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Charcoal Production in sub-Saharan Africa, Greenhouse Gas Emissions, Forest Change, Livelihoods and Household Expenditure on Schooling

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Abstract

Charcoal production supplies urban energy and rural income across sub-Saharan Africa, but its climate, forest and social consequences are seldom examined together. We mapped evidence on greenhouse gas emissions, forest change, livelihoods and household expenditure on schooling. Four Crossref search strings covering 2000–2026 were supplemented by institutional searches. Of 1,100 records, 15 duplicates were removed; 1,085 titles and abstracts were screened, 71 full texts or structured records were assessed, and 57 studies were included following PRISMA 2020. Livelihoods were addressed in 32 studies, forests in 26, emissions and technologies in 23, governance in six and education in five. Traditional earth kilns had variable yields and generated products of incomplete combustion. Charcoal provided essential liquidity, although returns and risks were unevenly distributed. Forest outcomes depended on wood harvesting, subsequent agricultural conversion, access rights and regeneration. Direct evidence on school expenditure remained scarce. A coherent transition requires improved conversion, resource governance, spatial monitoring and protection of livelihoods. Linked household, kiln and forest-plot observations would be particularly valuable in Benin.

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Wood charcoal; greenhouse gases; forest degradation; livelihoods; school expenditure; sub-Saharan Africa.

Introduction

Wood charcoal remains a major urban fuel across sub-Saharan Africa. Its energy density, ease of storage and availability in small purchases sustain demand even where electricity and liquefied petroleum gas are expanding. Household fuel choice is rarely a single-step substitution: price, reliability and the nature of cooking tasks encourage fuel stacking (Nabukalu and Gieré, 2019). As urban populations grow, the associated demand connects city markets to dispersed rural woodlands and to the households that harvest, carbonize, transport and sell the fuel.

This value chain converts a spatially dispersed woody resource into a tradable commodity. For rural households, charcoal sales can provide cash during the lean season, after a crop failure or when immediate expenses arise. Evidence from Uganda, Ghana, Malawi, Mozambique and Ethiopia describes both this safety-net role and unequal bargaining positions within the chain (Khundi *et al.*, 2011; Zulu and Richardson, 2013; Jones *et al.*, 2016; Smith *et al.*, 2017; Tassie *et al.*, 2021). The distribution of benefits matters: a positive gross receipt to a producer does not establish a positive net return once labor, wood, transport and informal charges are accounted for.

The environmental burden arises at several stages. Wood extraction changes the biomass stock; subsequent land conversion can prevent recovery; carbonization releases methane, carbon monoxide, particles and other products of incomplete combustion. Low conversion efficiency increases the wood required for each unit of charcoal. The climate balance also depends strongly on the nonrenewable share of harvested biomass and on the accounting boundary (Bailis *et al.*, 2015; Pennise *et al.*, 2001; IPCC, 2019). Comparisons that mix emissions per unit of wood, charcoal and delivered cooking energy can therefore lead to conflicting conclusions.

Forest effects likewise depend on the land-use pathway. Selective harvesting followed by effective coppicing or regeneration can result in temporary degradation, whereas extraction followed by agricultural conversion may result in persistent forest loss. Remote-sensing studies in Mozambique and Zambia, together with field studies in Angola and elsewhere, show why canopy change should be interpreted alongside production sites, access routes, tenure and the sequence of agricultural expansion (Chiteculo *et al.*, 2018; Sedano *et al.*, 2016, 2020, 2022). A detected loss of tree cover alone cannot identify charcoal as the sole cause. The education pathway is less frequently measured. Charcoal income may pay school fees, uniforms, supplies or transport, particularly when other cash sources are seasonal. Conversely, children's participation in production or trade can increase the opportunity cost of attendance. The direction of the relationship depends on who controls income, the production calendar and competing shocks. An observed association between charcoal participation and schooling therefore requires careful treatment of household selection and timing.

This review asks four linked questions: what production technologies and measurement choices shape reported emissions; how are forest changes attributed to charcoal; how are livelihoods and governance represented; and what evidence connects this value chain to school expenditure? It also identifies an integrated research agenda for the N'Dali and Wari-Maró forest landscapes of Benin, where the four outcomes have rarely been assessed in the same design.

Materials and Methods

Review framework

We conducted a systematic evidence map using PRISMA 2020 as the reporting framework (Page *et al.*,

2021). Four domains guided screening and extraction: conversion performance and emissions; forest and soil change; livelihoods and governance; and education. A thematic evidence map was appropriate because study designs, functional units and effect measures differed too substantially for a defensible pooled estimate.

