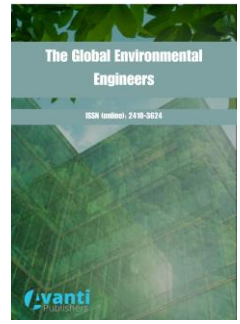
Published by Avanti Publishers
The Global Environmental Engineers
ISSN (online): 2410-3624



Charcoal-production, Air Pollutant Impacts on Ambient Environment and Associated Health Risks: A Systematic Review

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ARTICLE INFO

Article Type: Review Article

Academic Editor: Shifeng Lu

Keywords:
Fuel-wood
Health-risks
Air-pollutant
Charcoal-production
Ambient-environment

Timeline:
Received: October 25, 2024
Accepted: November 30, 2024
Published: December 08, 2024

Citation: Okimiji OP. Charcoal-production, air pollutant impacts on ambient environment and associated health risks: A systematic review. Glob Environ Eng. 2024; 11: 13-36.

DOI: https://doi.org/10.15377/2410-3624.2024.11.2

ABSTRACT

Charcoal is a widely utilised fuel produced from the carbonisation of organic materials, such as wood and other biomass sources. Regrettably, airborne contaminants from traditional charcoal producing techniques can negatively impact human health and the environment. This research explore air pollutant emissions from traditional charcoal producing methods and their impacts on human health and the environment. This study utilised a qualitative synthesis methodology, incorporating case studies, archival research, and discourse analysis, to elucidate the impacts of charcoal production. The results demonstrate that the traditional charcoal production method results in substantial carbon loss from fuelwood and emits by-products of incomplete combustion, exacerbating serious health risks and degrading air quality associated with community health problems. Empirical evidence indicates that the majority of charcoal manufacturing workers lack awareness of the health risks associated with their working circumstances and the respiratory problems they face. Unsustainable environmental practices highlight the social and ecological repercussions of charcoal production. It is advisable to apply air pollution mitigation methods around charcoal kiln facilities to protect environmental and community health. The Environmental Protection Agency must actively implement effective oversight and integrated management to improve air quality and safeguard communities from air hazards. This study recommends testing high-efficiency technologies in communities capable of maintaining and assessing their effects on environmental degradation. Both governmental entities and humanitarian organisations should prioritise educational activities centred on effective land management approaches, as this study's findings suggest.

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1. Introduction

Charcoal is a common fuel source produced through the carbonisation of organic materials, such as wood and diverse biomass types [1]. It is a renewable energy source with four principal applications: home use, chemical manufacturing, agriculture, and commercial enterprises [2-4]. Charcoal is an essential biomass-derived energy source extensively employed in developing countries [5, 6]. It fulfils functions outside the fuel and steel industries and provides multiple environmental benefits [7]. Charcoal improves agricultural production by lowering soil acidity [8] and providing essential nutrients and organic matter required for plant growth [9-11]. It is acknowledged for its capacity to stabilise agricultural soil and avert its degradation [12]. Charcoal efficiently addresses wastewater by adsorbing pollutants owing to its porous architecture [13, 14], and diminishes non-CO_2 greenhouse gas emissions from the soil [15].

Based on the point of view, charcoal can be produced from diverse wood sources, including palm oil shells, bamboo, mangroves, and melaleuca. The quality and productivity of charcoal production fluctuate according on the type of raw material utilised [16]. Charcoal can be generated by many techniques and apparatus, including furnaces, drum kilns, or conventional fire kilns [17]. Through these instruments, the raw materials (wood, solid waste, sludge) undergo a complex transformation into charcoal, a process often known as carbonisation [6]. This process encompasses intricate phenomena that transpire across an extensive temperature spectrum [18] and is categorised into distinct temperature phases based on the employed methodology: below 200°C, from 200°C to 280°C, from 280°C to 500°C, and above 500°C [19]. As a result, several compounds are generated at each phase, including charcoal, tar, pyroligneous acid, and gases. Approximately 33% is attributed to charcoal (80% fixed carbon), 35.5% to pyroligneous acid, 6.5% to insoluble tar, and 25% to noncondensable gases [19].

Furthermore, charcoal possesses a multitude of applications across various industries, functioning as a reducing agent in metal ore smelting, pharmaceutical production, fireworks manufacturing, artistic materials, CO_2 sequestration, soil improvement, syngas generation, wastewater treatment, and as cost-effective adsorbents for soil and energy generation [20, 21]. It serves as an activated carbon with substantial adsorption capacity for applications including bleach degassing, water treatment [22], wine purification [23], and diverse medicinal uses, as well as a carbon source for the production of carbon tetrachloride, cyanide, and sulphide [2, 3]. In agriculture, it improves soil and water quality, acts as a substantial bioenergy source, and promotes air quality [24].

Subsequently, charcoal is predominantly utilised as a fuel in the lime, cement, boiler, ceramics, thermal energy, civil construction, and metal extraction industries. The choice of these organic materials is determined by their availability, carbon content, and appropriateness for generating high-quality charcoal [25, 1]. Africa relies heavily on charcoal for cooking, with more than 90% of rural households and 80% of urban households utilising it as their main cooking fuel [26]. Charcoal production in Africa accounts for about 65% of global output [27]. Approximately 2.4 billion individuals worldwide rely on solid fuels (including wood, dung, crop residues, and charcoal) for cooking, heating, and other domestic requirements, which are considered cleaner choices for emissions [28]. This figure may reach 3 billion if coal is considered [29]. Three primary categories of solid fuels utilised for residential purposes are coal (a fossil fuel), biomass (derived from animal and plant sources), and charcoal.

In this regard, charcoal emissions provide considerable challenges, especially in sub-Saharan Africa, where indoor cooking is common. Nonetheless, burning charcoal presents fewer health hazards than burning wood, rendering it a favoured fuel in residential environments due to its diminished smoke emission [30]. Charcoal is utilised throughout multiple sectors and applications. It is a carbon-rich solid material generated through the slow pyrolysis of biomass [31]. The pyrolysis process entails the irreversible thermochemical decomposition of the major constituents of biomass (lignin, cellulose, and hemicellulose) [32] at temperatures starting from 200°C [33]. Besides charcoal, pyrolysis produces two other notable products: a liquid fraction, referred to as bio-oil, which contains various water and organic compounds, and a gaseous fraction that prevents the development of prismatic species, rendering it flammable [34].

However, charcoal manufacture yields three primary products: liquid, gas, and charcoal. The results are affected by the operational parameters and configuration of the biomass, particularly the carbonisation temperature and heating rate [35, 36]. Charcoal burning produces less smoke than wood combustion [37]; however, the manufacturing process is markedly inefficient. The predominant production of charcoal occurs in rural areas next to main thoroughfares, employing inefficient earth kilns; wood is arranged beneath sod and dirt and is progressively combusted over a period of two to four weeks [35]. The completed product is packaged in sacks and placed onto heavy-duty diesel vehicles for transfer to metropolitan regions, mostly for domestic and commercial culinary applications [38]. Aerosols and trace gases are emitted throughout the charcoal supply chain [39] and then interact with the atmosphere to produce secondary pollutants.

