Open Access

Recent Progress in Materials

Review

Reuse of Sawdust in Developing Countries in the Light of Sustainable Development Goals

Udeme Udokpoh [1], Chidozie Nnaji [1, 2, 3, 4, *]

1. Department of Civil Engineering, Akwa Ibom State University, Akwa Ibom State, Nigeria; E-Mails: udemeudokpoh@aksu.edu.ng; chidozie.nnaji@unn.edu.ng
2. Department of Civil Engineering, University of Nigeria, Nsukka, Enugu State, Nigeria
3. Faculty of Engineering and Built Environment, University of Johannesburg, South Africa
4. Africa Centre for Sustainable Power and Energy Development (ACE-SPED), University of Nigeria, Nsukka

* **Correspondence:** Chidozie Nnaji; E-Mail: chidozie.nnaji@unn.edu.ng

Academic Editor: Mohamed Alwaeli

Special Issue: Technologies of Using Waste as Substitutes for Primary Raw Materials

Recent Progress in Materials
2023, volume 5, issue 1
doi:10.21926/rpm.2301006

Received: September 02, 2022
Accepted: January 03, 2023
Published: January 12, 2023

Abstract

The several furniture-making phases, from cutting to processing to polishing, produce a significant volume of sawdust of differing grades. The extraction and disposal of such waste in developing countries with no established or sustainable methods is an increasing problem, frequently posing environmental challenges. Sawdust is one of the most underused wood waste portions, with mounds dispersed around the region, detracting from its visual appeal and causing other ecological concerns. This study investigated potential applications of sawdust as it concerns sustainable development. It sought to employ an extensive systematic literature review to establish that sawdust, which is often a nuisance at sawmills, may be put to beneficial uses. Four cardinal focus areas of this study are (i) energy generation, (ii) environmental protection/pollution containment, (iii) building construction, and (iv) water treatment/supply. Specifically, the study dealt with the feasibility of energy generation from sawdust through sawdust cook stoves, briquetting, and pyrolysis; pollution containment through sawdust-derived adsorbent; affordable building construction through sawdust-based ceiling boards and particles boards; and (iv) water treatment using point of use (PoU) sawdust-clay water filter. Based on over two hundred (200) published papers consulted in this study, it was strongly established that sawdust had found successful wide application in all four thematic areas with strategic connection to the objectives of SDGs 3.0, 6.0, 7.0, 9.0, 11.0 and 12.0. This research believes that emphasis on sustainable sawdust management can help transform the over 1.5 million tonnes of sawdust waste burned or dumped indiscriminately into value-added products each year.

Keywords
Absorbent; biomass; briquettes; renewable energy; sawdust; sawdust stove; sustainable management

1. Introduction

The global population and economy have grown significantly during the last two decades. This growth has also resulted in an unprecedented increase in the volume of solid waste. The management of this volume of waste has been difficult [1, 2]. The four main causes for the large increase in total waste generation in developing countries are urbanization, rising population, industrialization, and rising living standards [3]. One percent increase in any country's national revenue corresponds to a 0.69% increase in a waste generation [4]. Compared to several highly developed nations, such as Germany, Sweden, Japan, and the United States, developing countries lag far behind in solid waste recycling and reuse, treatment technologies, and management strategy. Several countries and municipal authorities have grappled with ever-increasing solid waste menace [5]. Reports from various countries indicate that the burden of the cost associated with municipal solid waste management appears too heavy for many municipal government councils.

Nevertheless, the widespread inefficiency of solid waste management that has become the signature of many cities in developing and even some developed countries cannot be placed solely at the doorstep of insufficient funds. Municipal councils are usually confronted with myriad adverse factors that mitigate the enormous efforts into solid waste management [6]. On a very basic level, solid waste management will remain a mirage without proper consideration and contemplation of the composition of the waste generated. It has been established that municipal solid waste composition strongly depends on demographic and socio-economic variables [7].

The composition of solid waste differs greatly between municipalities, cities, and countries. Lifestyle, financial status, waste management policies, and industrial structure determine such diversity. The volume and content of municipal solid waste are crucial for selecting effective management and treatment strategies. Municipal wastes are often generated from a wide range of anthropogenic activities. According to several studies, most municipal solid wastes generated in emerging economies are from households (55 to 80 percent), followed by the market or commercial sectors (10 to 30 percent). The latter consist of varying quantities of the industrial, street, institutional wastes and various other sources [8]. The physical and chemical properties of wastes from these diverse sources vary widely, depending on their origin. Though not among the predominant constituents of domestic solid waste, wood waste form a very important component of municipal solid waste. Wood waste is generated by the wood industry and comprises wood chips and particles from large-scale timber processing. These industries generate enormous quantities of wood waste, which must be used, sold, or disposed of efficiently. Throughout the year, wood wastes are common in the wood industry. This residue is generally considered useless, thus leading to open burning, dumping in bodies of water, or open dumping and the attendant environmental backlash. In 2010, sawmills in Nigeria generated over 1,000,000 cubic meters of wood waste, while plywood mills contributed over 5000 cubic meters of waste [9]. Wood and timber products, like most natural resources used by man, generate a significant amount of unwanted or used products (waste), such as tree cut-offs, sawdust, tree bark, scrap lumber, sander dust, planer shavings, trimmings, split wood, and so on. Aggressive urbanization exerts an increasing demand for timber products used in construction and furnishing. Timber emits large amounts of wood waste, from the cradle (logging) to the finished product.

Nigeria generates approximately 1.8 million tonnes of sawdust and 5.2 million tonnes of wood waste annually [10-12]. Sawmills generate a significant quantity of wood waste, such as sawdust, as much as 93 percent [13]. The impact of inappropriate waste wood disposal on terrestrial and aquatic environments is enormous. In addition, burning wood waste emits greenhouse gases into the environment, thus triggering a plethora of health issues. The reuse/recycling of these wood wastes will relieve strain on our rapidly depleting forests, decrease pollution, and create jobs and revenue. Effective sawdust management must be based on the three-pronged principle of recovering, reusing, and recycling (Figure 1). Even if efficient conversion mechanisms or technologies are in place, they would be of little or no value without proper strategies for an effective and total recovery of waste materials.

Figure 1 Effective sawdust management.

Global population explosion and industrialization are responsible for global energy consumption, an increase in waste generation, and the depletion of fossil fuels [14]. Landfilling has traditionally been the most popular technique of garbage disposal. However, it has several drawbacks, including long-term surface occupation, greenhouse gas emissions (primarily CO_2 and CH_4), leachate formation, unpleasant odors, and the risk of fires/explosions or landslides, posing a risk to both the environment and human health and necessitating the development of alternative options [15-17]. However, in light of resource conservation, responsible consumption, and sustainable development, landfilling of sawdust is a counterproductive and retrogressive management strategy. This is because sawdust is a production by-product and not necessarily a waste material as is generally perceived. Sawdust may not find the same application as other customized timber boards, but it can be used for various other purposes either as is or upon further processing. Given the risks associated with improper waste management, particularly with wood waste, this study aims to review the sustainable management of wood waste (sawdust) for reuse, with a high premium placed on recycling, potential energy generation, heavy metal absorbent, and clay filter for water treatment. Hence, this paper sought to answer the general research question: “can sawdust (wood waste) find general useful applications in the light of sustainable development”? Was the question then further refined as follows: “has sawdust been successfully applied in specific areas such as energy generation, pollution containment, building construction, and water purification” (Figure 2)? The conceptual framework of the study is presented in Figure 3. Specific cases of how sawdust has found sustainable applications have been used as the basic building blocks of this research. All cases shall be properly tied to the objectives of the sustainable development goals.