Information sources and searches

The principal Crossref search covered publications dated 1 January 2000 to 14 September 2026. Supplementary searches considered FAO, IPCC, CIFOR-ICRAF, AJOL, HAL and reference lists of relevant papers. The PRISMA counts refer to the four Crossref exports, which formed the reproducible set used for deduplication. Search expressions and record counts are reported in Table 1; supplementary sources informed interpretation and reference checking.

Eligibility and selection

Records were deduplicated by DOI and then by normalized title. Titles and abstracts were screened before full texts or available structured records were assessed. Fourteen items were excluded at the final stage: non-African or nontransferable context ($n = 5$), outcomes outside the review domains ($n = 4$), insufficient methodological description ($n = 3$), and redundant population or publication ($n = 2$). Extracted fields included publication year, country, design, technology, emissions, forest indicators, income, governance and education. Table 2 specifies the eligibility criteria.

Appraisal and synthesis

Critical appraisal considered sampling, measurement validity, confounding, transparency of units and precision. For spatial studies, we examined temporal coverage and independence of validation data; for socioeconomic studies, selection bias and the distinction between gross and net income were central. We synthesized patterns by domain, retaining differences in design and unit rather than pooling unlike estimates.

Results and Discussion

Composition of the evidence base

The 57 included studies were published between 2008 and 2025. Thirty-seven (64.9%) appeared in 2019–2025. The largest annual count was eight in 2019, followed by seven in 2022 (Figure 2). These counts describe the

assembled corpus and should not be interpreted as the total output of the field.

Nigeria accounted for 12 studies; Ethiopia and Ghana for six each; and Uganda and Mozambique for four each. Multicountry studies can contribute to more than one geographic category. No study focused on N'Dali or Wari-Maró jointly measured kiln activity, greenhouse gases, forest dynamics and school expenditure (Figure 3).

Coverage of outcome domains

Livelihoods and income were addressed in 32 studies (56.1%), forests in 26 (45.6%), emissions and technologies in 23 (40.4%), sustainable production in seven (12.3%), governance in six (10.5%) and education in five (8.8%). Categories overlap, so percentages do not sum to 100% (Figure 4).

Education is less frequently examined than the livelihood uses of charcoal income discussed in qualitative accounts. Publications more often estimate total income, margins or participation than the allocation of income to individual children. Consequently, increased charcoal receipts cannot by themselves establish improved educational outcomes.

Conversion technology and emissions

Earth kilns remain common because they require little capital and can be built near the wood source. Yield varies with wood moisture and density, stacking, kiln sealing and operator experience (Schure *et al.*, 2019; Hoffmann *et al.*, 2018). This variation makes a single conversion factor unsuitable for all sites and seasons.

Experimental studies suggest that retorts, brick kilns and improved thermal control can increase conversion efficiency under specified conditions. Tazebew *et al.*, (2023) reported improvements in traditional production with potential income and environmental benefits; Pennise *et al.*, (2001) measured CO₂, CH₄, N₂O, CO and hydrocarbons during carbonization. Performance under routine operation still depends on maintenance, fuel characteristics and operator practice.

Comparable emission estimates require the same functional unit and boundary. Emissions per tonne of dry wood, per tonne of charcoal and per unit of delivered energy are distinct quantities. The most informative reports provide dry feedstock mass, moisture, charcoal

output, production time, gas-specific emission factors and uncertainty.

Higher kiln efficiency does not necessarily reduce total emissions across a territory. If profitability stimulates production while access to wood and market demand remain unconstrained, an increase in activity can offset unit-level savings. Conversion efficiency thus needs to be considered together with wood sourcing, traceability and regeneration.

Forests, soils and landscapes

Chidumayo and Gumbo (2013), Chiteculo *et al.*, (2018), Sedano *et al.*, (2016, 2020, 2022) point to the importance of the subsequent land-use trajectory. Diffuse harvesting initially reduces stem density and biomass; later conversion to farmland may turn degradation into lasting forest loss. Attribution requires evidence on extraction and the competing drivers of landscape change.

Landsat and Sentinel time series are more persuasive when checked against plots, stump counts and production sites. A two-date comparison can confound harvesting with seasonality, fire and agriculture, especially where woodland cover fluctuates strongly.

Carbonization sites concentrate ash and pyrogenic carbon and can alter soil physical properties (Oguntunde *et al.*, 2008). Such local effects should be interpreted at the scale of the kiln site and do not compensate for landscape-scale biomass removal.