Additionally, charcoal is acknowledged as a major source of carbon dioxide (CO_2) and methane emissions in both tropical and global contexts [40, 41] and contributes to forest degradation and loss due to unsustainable and intensive tree harvesting [42, 43]. The urban demand for charcoal has led to deforestation and environmental deterioration due to the reliance on unsustainable production methods to satisfy this increasing demand [1]. Africa has the largest annual charcoal production, including around sixty-four percent in 2018 [44], followed by America and Asia, mainly Latin America [45]. Approximately 250 million individuals employ charcoal for domestic energy production on a weekly basis, predominantly in Africa, specific areas of Asia, and Brazil [29]. Indonesia is the primary exporter of charcoal, valued at $309 million, whilst Germany is the principal importer, with a value of $127 million [46]. Brazil is recognised as a leading global producer of charcoal, predominantly utilising its whole output for domestic purposes, chiefly in the steel industry, with the surplus designated for home cooking and grilling. Prominent charcoal enterprises exist in Africa, Latin America, Asia, and Europe [47, 48].

More so, charcoal can be derived from several wood sources, such as palm oil shells, bamboo, mangroves, and melaleuca [6]. The quality and productivity of the produced charcoal varied according on the type of raw materials utilised. Charcoal can be produced utilising various equipment, including kilns, furnaces, traditional fire kilns, and drums [17]. These equipment and raw materials undergo a complex process and are ultimately converted into charcoal, generally known as carbonisation. Nevertheless, specific kilns have demonstrated technological progress, especially in process monitoring, control, and by-product energy recovery. Consequently, the majority of worldwide charcoal manufacturers depend on batch-operated earth or brick kilns due to their simplicity, available expertise, low technological requirements, and minimal capital investment [3, 49].

Unfortunately, diminished charcoal yields correlate with the utilisation of conventional low-tech kilns, resulting in substandard charcoal quality and heightened environmental impacts in proximity to production sites due to the release of pyrolytic gases and liquids [40, 50]. Charcoal production processes are diverse, ranging from primitive and rudimentary to advanced and efficient procedures. The effectiveness of these methods substantially influences both the volume and quality of charcoal generated, along with the environmental impacts of its production [6, 51, 52]. Consequently, deforestation, land degradation, and air pollution have prompted extensive research focused on enhancing the efficiency and cleanliness of charcoal production methods through the integration of traditional indigenous practices [53, 54]. Solid biomass, such as charcoal, wood, dung, and agricultural waste, contributes to more than 25% of black carbon emissions [55, 7].

Notwithstanding the growing data about the health risks linked to charcoal [56, 30, 16], this issue has been explored in only a limited number of systematic investigations. Limited research has particularly investigated the health impacts of charcoal according to activity type. This integration of knowledge is crucial for guiding policies and initiatives that can detect health problems. Such policies may provide solutions to alleviate identified health issues. This study sought to perform a thorough evaluation of existing data to consolidate an understanding of the health issues related to charcoal production and use worldwide. This study aims to evaluate existing research and consolidate evidence regarding (i) air pollutant emissions from the traditional charcoal production process, and (ii) the impact of conventional charcoal manufacturing on human health and the environment.

1.1. Background to the Study

A literature assessment on worldwide charcoal production and supply chains reveals that the demand for this energy source is anticipated to rise substantially by 2030 [57]. In countries with high electrification rates, like

Nigeria and Ghana, where 60–70% of the population still relies on charcoal for cooking and heating [58], this finding contradicts the traditional energy ladder paradigm, as shown in several studies. In some undeveloped countries, like Liberia, where less than one percent of the population has access to the electricity grid, ninety-five percent rely on traditional biomass fuels, namely wood and charcoal [59]. Current initiatives to mitigate the adverse effects of charcoal in developing nations by promoting electrification and enhanced fuels are based on the classic energy ladder concept.

More so, studies from many Asian [60] and South American countries support this paradigm, demonstrating that as urban households in developing nations increase their annual income, their fuel consumption shifts from biomass to superior energy sources [61]. A multitude of country-specific case studies has been done by [62]. Although South Africa is regarded as the most electrified country in Africa, research indicates that 90% of households continued to utilise woodfuels (charcoal) ten years after gaining access to electricity [63]. Similar results have been noted in Ghana, Tanzania, Zimbabwe, Botswana, and various other countries across the continent [64, 65].

The findings suggest that economics is less impactful than once assumed, and that additional factors also limit the adoption of advanced fuels, especially in emerging nations where solid fuels considerably affect energy dynamics. Wood fuel is a crucial source of energy and economic activity in numerous places worldwide, with global use estimated at roughly 1.86 billion m^3 in 2016 [2]. Oliveira [66] asserted that the essential density must surpass 500 kg/m^3 for the efficient transformation of wood into charcoal. Several studies including Vale *et al*. [67], Carneiro *et al*. [62], observed that use wood with diminished densities produces low-density charcoal. Leme [68] stated that wood with a moisture content over 30% extends the carbonisation period, thereby reducing the output.

Meanwhile, total wood fuel consumption has either diminished or stabilised in Asia and South America, the demand for wood fuel in sub-Saharan Africa has continued to rise. The collection of fuelwood in developing countries is crucial to compete with alternative energy sources for domestic use [69]. The demand for fuelwood is rising due to population growth, with annual increases ranging from three to four percent, varying by country [70]. Consequently, deforestation in developing countries is exacerbated by low-income households' reliance on fuelwood for cooking, while meeting the energy demands of a growing population remains a persistent concern [70]. Biomass accounts for more than 60% of the total energy demand in sub-Saharan Africa, with considerable disparities among countries [71, 72].

Despite established global objectives, such as Sustainable Development Goal No. 7, which seeks to ensure access to sustainable energy by 2030, particularly electricity, natural gas, and Liquid Petroleum Gas in urban areas of the least-developed regions [73, 74], more than 90% of households in sub-Saharan Africa remain reliant on fuelwood for domestic use. Without substantial energy changes, the biomass-dependent population in sub-Saharan Africa is anticipated to reach 820 million by 2030, representing 56% of the entire population [71]. Firewood is predominant in rural areas; nevertheless, charcoal is a common cooking energy source in urban centres of sub-Saharan Africa, with its usage expected to increase in the next decades [75]. The majority of charcoal is produced, processed, and transported informally, so evading established legal regulations [76, 77].

In this regard, the transformation of biomass into charcoal requires pyrolysis, a thermochemical process that breaks down organic materials into gases (both non-condensable and condensable) and solid products (charcoal and biochar) in a low-oxygen environment [78]. In less-developed nations, most charcoal is produced using traditional earth mound kilns, often yielding a quality of 13% to 15% [79]. Due to the absence of quick alternatives to charcoal [75] and the expected continuous increase in demand in developing nations [71], it is essential to devise strategies to improve the sustainability of charcoal value chains. The majority of timber harvested from worldwide forests is employed for energy production, particularly for residential use in developing countries and for electricity generation in industrialised ones [80]. In Africa and Asia, almost 60% of energy consumption is derived from wood harvesting. Approximately 17% of the wood employed as fuel is converted into charcoal [81].

Ironically, charcoal serves as a crucial domestic energy source in many impoverished countries, constituting 14% of global household energy use [40]. Moreover, charcoal production increases employment, tax revenue, and rural income, therefore enhancing profitability [82]. African countries account for over 63% of the world's charcoal production, due to its use in both rural and urban communities [83]. This portion of the traditional energy supply chain is considered the most environmentally harmful [84, 85]. Charcoal is an essential energy source for rapidly growing urban populations and substantial segments of the rural populace, having been utilised historically for generations [80].