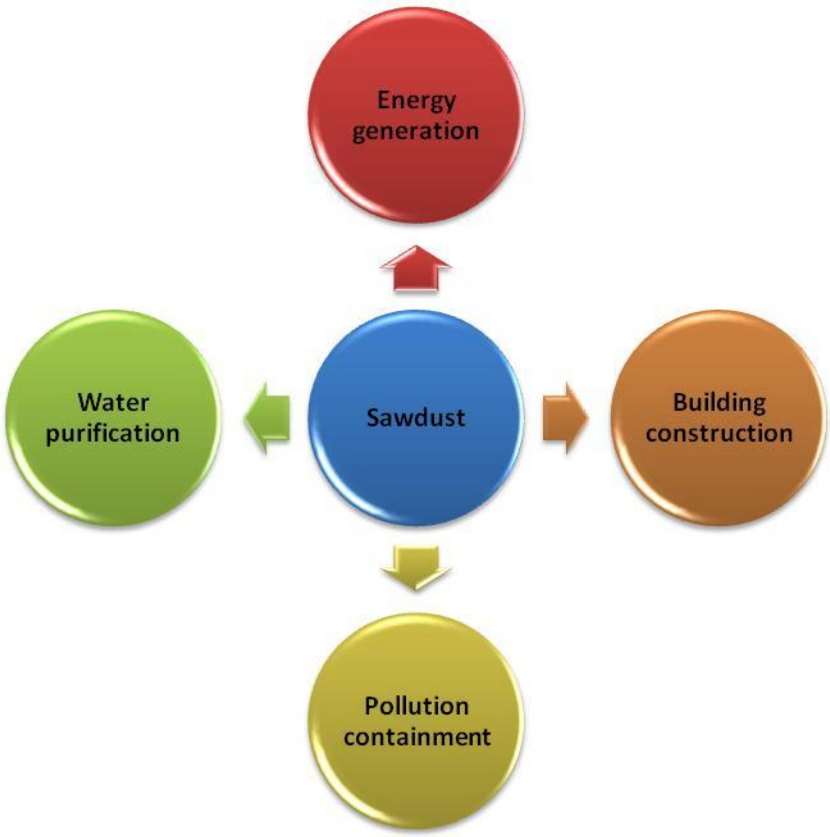

Figure 2 Key areas of application of sawdust.

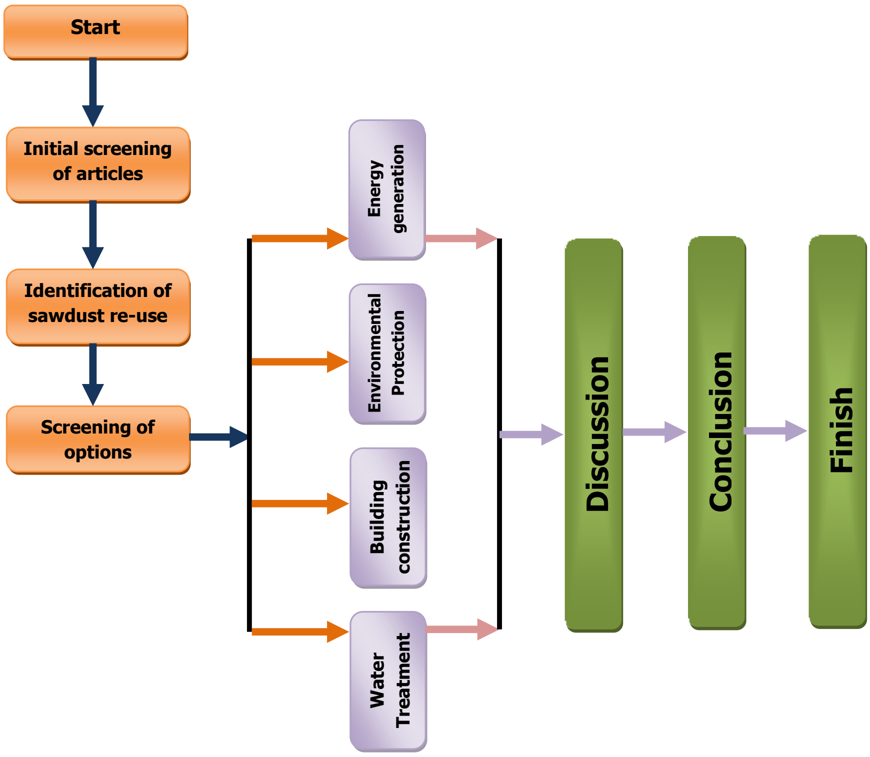

Figure 3 Conceptual framework for the study.

2. Energy Generation

Many developing countries are still grappling with the teething challenge of power supply. Intermittent power supply and even total blackouts lasting several weeks are common in many low and middle-income countries, resulting in colossal economic losses for businesses and crippling small and medium enterprises. This has led to over-dependence on electric power generators by households and businesses. Using Nigeria, with an estimated 28 million households regularly using generators as a typical example, generators supply about 50% of the total power consumption. With hundreds of millions of spent annually on the importation of generators and much more spent on daily operations, Nigerian households and businesses spend a substantial part of their income on the self-help power supply. No significant industrial and economic growth can happen under such debilitating circumstances. The industrial revolution would not have been possible without a reliable power supply, and the same holds for the fourth industrial revolution.

Apart from the exorbitant running cost of electric power generators, the fact that they are major air polluters should stimulate a paradigm shift to renewable energy resources. Alternative fuels are becoming more popular worldwide, with nations such as Japan, Switzerland, the United States, Belgium, Germany, and France taking the lead [18]. Renewable energy sources are chosen based on their renewability and environmental friendliness. Many researchers have examined the issue of renewable energy potentials [19, 20], although most have focused on solar and wind energy sources [19, 20]. Solar energy has been discovered to have a larger potential in arid environments because high-intensity sunlight is constantly accessible for most of the day [19].

Furthermore, wind power has been observed to be of moderate strength in semi-arid regions [21]. While solar and wind energy resources in semi-arid and polar regions are not unexplored, it is important to note that biomass resources are abundant in the most of these locations. However, wind and solar power plants require heavy financial investments and are, therefore, usually beyond the reach of many.

Biomass energy is a renewable resource that may be utilized to generate power, heat, and transportation fuels even on a modular scale for households as well as small and medium-scale enterprises. Although biomass may be derived from various sources, wood is by far the most prevalent [22]. The use of wood biomass for energy generation can help to balance the usage of fossil fuels such as coal, gasoline, natural gas, and oil. This method can boost economic growth and encourage new industries to produce bio-based products. It was discovered that over 90% of wood processors utilize diesel generators to power their machinery. At a conversion efficiency of approximately 50% [23], up to 5.2 million metric tonnes of wood waste are generated annually in Nigeria [24], with a significant portion of this originating from the country's southern region. This is because the region includes states in the tropical rain zone, which has more forest reserves and sawmills than any other part of the country.

SDG 7 focuses on providing access to reliable, affordable, sustainable and modern energy sources. The woody and high calorific value of sawdust naturally indicates that with proper handling and technology, the enormous amount of sawdust generated globally can be a valuable source of affordable and reliable energy, especially for rural dwellers and urban poor in developing countries. Given the massive amount of sawdust generated each year, a sawdust power plant's usage is a potential power source. According to reports, several nations use the energy produced from biomass resources to partially cover their energy needs [25]. Though sawdust holds great potential for wide useful applications, most of it is still disposed of arbitrarily in many developing countries or used in extremely basic ways in rural areas. Understanding the energy content of woody biomass resources is necessary for their growth as energy sources, especially given the diversity of these wood species [26]. It has been argued that no one energy source can sustainably provide the energy needs of any nation [27, 28].