Recovery depends on species, cutting method, fire and the interval before reharvesting. Field inventories should record stumps, diameter classes, regeneration and land-use history, with repeated observations to distinguish temporary disturbance from persistent decline.

Income, poverty and value distribution

A consistent finding is charcoal's liquidity function. In Uganda, Khundi *et al.*, (2011) and Ainembabazi *et al.*, (2013) show that welfare associations differ across households. Studies from Ghana and Ethiopia similarly identify assets, forest access and market connections as determinants of participation and returns (Brobbe *et al.*, 2019; Belay *et al.*, 2024).

Gross receipts overstate benefits when family labor, feedstock, transport, levies, losses, credit and capital

costs are omitted. Producers may bear resource and enforcement risks while wholesalers and transporters capture substantial margins. Value-chain analysis needs to report the distribution of net returns, rather than treating sales value as household welfare.

Charcoal production frequently diversifies livelihoods instead of replacing farming. Evidence from Mozambique and Malawi describes flexible engagement during periods of low agricultural income (Jones *et al.*, 2016; Smith *et al.*, 2017). This flexibility can protect consumption while also prolonging reliance on extraction when alternative work is scarce.

Gender, age, tenure and position in the chain shape both opportunity and risk. Few studies identify who controls charcoal proceeds or who makes schooling decisions. Those intra-household processes are essential to understanding how cash earnings translate into educational spending.

Governance of production and trade

Access rights and credible rules affect resource outcomes. Blanket bans can push production into informal channels and increase unofficial payments. Cases from Senegal, Ghana, Kenya and Zambia indicate that decentralized management depends on clear rights, workable compliance costs and accountable enforcement (Doggart and Meshack, 2017; van 't Veen *et al.*, 2021).

A coherent framework can combine supply plans, traceable permits, volume monitoring, regeneration duties, access to improved technology and transparent levies. Recognition of producers can facilitate diffusion of improved practices, provided license allocation does not exclude small operators.

Performance should be judged jointly by unit and total emissions, net income, compliance, regeneration and access to energy. Optimizing one indicator may shift burdens to another actor or stage of the chain.

School expenditure and educational outcomes

Only five included studies had an explicit or indirect education link (8.8%). Most mention school fees among reported uses of charcoal revenue without measuring expenditure per child, payment timing or a credible comparison group. The evidence therefore supports a plausible financial pathway rather than a quantified causal effect.

Three mechanisms can operate in opposite directions: additional cash for schooling, greater demand for children's labor and an insurance effect when charcoal earnings cover school costs following a shock. The relative strength of each mechanism can change across seasons and household circumstances.

Future studies should record spending per child, enrollment, attendance, dropout and control over earnings. A household panel spanning production peaks and the start of the school year, paired with comparable nonproducing households, would better distinguish income effects from selection and seasonality.

The evidence positions charcoal simultaneously as an energy supply, a source of rural cash and a pressure on woody landscapes. These functions cannot be interpreted through a single indicator. Kiln yield does not reveal aggregate production, gross receipts do not reveal net welfare, canopy change alone does not attribute cause, and a reported use of income does not demonstrate a schooling effect. Integrated analysis must connect measurements at the kiln, household, value-chain and landscape scales.

For climate accounting, studies should specify system boundaries, moisture correction and functional units and propagate measurement uncertainty. Process emissions, end-use combustion, carbon retained in charcoal and the nonrenewable biomass fraction need separate treatment (Bailis *et al.*, 2015; IPCC, 2019; Pennise *et al.*, 2001). Default factors are useful for initial estimates, but technology- and season-specific measurements are needed to evaluate a local intervention. Reporting both gas-specific and carbon-dioxide-equivalent results would make comparisons more transparent.

Technology adoption should be assessed in relation to wood supply. Better kilns can reduce wood input per tonne of charcoal, yet wider uptake may also increase profitability and output. Monitoring should therefore capture both conversion efficiency and total harvested volume. Assisted natural regeneration, appropriate planting, fire prevention and repeated inventories can establish whether the resource base is actually recovering (Chidumayo and Gumbo, 2013; Schure *et al.*, 2019; Sedano *et al.*, 2020).

A viable transition must account for households that use charcoal as a financial buffer.

Figure.1 PRISMA 2020 flow diagram of study selection.