However, the production of charcoal causes environmental pollution at both local and regional scales, along with the decline of forest resources [86]. Charcoal releases significant amounts of sulphur dioxide, carbon monoxide, nitrogen dioxide, and particulate matter. These emissions significantly alter the atmospheric properties (both chemical and physical) and contribute to global warming [40]. Air pollution constitutes a major global concern in both industrialised and developing countries. Accelerated population expansion and increasing energy consumption have resulted in the emission of detrimental air pollutants, impacting the environment and human health throughout low-, middle-, and high-income countries [87]. Air pollution in rural and urban areas is projected to cause 4.2 million premature deaths worldwide annually, primarily due to exposure to particulate matter that leads to respiratory disorders, cardiovascular diseases, and cancers [88]. The atmospheric environment, vital for human survival, affects the quality of life. Air pollution has captured the interest of many segments of society.

In reference to studies, this topic is a significant focus of research in geography, ecology, environmental science, and related disciplines [89, 90]. Studies demonstrate that industrialisation affects multiple factors of air quality, such as population density, industrial structure, urbanisation levels, and economic development [91]. Industrial soot emissions and per capita gross domestic product (GDP) substantially influence air quality. Furthermore, the pollutants produced during charcoal production impact human health, influencing both workers and residents of nearby communities [92, 93]. Health problems linked to air pollution are significantly more prevalent in underdeveloped countries compared to industrialised nations [94].

Although, the manufacturing of charcoal is anticipated to be a benefit of fossil fuels, as it meets energy demands while contributing to outdoor air pollution [95]. These kilns emit several air pollutants that degrade air quality and present health risks to the human population [96]. Air pollution is the fourth leading contributor to the global illness burden and premature death [81]. The worldwide Burden of Disease reveals that more than 4.9 million premature deaths are globally linked to ambient air pollution [97, 98] and additional variables [89, 90].

Subsequently, individuals from any geographical region may encounter adverse impacts, irrespective of their origin [99]. Numerous studies have consistently shown increased rates of cardiovascular and respiratory illnesses in urban areas due to high pollution levels, especially among school-aged children and the elderly [99, 100]. This study aimed to assess the impact of air pollution in areas involved in charcoal production, focusing on environmental and occupational repercussions. Nonetheless, determining the criteria for study selection continues to be a substantial obstacle.

2. Methodology

2.1. Study Selection Procedure

This study employs qualitative data derived from an extensive methodological framework. This methodology is frequently favoured in environmental assessment studies because it facilitates a comprehensive investigation of the subjectivity inherent in systematic reviews. This is essential for comprehending the emissions of air pollutants from traditional charcoal producing methods and their impact on human health and the environment. A literature review was performed from January 2024 to October 2024. This methodological technique involved a systematic process for identifying and choosing relevant articles, evaluating them against defined criteria, extracting pertinent information, and synthesising related ideas to further the study objectives.

The study conducted a thorough assessment of relevant materials by extensively reviewing chosen papers from the ScienceDirect, Scopus, and Google Scholar databases, which were synthesised and integrated into the research. Empirical studies published in peer-reviewed academic publications were prioritised. The majority of the cited articles were published in the last three years, underwent stringent peer review, and were carefully evaluated and chosen for their uniqueness and relevance. The selection criteria required that each article offer insights into at least one of the following areas: the impact of air pollutants on the surrounding environment, the health risks associated with air pollutant emissions from conventional charcoal production, and the consequences for human well-being. A total of one hundred sixty-five (165) pertinent papers were meticulously picked, incorporated into the analysis, and integrated into the study. Hence, Fig. (**1**) Shows flowchart of the study based on process of identification, selection of relevant articles, clearly defined criteria, pertinent information extraction, and integration of related information to the research objectives.

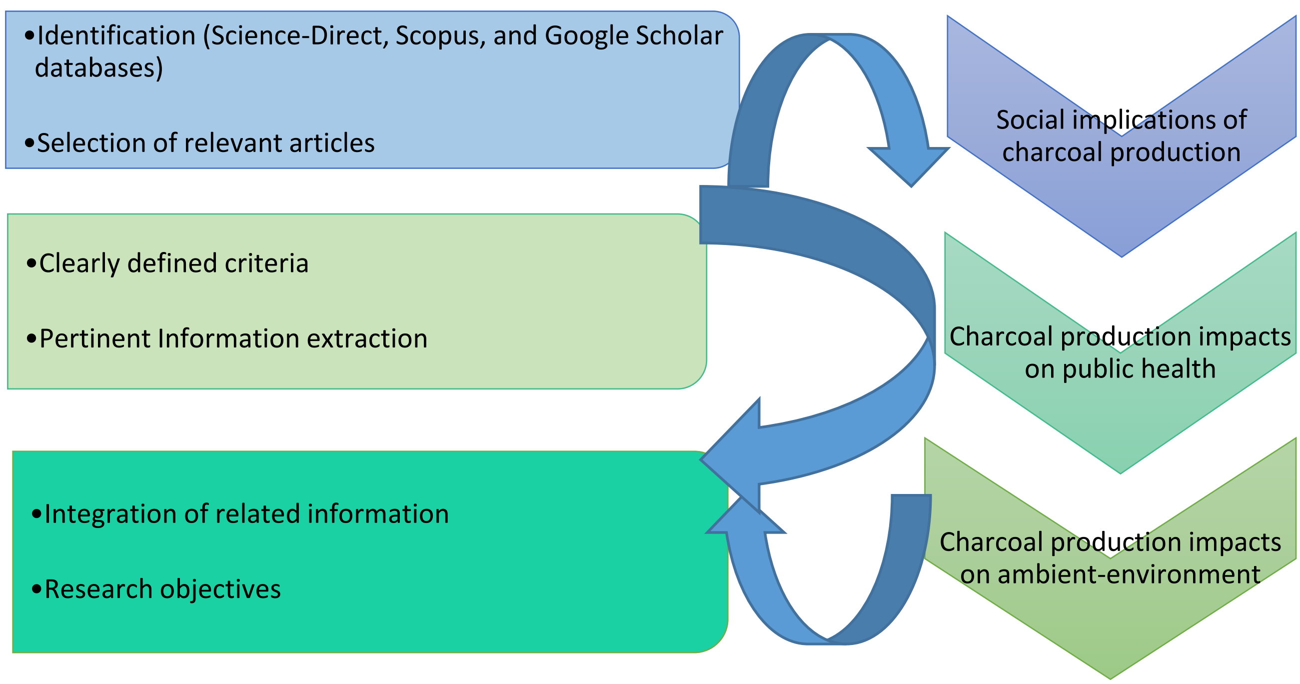

Figure 1: Flowchart of the study based on process of identification, selection of relevant articles, clearly defined criteria, pertinent information extraction, and integration of related information to the research objectives. Source: Author computation.

2.2. Searching Procedures

The literature review was categorised into two segments. A comprehensive search was initially undertaken for methodologies related to the effects of charcoal production, concentrating on the titles, abstracts, and keywords of pertinent studies in the field of environmental monitoring research. In the second step, the "snowball" method was utilised, which entailed examining the reference lists of relevant publications, the latest articles on connected research, and the referenced studies. This strategy was employed to acquire publications that significantly impacted the research topic, as the search results from most databases included newly published and highly referenced works. The primary search terms encompassed "charcoal production," "air pollutants," "health issues," "fuelwood," and "ambient environment," albeit the search was not restricted to these subjects. In this regard, Table **1** depicts the thematic analysis of papers on charcoal-production, air pollutant impacts on the ambient environment and associated health risks (between 2021-2024) of previous research contributions.