Limited practical and experimental data for the physico-chemical characterization of this bio-energy resource in the local environment are available. Mboumboue and Njomo [29] assessed the energy potential of wood-based wastes, estimating the calorific value of hog wood to be 19.40 MJ/kg. According to Ackom et al. [30], the calorific value of wood thinning generated in Cameroon is 18.30 MJ/kg. Elehinafe et al. [26] investigated the feasibility of using sawdust from various wood species as an energy resource. They found that the calorific values of the sawdust samples with roughly 15% moisture content ranged between 11.29 and 26.10 MJ/kg, with Irvingiagrandifolia and Naucleadiderrichii providing the lowest and highest values, respectively. Up to 13 of the wood species have calorific values of 20 to 26 MJ/kg, which are equivalent to coal and might be used as energy supplies. Veeyee et al. [31] studied the feasibility of using sawdust generated by wood transformation units (WTU) in Cameroon to create syngas in a gasification process to make them self-sufficient in terms of power consumption using both qualitative and quantitative methodologies. The sawdust sample's gross calorific value was 20.08 MJ/kg, with 290 tonnes of sawdust generated in Yaounde municipalities per week; sawdust theoretically holds a latent power potential of 713 GJ per week.

2.1 Sawdust Cooking Stove

With the growing urban population and industrialization, global energy demand has been skyrocketing. The situation has further been exacerbated by shrinking natural resources. Besides, the adverse environmental effects of burning fossil fuels, the most prominent of which is climate change, have forced a paradigm shift to renewable energy resources. Among the numerous renewable energy sources, biomass is distinctive due to its large yearly production rate and geographically extensive global distribution [32, 33]. According to [34, 35], biomass is the world's fourth greatest energy source for cooking. It is regarded as the most potential replacement for traditional fossil fuels and feedstocks [36, 37]. Humans have long recognized and utilized wood as a source of fuel for cooking in both urban and rural areas of developing countries [38]. According to statistics, more than 2.5 billion people in the globe rely on wood and charcoal for cooking [39]. This has resulted in massive amounts of wood being utilized, resulting in deforestation. Most people live in developing-country rural regions [40, 41]. About half of households in developing countries still cook and heat their homes using solid fuels with open fires and leaky stoves [42, 43]. Many of these people cook using open fires with low thermal efficiency and a high emission rate of air pollutants due to poor burning characteristics [32]. The health risks associated with air pollution from cooking fires are further exacerbated in indoor environments [44].

In developing countries, using open flames for cooking consumes more energy than any other end-use service [45]. When compared to upgraded biomass cooking stoves [46], the traditional open-fire (three-stone) stove has a lower efficiency (approximately 15.6%) and greater fuel consumption [47]. The traditional three-stone cooking arrangement exerts enormous demand on natural vegetation. It causes depletion of forest resources, leading to a scarcity of wood fuel for cooking in certain developing countries [48]. Despite the environmental and public health outfall of open fire stoves, it remains a source of succor to many families in rural areas as well as the poor population in urban fringes who cannot afford kerosene stoves or cooking gas setups. The performance in terms of thermal efficiency and emissions from biomass cooking stoves are influenced by various factors such as stove design, fuel feeding method, illuminating, and combustion temperature [35]. Sustainable biomass fuel use and improved cooking stove thermal efficiency can be achieved by using good insulating materials, clean fuel, or adopting innovative designs that facilitate better fuel combustion [49, 50]. Improving the combustion chamber design of biomass cooking stoves reduces heat loss through the walls of the stove, resulting in high combustion chamber temperature, improved combustion efficiency, and overall thermal efficiency [46-51].

One of the affordable and sustainable solutions to the traditional three-stone stove is the sawdust cook stove. This is because sawdust is an abundant waste material generated during the logging and sawing of timber. Harnessing sawdust waste as a cooking fuel keys firmly to the sustainable development goals (SDG 11). Total conversion of all sawdust generated into fuel for cooking will cause a significant reduction in the quantity of solid waste to be disposed of or landfilled as well as the rate of soil and water pollution by sawdust-bound contaminants. In addition, sawdust has been described as a biomass solid waste fuel and insulator that may be utilized to improve the thermal efficiency of cooking stoves [51-55]. Though a sawdust cook stove is far cheaper than a regular kerosene stove and sawdust is a free waste resource, studies indicate that a kerosene stove does not necessarily cook faster than a sawdust stove. A certain study [38] reported that a sawdust stove cooked 0.4 kg of rice faster than a kerosene stove, though there was no significant difference in specific fuel utilization. Both researchers and entrepreneurs have developed various versions and designs of the sawdust stove. In Uganda, Okino et al [46] developed a hybrid stove made of 1:1 mixture of clay and sawdust as an insulator to improve the cooking stove's thermal efficiency. A water boiling test was conducted to assess the new design's performance using indigenous wood fuels commonly found in rural Uganda. The obtained data demonstrated improved thermal efficiency during the cold start phase compared to typical stoves. This design integrates several desirable features: reduced emission, minimal biomass utilization, time saving, and cost effectiveness. In Sokoto, Nigeria, Aliyu and Buba [56] assessed the thermal efficiency of a twin-hole sawdust stove. Different biomass wastes, such as sawdust, rice husk, and millet husk, were individually used to test the stove's efficiency, and a comparison was conducted to determine the optimal fuel for the stove used. For sawdust, rice husk, and millet husk, the burning test results were 0.0983 kg/min, 0.0473 kg/min, and 0.0664 kg/min, respectively. It uses less fuel and has superior thermal efficiency. Although sawdust stoves have been shown to be more efficient than kerosene stoves, it has witnessed a slow and low rate of adoption among households in developing countries.

This could be partly because sawdust is not as readily available as firewood which can be fetched from the back yard Sawdust is not a common commodity sold in any market. Instead, those who need it need to travel to the nearest timber market, which might be located at the other end of the city. Even where it is readily available, its use appears limited to a few persons living in rural and semi-urban areas and poor households in the urban fringes, with very few using it as their primary source of cooking consistently. Another factor responsible for the slow adoption of sawdust as cooking fuel is the stress associated with the use of sawdust cooking stoves: difficulty in ignition, manual compaction, smoke emission, and control issues. Sawdust must be manually compacted into a dense mass to make it semi-rigid and regulate the combustion rate. This requires a reasonable amount of energy. Besides, one can easily light and turn off a kerosene stove or gas cooker at will, but this is not the case with a sawdust cooking stove. The usual practice is to sprinkle kerosene on the central hollow surface of the compacted sawdust to facilitate ignition and to sprinkle water on the burning biomass to quench the fire. Modern designs are equipped with mechanisms that shut out air from the system so the fire dies out gradually. The setbacks associated with the sawdust stove suggest that there are lots of room for improvement of the system to a level of total or semi-automation to reduce the stress of use and increase acceptance.

Interestingly, to eliminate the issues associated with the usage of sawdust stoves, some researchers have developed a new model similar to the traditional sawdust stove but with a change; a sawdust ash compartment that splits the stove into two parts (Figure 4). This partition is made by splitting the cylindrical stove into a burner compartment and an ash chamber using a thin metal sheet that functions as a divider. This new feature reduces the risk of ash and partially burned sawdust clogging the stove's ventilation duct because all ash produced is collected at the stove's base directly beneath the ash compartment. This will go a long way toward improving the stove's air intake and, as a result, reducing smoke emissions. As a result, the efficiency of sawdust combustion will improve, and hazardous emissions from the stove will be reduced. Because of the inclusion of an ash container, the stove is often costlier. To overcome the control issue, the stove is designed with variable airport diameter and air inlets. As a result, the heat generated by the stove may be controlled by changing the air input with one from a smaller airport. This alteration would significantly improve the efficiency of the stove, resulting in higher control and efficiency.

