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Technoeconomic Feasibility of Torrefaction-Densification Value Chains for Sawmill Waste in Sub-Saharan Africa: A Systematic Review and Adjustment-Based Cost-Benefit Synthesis

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Abstract

The techno-economic viability of sawmill wastes in Sub-Saharan Africa (SSA) as a precursor for an energy-dense biofuel via torrefaction and densification has been poorly studied. All monetary values in this review, including the abstract, are expressed in 2023 USD unless otherwise stated. This review synthesizes 70 articles to propose a cost-benefit model for torrefied densified sawmill waste in the region, accounting for zero feedstock cost, low labour intensity, and high capital intensity. Five findings are reported: (1) the torrefaction reactor is the largest cost driver, at 34-51% of equipment costs; (2) the low moisture of tropical sawdust (6-16% in West Africa) allows near-complete energy recovery during torrefaction, eliminating external fuel needs; (3) a 40,000 t/yr plant yields a minimum selling price (MSP) of USD 85-98/t at a 10% discount rate and USD 100-122/t at 15% (SSA scenario), versus USD 270-540/t for Kenyan charcoal briquettes; (4) 20,000 t/yr is the minimum profitable domestic scale, while 40,000 t/yr is needed for viable, narrow-margin exports given ISO certification costs; and (5) a 15% discount rate raises MSP by ~18-22% relative to the 10% base case, while the full weighted average cost of capital (WACC) scenario for SSA raises MSP by 18-24% across all sizes. The value chain is techno-economically viable at these cost levels. The review recommends concessionary lending to lower the cost of capital and a national standard differentiating local from imported biomass briquettes at the point of sale.

Keywords: Densification; Sawmill waste; Sub-Saharan Africa; Torrefaction; Techno-economic analysis

1. Introduction

Modern bioenergy constitutes the largest portion of renewable energy sources, accounting for over 50% of global renewable energy and more than 6% of world primary energy (IEA, 2023). Solid biomass is the primary energy source in low- and middle-income economies because of limited access to electricity networks (World Bioenergy Association, 2024). In Sub-Saharan Africa (SSA), the situation is characterized by biomass in its natural state being predominantly combusted for energy, with 80-90% of total energy consumption accounted for by solid fuels and 80% of the World Health Organization (WHO) African region population cooking on open fires or with inefficient stoves (Benti et al., 2021; WHO, 2023). 1.1 million preventable deaths occurred in Africa in 2019, with 30 percent of these deaths resulting from SSA household air pollution, which is a significant contributor to the high under-five mortality rate, with an odds ratio of 1.33 in 14 surveyed SSA countries (Bickton et al.,2020; State of Global Air, 2024).

The problem is not resource availability but the lack of value chains that process the local abundance of low-grade biomass into standardized, high-energy-density solid fuels. These can be produced through torrefaction-densification, a thermochemical pretreatment at 200-300°C and near-anoxic conditions followed by mechanical compression, which removes nearly all moisture from biomass, retaining 90% of energy content and reducing dry mass by 30%, increasing higher heating value (HHV) by 17% and reducing equilibrium moisture by 73% (Tumuluru et al.,2011; Fajobi et al.,2022). The processed fuel is hydrophobic, has a brittle structure comparable to coal, and thus is a viable option for both domestic and European Union (EU) co-firing markets. Sawmill residue appears to be the most promising feedstock for the region, constituting 40-55% of the logs processed in sawmills globally (Food and Agriculture Organization, FAO,1990), 51-59% in the longitudinal section in the US (Blatner et al.,2012) and 46-56% in Nigerian sawmills (Olufemi et al.,2012). Specifically, in Benin City, 20.64% of logs are converted into slabs, 10.28% into sawdust, 7.3% into wane, and 6.31% into bark (Izekor & Kalu, 2008).

The potential biomass feedstock in Nigeria in 2010 alone exceeded 1,000,000 m3 (Simonyan & Fasina, 2013). The prevalent tree species in Nigerian sawmills is Gmelina arborea (Robx), a hardwood with lignocellulosic composite of 40-55% of cellulose, 24-40% hemicellulose and 18-25% lignin in terms of dry matter content (Abo

et al., 2021), with hemicellulose being partially volatilized during torrefaction at 200-300°C, while lignin contributes to the formation of hydrophobic surfaces (Cahyanti et al., 2020). Preheating improves the plasticizing ability of lignin and reduces the pressure needed for densification. Although rice husk briquettes produced at 2625 kg/cm2 (257 MPa) failed to withstand compression, preheating at 225°C improved the outcome tremendously (Shrivastava et al., 2026). The same pretreatment allows wood-pellet production at 1,227.55 kg/m³ bulk density, 98.10% durability, and 96.65% hydrophobicity (Moreira et al., 2021), while also reducing the motor energy consumption for briquetting by approximately 10.2% (Kpalo et al., 2020) — an economically important metric that has not been analyzed within the context of an SSA industry. When torrefied at 200°C, calorific value increases to 18.1 MJ/kg, compared to 9.7 MJ/kg for the untreated sawdust at 12% moisture content (Gaitán-Álvarez & Moya, 2016), which can be obtained at zero or near-zero cost — an advantage unique to sawmill residue relative to purpose-grown energy crops.

Several studies have conducted techno-economic analyses of torrefaction densification biorefineries for solid biofuel production in the published literature. The minimum selling price at the gate is estimated between USD 103-105/t at 40,080t/yr (Sarker et al., 2023) and USD 197-207/t at 100,000t/yr (Manouchehrinejad et al., 2021). Capital expenditure (CAPEX) is projected at USD 37.4M-65.1M for facilities with a capacity of 60,000-100,000 t/yr (Batidzirai et al., 2013). The torrefaction reactor accounted for 34% of the total capital expenditure in producing solid biofuel (Sarker et al., 2023). The torrefaction cost at 25 t/h capacity is USD 17.5/t, whereas it can be reduced by up to USD 5/t by proper heat integration (Shah et al., 2011). This cost consideration applies to an Organization for Economic Co-operation and Development (OECD) context; however, it does not account for significantly higher WACC in the SSA, unreliable electricity supply, inert gas supply chains, and inferior labour productivity, while biomass supply costs are near zero in the region, completely overriding the advantage of lower torrefaction costs. This review provides the foundation for a cost-benefit analysis of torrefaction densification of sawmill waste in SSA.

The published literature on the economics of biomass utilization in SSA focuses exclusively on raw materials and small-scale domestic resource chains. In Nigeria, the only analysis concerning the use of agricultural residues for the production of briquettes was performed at the level of individual herders and farmers producing the fuel for personal use, with Bot et al. (2022) and Kpalo et al. (2022) reporting production costs of USD 0.16/kg and net present value (NPV) of USD 6,759.91 for the cost of USD 0.26/kg, respectively. Obi et al. (2023) identified a lack of appropriate supply chains and infrastructure and the absence of air quality standards as barriers to the commercialization of bioenergy in Nigeria, where no studies have been published on costs. In terms of processing facilities, Sokoto Energy Research Centre's 13kg/h extruder, Obafemi Awolowo University (OAU)'s 4kW screw press producing 10kg/h of 17.8MJ/kg fuel at 67.94% thermal efficiency (Emodi & Boo, 2015) and Raw Materials Research and Development Council-Abubakar Tafawa Balewa University (RMRDC-ATBU)'s 40kg/h piston press (Danjuma et al., 2013) allow to estimate the processing capacity. However, no analysis of their CAPEX, NPV, or MSP has been published. Finally, no techno-economic analysis relevant to the SSA context has been published for the torrefaction densification of sawmill waste, considering any of the aforementioned market options and the factors influencing them.

This study is novel in three respects. Firstly, it is the first techno-economic synthesis that applies a formal cost-benefit framework to the torrefaction-densification of sawmill waste in a Sub-Saharan Africa (SSA) context, rather than imposing OECD-horseshoe unit costs on the analysis; previous techno-economic assessments pertinent to SSA only focused on the economics of raw-biomass (Bot et al., 2022; Kpalo et al., 2022) or torrefaction chemistry (Abo et al., 2021; Cahyanti et al., 2020), but none have combined both at a commercial level. Second, the review is the first to quantify, from tropical-species data (Bello et al., 2024; Gaitán-Álvarez & Moya, 2016), the near-zero drying and energy-penalty advantage that low-moisture tropical sawdust confers over temperate feedstocks in torrefaction economics - an advantage that is structurally unavailable to the North American and European studies from which most published minimum selling price (MSP) benchmarks are drawn. Thirdly, the adjustment-based synthesis approach is also innovative in this literature because it does not take SSA as a modification of OECD benchmarks through a particular discount rate, but instead, re-establishes the cost of feedstocks, labour, capital imports, and electricity based on the evidence specific to the region (ILO, 2023; IMF, 2023; World Bank, 2020) and reports the sensitivity of the findings. This allows policymakers and investors to identify the most plausible range of MSPs, which was not available before this study.