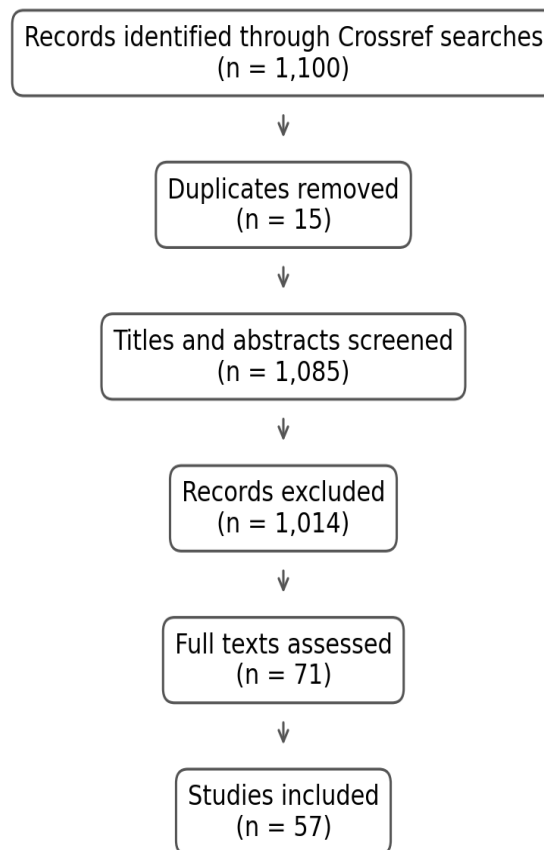


Figure.2 Annual distribution of the 57 included studies.

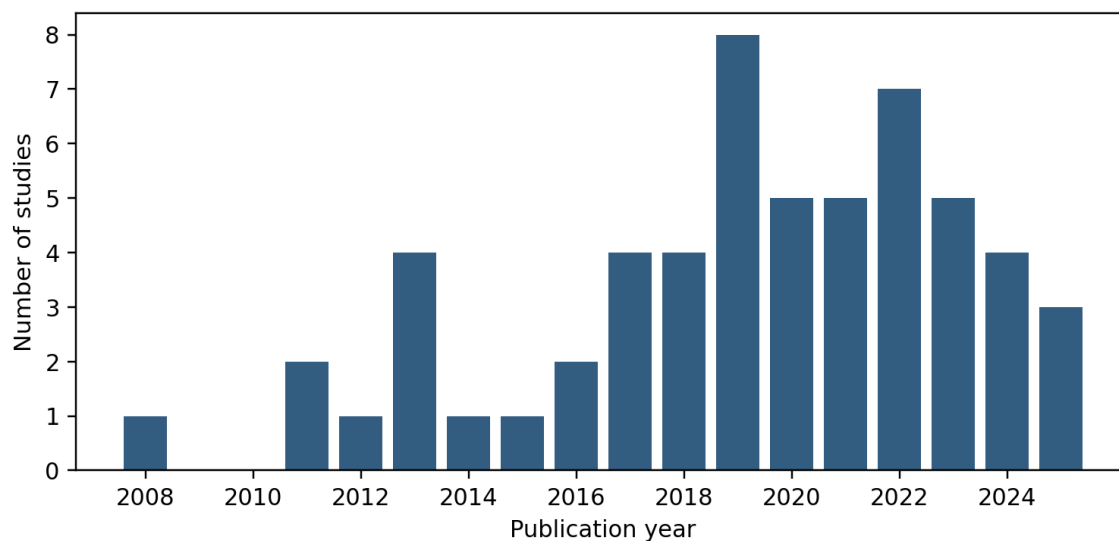


Figure.3 Geographic distribution of the evidence base. Multicountry studies may occur in more than one category.