Table 1: Thematic analysis of papers on charcoal-production, air pollutant impacts on ambient environment and associated health risks (between 2021-2024) of previous research contributions.

S/n	Year	Authors	Study Area Focuses	Research Insight
1	2022	Ahmad *et al*.	Coconut shell biomass, thermochemical conversion, charcoal, characterization, analytical techniques	Exploring the potential of coconut shell biomass for charcoal production
2	2024 [101]	Albuquerque *et al*.	Carbonization process, Kiln performance, Charcoal quality	Mini-Rectangular Kiln to Produce Charcoal and Wood Vinegar.
3	2022	Ankona *et al*.	Earth kilns, charcoal production, ecological retort system (ERS), traditional earth kilns, air pollution prevention	The Eastern Mediterranean charcoal industry: Air pollution prevention by the implementation of a new ecological retort system.
4	2023	Bashir *et al*.	Brick klins, greenhouse gases, specific energy consumption, terrestrial acidification, emission factors	Investigating the impact of shifting the brick kiln industry from conventional to zigzag technology for a sustainable environment.
5	2023	da Silva *et al*.	Charcoal Production, Earth Kiln, Soil Properties, Guinea Savanna, Soil	Kiln-furnace System: Validation of a Technology for Producing Charcoal with Less Environmental Impact in Brazil.
6	2022 [102]	Hussain *et al*.	Air pollution, brick kiln, sulfur dioxide, nitrogen oxide, carbon monoxide	Brick kilns air pollution and its impact on the peshawar city.
7	2023	Idowu *et al*.	Health risks, production and usage of charcoal, Emissions from solid fuels, charcoal, packaging and transportation, charcoal users.	Health risks associated with the production and usage of charcoal: a systematic review.
8	[2024]	Getahun *et al*.	Bricks, Charcoal, Carbonization, Scrubber, Emission gas control	Towards sustainable charcoal production: Designing an economical brick kiln with enhanced emission control technology.
9	2023	Ishaya *et al*.	Charcoal, Ambient, Air Quality, Vicinity, pollutant level	Assessment Of Ambient Air Within the Vicinity of Charcoal Production Site In Kunguni Community, Kwali Area Council in Abuja, Nigeria.
10	2023 [103]	Sahu *et al*.	Megacity, Emission Inventory, Hotspots, Air quality, Anthropogenic Emission,Major/Minor Sources, Mitigation Strategies	Decadal Growth in Emission Load of Major Air Pollutants in Delhi.
11	2023	Toan *et al*.	air pollutant emission; air pollution reduction; charcoal-making kiln; fuelwood	Emission and Reduction of Air Pollutants from Charcoal-Making Process in the Vietnamese Mekong Delta.
12	2022	Mangaraj *et al*.	Anthropogenic sources, emission inventory, megacity, air quality	A comprehensive high-848 resolution gridded emission inventory of anthropogenic sources of air pollutants in Indian megacity Kolkata,
13	2021 [104]	Raza and Ali	respiratory problems, spirometry, lung function, District Kasur, Pakistan	Impact of Air Pollution Generated by Brick Kilns on the Pulmonary Health of Workers.
14	2022	Charvet *et al*.	biomass; wood; gas; charcoal; pyrolysis; carbonization; kiln	Charcoal Production in Portugal: Operating Conditions and Performance of a Traditional Brick Kiln
15	2022	Bekele and Kemal	Challenges, charcoal, opportunity, producer, sustainability	Determents of sustainable charcoal production in AWI zone; the case of Fagita Lekoma district, Ethiopia,

3. Observation and Discussion

3.1. Diverse Air Pollutants Emitted from Charcoal Production

Charcoal is conventionally generated in kilns through the pyrolysis of wood at elevated temperatures in an anaerobic environment [105]. Pyrolysis, which transforms biomass into charcoal, results in the substantial removal of volatile chemicals [106]. Nonetheless, conducting pyrolysis at low temperatures and for brief periods can yield an increased volatile content in the charcoal [107, 108]. Elevated volatile values result in erratic and smoky combustion [109], leading to the emission of CO, HCs, PM2.5, and benzene [110, 108].

Moreover, charcoal kilns exhibit considerable variation in design and dimensions, ranging from earthen mounds to brick constructions to substantial metal frameworks [111]. Earth mounds and brick kilns are widely employed for charcoal production in Africa [50]. These kilns lack control methods and, due to their prolonged presence in the same site, may contribute to local air pollution issues. The manufacturing of charcoal results in localised environmental contamination and depletion of forest resources [86]. Charcoal kilns emit substantial quantities of particulate pollution, carbon monoxide, nitrogen dioxide, and sulphur dioxide [111]. These emissions substantially modify the physical and chemical properties of the atmosphere and contribute to global warming [40].

In spite of this, charcoal has been recognised as a significant contributor to greenhouse gases, including methane and carbon dioxide (CO_2), in both tropical and global contexts [41]. It also contributes to forest degradation and loss due to extensive and unsustainable timber extraction [43]. Every phase of the charcoal supply chain results in the emission of ephemeral trace gases and aerosols [39], which pose risks to human health and influence climatic conditions. Trace gases and aerosols are released during the charcoal supply chain [39] and undergo atmospheric reactions to produce secondary pollutants, including ozone and secondary inorganic and organic aerosols (OAs). Ozone and aerosols, particularly PM2.5 (particles with an aerodynamic diameter of less than 2.5 µm), pose health risks and influence the Earth's radiative equilibrium [112].

Considerably, Charcoal is generated through the charring of biomass via an incomplete combustion process, regulated by the oxygen supply [16]. Slow charring yields a black carbonaceous substance known as charcoal, which emits comparatively minimal smoke while use [16]. Biomass combustion is linked to inefficient burning and the release of various toxic substances [113], such as carbon monoxide (CO) [114], volatile organic compounds [115], nitrogen oxides (NO_x) [116], polycyclic aromatic hydrocarbons (PAHs) [117], fine particulate matter (PM) [118], trace metals, and additional minor pollutants [119, 110, 120]. Further analysis revealed that charcoal is a carbon-dense, porous substance created from the pyrolysis of organic matter, such as wood, under regulated conditions, usually at temperatures ranging from 200 to 400°C [121]. Charcoal smoke comprises a complicated amalgamation of liquid, solid, and gaseous constituents.

To this end, numerous substances are deleterious, including, but not confined to, nitrogen, sulphur oxides, benzene, aldehydes, acrolein, organic acids, polycyclic aromatic hydrocarbons (PAHs), and hazardous particulate matter such as PM2.5 (particulate matter with diameters <2.5 µm) [16]. The combustion process of solid biofuels comprises several distinct phases: i) an initial drying phase, wherein moisture in the biofuel evaporates; ii) devolatilization (pyrolysis), during which volatile components are released; iii) combustion of volatile matter; iv) char combustion; and v) the extinguishing phase [122, 123]. The duration of these phases may fluctuate based on parameters such as fuel qualities, kind and size, moisture content, temperature, and combustion circumstances. The properties of charcoal display considerable variety and are affected by numerous elements that dictate the features of the final product. Critical elements encompass the wood species utilised, the plant components employed (branches or stems), the temperatures and conditions applied during the pyrolytic process, and the type of kiln utilised [109, 124].