SSA's bio-briquette markets are fragmented and localised: most producers sell directly to consumers, with few standardised products competing with charcoal (Mwampamba et al., 2013). In Kenya, the most developed bio-briquette market in SSA, retail prices of charcoal briquettes range between USD 0.3-0.77/kg, with wholesale prices varying between USD 270-540/t and a typical margin of 20-30% for small-scale businesses (Beyondforest, 2024; Njenga et al., 2013). The Nigerian bio-briquette industry is at a similar early stage to Kenya in 2004; Obi et al. (2023) observed that there is no single standard commercial-scale cost in the country.

Torrefied pellets can be presented as an innovative solution compared to coal in the international market because, according to Nunes et al. (2014), they are a potential replacement option for coal for co-firing purposes due to their high energy density and stability through the torrefaction process. The production of torrefied pellets is of particular interest to the EU, which recognizes biomass as a zero-carbon fuel under the Renewable Energy Directive II (Directive 2018/2001/EU). Starting in 2026, the Carbon Border Adjustment Mechanism (Regulation EU 2023/956) will impose a carbon price on imports from third countries based on the average auction price of the EU ETS, which constitutes a significant cost advantage for domestic biomass over foreign competitors (Batidzirai et al., 2013; Rentizelas & Li, 2016). Whether an SSA producer can meet the requirements of domestic or international markets and maintain a cost advantage over competitors remains to be seen.

The Nigerian Energy Transition Plan (Tijjani et al., 2025) aims to shift a quarter of gas use to biomass by 2030 and achieve carbon neutrality by 2060, given that biomass provides 43% of the country's primary energy. The National Clean Cooking Policy (2024) designates briquettes as a technology of choice to replace firewood with cleaner alternatives by 2030 in 80% of Nigerian households. This review's findings can be used to inform the following areas of research: (1) capital and operational cost structure under the conditions of the Nigerian economy and similar low-income settings; (2) the torrefaction energy penalty as a function of initial moisture and reactor design; (3) determination of gate MSP for local and international markets; (4) identification of minimum viable processing rates and supporting government interventions, and (5) determination of the minimum viable processing plant size and capital investment for an SSA context. Mass and energy yields and MSP will be determined per standard industry practice: as a per cent retained of feedstock's dry mass, as a per cent retained of feedstock's energy, and a gate price corresponding to zero NPV, respectively. The capital charge will be calculated according to standard practice: annualized CAPEX divided by tons of fuel produced. To begin with, this research was undertaken to fill a literature gap: the absence of techno-economic analyses (TEA) of torrefaction-densification value chains for sawmill waste in the SSA region. Prior studies assessing the economic feasibility of torrefaction in the region mostly originate from OECD countries. At the same time, those that include SSA-specific considerations evaluate only the economics of raw biomass utilization at the artisanal level.

The novelty of the current study mainly lies in the approach used to fill the identified literature gap. Instead of collecting a significant amount of data in order to structure a primary data set, the adjustment-based cost-benefit synthesis was applied. In particular, the international TEA literature data on capital expenditures (CAPEX), operational expenditures (OPEX) and minimum selling prices (MSP) of the torrefaction densification technology were adjusted using the SSA-specific data on feedstock, labor, capital import and electricity costs in order to estimate the literature-based ranges of MSP, minimum viable scales, and sensitivity levels for the first time.

2.0 Materials and methods

2.1 Review Design

This is a systematic review with embedded quantitative benefit-cost synthesis: a narrative review would have been inadequate in assessing the relative value of different bioenergy options in terms of MSP/CAPEX/IRR (internal rate of return) without benefit-cost normalization, while a formal meta-analysis was not feasible due to the heterogeneity of plant configurations, feedstocks, system boundaries, and cost-year assumptions across the considered studies. The review followed the (1) Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020)-compliant search and screening procedure (Page et al., 2021), and (2) quantitative synthesis based on the four pillars of cost-benefit assessment for the selected region: feedstock supply chain, torrefaction process, densification, and end-market pricing.

2.2 Search Strategy

The search was conducted in Web of Science, Scopus, Google Scholar, and African Journals Online (AJOL, to mitigate geographic bias) for the 2010–2025 timeframe, with pre-2010 references included if later substitutes were unavailable (Shah et al., 2011; Batidzirai et al., 2013). The following grey literature sources were explored separately: IEA Bioenergy Task 32 reports, International Renewable Energy Agency (IRENA) regional bioenergy assessments, FAO forestry statistics, World Bank technical papers, country-specific bioenergy strategies (e.g., Nigeria, Kenya, Ghana), and industry reports (Mordor Intelligence, Precedence Research, Allied Market Research). Boolean queries were designed to capture technology-economics-geography/feedstock combinations, e.g. ("torrefaction" AND "briquette" OR "pellet" OR "densification") AND ("techno-economic" OR "cost-benefit" OR "minimum selling price" OR "CAPEX" OR "OPEX" OR "NPV" OR "IRR") AND ("Sub-Saharan Africa" OR "Nigeria" OR "Kenya" OR "Ghana" OR "sawmill waste" OR "sawdust"), with some terms limited to title/abstract fields. The search also included a dedicated "*Gmelina arborea*" query and manual reference screening.

2.3 Screening, Extraction, and Quality Assessment

Duplicates were removed (Mendeley) and the remaining items were screened (title, abstract, full text) using inclusion/exclusion criteria related to publication source, timeframe, technological scope (i.e., 200–300°C torrefaction, briquetting/palletization), feedstock type (availability in local sawmill waste/lignocellulosic), economic content (explicit consideration of at least one of CAPEX, OPEX (Operating Expenditure), MSP, NPV, IRR, payback period, or Levelized Cost of Energy (LCOE), geographic focus, and language. Specifically, out of the initial 1,247 records, 318 duplicates and 671 title/abstract rejects were removed, leaving 258 items for full-text screening: 188 were excluded (non-peer-reviewed: n=20; n=15 conference abstracts; methodological insufficiency: n=47; timeframe: n=64; primarily descriptive costs: n=29; non-English: n=13), leaving 70 items for analysis: 10 primary techno-economic analysis (TEA) studies, 25 process/material analyses, 18 regional market/policy reports, and 17 grey-literature sources (Figure 1).

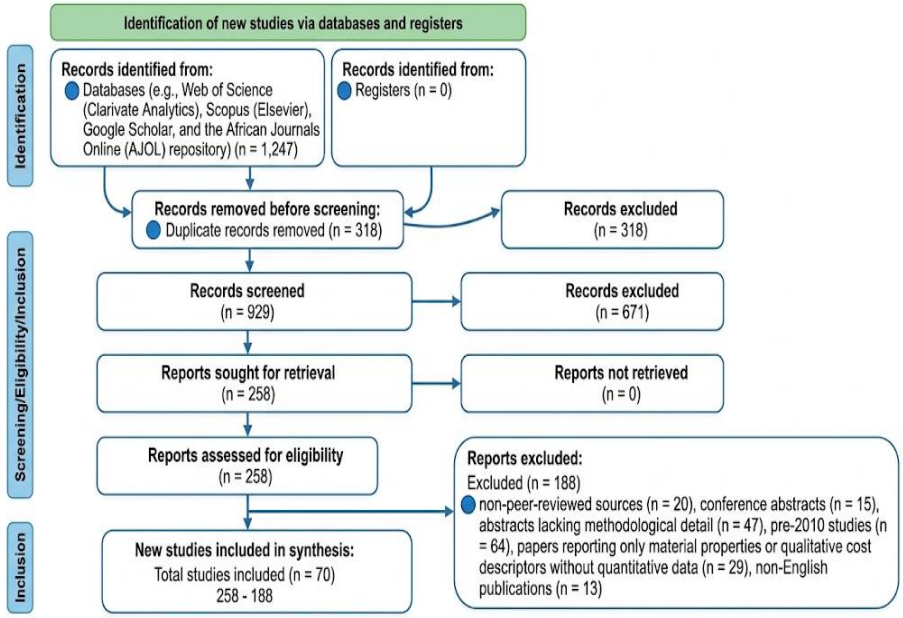

Figure 1: PRISMA 2020 flow diagram for systematic literature search and selection