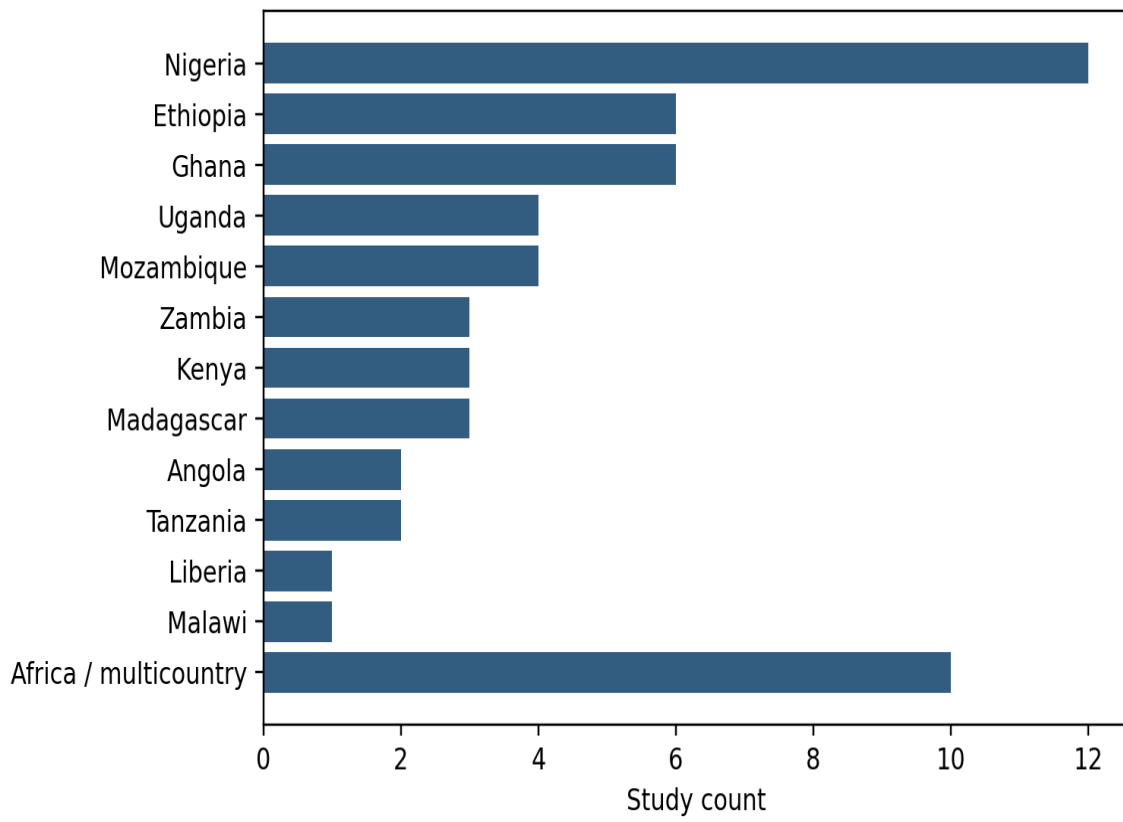


Figure.4 Outcome domains covered by the included studies.

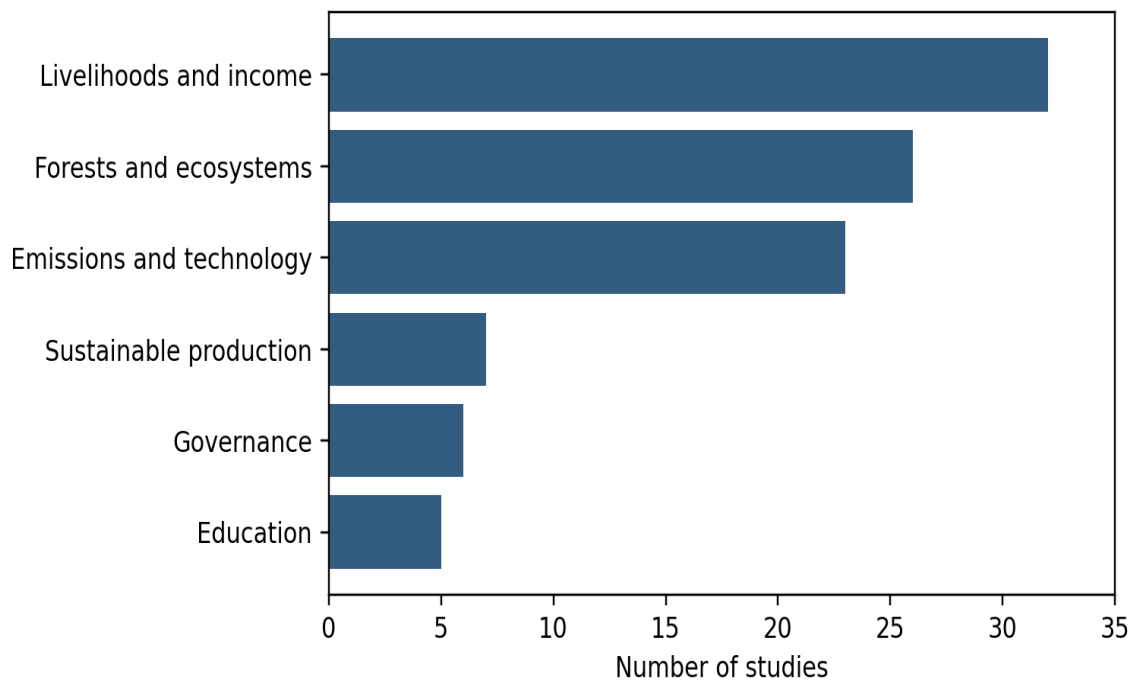
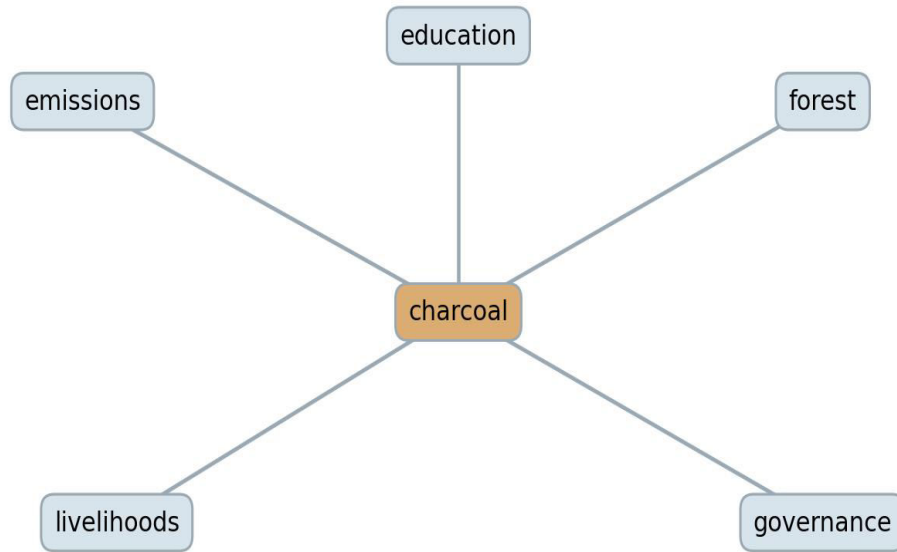