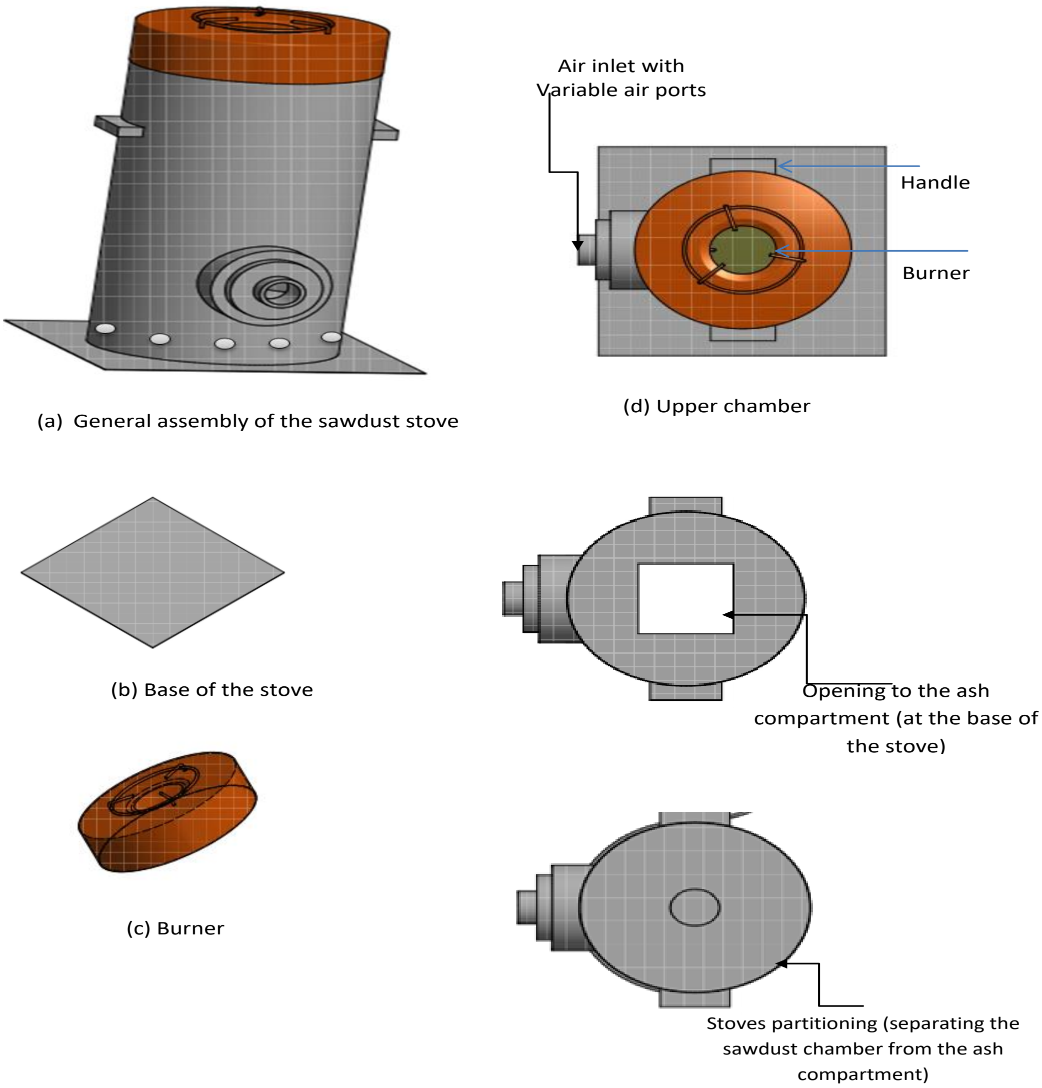

Figure 4 General outlet of new model developed sawdust stove.

2.2 Sawdust Briquettes

With a teeming global population [57-60] and increased industrialization [61], biomass-to-energy is a viable alternative energy technology [62]. Energy use based on nonrenewable energy resources contributes to greenhouse gas emissions and promotes resource depletion. Biomass (woody bio-residue) has gained recognition as a popular renewable energy fuel source. This benefit stems from contributing to net greenhouse gas emissions reduction and energy supply security [63]. Regardless of the health consequences, most developing countries utilize wood as a primary energy source for the household (mostly for cooking). Over 2.5 billion people in developing countries still rely on biomass as their major energy source for cooking [64]. With the upswing in the price of gas due to the Russia-Ukrainian conflict and the global economic recession, more people living in middle and low-income countries are likely to return to firewood as fuel for cooking. This grim scenario threatens to reverse some of the gains made so far in climate change mitigation. Besides, air pollution is becoming a major contributor to poor health worldwide, particularly respiratory disorders, with emissions from "dirty fuel" (e.g., wood) being a major contributor. According to World Health Organization research [65], the disease burden attributed to indoor smoke from solid fuels in developing countries is approximately 1.9 million premature deaths annually. Aside from health problems, the over-exploitation of wood is a major cause of deforestation and pollution. For instance, Ghana has lost 85% of its forests in the previous 100 years and has one of the world's highest deforestation rates of 2% per year, 60% of which is exploited to supply wood demand [64]. This is due to the failure to make a concerted effort to induce, particularly rural dwellers who find it economically unattractive to switch from firewood to liquified petroleum gas (LPG) or processed agricultural waste fuel like briquette, which they can produce themselves. Using renewable residues such as sawdust, coconut, and rice husk to make cooking fuel can help reduce the demand for forest resources and, by extension, mitigate climate change.

Aside from the health and environmental challenges posed by the excessive use of wood and charcoal, there are also economic costs, such as lost productivity and wasteful or inappropriate resource exploitation. Productivity loss might occur owing to poor health due to contaminated air or time spent gathering wood to the detriment of studying or working. Briquette is an energy source that may be made from the household, agricultural, and industrial waste streams of biomass. Briquette's use is environmentally benign, healthful, and does not rely on fossil fuels. Charring feedstock before pelletization into briquettes can maximize calorific value while lowering combustion emissions [66]. As a result, there is a need for low-cost and widespread manufacturing of charred briquettes to boost their potential to replace firewood, charcoal, and fossil fuels as home cooking and heating fuels. Biomass briquettes have a lower carbon footprint and surpass alternative cooking fuels such as wood in heat output per unit mass, moisture content, and storage space. Just like Bonsu et al. [67] observed, appropriate briquette use would help mitigate climate change impacts by reducing the over-reliance on wood for household and commercial heating.

Furthermore, briquetting agricultural waste might help to enhance sanitary conditions. Woody bio-residues have maintained a high level of interest and attention due to their renewability, greenness, and universal availability [68, 69]. These woody bio-residues have great potential as long-term sources of household fuel and can serve as renewable alternatives to traditional energy sources such as coal and firewood [70]. However, only a small percentage of these woody bio-residues are used as fuel in sustainable energy solutions. This claim is based on their bulkiness and the high moisture content [71]. Because woody bio-residues are always present in their loose state, they are not readily available as efficient sources of energy fuel. For instance, sawdust presents in a granular and particulate form, making it unsuitable as cooking fuel. Even the sawdust cooking stove, popular among some rural dwellers, requires that the sawdust undergoes some form of densification to conform to the stove’s shape and allow for forming a firm fire hole. So the major turnoff for many potential users of sawdust as cooking fuel is that it cannot be used as is and, therefore, must be subjected to a degree of processing. Thus, briquette densification of bio-residues is a potential step toward improving their combustion and handling properties on the one hand and reducing the emission of noxious gases on the other. This technique will aid in the resolution of logistical problems in sustainable energy solutions [72].