Extracted parameters from the included studies consisted of feedstock type/moisture, throughput, torrefaction temperature/residence time, reactor type, system boundary, cost year/currency, CAPEX/OPEX by item, MSP/NPV/IRR, discount rate, project lifetime, mass/energy yields, thermal efficiency, heating value of output, and sensitivity variables; the latter additionally recorded product type, market segment, price, source type for the 18 market studies. Non-USD costs were converted using the exchange rate of the International Monetary Fund (IMF) for the year of publication; all values were inflation-adjusted to 2023 using the Chemical Engineering Plant Cost Index (CEPCI) to obtain Eq. (1):

$$Cost_{_{2023}} = Cost_{reported} \times \left(\frac{CEPCI_{2023}}{CEPCI_{reported\ year}}\right) \quad (1).$$

The inclusion criteria were applied using a five-criteria tool, each scored 0-2 (maximum 10), with 0-3: low quality (qualitative analysis only), 4-6: moderate (significant uncertainty identified), 7-10: high (primary quantitative evidence base). Of the 10 techno-economic analyses (TEA) included, seven (7) were high, two (2) moderate, and one (1) low.

2.3 Cost-Benefit Framework

Total cost per unit production (USD/t output) was disaggregated into Eq. (2):

$$C_{total} = C_{feedstock} + C_{drying} + C_{torrefaction} + C_{densification} + C_{ancillary} + C_{capital\ charge} \quad (2)$$

where feedstock cost covers gate price and aggregation transport; drying reflects pre-torrefaction moisture reduction; torrefaction covers reactor energy, inert gas, maintenance, and labour per tonne output after mass-yield loss; densification covers press energy, die maintenance, binder, labour, and cooling; ancillary covers grinding, handling, storage, and packaging; and capital charge is annualized capital expenditure (CAPEX) at a 15-years project lifetime using the annuity method for the specified discount rate (annuity method).

Explicitly, the annualised capital charge $C_{\text{capital charge}}$ in Eq. (2) is CAPEX multiplied by the capital recovery factor (CRF) in Eq. (3), and the resulting MSP at each discount rate is the $C_{\text{total value}}$ at which project NPV equals zero, Eq. (4):

$$CRF = {r(1+r)^{n}}\Big/{[(1+r)^{n} - 1]}, C_{capital\ charge} = CAPEX \times CRF \ / \ annual\ tonnage \quad (3)$$

$$MSP = C_{feedstock} + C_{drying} + C_{torrefaction} + C_{densification} + C_{ancillary} + \left(\frac{CAPEX \times CRF}{Q}\right) \quad (4)$$

where r = the discount rate, n = the project lifespan (15-year) (10/20 years in sensitivity analysis), and Q = annual tonnage at the stated utilization rate. This is the standard fixed-charge-rate/annuity method as used in the source TEAs (e.g., Sarker et al., 2023; Manouchehrinejad et al., 2021): it is used consistently at 10% and 15% to get the two discount-rate scenarios reviewed in Section 3.5; and the higher CRF at 15% than 10% (for n = 15) automatically boosts the capital-charge component of MSP by the amounts shown in Table 3, independent of any changes to OPEX.

Computations were performed for gate prices of 1,000 t/yr (prototype currently under development for Nigerian institutional cooking), 20,000 t/yr (pilot-scale), and 100,000 t/yr (commercial-scale) plants at 10 and 30% moisture (representative of observed 6- 16% for G. *arborea*). A 10% discount rate was adopted as a default, consistent with the main sources (Sarker et al., 2023; Manouchehrinejad et al., 2021) and reflecting 12- 20% interest rates in domestic (SSA) lending (IMF, 2023). The project lifetime was set at 15 years (10/20 years for sensitivity analysis). Utilization was set at 75% (60% in the worst-case scenario). At the same time, the stumpage/acquisition price of sawmill residue itself is set to USD 0/t, as its current status as waste in the mill gate (Ohwo et al., 2020), however this doesn't mean that the feedstock is free to the plant. The baseline model therefore adds a mandatory local aggregation, handling, and haulage charge to every scenario, with a cost of USD 8-15/t within a 50 km catchment radius, which is the only SSA-relevant benchmark identified in the literature (IRENA, 2017), and a USD 20/t pessimistic sensitivity ceiling to reflect poor road conditions or a wider catchment.

Feedstock import duties (12-20%) and freight (8-12%) applied to equipment, with local fabrication reducing costs by 30-40%. In addition, labor costs were scaled down according to the Nigerian (USD 1.5-5.0/hr; ILO, 2023) to North American (USD 18-25/hr) exchange rate; civil works were quoted at 60-70% of European construction costs (World Bank, 2020); and grid tariffs in several SSA economies remain in the low single-digit-cents range once converted from local currency (Babatunde et al., 2020; Adebayo et al., 2024), while diesel-based generation costs are consistently reported at 3–10× grid rates, spanning roughly USD 0.22–0.44/kWh depending on generator scale and country (Oseni, 2017), against a backdrop of sub-50% reliable grid access in multiple SSA countries (Babatunde et al., 2020). Given the risk of continuous grid supply, the base operating-cost scenario is a mix of grid and diesel-backup power in the ratio of 70:30 which represents the 55-70% grid-hours availability recorded for the SSA milling regions (Obi et al., 2023), yielding a compounded base electricity price of USD 0.10-0.13/kWh; the all-grid and all-diesel prices above are held as best- and worst-case extremes, respectively, as opposed to the default assumption.

Technical viability was determined relative to domestic SSA cooking-fuel prices (gate) and export prices (torrefied pellets, Cost, Insurance, and Freight (CIF) Europe, net of freight). If the total production cost (C_{total}) did not exceed the reference prices under baseline conditions, the technology was considered potentially viable; if (C_{total}) exceeded the reference prices, it was deemed conditionally viable with the identification of the level of support (carbon credits, feedstock subsidy, co-firing premium) required to render it economically attractive. Finally, a one-at-a-time sensitivity analysis was performed by varying CAPEX, feedstock moisture, labour costs, discount rate, utilization, feedstock price, and output price by +/- 30%, with the resulting MSP reported as an elasticity indicator. For inputs with high elasticity (>0.5), low/base/high scenarios were explored to delineate pessimistic and optimistic bounds for selected variables. A full Monte Carlo analysis with independently parameterised inputs is unavailable for the SSA context, as primary joint-probability distributions for the inputs are unavailable, but as a demonstration of the insufficiency of the OAT method to interrogate models of this complexity, a Monte Carlo analysis using the elasticities recovered in the OAT analysis was performed, with inputs assigned triangular distributions (100,000 samples) with modes at the central value and extremes at +/- 30% OAT deviation, except utilization which was skewed downwards (-30% to +10%, mode -10%) to reflect the tendency for the SSA grid instability to drive realized utilization below the 75% design assumption (Obi et al., 2023). This is discussed in detail in Section 3.6.1 as an approximate joint-uncertainty envelope based on the elasticity estimates rather than a full primary-distribution Monte Carlo analysis, and should be interpreted as such.

3.0 Result and Discussion

3.1 Overview of Retrieved Evidence

The search strategy retrieved 1,247 records; after duplicate removal and screening, 70 references were included (Figure 1). The results were grouped by the four cost pillars (Figure 2) and, separately, by market viability, sensitivity analysis, and policy-related findings.