Figure.5 Conceptual co-occurrence network of normalized keywords.

Information sources and searches

Code	Search expression	Records
S1	Title: “charcoal production”	500
S2	charcoal production AND greenhouse gas/emission AND Africa	200
S3	charcoal production AND livelihood/income/welfare AND sub-Saharan Africa	200
S4	charcoal production AND education/school/expenditure AND Africa	200

Eligibility and selection

Criterion	Include	Exclude
Setting	Sub-Saharan Africa or transferable technical study	Other settings without transferability
Phenomenon	Wood-charcoal production or value chain	Coal, medical activated carbon or metallurgy
Outcomes	GHGs, yield, forests, soils, income, governance or education	Combustion alone, adsorption or materials
Documents	Articles from 2000–2026 in English or French	Editorials, records without methods and duplicates

School expenditure and educational outcomes

Relationship	Evidence	Research priority
Technology–yield	Moderate to high	Comparable operating conditions
Technology–emissions	Moderate	CH ₄ and N ₂ O in West Africa
Production–forest	Moderate	Link flows, production sites and pixels
Income–welfare	Moderate	Panel data and net income
Income–schooling	Very limited	Child-level data and causal identification
GHGs–forest–income–education	Almost absent	Integrated N’Dali–Wari-Maró study

Accessible formalization, affordable equipment finance, clearer market margins and diversified income opportunities can reduce dependence on unregulated extraction without abruptly removing cash income (Jones *et al.*, 2016; Zulu and Richardson, 2013). Distributional analysis should distinguish producers, carriers, traders, women and poorer households; an aggregate gain may conceal a loss for those with the least bargaining power.

In N'Dali and Wari-Maró, a linked design could combine direct kiln measurements, repeated forest plots, satellite time series, a value-chain survey and a panel of producers and comparable households.

Measuring household and child-level school spending at the same visits would test whether income reaches education, while recording labor allocation would capture the competing pathway. Household fixed effects or carefully justified propensity-score weighting could improve interpretation, although neither substitutes for sound measurement of confounding and timing.

The assembled literature is concentrated in a limited set of countries and methods. Transfer to Benin should be evaluated against local species, tenure, trade routes, enforcement and school calendars. The most defensible contribution of a Benin study would be a common observation frame that tests the relationships among physical emissions, forest recovery, net returns and children's educational expenditure rather than assuming those relationships from separate studies.