Briquetting is a densification process in which loose biomass is compressed under pressure to increase the density of biomass wastes to around 1000-1200 kg/m^3 and the volume by 8-10 times [73]. Depending on the nature and state of the feedstock, other preliminary treatments such as drying, grinding, sieving and mixing might be necessary (Figure 5). The briquetting process can be classified according to whether or not a binder is used. For biomass densification, briquetting with or without a binder necessitates the application of compaction pressure [61]. The production of fuel briquettes from the forest and agro-residue mixes demonstrates the possibility of proper technology for using biomass leftovers as energy fuel [74]. Recent research [61, 75-78] has demonstrated the densification of various combinations of bio-residues from agricultural products and food sectors with other additives for heating applications. According to the research, particular biomass in densified mixtures acts as a natural binder, increasing the durability of the generated fuel briquettes [61, 75]. According to Xiao et al. [79], increasing the usage of charred briquettes made from renewable biomass waste streams can significantly decrease deforestation and harmful gas emissions. Azasi et al. [80] and Obeng et al. [81] both concluded that increased usage of charcoal briquettes adds significantly to energy sufficiency and the reduction of reliance on fossil fuels in developing nations. However, variables such as cost, availability, convenience of use, quality, and education on the benefits of utilizing briquettes influence the rising usage of burned briquettes [82].

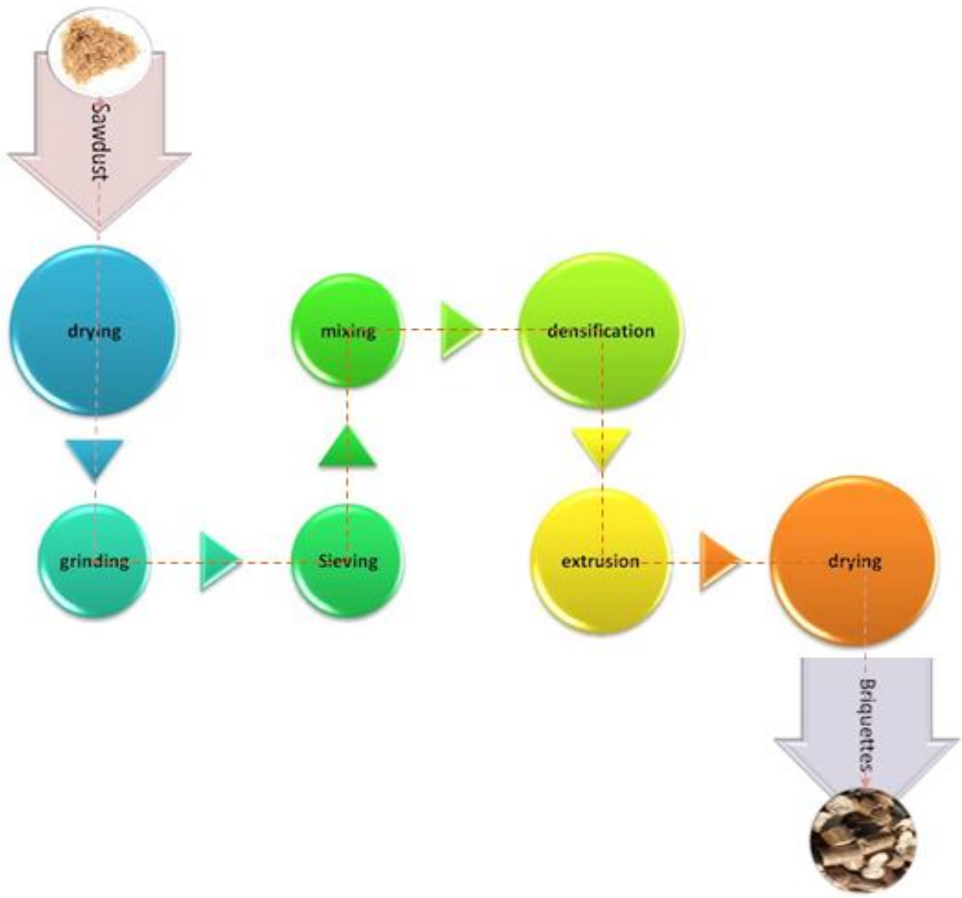

Figure 5 Flowchart for production of briquettes.

Several studies on biomass briquetting have been published. Kuti and Adegoke [69] investigated the performance of biomass briquettes made from sawdust and burnt palm kernel shell and found that it lagged slightly behind kerosene in cooking time for beans. Emerhi [83] studied the physical and combustion parameters of briquettes made from sawdust of three hardwood species (Afzeliaafricana, Terminalia Superba, and Meliciaelcelsa) using various organic binders (cow dung, ash, and starch). The study's findings indicated that the briquettes have calorific values ranging from 10.04 to 13.03 MJ/kg. In this investigation, Kuti [84] also assessed the performance of biomass briquettes made from sawdust and palm kernel shells bonded by starch gel. The briquettes produced were claimed to be acceptable for residential use since they boiled water between 15 and 30 minutes. Stephen et al. [85] reported that ad-mixing sawdust into corn cob briquettes improved the physico-mechanical characteristics of the briquettes. Ajimotokan et al. [86] that at a densification pressure of 5 MPa and 5 minutes dwell time, briquettes made from charcoal and sawdust of various wood species, the fixed carbon content and heating value of the briquettes increased with increase as the particle sizes of the charcoal increased. The greatest was the heating value (24.9 MJ/kg) and ash content (6.0%) of the briquette formed from pure charcoal particles. Its carbon, hydrogen, and oxygen levels were 44.6-50.1%, 5.1-5.6%, and 34.4-41.5%, respectively.

Apollo et al. [64] studied the potential of charred briquettes of sawdust, rice, and coconut husks in satisfying household cooking energy demands. The study's biomass consumers' willingness to replace their present fuels with burnt briquettes was determined in a subsequent phase. The burnt briquettes had a calorific value of 24.69 MJ/kg. When a multi-feed gasifier stove (MFGS) was employed, the maximum combustion efficiency of briquettes was 34.7%. When briquettes were used instead of charcoal in the MFGS, particulate matter and carbon monoxide emissions were reduced by 14% and 80%, respectively. A user acceptance study revealed that around 40% of respondents were willing to purchase briquettes if they were marketed for Gh2.48. This study determined that briquettes are a good alternative to wood and charcoal if their full potential is realized and the energy consumption efficiency of biomass briquettes (sawdust, rice, and coconut husks) is established. In a comparable study, Anggraeni et al. [87] examined the influence of particle size and content of sawdust and carbon from rice husk (CRH) on briquette performance. They reported that a low concentration of CRHs contributed to high bulk, compressed, and relaxed density values, as well as an increase in briquette relaxation ratio. However, a high concentration of CRHs reduced compaction ratio, water resistance, and durability and was unsuitable for briquette. Briquettes with smaller particle sizes had higher wet moisture content and compaction ratios.