3.2. Charcoal Production as a Regional Nuisance: Social Implications of Charcoal Production

A comprehensive literature review and analysis of charcoal production and its societal impacts reveal a consistent dependence on charcoal, although considerable initiatives to provide reliable energy and fuel infrastructure. This dependence presents numerous problems regarding the sustainability of the charcoal business, including its economic importance, efficient forest resource management, and the livelihoods of people principally involved in its production. The charcoal industry provides supplementary income for numerous persons in these areas and, for others, represents the primary source of financial sustenance for their families [125].

Consequently, charcoal production creates jobs, increases the wages of local workers, promotes socioeconomic development, and maintains cultural characteristics [126, 127]. Furthermore, charcoal companies in major producing countries, such as Tanzania and Uganda, employ tens of thousands of persons, a substantial percentage of whom obtain up to 70% of their annual income from this sector [59, 85]. In countries with more progressive rules regarding the charcoal industry, producers often face disadvantages in income generation and labour support [128].

However, investigations of the commodity chain of Senegal's charcoal industry indicated that, despite substantial regulations, the majority of economic and sociopolitical advantages are concentrated among merchants and distributors rather than producers [129]. Rural producers, who frequently constitute the predominant segment of the workforce, generally lack the capital required to augment their earnings or maintain subsistence income [130]. This is particularly alarming, given that the charcoal trade is one of the most organised industries in the region, consisting of more than eighty-five cooperatives and significant government resources allocated for its regulation.

On the other hand, research indicates that in 2018, Africa produced the largest volume of charcoal, constituting over 64% of world output [44], followed by Asia and the Americas, especially Latin America [45]. Thus, additional social threats encompass widespread child labour, gender disparities in educational and production results, substantial price volatility often influenced by merchants [129], and the lack of effective strategies for poverty reduction through current production techniques [131]. Nonetheless, charcoal occurs beyond the formal economy [132]. Notwithstanding considerable endeavours to mitigate the deterioration of forest resources via technological innovations, a significant deficiency remains in the investigation of the real health impacts faced by these particularly susceptible communities.

3.3. Perceived Impacts of Charcoal Production on the Public and its Associated Health Risks

The preceding section and subsequent analysis indicate that charcoal production directly exposes workers to smoke from wood, comprising a mixture of liquid, gaseous, and solid particles emitted from charcoal production kilns [133, 134]. Individuals frequently subjected to elevated ambient temperatures, increased concentrations of hazardous gases, and charcoal dust may face health risks. Da Silva Viana Jacobson *et al*. [134] assert that young infants may have adverse consequences from air pollution resulting from biomass combustion, especially from prolonged exposure to particulate matter and black carbon.

Moreover, charcoal workers encounter numerous potential health risks, such as physical injuries, disorientation, eye irritation, and respiratory infections [135]. Studies demonstrate that inhalation of these pollutants leads to eye and skin irritation and may also exacerbate pharyngitis, allergic rhinitis, pulmonary fibrosis, diarrhoea, asthma, bronchitis, coughing, emphysema, intestinal infections, reduced lung function, and low birth weight [104, 136, 137]. Employees exposed to prolong levels of carbon monoxide (CO) often display symptoms like headache, dizziness, and nausea [138]. The combustion of coal for domestic heating may contribute to ambient air pollution, thereby impacting human health, especially in residential zones [139, 140].

In view of this, the combustion of biomass generates various air pollutants, including formaldehyde, benzene, 1,3-butadiene, nitrogen oxides (NO_x), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAH), sulphur oxides (SOx), and particulate matter, which encompasses carcinogens such as organic compounds and benzo[a]pyrene, all detrimental to human health [141]. Exposure to these air pollutants correlates with reduced birth weight, heightened early mortality in children, pneumonia, acute respiratory infections (ARI), and chronic bronchitis and chronic obstructive pulmonary disease (COPD) in adults [142].

Essentially, additional health ramifications encompass TB, nasopharyngeal and laryngeal carcinoma, asthma, pulmonary cancer, newborn complications, and ocular disorders, including cataracts and blindness [143-145]. Tzanakis *et al*. [146] noted in their study of charcoal workers in Greece that wheezing, dyspnoea, expectoration, and coughing were significantly more prevalent among those exposed to smoke than among unexposed persons. The rising prevalence of respiratory diseases may stem from genetic alterations triggered by environmental variables that elicit allergic reactions [147]. Acute exposure to wood smoke correlates with an increased risk of respiratory symptoms [148]. The significance of air is highlighted by the average daily adult necessities of roughly

1.4 kg of food, 2 kg of water, and 14 kg of air. This underscores the importance of ongoing study on air pollution [144].

Based on the view point, coughing, along with symptoms including sneezing, nasal discharge, and sputum production, has been recognised as a common symptom in prior studies conducted by Swiston *et al*. [149], Keraka *et al*. [150], and Adewole *et al*. [151], which examined the health effects of charcoal exposure. The combustion of coal significantly impacts air quality by emitting sulphur dioxide (SO_2) and PM2.5 [152]. Charcoal makers are exposed to contaminants from biomass carbonisation during manufacturing, with respiratory issues being the primary health consequence among workers. Substantial connections have been shown between charcoal exposure and respiratory health impacts [133, 153, 154], including tuberculosis [155], observed at various stages of charcoal manufacturing.

Considerably, wood smoke is linked to an increased risk of respiratory symptoms, asthma, and chronic obstructive pulmonary disease (COPD) [156]. Research indicates that entering a kiln, loading it with new wood, and extracting previously fired charcoal are the most significant activities associated with wood smoke exposure and charcoal dust [133, 157].

Maia and Francisco [158] and Alfaro and Jones [159] indicated that the risk of physical injuries associated with charcoal manufacture includes burns to the lower limbs and moderate to severe lacerations, particularly in the lack of sufficient workplace regulations [159]. Wood smoke impacts human health via particulate matter, resulting in biological changes [160].

Hence, charcoal manufacture produces additional emissions such as toluene, modified naphthalene, oxygenated monoaromatics, polycyclic aromatic hydrocarbons, naphthalene, and benzene [161]. Evidence indicates the mutagenicity of wood smoke fractions [162]. The combustion of charcoal results in exposure to hazardous substances, such as particulate matter, carbon monoxide, and smoke emissions, akin to cigarette smoke, and is associated with decreased body weight and BMI [163, 164]. Moreover, research has demonstrated associations between $PM_{2.5}$ [165], CO exposure [166], and black carbon with changes in systolic blood pressure.

In the same vein, a 2015 global study on blood pressure changes revealed the most pronounced increases in Eastern Europe, Central Europe, South Asia, and sub-Saharan Africa [167]. Arku *et al*. [168] found variables such as ambient temperature, ventilation, and physical activity that may affect the measured blood pressure. Additional investigation is required to validate these results. Ismaili *et al*. [169] identified a link between exposure to charcoal smoke and lung cancer. A prior report indicated that squamous cell carcinoma was more prevalent than adenocarcinoma, which correlated with heightened passive smoking exposure.

In contrast, Muscat *et al*. [170] reported that adenocarcinoma is more common than other forms of lung cancer. Furthermore, smoke from wood, containing ammonia, carbon oxides, nitrogen oxides, volatile organic compounds, and sulphur [73], leads to persistent respiratory irritation and aggravates pre-existing asthma and chronic bronchitis [156]. In contrast, previous studies indicate that local exhaust ventilation may effectively purify contaminated air, and its consistent application substantially reduces occupational hazards to levels beneath the threshold limit [171, 172]. The lack of regulations in the charcoal business presents considerable safety risks and potential for exploitation [173].