In conclusion, Across 57 studies, charcoal production provides important cash income while its emissions and forest effects vary with conversion technology, harvesting patterns and governance. Improved kilns offer a pathway to lower unit emissions, but landscape outcomes depend on total production and wood regeneration. The clearest evidence gap concerns whether and when charcoal earnings affect school expenditure and attendance. An integrated study in N'Dali and Wari-Maró that combines physical measurements, forest inventories, spatial analysis and a household panel could address that gap. Policy should align conversion efficiency, traceability, resource recovery and protection of household investments in education.

Declarations

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Data availability. The study list and search strategy are provided in the appendices.

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Appendix.1 Included studies

ID	Year	First author	Country	Domains	DOI
E01	2025	ADEDOTUN ABDULMOROOF	Nigeria	Forests/ecosystems; Income/livelihoods	10.55197/qjoest.v6i4.251
E02	2025	Gbigbi Theophilus Miebi	Nigeria	Forests/ecosystems; Income/livelihoods; Education	10.33462/jotaf.1414101
E03	2019	Schure Jolien	Africa	Emissions/technology; Income/livelihoods	10.19182/bft2019.340.a31691
E04	2021	Tassie Kassahun	Ethiopia	Emissions/technology; Income/livelihoods	10.1155/2021/6612720
E05	2019	Ekhuemelo David	Nigeria	Income/livelihoods	10.7770/safer-v0n0-art1557
E06	2018	Akanni Soaga Jubri	Nigeria	Emissions/technology; Income/livelihoods; Education	10.34062/afs.v5i3.5265
E07	2014	Awodele DO	Nigeria	Emissions/technology; Education	10.4314/joafss.v11i1.16
E08	2021	van 't Veen Hanneke	Multi- country/transferable	Emissions/technology; Forests/ecosystems; Income/livelihoods; Governance	10.1088/1748-9326/abe14d
E09	2021	Nyarko Isaac	Africa	Emissions/technology; Forests/ecosystems; Income/livelihoods	10.3390/f12050568
E10	2022	Ansah Patrick K.	Africa	Emissions/technology; Forests/ecosystems; Income/livelihoods; Governance	10.5539/jsd.v15n2p16
E11	2020	Ekpo A. S.	Nigeria	Emissions/technology; Forests/ecosystems	10.9734/jgeesi/2020/v24i230204
E12	2020	Sedano F	Mozambique	Emissions/technology; Forests/ecosystems	10.1088/1748-9326/ab3186
E13	2020	Salamatu Ekpo Abraham	Nigeria	Income/livelihoods	10.9734/jgeesi/2020/v24i330206
E14	2018	Chiteculo Vasco	Angola	Forests/ecosystems; Income/livelihoods	10.3390/environments5110113
E15	2023	Sakala Dabwiso	Africa	Emissions/technology; Forests/ecosystems	10.1111/gcbb.13037
E16	2023	EL Agha Razafindrazanakolona A. D.	Madagascar	Forests/ecosystems; Income/livelihoods	10.33258/economit.v3i2.875
E17	2022	Sedano Fernando	Zambia	Emissions/technology; Forests/ecosystems	10.3390/rs14143352
E18	2019	Nabukalu Catherine	Uganda	Emissions/technology; Forests/ecosystems; Income/livelihoods	10.3390/resources8040183
E19	2011	Salami Kabiru K.	Nigeria	Forests/ecosystems; Income/livelihoods	10.2190/iq.31.4.e
E20	2024	Tazebew Ewunetu	Ethiopia	Emissions/technology; Income/livelihoods	10.1007/s10661-024-12354-2