In contrast, large particle size increased bulk, compressed density, relaxed ratio, dry moisture content, water resistance, durability, specific fuel consumption, and burning rate. The influence of sawdust particle sizes on the quality of briquettes was further confirmed by Mitchual et al. [88], who examined the influence of species, particle size, and compacting pressure on the relaxed density and compressive strength of briquettes made from tropical hardwood sawdust. A laboratory hydraulic press was used to make briquettes. According to the regression models, species density, particle size, and compacting pressure were good predictors of relaxed density and compressive strength in the cleft of briquettes made from sawdust of tropical hardwood. Zepeda-Cepeda et al. [89] studied the impacts of different sawdust particle sizes in mixes on some physical, mechanical, and energy properties of briquettes derived from Pinus duranguense sawdust, as well as established the ranges within the appropriate values determined to reach desired values. The surface response approach was utilized to determine optimum combinations under a three-factor simplex-lattice model. The particle density ranged from 0.92 to 1.02 g cm^{-3}, and the volumetric swelling ranged from 0.96 to 3.9%. The maximum compression resistance was 37.01 N mm^{-1} and the IRI ranged from 53 to 107%. The gross calorific values ranged between 19.35 and 21.63 MJ kg^{-1}. The use of varied particle sizes in the combinations improves the briquette quality. Araque et al. [90] also investigated the mechanical behavior of a compacted mixture of pine sawdust and rice husk by altering the mass percentages of both biomasses resulting in briquettes for commercial purposes. The finite element program ANSYS was utilized to validate the results for the samples which have rice husk mass percentages of 25, 50, and 75, respectively. All samples had Young's moduli ranging from 651 to 813 MPa and a Poisson's ratio of 0.8 in the computer simulations. Von Mises stresses of 87 to 90 MPa, and Von Mises strains of 0.09 to 0.12 m/m were measured in the compressive test. However, no defined stress and strain behaviour was obtained for the impact tests since the heights of 2 m and 5 m and the masses established for the specific simulation models, increasing the value of Young's modulus and compressive strength. This was indeed a positive indication about the strength of the formed briquettes in case they were also required to be transported for commercial purposes.

2.3 Pyrolysis and Bio-gasification

The effects of fossil fuels on the climate and environment highlight the need for alternative energy options. One such approach for potentially reducing reliance on fossil-based energy is using waste wood. As an energy source, forest and agricultural waste is of interest. On a global scale, biomass accounts for roughly 15% of primary energy consumption, rising to more than 35% when only emerging economies are considered [91, 92]. Biomass is the world's third biggest main energy source [93]. Sawdust is one of the most abundant waste biomass begging for efficient conversion into value-added products and services. It has high carbon content and may be obtained at little or no cost. For biomass conversion and energy recovery, thermo-chemical techniques are commonly utilized. Combustion, gasification, liquefaction, hydrogenation, and pyrolysis are examples of these processes [94].

Burning sawdust with a restricted supply of air or oxygen is known as gasification. Gasification is an option from the perspective of energy-saving and diversification strategies [95]. Aside from that, gasification will aid with the difficulty of handling and using waste from wood products. It involves a combination of physico-chemical reactions such as drying, heating, pyrolysis, partial oxidation, and reduction. Gasification generates carbon (ii) oxide, carbon (iv) oxide, hydrogen, and methane. Besides carbon (iv) oxide, the liquid and gas are combustible and might be used as fuel or fuel feedstock. The nominal composition of gasification in air, excluding water vapor, is indicated in Table 1 below. Because the final result is a combination of simple gases, the composition of the gas is generally independent of the content of the feedstock. If the feedstock contains a substantial amount of sulfur, hydrogen sulfide may be produced [96]. This is usually removed by running the gas through the water. Furthermore, when the air supply is replaced with pure oxygen, as in the proxy process, the nitrogen component is removed, and the energy density can reach 9 MJ/m^3. Another technique for producing greater BTU gas is hydro-gasification, which involves adding hydrogen to the carbon (II) oxide to form hydrocarbons.

$$\mathrm{CO} + 2\mathrm{H_2} \rightarrow \mathrm{CH_4} + \mathrm{H_2O}.$$

Table 1 Typical composition of sawdust produced by gasification in air [96].

Compounds	Percentage by volume (%)
Hydrogen (H_2)	20
Carbon (ii) oxide (CO)	25
Carbon (iv) oxide (CO_2)	10
Methane (CH_4)	3
Higher hydrocarbon	1
Nitrogen	40
Others	1
Total	**100**

Gasification is an essential conversion type because it can efficiently decentralize power generation and apply heat usage.

According to Higman and van der Burgt [97], the gasification process phases are as follows: The water content of solid fuels is evaporated by heat absorbed from the oxidation process during drying. This reaction is located at the reactor's top and has the lowest temperature in the reactor, which is less than 150°C. The drying process is critical for the burner to ignite faster and more consistently. In this reaction, water-containing fuel is eliminated via evaporation, and the process requires around 2260 kJ of energy to complete, resulting in a long-running period. Reduction or gasification is a succession of endothermic reactions that get heat from combustion. Combustible gases such as H_2, CO, and CH_4 are produced in this process. The essential process in the gasifier is oxidation or the burning of charcoal. This method generates all of the heat energy required for endothermic processes. The gasifier's provided oxygen interacts with combustible chemicals.

Partial gasification is another term for pyrolysis or de-volatilization. The pyrolysis process produces char, oil, and gases, and their distribution and composition are primarily determined by temperature, heating rate, and pressure. Fast pyrolysis can give very high pyrolysis oil yields while retaining up to 70% of the energy in the biomass feed [98]. During the pyrolysis process, which begins slowly at 350°C and accelerates when the temperature exceeds 700°C, a succession of physical and chemical processes occurs. The arrangement of products is affected by temperature, pressure, and gas composition during pyrolysis. Thermally unstable components, such as lignin in biomass, break and vaporize with other components. Tar and PAH (polyaromatic hydrocarbon) are in the vaporized liquid. Pyrolysis products are classified into three types: light gas (H_2, CO, CO_2, H_2O, and CH_4), tar, and charcoal. Certain bio-oil features, however, considerably limit its broad applicability. Low heating value, incomplete volatility, and acidity are among these qualities [98]. These unfavorable features of pyrolysis oil are caused by an unusually high concentration of several kinds of oxygenated organic molecules. Removing oxygen is thus required to transform the oil into usable and commercially appealing fuel. To produce a high liquid yield, fast pyrolysis for energy recovery has been performed on various wood samples under various circumstances. Waste furniture sawdust [99], Larix Leptolepis sawdust [100], Pine sawdust [101], and Douglas Fir sawdust [102] are among the sawdust samples that have been pyrolyzed and documented.

Pine sawdust subjected to various thermo-chemical processes such as combustion, torrefaction, pyrolysis, and gasification Chaula et al. [103] examined pine sawdust for thermal and chemical conversions such as combustion, torrefaction, pyrolysis, and gasification. The analytical methods used included proximate analysis, ultimate analysis, heating value, and thermal breakdown to determine the biomass properties. Regarding elemental composition, pine sawdust has a lower energy content of 15.01 MJ/kg than bituminous coal, which has around 31.8 MJ/kg. The kinetic parameters of pine sawdust characterized the individual component degradation; hemicelluloses were the quickest to decompose, followed by cellulose and lignin. Under inert conditions, the heat released during the thermal deterioration of pine sawdust was-4380 J/g, demonstrating pine sawdust's potential for energy generation during combustion.

Mansur et al. [104] used a downdraft gasifier to examine the gasification of sawdust (SW), sawdust pellet (SWP), and sub-bituminous coal (SBCoal). Using air as an oxidizing agent, gasification was carried out in a lab-scale fixed-bed gasifier. The product gas and gasification performance of raw biomass, processed biomass, and coal were compared at a fixed gasification temperature of 750°C and an equivalency ratio of 0.25. The gasification performance was recorded in terms of syngas calorific value (HHVsyngas), gasification efficiency (XCGE), and carbon conversion efficiency (XC). Sawdust pellet was found to generate the most H_2 and the least CO_2. Furthermore, among the three feedstocks, SBCoal had the best gasification efficiency. The effect of temperature on SW, SWP, and SBCoal was examined at an equilibrium ratio of 0.25.