Nevertheless, research has investigated the social and health implications linked to the production of this highly coveted fuel. The use of wood fuel significantly impacts the livelihoods and public health of rural communities, particularly affecting women and small children. These individuals sometimes suffer additional adverse effects of fuel burning, including respiratory diseases, due to the inhalation of high levels of particulate matter [174, 111]. Government reports and academic literature depict the working circumstances of charcoal producers as perilous [84, 175]; both government officials and research papers recognise these 'hazards' superficially.

As a result of this, the lack of regulations and dependence on conventional production techniques continue to prevail in the business. The kiln preparation period before production may last up to two weeks, during which manufacturers construct a pit and save the soil for future use [176]. The numerous standards established about 30 years ago underscore the gravity of the hazards linked to these working conditions. However, inadequate knowledge, institutional ability, and financial resources impede the execution of safety measures in most charcoal-producing areas for residential use, worsening the occurrence of moderate-to-severe injuries and illnesses.

3.4. Perceived Impacts of Charcoal Production on Ambient-Environment

Empirical evidence demonstrates that the environmental repercussions of diverse charcoal production systems are significant. Traditional methods often include unsustainable timber exploitation, leading to deforestation and environmental degradation [1]. Incomplete combustion in traditional kilns releases substantial amounts of volatile organic compounds, particulate matter, and greenhouse gases, worsening climate change and air pollution [177, 102, 31, 7]. The traditional method of charcoal manufacture produces air pollution that is above environmental limits, especially during the last three days of combustion [178].

However, air emissions from charcoal manufacturing significantly influence the environmental impact of charcoal production and consumption systems [179]. As a result, significant volumes of gases and other by-products are released into the atmosphere. Residents and workers in these regions are subjected to pollutants released by these kilns, leading to health issues due to the inhalation of these toxins [180, 181]. The principal non-condensable gases produced are carbon dioxide, hydrogen, methane, and carbon monoxide [182]. The increased demand for charcoal [61] and its unsustainable production may threaten ecological services, agricultural productivity, and human health [183].

In this regard, the production of charcoal causes environmental degradation, reduced forest cover, decreased clean water supplies, and a shortage of arable land, which in turn leads to increased hunger, disease, poverty, and fewer livelihood opportunities [184, 185]. Suboptimal process efficiency, along with the unregulated activities of various producers, leads to the exploitation of substantial amounts of wood from neighbouring forests [186]. The FAO [187] recognised Nigeria as a country undergoing substantial deforestation. Indigenous trees are heavily utilised for their high-quality wood fuel, neglecting the prolonged regeneration of these species.

Hence, Nigeria has recently become one of the leading global producers and users of charcoal [188]. Nwofe [189] noted that the lack of available and affordable alternative fuels in many locations of Nigeria forced numerous households to utilise charcoal for domestic cooking. Historically, all tree species have been carbonised to generate charcoal; however, specific species are preferred due to their enhanced charcoal quality and yield [69]. The relationship between environmental degradation and rural livelihoods is apparent in the utilisation of forest resources [176]. These practices have further implications for soil composition, water resource availability, accessibility, and site productivity [190], all of which are directly connected to rural livelihoods. Larson and Ribot [191] provide substantial evidence demonstrating that forestry legislation and policies in developing nations often favour the elite [191].

More so, this issue is exacerbated by dependence on traditional methods of charcoal production, stemming from insufficient educational resources and a lack of critical information. As a result, marginalised groups have difficulties in the sustainable management of natural resources, leading to reduced livelihood opportunities and a decrease in biodiversity [184]. The national-level study highlights the significant threats that modern manufacturing methods pose to society and the environment. Mwampamba [42] examined current and anticipated deforestation rates by employing survey data on the extraction and replenishment techniques of rural charcoal producers in Tanzania, the leading charcoal producer in sub-Saharan Africa.

Furthermore, studies have shown that, without policy interventions, public forest resources will be depleted by 2028 [192]. Namaalwa *et al*. [47] similarly identified a disruption in the Ugandan charcoal supply chain in 2019 [193]. Despite numerous less-developed countries being significant producers of charcoal in the region, these findings carry significant implications for other nations whose populations heavily rely on wood-based fuels. Further research at sub-national or local levels might furnish decision-makers with insights into patterns in geographical energy dynamics. Efforts to penalise this behaviour through fines, increased taxes, and production restrictions are widespread.

However, they intensify the economic burden on rural communities, leading to a countrywide disparity in charcoal distribution. The production of charcoal presents considerable obstacles for immediate action, and its procurement and utilisation are intricately linked to the economic, cultural, and practical dimensions of everyday life, making viable alternatives to this fuel highly unlikely. While charcoal is expected to remain a crucial component of the energy mix in urban African households [84, 85], a deeper comprehension of urban energy consumption patterns shaped by social, economic, and environmental factors will assist in alleviating the uncertainties in future carbon emission forecasts associated with charcoal utilisation.

3.5. Solutions for Sustainable Charcoal Use and Current Relevant Government Policy Issued and Technical Innovation

Consequently, the production of sustainable charcoal continues to encounter legislative obstacles that require effective resolution. Challenges associated with wood fuel are increasingly perceived as stemming from systemic, albeit location-specific, factors, including land tenure, fiscal and incentive policies, urban energy markets, and the misallocation of forests and agricultural land, all of which influence the charcoal production chain [194].

Moreso, a substantial transition from open-access forests to secure tenure is essential for sustainable forest management, since it necessitates the establishment of clear and secure long-term forest tenure by granting appropriate property rights to landowners, including communities [194]. Improving policy and program legitimacy via multi-stakeholder engagement and alignment with globally acknowledged principles, objectives, and pertinent international frameworks, such as the Millennium Development Goals (MDGs), is crucial for ensuring the environmental and socio-economic sustainability of charcoal production in tropical forest ecosystems [194].

Therefore, it is essential to reassess the processes involved in charcoal production and use chains (Girard, 2002). A requisite adaptation is a demand-driven methodology and technological advancement.

i. Need-based Approach

This encompasses batch-type retorts that utilise an external heat source for wood carbonisation; metal kilns fitted with vapour incinerators; and Lambiotte-type continuous retorts, which allow for wood introduction at the top of the kiln and charcoal extraction from the bottom, with the generated vapours combusted to fulfil the process's thermal demands. All of these necessitate substantial investments and are typically prohibitive for small-scale charcoal producers in tropical nations [194].

In this regard, semi-industrial charcoal production methods that incorporate the combustion of pyrolysis gases and heat recovery may effectively optimise sawmill by-products, given that these mills possess the requisite technological and human resources [195]. Girard [194] posits that charcoal usage is likely to decline in the foreseeable future, both locally and in specific nations, whether developing or developed. Nonetheless, it may still rise due to the emerging potential in the industrial green energy market. Consequently, forest services and energy agencies ought to prioritise the sustainable production and utilisation of charcoal. Effective measures may encompass, among others:

- Implementation of forest management initiatives to prevent deforestation caused by the overharvesting of species appropriate for charcoal manufacture.
- The sector's professionalization would include that charcoal producers engage in charcoal manufacturing as their primary occupation, whereas infrequent production by non-professionals would be mitigated through suitable policies and training initiatives [194].
- Offering charcoal producers a variety of appropriate technical approaches to select from instead of a one "optimal" technical option.
- Advocacy for charcoal derived from wastes and timber from forest plantations via pricing strategies and suitable policies [194].