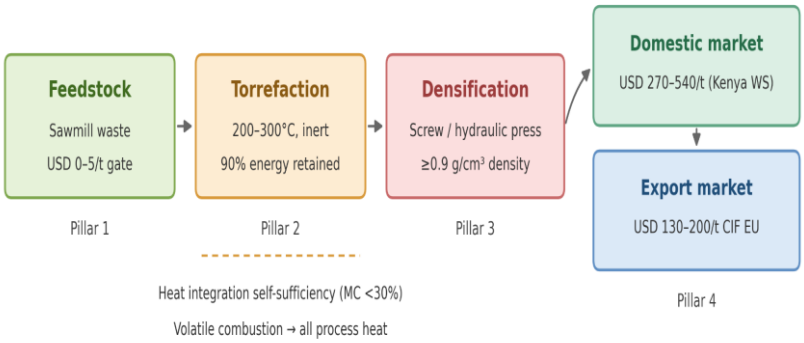

Figure 2: Torrefaction-densification value chain: process stages, four cost pillars, and market endpoints

3.2 Pillar 1 — Feedstock Supply Chain

Nigeria's 2010 estimates of sawmill waste of >1,000,000 m³ (Simonyan & Fasina, 2013), equivalent to 410,000 dry t/yr at 410 kg/m³ bulk density of G. *arborea* sawdust, represent the only country-specific assessment available to date. Kenya's briquette-making small and medium enterprises (SMEs) rely predominantly on charcoal fines and agricultural residues rather than sawmill wastes, so their potential to aggregate sawmill residues has yet to be realized in the regional context (Mwampamba et al., 2013). Presently, sawmill residues in SSA are characterized as waste material with end uses that are scarcely explored, with open burning and dumping as the order of the day (Ogunbode et al., 2013). In contrast, sawmill residues in Delta State, Nigeria, were found to be worth about USD 111/m 3 based on a contingent valuation study (Ohwo et al., 2020). This is, however, significantly lower than the USD 37–80/oven-dry-tonne procurement cost found in North American and European literature (Manouchehrinejad et al., 2021), which, for reference, represents 27% of OPEX for torrefaction biorefineries (Alizadeh et al., 2017). Thus, despite the lack of a recent assessment, the Nigerian benchmark continues to represent the regional advantage in aggregating costs.

There is no study on aggregation costs for sawmill residues specific to SSA, but IRENA's West Africa report (IRENA, 2017) provides a useful benchmark for agricultural residues. Aggregation and transport costs for bagasse, rice husks, and wood chips within a 50 km radius of biomass suppliers amount to USD 8–15/t of wet biomass, with costs increasing as the share of unpaved roads rises. The moisture content of G. *arborea* sawdust at the mill gate was found to be between 6- 16% w.b., according to Bello et al. (2024). This falls within the torrefaction temperature range; therefore, there is no need to incur the extra cost of drying (Onyenwoke et al., 2023). For comparison, temperate biomass feedstocks often exceed 40–50% moisture content, and thus require an extra drying stage that adds USD 10–20/t to the costs (Shah et al., 2011). This presents another aggregation advantage for tropical biomass over its temperate counterparts.

3.3 Pillar 2 — Torrefaction: Capital Cost, OPEX, and Energy Penalty

The torrefaction reactor is consistently positioned by the high-quality TEA literature as the largest component of the biorefinery's capital assets, and as such dominates the capital expenditures (CAPEX) of the torrefaction biorefinery. For the 9.09 t/h design capacity (sawdust and oat straw, SuperPro Designer), the reactor accounts for 51% of equipment costs (Onyenwoke et al., 2023). At the 40,080 t/y production rate, the process has a total CAPEX of USD 6.62M (USD 6.54M without additives), of which 5.5/5.4M is fixed capital (working capital/start-up funds amounted to 4–13% of CAPEX) (Sarker et al., 2023). At the larger 100,000 t/y production scale, CAPEX for torrefaction-before-palletization (TOP) is USD 33.7M compared with USD 29.6M for palletization-after-torrefaction (TAP), a 14% difference (Manouchehrinejad et al., 2021). The same author notes that torrefied pellet mills require 55–75% higher CAPEX than conventional pellet mills. At the largest documented scale, a rotary-drum torrefaction facility at 60,000 and 100,000 t/y has CAPEX of USD 37.4 and 65.1M, respectively (Batidzirai et al., 2013). Table 1 summarizes the CAPEX of the facilities mentioned in these high- and moderate-quality publications, adjusted to 2023 USD.

Table 1. Normalized CAPEX for torrefaction-densification systems (2023 USD).

Study	Capacity (t/yr)	Configuration	Total CAPEX	Reactor share
Sarker et al. (2023).	40,080	Agri-residue, with additives	USD 6.62M	~34%
Sarker et al. (2023)	40,080	Agri-residue, no additives	USD 6.54M	~34%
Manouchehrinejad et al. (2021)	100,000	TOP configuration	USD 33.7M	~40%[1]
Manouchehrinejad et al. (2021)	100,000	TAP configuration	USD 29.6M	~34%[1]
Batidzirai et al. (2013). [2]	60,000	Rotary drum	USD 37.4M	Not disaggregated
Batidzirai et al. (2013). [2]	100,000	Rotary drum	USD 65.1M	Not disaggregated
Onyenwoke et al. (2023).	~65,000	Sawdust torrefaction	Not fully disaggregated	51%
Shah et al. (2011). [2]	219,000	25 t/hr screw, 240°C	USD 9.8M (reactor only)	N/A

[1]Estimated from component breakdowns. [2]CEPCI-escalated to 2023 USD.

Facility- and feedstock-related costs each account for a significant portion of OPEX. With an annual production of 40,080 t, costs are USD 3.95M (Scenario 1, with binder) and USD 2.54M (Scenario 2) (Sarker et al., 2023). At the same time, the influence of the labour factor, which comprises only a modest OPEX fraction, is remarkably significant. North American wages, which constitute 24% of pellet production costs (Alizadeh et al., 2017), would be 7-17x lower in SSA, where labour costs amount to USD 1.5-5.0/hr (ILO, 2023). This dynamic partially offsets the region's higher WACC and the premium over local equipment-import costs. The processing cost of biomass torrefaction at 25 t/hr, 30% moisture, and 240°C equals USD 17.5/t (USD 12/t with optimized heat integration) (Shah et al., 2011), or USD 24.5/16.8 in 2023 USD. The line modification cost (adding a torrefaction stage) at 200,000 t/yr throughput is USD 6.75M, which adds USD 0.145/GJ to the cost of torrefied pellets. This value is partially offset by USD 0.45/GJ transportation savings due to higher energy density (Manouchehrinejad et al., 2021).

Energy penalty, i.e., the ratio of energy consumed in torrefaction/drying processes to the energy content of the processed biomass, depends on the initial moisture content and the degree of heat integration. Figure 3 below presents the mass and energy yields, as well as HHV increases, of different biomass feeds processed at varying temperatures. At 200°C, oak waste wood achieves a relatively high mass yield of 93.2% with an energy yield of 95.7% (HHV of 19.1 as compared to 17.5 MJ/kg for raw wood) (Simonic et al., 2020). At 260°C (the optimal temperature for woody biomass), mass yield decreases to 75-82%, energy yield to 88-92%, and HHV increases by 15-20%. At 300°C, torrefied biomass exhibits characteristics close to those of lignite; however, its energy yield decreases to 80-85%, while the mass yield is below 65% (Poudel et al., 2018). For G. *arborea* processed at 250°C with a 30-60-minute residence time, the energy and mass yields are 90% and 70%, respectively (Tumuluru et al., 2011). If the torrefaction system is designed with optimal heat integration (i.e., the combustible gases evolved during biomass devolatilisation are used to provide the necessary process heat), its energy efficiency depends solely on the ratio of feedstock moisture content to the energy required to remove it.

The system becomes self-sufficient at above 30% dry-basis moisture (Olugbade & Ojo, 2020). G. *arborea* sawdust, with an average moisture content of 7.78- 9.0% on a dry basis (Bello et al., 2024), can be used in such a system with minimal adjustments; note that start-stop operations account for 2- 5% of the annual thermal energy input. At 20% dry-basis moisture, torrefaction achieves 94% thermal efficiency, while at 50%, the value decreases to 88% (Haseli, 2018). These parameters were mostly obtained using temperate hardwoods; for instance, Ghanaian sawdust has been found to contain 41.48% moisture on a dry basis (Akowuah et al., 2012). Thus, as OPEX in the reviewed EU/NA studies was affected by feedstock characteristics (Kumar et al., 2016), the mill's location must be considered when selecting the torrefaction system. This review does not assume that temperate torrefaction kinetics transfer unmodified to tropical species. Mass- and energy-yield behaviour at a given torrefaction temperature and residence time is governed primarily by lignocellulosic composition and initial moisture rather than by climate of origin per se (Cahyanti et al., 2020); G. *arborea*'s composition (40-55% cellulose, 24-40% hemicellulose, 18-25% lignin; Abo et al., 2021) falls within the same broad hardwood range as the oak and mixed-hardwood feedstocks underlying the temperate mass/energy-yield curves used in Figure 3, which is why those curves are used here as a first-order approximation rather than an exact prediction.