The preceding highlights numerous efforts that have been made toward converting sawdust into a valuable energy resource. Hence, it can be emphatically argued that sawdust has been successfully applied to energy generation, especially on a micro-domestic scale. Conversion of sawdust waste into cooking fuel keys is in line with SGD 7.0 – *ensure access to affordable, reliable, sustainable, and modern energy*. Sawdust cook stove caters to the energy need of rural dwellers and urban poor of developing countries. Sawdust is a more sustainable alternative to firewood which encourages the wasteful and senseless depletion of forest resources just to provide fuel for cooking. Sawdust is a by-product of the processing of timber into valuable products. Though sawdust is a renewable resource, using it for cooking causes air pollution, except some measures are adopted to minimize the types and rates of emission. Some of the studies invoked in the preceding sections indicate that considerable progress has been recorded. Research is still ongoing to produce more environmentally-friendly sawdust cookstoves. One of the biggest gains from using sawdust as a domestic fuel source is that it reduces the overall cost of solid waste management, especially concerning hauling cot and landfill space. Besides, it is one of the cheapest sources of energy for the poor section of society.

The use of sawdust as a source of no domestic fuel has faced the problems of low penetration, poor adoption, and low acceptance. This is partly because of the inconveniences of obtaining sawdust and the process required for the point-of-use application. The above problems have been largely solved by converting sawdust into briquettes. Processing sawdust into briquettes makes it acceptable and convenient for procurement, storage, and use. Studies highlighted so far indicate that the thermo-physical properties of sawdust briquettes can be improved when admixed other types of organic wastes such as corn cob and rice husk. Still, in the light of sustainability, cleaner and more reliable fuel can be derived from sawdust through thermo-chemical processes such as pyrolysis and gasification to generate gaseous, liquid/oil, and solid fuels with wide domestic applications. With proper processing, the gas and liquid fuels can be easily adapted for use in conventional kerosene cook stoves and gas cookers. Figure 6 shows that the thermo-chemical conversion of sawdust to produce fuel is more desirable than firewood and unprocessed sawdust.

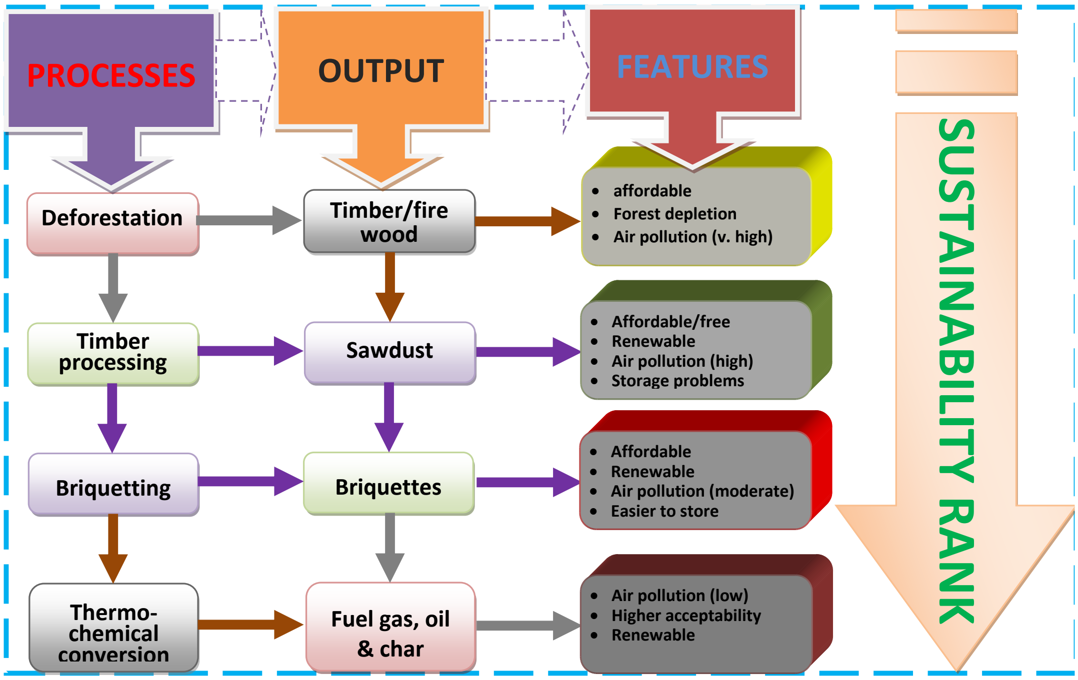

Figure 6 Sustainability sequence of sawdust-derived fuel.

3. Pollutant Containment: Sawdust as an Adsorbent

Environmental deterioration due to hazardous material pollution has risen due to a geometric increase in anthropogenic activities. The proliferation of industries has precipitated an unprecedented degree of release of toxic substances, especially heavy metals into the environment. Besides, there has been a rise in the concentration and number of pollutants in wastewater effluent owing to various household and agricultural chemicals. If not properly treated before discharge, these contaminants will accumulate in the soil, plants, and water which, when eventually consumed by man, causes severe health issues and even death. Heavy metals are of major interest in this regard because of their increasing concentration in the immediate environment of man and their toxicity. Heavy metal intake by humans usually occurs by three dominant pathways: inhalation of particulate forms, ingestion of compromised food or contaminated soil, and dermal contact with contaminated dust or soil. Each of these pathways can still be linked to effluent discharge. Heavy metals are preponderant in wastewater from various businesses, including electroplating, tanneries, batteries, fertilizers, paints, metal refining, and pesticides [105]. These heavy metals are normally harmful to live species at specific threshold quantities, persistent, non-biodegradable, and tend to accumulate in the food chain [106]. These metals, particularly Cu, Pb, Zn, Cd, As, Hg, Ni, Cr, Fe, and Mn, usually exist in an aqueous form in wastewater [107]. Because of their persistence in the environment, non-biodegradability, and tendency to accumulate, heavy metals can represent a major hazard to the environment and humans [108]. Some heavy metals are potent enzyme inhibitors that cause kidney and liver damage in animals and people [109], kidney tubular impairment, altered ion control, calcium metabolism, and bone calcification [110], stomach discomfort, vomiting, impairment of blood and brain function, diarrhea, and a choking sensation [111, 112]. Hence, it is pertinent to reduce the concentration of individual metals to acceptable guideline levels before effluent discharge.

Several strategies for eliminating these pollutants from wastewater have been proposed with various success, including chemical precipitation, oxidation, coagulation, reverse osmosis, ion exchange, electroplating, solvent extraction, membrane separation, and adsorption [113-115]. Adsorption is one of the most successful strategies for heavy metals containment and has sparked considerable attention due to its simplicity and low sensitivity to harmful contaminants [116]. Aside from being effective, adsorption is also cost-efficient [117], and the removal of low-concentration metal ions is also conceivable due to its excellent selectivity and efficiency [118]. Adsorption is a mass transfer technique that transports metal ions from an aqueous solution to the surface of a sorbent, where they are bound by physical, chemical, or physic-chemical forces [119, 120]. Because of their high surface area and the different functional groups present on their surface, commercial adsorbents are excellent for removing heavy metals from wastewater. To remove heavy metal ions from wastewater, commercial adsorbents such as graphene [121], activated carbon [122], and carbon nano-tube [123] are utilized as complexing adsorbents. Studies on heavy metal adsorption have centered on using activated carbons [124]. It is, however, very expensive, with relatively high operational costs. As a result, researchers have been searching unrelenting for low-cost and environmentally friendly adsorbents to extract heavy metals from aqueous solutions.

