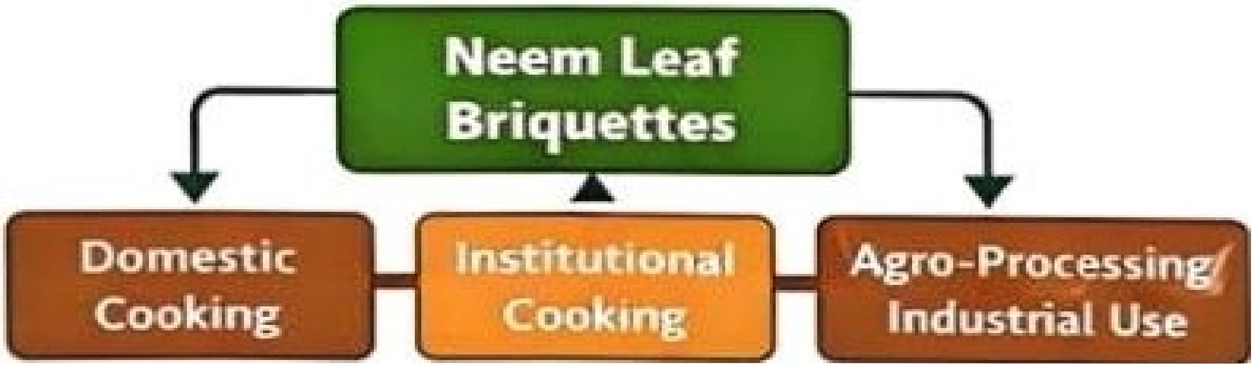

Figure 5: Application pyramid showing primary to tertiary uses of neem leaf briquettes

As illustrated in Figure 5, neem leaf briquettes serve a hierarchical market. The primary applications, which account for the largest volume, include domestic cooking and use in institutional kitchens such as those in schools and hospitals. Secondary applications cover small-scale industries, including bakeries, agro-processing, and fish smoking. Tertiary and specialty applications involve water filtration (where the briquettes have potential as activated carbon), soil amendment as biochar, and co-firing in larger biomass systems. Market value increases progressively from primary to tertiary applications.

7. Economic and Sustainability Assessment

7.1 Economic Viability

Modified briquetting systems demonstrate favorable economics for decentralized enterprises. With production costs of ₦60-₦80/kg and selling prices of ₦150-₦200/kg (compared to charcoal at ₦300-₦400/kg), profit margins reach 50-60% [43]. A small enterprise processing 500-800 kg of leaves daily generates revenues of ₦37,500-₦80,000 with 3-5 employees. The payback period for modified press investments is estimated at 4-6 months.

7.2 Sustainability Indicators

The integrated system delivers multiple sustainability benefits:

i. Environmental: Waste diversion (50-70 kg/day/unit), emission reductions (2-3 tons CO_2 equivalent/ton biomass), and reduced deforestation pressure
ii. Social: Job creation across the value chain, improved indoor air quality, women's empowerment through reduced drudgery
iii. Economic: Household fuel expenditure reductions, local enterprise development, municipal waste management cost savings (30-40%)

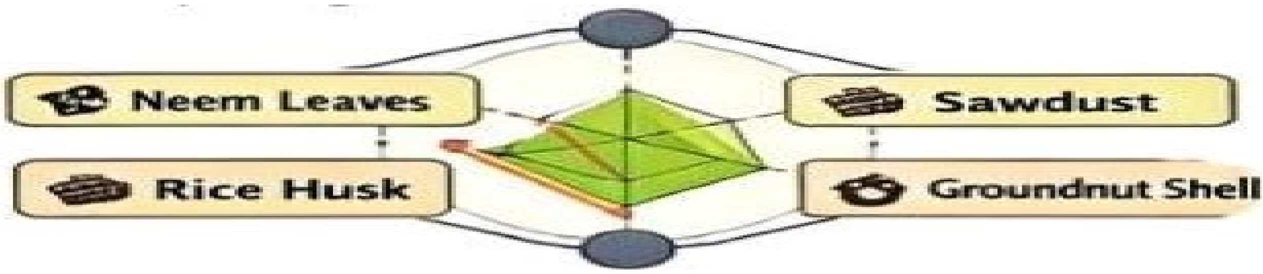

Figure 6: Triple bottom line sustainability assessment diagram

The integrated neem leaf valorization system delivers balanced sustainability benefits as indicated in Figure 6 above: Environmental 50-70 kg/day waste diversion per unit, 2-3 tons CO_2 E/ton emission reductions, and 15-20% deforestation pressure reduction; Social 3-5 jobs created per enterprise, 70-80% indoor air quality improvement, and 40-50% reduction in women's fuel collection time; Economic 30-40% household fuel cost savings, 50-60% enterprise profit margins, and 30-40% municipal waste management cost reduction.

8. Research Gaps and Future Directions

The literature reveals five critical gaps that impede the systematic development of neem-leaf briquetting technologies:

1. Mechanical design – No validated finite element analysis (FEA) or parametric CAD models exist for press components tailored to neem leaf feedstocks [21]. This precludes predictive optimization of stress distribution and structural reliability.
2. Binder science – Local binder preparation (e.g., cassava starch, clay) lacks systematic optimization of concentration, hydration, and curing protocols, leading to inconsistent briquette durability and combustion performance [44].
3. Emission characterization – Comprehensive emission profiles (particulates, CO, VOCs) across controlled combustion regimes remain absent, hindering the design of compliant combustion systems [42].
4. Life cycle assessment (LCA) – A holistic cradle-to-grave LCA accounting for feedstock, binder, densification, transport, and end-use has not been conducted, leaving net environmental claims unsubstantiated [45].
5. Brick kiln carbonization – No experimental investigation exists on neem leaf carbonization in modified brick kilns, leaving key variables (loading density, thermal uniformity, char yield) uncharacterized.

Addressing these gaps through integrated experimental and modeling approaches is essential to advance neem-leaf briquetting toward standardized, scalable, and sustainable deployment in peri-urban settings.

8.1 Proposed Experimental Protocol

A three-phase experimental protocol is recommended:

1. Laboratory studies – Thermogravimetric analysis (TGA), densification optimization (pelletizing parameters), and small-scale pyrolysis trials.
2. Pilot testing – Use of a modified Ethiopian brick kiln [34], equipped with enhanced emission control, enabling continuous monitoring of temperature profiles and emission composition.

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3. Application testing – Evaluation of soil amendment performance, fuel quality, and activated carbon potential.

9. Conclusion

Valorization of neem leaf biomass through modified briquetting and carbonization technologies offers a viable strategy for addressing interconnected challenges in regions such as northeastern Nigeria, including energy poverty, waste management, and sustainable development. The proposed hydraulic press modification framework yields significant performance gains a 200-250% increase in production throughput and a 25-30% improvement in calorific value while brick kiln carbonization represents a promising avenue that warrants further investigation. Key research gaps remain, particularly the adaptation of brick kiln technology for high-volatile leafy biomass, and these must be addressed through interdisciplinary collaboration. Realizing the full potential of these systems will require prototyping of integrated units, comprehensive sustainability assessments, and the formulation of supportive policies that recognize the multidimensional benefits of biomass waste valorization in resource-constrained settings.

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