Hence, If charcoal production is perceived as a means of additional money or as a task primarily for women, investment in training is less probable, leading to a preference for less labour-intensive and less productive ways, hence constraining potential advancements [194]. The education and training of forest planners, extensionists, and charcoal producers, coupled with the adoption of more sustainable charcoal production technologies, may be critical in enhancing working conditions in the sector, as well as mitigating environmental impacts and improving energy efficiency [194].

ii. Technical Innovation

The development of energy-efficient charcoal stoves is crucial, as the majority of existing stoves are inadequate for charcoal derived from lightweight species, combusting it too rapidly and intensely to satisfy customer requirements [194]. Contemporary technology may encompass high-efficiency cooking burners that utilise locally sourced, sustainable biomass. The gasification of sustainable biomass and waste offers benefits comparable to fossil fuel-based cooking gas, eliminating reliance on imports and the related environmental harm [196].

iii. Briquetting Technology

Charcoal briquettes produced from agricultural waste and biomass residue offer a sustainable alternative to traditional charcoal, provided they are reasonably priced. The briquetting method facilitates the transformation of biomass waste into consistently formed charcoal bricks (briquettes) that are convenient for use, transport, and storage [196]. Briquettes are produced by compressing dry biomass materials, including charcoal dust, sawdust, coconut shells, sugarcane bagasse, maize cobs, cow dung, and paper [196]. For materials exhibiting minimal agglomeration or binding capacity, a binder, such as soil, was utilised, and water was included into the combination.

The amalgamation is consolidated by basic methods, including manual moulding with bare hands, repurposed plastic containers, or manual presses made of metal or wood [196]. Large equipment powered by electricity is utilised for the mass manufacture of briquettes to densify the mixture. Briquettes have superior physical strength and combustion characteristics compared to the original trash [196]. Briquettes can be utilised with efficient cooking burners in houses, necessitating minimal alterations to current cooking methods.

Briquettes possess greater energy content, ignite more rapidly, and generate less smoke compared to wood charcoal [196]. The solid units were subsequently sun-dried and utilised for cooking, akin to firewood or charcoal. It is a straightforward local innovation that disseminates either organically or with external assistance [196]. Fuel-briquette enterprises generate work opportunities for women and youth, thereby empowering them. Briquette-making groups additionally fortify community-based institutions by improving social networks, informal savings, and credit mechanisms. This technique aids in environmental management by recycling garbage and conserving trees [196].

iv. Improved Earth Kiln

The enhanced earth kiln provides superior carbonisation, yielding around 25-30 percent, in contrast to the 20-25 percent yield of conventional kilns, and produces higher-quality charcoal. Enhancements in efficiency can be realised by pre-treating fuelwood before carbonization [196]. Wood is often chopped to suitable dimensions for efficient stacking and permitted to dry for 8-10 days to decrease moisture content. Wood is arranged as compactly as feasible, with smaller pieces inserted into interstices to enhance heat transfer [196]. The principal technological innovation is the implementation of a metal chimney (constructed from oil drums), positioned at the opposite end from the ignition point of the stack, thereby guaranteeing even heat dispersion throughout the stack. The stack was enveloped in a dense layer of plant and soil to avert total combustion caused by air infiltration [196].

v. Brick / Earth Kilns

Brick and earth kilns may be rectangular or dome-shaped, exhibiting diverse dimensions and styles. They are optimal for generating high-quality charcoal in substantial volumes and with enhanced efficiency (30-35 percent), making them most appropriate for industrial-scale charcoal production [196]. Kilns have superior structures compared to traditional earth kilns, can function throughout the year, and are less vulnerable to inadequate operator behaviours [196]. Brick kilns are costly to construct and necessitate specialised expertise in brick production and layering, rendering them potentially unsuitable in areas where soil conditions are unfavourable for brick manufacturing [196]. Nevertheless, brick kilns can be readily acquired, and in locations with a reliable long-term supply of fuelwood or biomass, they can be established as permanent facilities for the economical production of charcoal [196].

vi. Steel / Metal Kilns

Steel/Metal Kilns are generally cylindrical and can be orientated either vertically or horizontally, contingent upon their design and capacity. Numerous instances of repurposed oil drums for kiln construction exist in sub-Saharan Africa. Certain types of steel kilns are mobile and possess limited capacities [196]. Portable kilns can be disassembled, usually into three components—the drum body, a conical top for vertical designs, and the chimney—facilitating relocation [196]. Non-portable steel kilns, which are heavier, possess greater capacities, have sturdy construction, and demonstrate reduced turnaround times. Nonetheless, steel kilns are costly to construct, and their operational lifespan of 2-3 years renders them viable only when capital costs are minimal. These kilns are comparatively more advanced, necessitating training for kiln workers [196].

3.5.1. Policy Recommendations

i. Establish a uniform national definition of forest.

ii. Waste and Residue: Data regarding the quantity, classification, and location of wood waste and agricultural leftovers is essential for planning briquette manufacture.

iii. Population and Employment: Although the majority of countries conduct censuses and collect statistics on urban and rural populations, employment, gender, and other demographics, it is essential to analyse this data through the lens of the charcoal industry to provide a clearer understanding of the individuals engaged directly or indirectly in the charcoal trade [196].

iv. Enhance Capacity for Sustainable Woodlot Management for Charcoal Producer Associations: This encompasses governmental entities and private stakeholders. A Charcoal Taskforce at the national level can facilitate the creation of training materials and trainers, such as senior forest officials, who can then conduct local-level training [196].

v. Obtain Support from Community Leaders: Acknowledging the social dynamics of rural sub-Saharan Africa and the authority of village elders, governments must engage with local community leaders and village elders to advocate for sustainable woodlot management.

vi. Form Cooperatives: Engaging charcoal producers necessitates new strategies that consider current social frameworks and progressively foster trust, enabling producers to recognise the enduring benefits of sustainable practices [196]. The government must establish a procedure for the annual or periodic renewal of licenses for charcoal producers' cooperatives [196].

vii. Formulate Policies and Strategies: Sustainable Woodlot Management Plan: Enhanced woodlot management can augment forest production, yielding greater cubic metres of wood per hectare. Participatory forest management: Establishes conducive environment and incorporates local stakeholders.

viii. Formulating a Forest Code: This document may be present in several countries in diverse formats. The Forest Code aims to represent a nation's existing forestry conditions, including aspects such as forest definitions, types and extents of forests, legislation, and stakeholder entitlements.

ix. Advocate for Particular Kilns: Policy details about carbonisation are ambiguous in numerous nations, as regulations frequently fail to clearly reference specific kiln types, instead only endorsing the utilisation of efficient kilns [196].

x. Introduce Briquetting: Likewise, there are no prominent policies that advocate for briquette production, and existing initiatives are solely propelled by the private sector.

xi. Advocacy for the Utilisation of Efficient Kilns: This should be emphasised in all national forestry papers, including the Forest Code, National Forestry Plan, and energy-related documents, such as National Energy Efficiency Plans and Energy Codes [196]. A regulated taxation system can be established in which charcoal produced from efficient kilns is taxed at a reduced rate compared to charcoal produced by conventional methods.

xii. Enhance the Professionalism of Transport and Distribution Stakeholders: Develop a database of charcoal transporters and distributors, implement a licensing system for charcoal transporters and distributors, and facilitate the formation of transporter/distributor associations [196]. Facilitate Producers' Transportation Capabilities: An alternative to leasing trucks for charcoal producers' groups is to acquire trucks, thereby enhancing transport autonomy and obviating the necessity for intermediaries.