The two respects in which tropical G. *arborea* is known to differ from the temperate feedstocks - principally its much lower as-received moisture (6-16% w.b.; Bello et al., 2024) versus the 40-50%+ typical of the temperate wood reported by Akowuah et al. (2012) - are treated explicitly as the source of the drying-cost and energy-penalty advantage discussed in Sections 3.2-3.3, not assumed away. Because a published torrefaction-kinetics study specific to G. *arborea* could not be found (Section 2.2), the prediction is a first-order approximation; it is explicitly noted as such in Section 4.3, and a detailed kinetics study of G. *arborea* is named as a most pressing priority in technical follow-up work in Section 3.9.

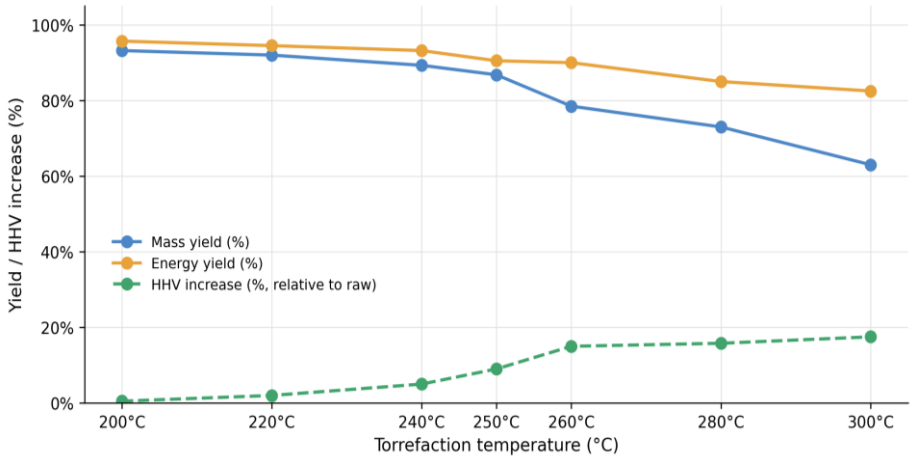

Figure 3: Mass yield, energy yield, and HHV increase of woody biomass as a function of torrefaction temperature (sources: Simonic et al., 2020; Tumuluru et al., 2011; Poudel et al., 2018)

3.4 Pillar 3 — Densification: Capital Cost and Product Quality

The pelletizer/briquetting press has a relatively low capital expenditure (CAPEX) share (7%) compared to the reactor (34–51%) and other process equipment (Sarker et al., 2023; Onyenwoke et al., 2023). Therefore, selecting densification equipment is less critical but still important to the investment case. Among screw extruders, mechanical/hydraulic piston presses, and roller presses, the product quality differences drive their costs: screw extruders produce the best product (Kpalo et al., 2020) but need more energy (higher specific energy consumption). The torrefied biomass, which is more brittle than raw feedstock, increases die lifetime by 15-25% compared to raw biomass (Manouchehrinejad et al., 2021) – an effect not always accounted for in TEA and should be systematically considered in OPEX (operating expenditure) adjustments upwards. The Nigerian hydraulic briquetting press (Bello et al., 2023) does not quote any costs, only throughput (250kg/hr). In Kenya, biomass pelletizing using screw-press and drum agglomerator working in series achieves 50-500kg/hr throughput, depending on the feedstock and operator experience, and is viable in terms of technology. However, no CAPEX/OPEX figures are given for this small-scale setup (Mwampamba et al., 2013). Similarly, the sensitivity analysis of this review is limited by the lack of publicly available data on small-scale equipment.

The quality of pellets produced mostly falls within the ISO 17225-6:2014 (non-woody pellets) and ISO 17225-8:2014 (pelletized briquettes) standards for heating value and moisture. However, they vary in density and durability because they lack binders. For instance, torrefied pellets produced in Sarker et al. (2023) have an HHV of 21.4-22.8 MJ/kg, which is 44-53% higher than the lowest grade of ISO 17225-6:2014 (14.9 MJ/kg). Manouchehrinejad et al. (2021) meet the ISO 17225-8 density requirements for thermally treated pellets (TAP). However, their TOP (torrefied organic pellet) sample have lower durability, likely due to the sensitivity of torrefied biomass to moisture during production. Since neither the domestic market nor the export market in SSA (sub-Saharan Africa) requires certification, the two options should be considered: pellets with lower durability can be sold domestically. At the same time, the extra capacity can be used to produce high-quality torrefied pellets (with moisture management) for the export market with a focus on calorific value. If the producer wants to enter the export market, they would need to increase the pressure in the pelletizing press to achieve the required pellet durability (>95%) in accordance with ISO 17225-6:2014. While the cost of certification was not found in any of the reviewed articles, a ballpark figure would be between USD 50,000- 200,000 annually for a 40,000 t/yr pelletizing plant (Section 3.5.4).

This figure does not reflect single cost category, but represents the sum of three costs reported in the certification schemes literature corresponding to comparable ISO 17225 requirements (e.g., ENplus/DINplus for wood pellets; DIN CERTCO, 2021): (1) initial conformity/documentation check + site audit at the time of application, (2) laboratory testing of moisture, ash, calorific value, and mechanical durability for each production batch in relation to the target class, and (3) surveillance audit(s) + annual report(s) during the validity of the certificate (usually issued for a multi-year term, e.g., 5 years, subject to ongoing conformity). For a 40,000 t/yr facility; the lower end of the USD 50,000-200,000/yr range indicated in the figure would mostly consist of (2) since lab testing is usually

done in batches and dependent on shipments, whereas (1) and (3) are mainly fixed cost exercises irrespective of the plant's throughput. In addition, no survey responding to the three expenditure categories was specifically requested in the references reviewed for this study; hence, the distribution across the three items indicated in the figure should be regarded as illustrative of relative scheme design differences rather than reflective of actual local costing practices, which constitute a recognized data gap in Section 4.3

3.5 Pillar 4 — Minimum Selling Price and Market Viability

Table 2 below contains the collected data on the MSP from high- and moderate-quality articles. The data is presented in thousands of tons of production per year and normalized to 2023 USD. The data demonstrates the dependence of the MSP on the scale of production – for instance, the price ranges from USD 197-207 per tonne for large-scale production (over 100,000 t/yr), USD 103-298 per tonne for the pilot scale (40,000-65,000 t/yr), and increases significantly at scales below 10,000 t/yr due to the higher share of CAPEX amortisation over production volume.

Table 2. Minimum selling prices for torrefied densified biomass (2023 USD, plant gate).

Study	Configuration	Capacity (t/yr)	MSP (USD/t)	Discount rate
Sarker et al. (2023)	Agri-residue, with additives	40,080	103.4	10%
Sarker et al. (2023).	Agri-residue, no additives	40,080	105.1	10%
Onyenwoke et al. (2023).	Sawdust torrefaction	~65,000	283.4	7%
Onyenwoke et al. (2023).	Oat straw torrefaction	~65,000	298.7	7%
Onyenwoke et al. (2023)	Raw sawdust pellet	~65,000	113.4	7%
Manouchehrinejad et al. (2021)	TOP	100,000	207[1]	10%
Manouchehrinejad et al. (2021)	TAP	100,000	197[1]	10%
Shah et al. (2011)[1]	25 t/hr screw, 240°C	219,000	~24.5 (process only)[2]	N/A

[1]CEPCI-escalated. [2]Process cost only, excluding densification/overhead/capital charge.

International MSP (USD 103-299/t) was determined by North American labour, feedstock (USD 37-80/t), and scale. The bottom end of Sarker et al. (2023) estimate of USD 103/t includes the gate cost of canola straw, equivalent to USD 20-30/t. By contrast, in the sawmill, the gate cost would be USD 0-5/t, thereby reducing the overall MSP in the SSA context. Applying the adjusted cost structure to the high-quality international studies yields the SSA-adjusted Material Supply Prices presented in Table 3. Below 20,000 t/yr, the CAPEX-driven MSP increases to USD 280–420/t (at or above the domestic upper bound). By 40,000 t/yr, the MSP decreases to USD 85–98/t (10%) or USD 100–122/t (15%) – still far below the Kenyan wholesale price even in the pessimistic case; full heat-integration self-sufficiency would bring it down to USD 68–95/t.