E21	2024	Getahun Zelalem	Multi-country/transferable	Emissions/technology	10.1016/j.heliyon.2024.e27797
E22	2024	Okimiji Oluwaseun Princess	Multi-country/transferable	Emissions/technology	10.15377/2410-3624.2024.11.2
E23	2022	Nketiah K.S.	Ghana	Forests/ecosystems	10.1505/146554822835224847
E24	2021	van 't Veen Hanneke	Multi-country/transferable	Forests/ecosystems; Income/livelihoods; Governance	10.1088/1748-9326/ac462d
E25	2021	M.O. Okode	Kenya	Emissions/technology; Forests/ecosystems; Income/livelihoods; Governance; Education	10.53555/eijaer.v6i1.64
E26	2019	Oluwasola Babatunde, Taiye	Nigeria	Emissions/technology; Income/livelihoods; Education	10.9734/ajaees/2019/v35i330226
E27	2013	Ainembabazi John Herbert	Uganda	Forests/ecosystems; Income/livelihoods	10.1017/s1355770x1300017x
E28	2025	Lisboa Sá Nogueira	Mozambique	Forests/ecosystems	10.1111/aje.70066
E29	2022	Asare Francis	Ghana	Production/durabilité	10.1016/j.esd.2022.04.013
E30	2022	Oluwaseun Ifabiyi	Nigeria	Production/durabilité	10.33794/qjas.2022.133137.1033
E31	2019	James Rotowa Odunayo	Nigeria	Forests/ecosystems	10.11648/j.ijep.20190706.12
E32	2013	Tunde AM	Nigeria	Production/durabilité	10.4314/afrev.v7i2.1
E33	2012	Sjølie Hanne K.	Tanzania	Emissions/technology	10.1016/j.jclepro.2012.01.008
E34	2008	Oguntunde Philip G.	Ghana	Emissions/technology; Forests/ecosystems	10.1002/jpln.200625185
E35	2023	Tazebew Ewunetu	Ethiopia	Income/livelihoods	10.1016/j.heliyon.2023.e19787
E36	2023	Calvin Esagu John	Uganda	Forests/ecosystems; Income/livelihoods	10.14710/jbes.2023.19260
E37	2018	Oladeji Sunday Oladipo	Liberia	Emissions/technology; Income/livelihoods	10.5296/emsd.v7i2.11770
E38	2016	Sedano F	Mozambique	Forests/ecosystems	10.1088/1748-9326/11/9/094020
E39	2013	Zulu Leo C.	Africa	Income/livelihoods	10.1016/j.esd.2012.07.007
E40	2011	Khundi Fydess	Uganda	Income/livelihoods	10.1016/j.forpol.2010.11.002
E41	2024	Belay Biruk	Ethiopia	Income/livelihoods	10.1016/j.ssaho.2024.101187
E42	2023	Kissanga Raquel	Angola	Emissions/technology; Forests/ecosystems	10.3390/f15010078
E43	2022	Ablo Austin Dziwornu	Ghana	Forests/ecosystems; Income/livelihoods	10.1016/j.esd.2022.09.001
E44	2022	Bekele Birhanu	Ethiopia	Production/durabilité	10.1016/j.heliyon.2022.e11963
E45	2020	Andaregie Adino	Ethiopia	Emissions/technology	10.1016/j.tfp.2020.100020
E46	2020	Aabeyir Raymond	Ghana	Forests/ecosystems; Governance	10.1016/j.sciaf.2020.e00572
E47	2019	Chidumayo Emmanuel Ngulube	Zambia	Forests/ecosystems	10.1016/j.biombioe.2019.04.010
E48	2019	Brobbeey Lawrence Kwabena	Ghana	Income/livelihoods	10.1016/j.esd.2019.03.003
E49	2019	Kiruki Harun M.	Kenya	Income/livelihoods	10.1007/s10668-019-00521-2
E50	2018	Hoffmann Harry	Tanzania	Emissions/technology	10.1007/s12571-018-0786-3

E51	2017	Smith Harriet Elizabeth	Malawi	Income/livelihoods	10.1016/j.esd.2016.10.001
E52	2017	Mulenga Brian P.	Zambia	Income/livelihoods	10.1016/j.jfe.2017.01.001
E53	2017	Doggart Nike	Africa	Production/durabilité	10.3389/fenvs.2017.00027
E54	2017	Randriamalala Josoa Ramarolanonana	Madagascar	Production/durabilité	10.1016/j.foreco.2017.05.049
E55	2016	Jones Daniel	Mozambique	Income/livelihoods	10.1016/j.esd.2016.02.009
E56	2015	Gardner Charlie J.	Madagascar	Income/livelihoods; Governance	10.1017/s0030605315000071
E57	2013	Njenga Mary	Kenya	Production/durabilité	10.1080/09614524.2013.780529

Short reference	Reason
State of the art on slow carbonization kilns	Technique without a distinct African outcome
Commercial kilns using thermal control	Insufficient setting information
Mini-kilns for charcoal-making	Non-African study without a transferable outcome
Charcoal production in Portugal	Non-African setting
Charcoal from macadamia shells	Residue feedstock without forest or social outcomes
Modified biomass kiln	Insufficient methodological description
Ecological charcoal from agricultural waste	Outcome outside forest wood charcoal
Briquette characterization	Materials characterization only
Laboratory Acacia charcoal	Laboratory study without relevant outcomes
Circular economy in charcoal production	Not specific to Africa
Rice husk carbonisation	Feedstock outside eligibility criteria
Kiln for thermal therapy	Purpose outside the scope
Rocking kiln efficiency	Nontransferable setting
Activated charcoal in livestock	Activated carbon outside scope