xiii. Implement Charcoal Taxation: Addressing charcoal cartels necessitates a more comprehensive strategy to guarantee that current cartel participants remain employed within the charcoal industry [196].

xiv. Charcoal Bags: For instance, charcoal is categorised into legal and unlawful varieties. Legitimate charcoal is manufactured by authorised producers, utilising either traditional kilns ('black' charcoal) or sustainable methods ('green' charcoal). An eco-label system establishes tax rates, imposing a greater charge on conventional charcoal. Charcoal producers' groups officially registered with authorities must get 'green' or 'black' charcoal bags from local councils or tax collection agencies [196].

xv. Charcoal Revenue Agencies: These entities may consist of private businesses or former participants of charcoal cartels who are offered alternative income streams by remaining engaged in the charcoal trade, albeit in a legalised manner. These agencies may acquire charcoal bags from municipal regional authorities and subsequently offer them to village associations with an added commission [196].

xvi. Taxation of Illegal Charcoal: All charcoal generated by unregistered manufacturers and conveyed in unmarked bags is deemed illegal. Revenue agencies may be chosen via a bidding process, wherein the bidder offering the largest tax collection contracts receives a 50 percent advance payment [196].

xvii. Charcoal warehouses or deposits: Establishing charcoal depots in metropolitan locales might provide numerous advantages. In addition to functioning as a centralised hub to alleviate congestion from overloaded trucks, depots are also optimal for data collection. Producers and transporters can receive information about the daily purchase price of charcoal at the warehouse, akin to agricultural commodity prices, by text message at no cost [196].

3.5.2. Governance Recommendations

- Inter-ministerial Steering Committee: The formation of an inter-ministerial steering committee to deliberate on cohesive initiatives aimed at enhancing the charcoal value chain is very important for successful cooperation [196].
- The National Charcoal Taskforce comprises government entities and regulatory authorities, including those related to power, forests, and the Internet, which are prevalent worldwide. This agency, possibly established under a designated ministry, will serve as the federal entity responsible for coordinating and facilitating charcoal-related activities nationwide, including functioning as the national coordinating and managing entity (CME) for international donor financing and MRV (measuring, reporting, and verification) [196].
- The Charcoal Fund necessitates initial capital to initiate socioeconomic operations until they achieve self-sustainability. This can be accomplished via a dedicated 'charcoal fund,' which can be systematically monitored, reported, and validated to guarantee that the overarching objectives are fulfilled. It can also provide funding for Charcoal Taskforce initiatives [196].
- Charcoal Cooperatives: The bulk of private sector participants in the charcoal value chain operate autonomously. The establishment of cooperatives by these parties through official registration and licensing processes can yield numerous advantages, including the enhancement of collective bargaining power. At present, value chain stakeholders possess a restricted voice, impeding their capacity to contribute insights and perspectives on the formulation of laws and regulations [196].
- Facilitating Institutional Relationships: After the establishment of entities such as the steering committee, Charcoal Taskforce, and cooperatives, it is essential to cultivate effective collaboration and information exchange among these institutions [196].
- Decentralisation: Decentralisation has emerged as a key principle for effective government in certain Sub-Saharan African nations. The process involves reallocating functions, authority, and personnel from a central authority to regional, provincial, or district levels. To enable the formalisation of a charcoal value chain, governmental services must be decentralised and made available at the local level [196].

- Incentives: Alongside enhanced enforcement and effective governance, laws and regulations must be amended or formulated to augment incentives and diminish disincentives for compliance. Incentives may be offered through financial means (subsidies or tax incentives), technological support, or capacity development. Facilitating compliance is essential to mitigate disincentives [196].

4. Conclusion

This study assesses the emission of air pollutants from conventional charcoal production methods and their impacts on human health and the environment, which are interconnected with traditional charcoal manufacturing. This review's extensive research allows the study to achieve conclusive findings on the primary health effects of charcoal production and utilisation. The findings demonstrate that air pollutant emissions from the traditional charcoal production method are linked to an ineffective combustion process and the release of various toxic substances, including carbon monoxide (CO), volatile organic compounds, nitrogen oxides (NOx), polycyclic aromatic hydrocarbons (PAHs), and fine particulate matter (PM). Traditional charcoal production adversely affects human well-being, causing eye and skin irritation, and potentially leading to pharyngitis, allergic rhinitis, pulmonary fibrosis, diarrhoea, asthma, bronchitis, cough, emphysema, intestinal infections, reduced lung function, and low birth weight. Moreover, it substantially modifies the atmospheric physical and chemical properties and exacerbates global warming.

This study demonstrates that while the charcoal industry is economically important, it adversely affects the welfare of producers and contributes to environmental degradation due to inadequate and fragmented governmental policies that mostly benefit urban stakeholders. This review clearly linked charcoal production to respiratory health issues. The results indicate that charcoal workers in proximity to kilns are subjected to heightened emissions, presenting a possible health hazard, a relationship previously recognised by the World Health Organisation. Negative externalities arising from insufficient resources and land management, along with significant safety and health risks, are primarily borne by impoverished rural communities that provide affordable and reliable fuel. Coordinated efforts by the government, aid organisations, and charcoal unions highlight this gap, as most charcoal programs concentrate on technology aimed at reducing pressure on forest resources.

These policies neglect to account for the indirect, although significant, impacts on the vast labour force that often depends exclusively on revenue from charcoal production. Charcoal vendors are common in urban areas with minimal extortion possibilities, as government officials generally align with larger communities. Despite these findings, there is optimism regarding the willingness of communities to partner with local organisations and implement sustainable energy solutions, which can substantially reduce the adverse social and environmental impacts associated with charcoal production. This study's findings suggest that the focus on cutting-edge energy services should expand to incorporate widely used and conventional energy sources that have significant social, environmental, and economic impacts. From this perspective, governmental engagement should prioritise sustainable and economical fuel sources. The adoption of long-term solutions could alleviate the deforestation linked to tree extraction for charcoal production.

4.1. Recommendation

Based on the research findings, the following recommendations are proposed:

- Charcoal end-user policies must be augmented by programs that promote public health, protect the environment, and broaden access to emerging markets.
- Efficient land use management methods, including reforestation and the use of high-efficiency kilns, can significantly alleviate the negative impacts associated with a sector vital to the national economy.
- The execution of pollution mitigation strategies and public awareness initiatives would yield greater efficacy. This approach may effectively diminish harmful air emissions in areas adjacent to charcoal kilns.
- Regular exposure to these emissions may lead to chronic health problems if workers do not constantly utilise respiratory protection equipment.

- The government ought to control the charcoal production sector and offer environmentally sustainable technologies, such as fuel-efficient stoves, at accessible costs as alternatives to unsustainable charcoal production and consumption.
- It is essential to rapidly modify the charcoal production process and improve the market viability and byproducts of charcoal production.
- Priority must be given to research and technology advancements, financial support, training, and the development of legal frameworks and administrative solutions aligned with the current infrastructure and operations.

4.2. Limitations

This analysis includes evidence from a variety of published publications. Owing to this diversity, it was not consistently feasible to discover research of the same nature, both locally and globally, that investigated comparable health effects related to charcoal use and manufacturing. Thus, this constitutes a limitation of the current study. This assessment was limited as numerous health-related outcomes were corroborated by only a single study, even if the data indicated a robust correlation in multiple cases.

Conflict of Interest

The authors declare that they have no conflict of interest.

Funding

The study did not receive any financial support.

Acknowledgments

None.

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