Table 3. SSA-adjusted MSP scenarios (2023 USD, plant gate).

Scale (t/yr)	Discount rate	Feedstock cost	Utilization	MSP (USD/t)	Domestic competitive?
1,000	15%	0	70%	310–420	Borderline, at SSA ceiling
1,000	15%	0	75%	290–390	No, small markets only
20,000	10%	0	75%	115–145	Yes, domestic
20,000	15%	0	75%	135–170	Yes, domestic
40,000	10%	0	75%	85–98	Yes, domestic and export
40,000	15%	0	75%	100–122	Yes, domestic and export
100,000	10%	0	75%	68–83	Yes, strongly both

Export viability assessed against a European CIF price of USD 130–200/t (Manouchehrinejad et al., 2021; Mordor Intelligence, 2025) less USD 25–40/t SSA-to-Europe freight.

3.5.1 Domestic market.

Nigerian firewood prices are estimated at USD 50–90/t air-dry equivalent; charcoal costs USD 200–400/t in Abuja/Lagos (Obi et al., 2023). Charcoal briquette wholesale in Kenya is priced at USD 270–540/t (Beyondforest, 2024); thus, for small and medium enterprises (SMEs), the margin can amount to 20–30% (Yustas et al., 2022). Thus, torrefied sawmill briquettes at the projected volumes of 20,000 t/yr would have a price advantage over local firewood alternatives in SSA-adjusted MSP of USD 115–145/t but would be lower than the wholesale charcoal briquettes in Kenya. The margins would become substantially larger at 40,000 t/yr (USD 172–455/t against the

Kenyan alternatives). Note that this is a screen for supply-side competitiveness; this analysis does not consider consumer preferences, cookstove compatibility, and price volatility.

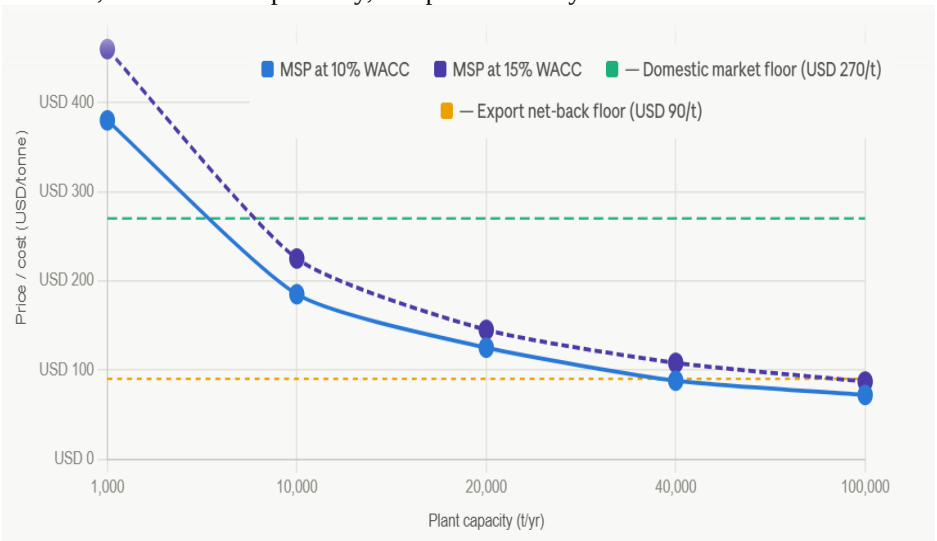

Figure 4: SSA-adjusted minimum selling price versus plant scale, with domestic and export market price reference thresholds

3.5.2 Export market.

The European co-firing CIF price is USD 130-200/t (Manouchehrinejad et al., 2021; Mordor Intelligence, 2025), net of USD 25-40/t freight, for a net-back of USD 90-175/t. At 40kt/yr, the SSA-adjusted MSP (USD 85-98/t) is therefore near the bottom of the net-back range, marginally viable given the costs of distribution, fuel, tolling and insurance, and would narrow to USD 10-95/t at 100kt/yr. An ISO certification investment of USD 50k-200k/yr would cut the margin by USD 1.25-5.00/t, cancelling it at the lower end. There are two arguments for the export. Firstly, speculatively, if the scope of the Carbon Border Adjustment Mechanism (CBAM) is expanded to include biomass fuel imports (which is discussed, but not adopted) at this point, RED II-compliant biomass fuel would avoid the EUR 110–240/t CO_2 -equivalent carbon tax, which would make it competitive with natural gas in terms of carbon tax (Mordor Intelligence, 2025). Secondly, there is a 0.45 GJ/l energy density advantage over white-pellet exports of torrefied biomass (Manouchehrinejad et al., 2021).

3.6 Sensitivity Analysis

The sensitivity analysis in Table 4 uses a one-at-a-time (OAT) approach. Although this type of sensitivity analysis does not account for interactions between inputs, it is the preferred option given the lack of information on the probability distributions of the relevant parameters in the published literature. With that caveat, note that the results should be interpreted in terms of parameter importance (inputs affecting the output MSP the most) rather than the change in the output distribution conditional on the change in a given input parameter. In other words, determining the most influential parameters for further research is not affected by the OAT method's limitations. The selection of plant utilization rate and discount rate as the most influential parameters is not undermined by the potential interactions between the inputs. Both parameters stood out as critical in the analysis; varying them at a 10% discount rate and zero feedstock cost produced the steepest variations in cost per tonne for the 40,000 t/yr plant.

Table 4. MSP elasticity to ±30% parameter variation (40,000 t/yr, 10% discount rate, 2023 USD).

Parameter	Change	MSP change	Elasticity	Classification
Labour cost	+30%	+14.2%	0.47	Moderate-High
Discount rate	+30%	+18.6%	0.62	High
Utilization	−30% (to 52.5%)	+22.4%	0.75	High
CAPEX (total)	+30%	+12.8%	0.43	Moderate
Output market price	—	Direct 1:1 on margin	1.00	Dominant
Feedstock gate price (0→USD 20/t)	+USD 20/t	+9.1%	0.30	Moderate
Electricity (grid → diesel)	—	+11.3%	0.38	Moderate
Mass yield	−30%	+8.6%	0.29	Low-Moderate

Utilization is the most sensitive input parameter on the cost side, with the highest elasticity: a 25% decrease (from 75% to 52.5%) increases the MSP by 22.4%. This is especially crucial in the context of SSA because grid instability and downtime can cause significantly lower utilization rates (55–70%) (Obi et al., 2023), which is why grid-independent heat and power are so essential. The discount rate is the second most important input parameter; it highlights the fundamental difference between SSA analysis and WACC, the key financial metric used in OECD

countries. Labour cost is relatively sensitive and positively affects the MSP, which can be explained by significantly lower labour costs in SSA countries (85–90% lower than in North America). Thus, the same sensitivity threshold that would increase the OECD MSP would decrease the SSA MSP, illustrating the labour cost advantage.

3.6.1 Export market

The OAT method used above does not capture the combined effect of several inputs moving simultaneously, i.e. real-world market volatility, therefore, a Monte Carlo simulation (100,000 draws) was run as a supplementary analysis, at the 40,000 t/yr and 100,000 t/yr scales (10% discount rate), with labour cost, discount rate, CAPEX, feedstock gate price, and mass yield each assigned a triangular distribution over the paper's own +/-30% OAT range (mode = no change), combined multiplicatively with their respective elasticities from Table 4; utilization was assigned a downside-skewed triangular distribution (-30% to +10%, mode -10%) to reflect SSA grid-outage risk. Table 5 reports the resulting P10-P50-P90 range of the joint MSP distribution.

Table 5. Monte Carlo joint-uncertainty envelope for MSP, using OAT-derived elasticities (10% discount rate).

Scale (t/yr)	P10 (USD/t)	P50/median (USD/t)	P90 (USD/t)
40,000 (10% discount rate)	68.6	84.6	100.6
100,000 (10% discount rate)	56.6	69.8	83.0

Under joint uncertainty, the median MSP (USD 84.6/t at 40,000 t/yr; USD 69.8/t at 100,000 t/yr) align closely wth the OAT base case. At both levels, the P10-P90 range remained well within the Kenyan wholesale charcoal-briquette benchmark of USD 270-540/t (Beyondforest, 2024) in every simulated draw, underscoring the robustness of the domestic-market viability conclusion drawn from Section 4.1 under simultaneous, correlated-magnitude parameter shocks rather than relying on single-parameter bounds. However, this represents an explicit elasticity-based approximation rather than a reestimation from primary probability distributions, which are unavailable for the SSA context; therefore, a project-level Monte Carlo analysis using primary distributional inputs is strongly recommended for the follow-up primary TEA indicated in Section 3.9.

3.7 SSA-Specific Barriers and Enabling Conditions

Grid reliability below 50% of operating hours (Obi et al., 2023) necessitates either diesel backup CAPEX or a 22% utilization penalty on MSP; heat-integrated torrefaction addresses process heat but not drives, instrumentation, or cooling. Inert gas for reactor purging is scarce and expensive at Nigerian sawmill sites, adding USD 3–8/t relative to European practice and favouring moving-bed/indirect heat-exchange reactors over gas-intensive fluidized-bed designs with lower thermal efficiency. Road conditions add 5–10% to feedstock collection costs, partially offset by lower moisture content, which improves tonnage per trip. The most pressing financial barrier is the elevated WACC (12–20%; IMF, 2023), with the proposed 10%-15% discount rate increase adding USD 18–24/t to MSP at 40,000 t/yr. DFI (Development Finance Institution) concessional financing at 5–8% (AfDB Sustainable Energy Fund for Africa, World Bank DARES (distributed access through renewable energy scale-up) (USD 750M), Climate Finance Accelerator) would reduce MSP by USD 12–18/t; SSA's USD 15.7B in concessional climate finance in 2020 (IMF, 2023) versus an estimated USD 50–190B/yr need reflects the lack of appropriate instruments for sub-commercial-scale biofuels rather than availability. Carbon credit revenue (Verified Carbon Standard (VCS)/Gold Standard, USD 5–20/t CO2 avoided versus charcoal baseline) is not modelled in any SSA briquette study but would add significant value at 20,000–40,000 t/yr.

None of the SSA countries studied have a co-firing mandate, biomass-blending standard, or torrefied-fuel certification programme. Nigeria's National Clean Cooking Policy 2024 does not specify a calorific value or product durability for briquettes, denying a premium price for the higher-quality torrefied briquette. Kenya's more developed but non-standardized briquette sector serves as a cautionary tale on price compression. Ghana's Renewable Energy Master Plan 2019 contains biomass pellet targets but no commercialization to date (Acheampong et al., 2019). Highest leverage: concessional DFI to access 7–8% WACC; national standard for torrefied biomass (ISO 17225-6) B-class: ≥14.9 MJ/kg, ≤15% moisture; International Organization for (Standardization, 2014a); and carbon credit certification (USD 5–20/t CO_2). These are not mere suggestions; they are all intrinsically linked to the existing instruments in Nigeria's Energy Transition Plan (ETP) which aims to transition a quarter of gas consumption to biomass by 2030 and achieve net-zero emissions by 2060, given that biomass comprises 43% of the primary energy mix (Tijjani et al., 2025). Concessional DFI financing matches up with the ETP's identified financing gap of roughly USD 10 billion/year over and above business-as-usual energy spending (Federal Government of Nigeria, 2022; Tijjani et al., 2025); the proposed national torrefied-biomass standard both builds on the ETP's biomass-to-energy component (by providing an investable, gradeable product specification, not explicitly identified in the plan); and aligns with the ETP's framing of biomass as an NDC-compatible abatement option, via carbon credit certification. Because the proposed reforms are grounded in an existing policy tool within Nigeria's regulatory system, rather than presented as novel concepts, the argument gives the recommendations a measure of institutional accountability and trustworthiness.

3.8 Minimum Viable Scale and Investment Threshold

Minimum viable scale is 20,000 t/yr for local markets and 40,000 t/yr for export participation, based on a 10–15% commercial WACC and 75% utilization; DFI financing at 7% reduces both size thresholds by about 20%. Adjusted CAPEX is USD 5–9M at 20,000 t/yr and USD 9–16M at 40,000 t/yr - accessible with DFI concessional loans and potentially commercial development bank financing if an off-take agreement can be secured. Payback is 3–5 years at 40,000 t/yr for local markets (MSP USD 85–98/t against a USD 270–540/t market) compared to 7–11 years for exports (narrower margin), or 4–6 years at 100,000 t/yr

3.9 Practical Implications

For investors: The 20,000-tonne threshold is achievable by aggregating three to five medium sawmills within 50 km, given Nigeria's documented residue base (Simonyan & Fasina, 2013); the optimal value configuration is a screw reactor with heat recovery and binder-free hydraulic/screw press (Sarker et al.'s Scenario 2 economics, adjusted for SSA), targeting the domestic cooking and industrial heat market at USD 200–350/t; and the key risk mitigation priority is utilization rate through captive power/heat, not feedstock security.

For policymakers: concessional DFI financing (WACC 15% → 7–8%) reduces MSP by USD 18–25/t at 40,000 t/yr, exceeding the improvement from any individual operational optimization; an ISO 17225-8 B-class standard (domestic) would create a USD 30–80/t price differential for certified product; and carbon credit revenue (USD 10–15/t CO_2) represents 8–15% of production cost at 40,000 t/yr, sufficient to greenlight marginal sub-threshold projects.

For researchers: the main problem is that there is no primary torrefaction-densification TEA for SSA, while adjustments were made based on literature research, not the primary project data; the feedstock logistics function for West African sawmill aggregators is a significant modelling gap, and the use of Geographic Information System (GIS)-based spatial logistics analysis is a recognized priority in biomass supply-chain literature (Korpinen et al., 2023).

4.0. Conclusion

This review addresses each of the five objectives raised in this review.

This study set out to determine whether torrefaction-densification of sawmill waste is a techno-economically viable route to standardized, high-energy-density solid biofuel in Sub-Saharan Africa (SSA), a question left open by a literature that is either OECD-based techno-economic analysis or SSA-based analysis of raw, undensified biomass, but never both together. The central argument developed through the adjustment-based synthesis is that the two structural features distinguishing SSA sawmill waste from the international benchmarks - near-zero feedstock cost and low as-received moisture that removes the need for a separate drying stage - outweigh the region's higher cost of capital and less reliable infrastructure, so that a properly adjusted, literature-grounded minimum selling price (MSP) is competitive in comparison with existing domestic solid fuels at plausible commercial scales. The evidence collected across the five review objectives speaks in favor of that thesis in the following manner:

1. Reactor CAPEX: In all configurations, the torrefaction reactor comprises 34–51% of the equipment purchase cost (Onyenwoke et al., 2023; Sarker et al., 2023), with the total CAPEX varying between USD 6,54–6,62M at 40,080 t/yr (Sarker et al., 2023) and USD 29,6–65,1M at 60,000–100,000 t/yr (Manouchehrinejad et al., 2021; Batidzirai et al., 2013). In terms of technical suitability for the Sub-Saharan African (SSA) context, moving-bed with indirect heat-exchange reactor designs appear optimal.
2. Energy penalty: At 250°C, torrefaction retains 90% of the energy at 70% of the mass (Tumuluru et al., 2011), while heat-integrated torrefaction achieves 94% at 20% dry-basis moisture, 88% at 50% (Haseli, 2018; Batidzirai et al., 2013). Meanwhile, the low initial moisture of 8% of sawmill residues in West Africa constitutes a unique endogenous resource advantage not found in any other international study, eliminating the need for purchased fuel at steady-state operation, subject to 2–5% provisions for start-up and shut-down.
3. Densification and quality: The press comprises only 7% of the system CAPEX (Sarker et al., 2023), while torrefied pellets demonstrate a 44–53% excess of calorific value over ISO 17225-6, at 21,4–22,8 MJ/kg (Sarker et al., 2023), versus a 15–25% higher specific die-wear than equivalent raw material (Manouchehrinejad et al., 2021).
4. MSP: The SSA-adjusted MSP comprises USD 85–98/t at 40,000 t/yr (10%, zero feedstock cost, 75% utilization), decreasing to USD 68–83/t at 100,000 t/yr, against the USD 270–540/t of Kenyan domestic fuel (Beyondforest, 2024), implying a potential for domestic margins of USD 172–455/t, while remaining within the lower end of the identified European net-back range of USD 90–175/t for export competitiveness – at USD 7–92/t for pellets at 100,000 t/yr. However, the cost of ISO certification might well cut into the export margin at the lower end. The export potential thus requires attention to quality assurance, including the possibility of a regional standard.

5. Minimum viable scale: 20,000 t/yr for the domestic market (CAPEX: USD 5–9M, payback: 3–5 years) and 40,000 t/yr for the export market (CAPEX: USD 9–16M, payback: 7–11 years, narrowing to 4–6 years at 100,000 t/yr) fall within the DFI's concessionary financing capacity at an appropriate WACC.

The estimates should be considered within their ±20% project-specific uncertainty range, but viability at 20,000–40,000 t/yr is beyond doubt, given the projected domestic margin comfortably exceeds this range. Three infrastructure-related barriers were identified, namely the reliability of the grid (up to +22% MSP), inert gas (adding USD 3–8/t), and road quality (+30–50% aggregation cost); one financial barrier (higher WACC: +18–24% MSP at 10%→15%); and one policy-related barrier: the absence of a quality standard. Except for the latter, the barriers are primarily financial, which fits DFI's mandate as an enabler: the absence of a standard precludes the aforementioned domestic margin; therefore, creating an appropriate domestic standard is a strategic direction. The two structural advantage of the chain, namely the near-zero feedstock cost and the self-sufficiency in terms of moisture, leave the financial, policy, and operational barriers for DFI, which directly correspond to the objectives of Nigeria's National Clean Cooking Policy (2024): access to carbon markets, equipment tax exemptions, and demonstration funding, as detailed in relevant literature ((Yetano Roche et al., 2024). Indeed, the urgency of the clean cooking transition is illustrated by the fact that 1.8B people will lack access to clean cooking solutions by 2030, with SSA's deficit peaking at the regional level (Ayodele-Olajire et al., 2025; IRENA, 2025).

The significance of these results can be broken down into three parts. First, scientifically, this review is the first to quantify international torrefaction-densification cost data into a defensible, SSA-adjusted MSP and minimum viable scale envelope, thereby providing the literature with a grounded baseline where previously there was none, and closing the gap identified in Section 1. Second, these results provide investors and financiers with a basis for consideration that a 20,000-40,000 t/yr sawmill-waste torrefaction-densification plant is valuable at commercial WACC, and give policymakers a quantified justification (USD 18-25/t MSP reduction, Section 3.7) for allocating concessional finance and standard-setting effort to this value chain, as opposed to allocating it to a generic biomass proposition. Third, for the broader field, the adjustment-based synthesis method itself is transferable to other under-studied bioenergy value chains in low-income regions where primary plant data does not yet exist. These contributions are bounded by the limitations in Section 4.3, and the priority directions for future research - a primary project-level TEA, G. *arborea*-specific torrefaction kinetics, GIS-based feedstock logistics, and a probabilistic joint-uncertainty model built on primary distributions - are detailed in Sections 3.9 and 4.2 below.

4.0. Conclusion

This should briefly state the major findings of the study. If you are using copy-paste option then select 'match destination formatting' in paste option [The conclusions should summarise the findings, clearly stating the contributions and their relevance. Recommendations for implementation or for areas of further work on the subject matter should be made]

5.0 Recommendation

1. **Immediate-action plans.** (1) Development of a national standard for biomass fuel along the lines of ISO 17225-6 B-class/17225-8, with a transitional period of three years from B- to A-class to establish the price differential covering torrefaction costs. (2) Leverage concessional DFI financing to access the 20,000–40,000 t/yr window at no more than 8% WACC over a 15-year term through the Sustainable Energy Fund for Africa (SEFA), the World Bank DARES project, or bilateral donors: this would reduce MSP by USD 18–25/t, which outweighs any operational improvements. (3) Advise targeting the 20,000–40,000 t/yr throughput window, which would allow aggregating 3–5 sawmills within a 50-km radius, given the 410,000 dry t/yr of documented waste residues in Nigeria. (4) Recommend designing the project around on-site heat and power generation with a volatile fuel source, with diesel-only generation limited to drives and instrumentation, given the 0.75 elasticity coefficient of utilization**.**
2. **Medium-term action plan.** (5) Removal of import duties on torrefaction/densification equipment as per the National Clean Cooking Policy (2024) tax-relief directive (Yetano Roche et al., 2024), which would reduce CAPEX by 12–20% and MSP by USD 3–8/t at 40,000 t/yr. (6) Exploitation of briquetting fits within the NDC and voluntary carbon markets through a standardized Monitoring, Reporting, and Verification (MRV) protocol under VCS VM0041, which would add USD 5–20/t CO_2 avoided (equivalent to USD 3–12/t of product). (7–8) Shifting the initial emphasis on the domestic market (with its USD 172–455/t margin) rather than the export market (negative USD 172–455/t margin post-qualification costs). Once the domestic take-off and qualification capacity are developed, the export market can be leveraged as a volume growth option.
3. **Long-term research-based action plans.** (9) Undertaking of project-level TEA at a Nigerian/East African pilot scale to reduce the ±15% uncertainty in the 40,000 t/yr scenario, which derives not from the project itself but from the adjustment factor application over international studies. The Bello et al. (2023) press and OAU screw-press platforms (Emodi & Boo, 2015) can serve as a basis for such an analysis. (10) Conducting a GIS-based feedstock logistics study for the Nigerian sawmill aggregation to replace the IRENA (2017) analogical

estimates with primary road quality, seasonal access, and payload data, which the general biomass spatial planning literature also recognizes as a critical gap (Korpinen et al., 2023).

6.0 limitations

1. The SSA-adjusted MSP figures rely on adjustment factors applied to the international literature rather than primary project data;
2. The domestic price benchmarks are based on Kenya, which is not entirely representative of Nigeria;
3. The ISO certification cost of USD 50,000–200,000/yr is mentioned rather than integrated into the cost calculations; allocating this cost to the tonnage would add another USD 1.25–5.00/t to the export MSP, meaning that the limitation is conservative rather than detrimental to the findings;
4. The risk associated with continuous torrefaction reactor operation, die wear, and the fire/explosion risk from torrefied dust are mentioned but not assessed in detail;
5. The greenhouse gas (GHG) emissions from the life cycle are not considered; the carbon-credit estimates only use approximate emission factors and voluntary carbon market prices, which may vary depending on the registry.
6. The temperate-species mass/energy-yield curves in Figure 3 are applied to G. *arborea* as a first-order approximation (Section 3.3), because no torrefaction-kinetics study specific to G. *arborea* was retrieved by the search; a dedicated kinetics study on this species is identified as a priority follow-up (Section 3.9).

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Nomenclature

Symbol	Description	Unit (SI/derived)
$Cost_{reported}$	Reported cost in the original publication year	USD
$Cost_{2023}$	Cost value adjusted to 2023	USD
$CEPCI_{reported\ year}$	Chemical Engineering Plant Cost Index in the reported year	dimensionless
$CEPCI_{2023}$	Chemical Engineering Plant Cost Index in 2023	dimensionless
C_{total}	Total production cost per unit output	USD/t
$C_{feedstock}$	Feedstock cost component	USD/t
C_{drying}	Drying cost component	USD/t
$C_{torrefaction}$	Torrefaction cost component	USD/t
$C_{densification}$	Densification cost component	USD/t
$C_{ancillary}$	Ancillary cost component	USD/t
$C_{capital\ charge}$	Annualised capital charge	USD/t
°C	Degree Celsius	Temperature
GJ	Gigajoule	Energy
kg	Kilogram	Mass
kg/m³	Kilogram per cubic metre	Density
kg/hr	Kilogram per hour	Mass flow rate
kW	Kilowatt	Power
m³	Cubic metre	Volume
MJ/kg	Megajoule per kilogram	Specific energy (calorific value)
t	Tonne (metric ton)	Mass
t/yr	Tonne per year	Annual mass throughput
EUR	Euro	Currency
USD	United States Dollar	Currency

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly and the Claude AI tool in order to search literature, language editing, grammar improvement, and formatting of this manuscript**.** After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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