Numerous locally available materials have been proposed as adsorbents for heavy metal removal from wastewater. Waste tea, peat moss, rice husk, coconut shells, and sawdust are being used. Sawdust [125-130], rich husk [131-134], coconut fiber [126], banana fiber [126], groundnut shell [135, 136], sugarcane bagasse [136], wheat bran [137], clay [138], zeolite [139], kaolinite, illite [140], sepiolite, soil [141], montmorillonite, and bentonite have all been used for the adsorption of heavy metals under varying physic-chemical conditions. Because of their low cost, selective sorption, no sludge production, metal recovery, and high efficiency, low-cost adsorbents, agricultural wastes are very effective in removing of heavy metals and dyes from wastewater. Clay minerals have been widely used as a low-cost alternative adsorbent for heavy metal removal from solution. However, clay minerals typically have limited adsorption capacity. However, treatment with acids or alkalis has considerably enhanced adsorption capacity due to impurity removal and increased surface area of clays [142]. Unfortunately, using these compounds for modification is costly and results in secondary contamination [113]. As a result, more cost-effective alternatives for heavy metals in wastewater must be sought.

Sawdust is one of the most promising agricultural/forestry waste constituents that can effectively remove impurities such as dyes and heavy metals from polluted water. Sawdust is readily and abundantly available at sawmills and, therefore, inexpensive. Sawdust's surface characteristics and chemical composition make it an interesting research focus for adsorption process. Scanning electron microscopy images clearly show that the surface area of sawdust is favorable for the adsorption and retention of contaminants (Figure 7). Many researchers have documented detailed reports of batch adsorption experimental studies. While some of these studies are exploratory and aimed at ascertaining feasibility, others go further to investigate parameters and conditions that enhance process optimization. Parameters affecting adsorption efficiency include particle size, pH, activation mechanism, adsorption temperature, ionic state of target solute, initial concentration of contaminant, contact time, and degree or intensity of mixing. It has been demonstrated that sawdust is a good adsorbent for ferrochrome black T with an optimum performance of 80% efficiency and 40.96 mg/g adsorption capacity at a pH of 4.0 [125].

The pseudo-second-order equation and the Langmuir model were shown to be very good fits for the batch adsorption process.

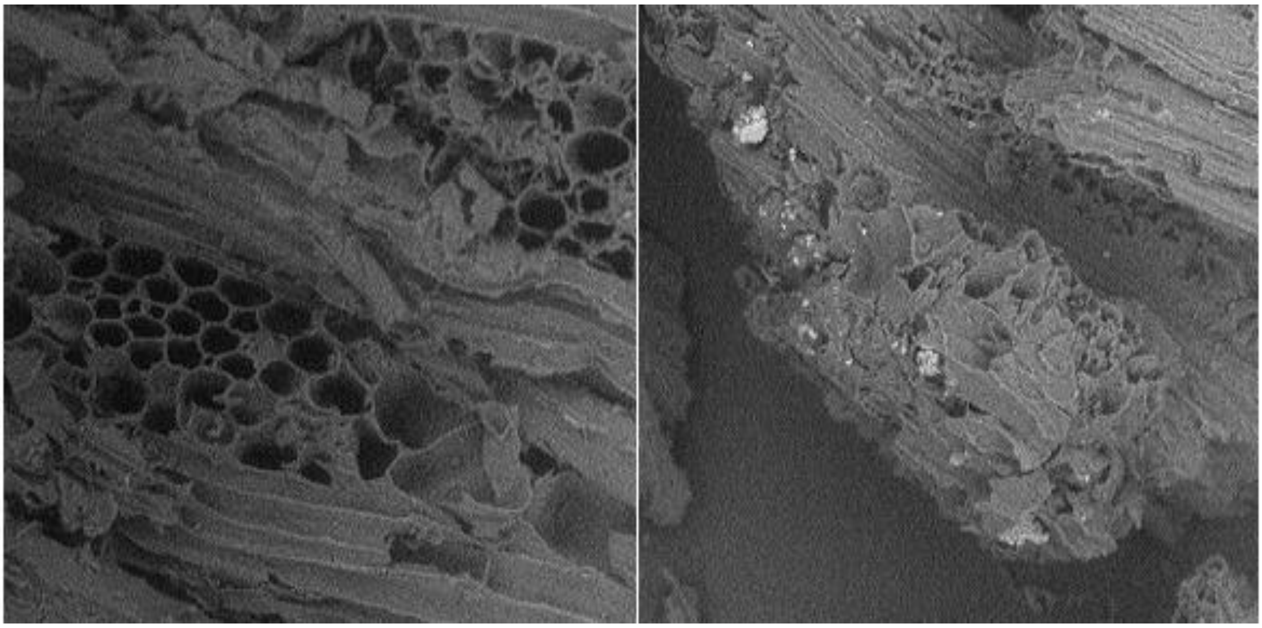

Figure 7 Scanning electron microscopy images of sawdust [143].

Further investigation of various critical process parameters indicates that the amount of sawdust adsorbing increased when the aqueous phase pH was reduced and dropped when the amount of sawdust was increased. Adsorption, a Physico-chemical process, has been found to respond markedly to the particle size of the adsorbent. A study of sawdust generated from two commonly wood species (*Khaya Ivorensis*and *Pycanthus Angolensis)* showed that optimum adsorption of lead was achieved at respective particle sizes of 0.85 mm and 1.18 mm with 100% efficiency of removal for an initial concentration of 10 mg/l [143]. Freundlich isotherms performed much better than Langmiur, Temkin, and Dubinin-Radushkevich isotherms for Khaya ivorensis and Pycnanthus angiogenesis with R^2 of 0.83 to 0.96 and 0.94 to 1.0 respectively. The mean sorption energies of 13.42 kJ/mol and 12.48 kJ/mol suggest that lead is transported into the internal surface of the adsorbent by an ion exchange mechanism. At the same time, a kinetic study showed that reaction kinetic follows a pseudo-first-order and an intra-particle diffusion model. This study is very important because lead remains one of the most toxic and recalcitrant water pollutants, with an ever-increasing concentration in both surface and groundwater. Another study [144] reported that Congo red dye was efficiently adsorbed by sawdust with smaller particle sizes (≤90 microns) and low initial solute concentration (10 mg/L). Sawdust has also been reported as an excellent adsorbent for methylene blue at an initial dosage of 250 mg/L, a temperature of 40°C, a pH of 7.0, and a contact time of 120 minutes [144]. Sawdust has also been reported to be efficacious in removing direct red 23, depending on the agitation period, adsorbent dosage, and initial adsorbate concentration [126, 127].

Khattri and Singh [128] explored the use of sawdust to remove crystal violet color from wastewater in a similar study. The feasibility of extracting crystal violet using sawdust was investigated by adjusting the agitation period, adsorbent dosage, dye concentration, temperature, and pH. The efficacy of adsorption was shown to be pH-dependent. A higher proportion of the dye was removed by lowering the original dye concentration and increasing the amount of adsorbent. Kinetic analysis revealed that the color gradually absorbed sawdust [128]. Sawdust was utilized by Suganya et al. [145] to adsorb methylene blue dye from a polluted solution. Adsorption input parameters such as contact time, initial dye concentration, solution pH, and adsorbent dosage were trial and error optimized to obtain maximal MB dye removal from wastewater. Experimental data were used to build multiple theoretical models to anticipate system behavior. Optimal conditions for MB dye removal from contaminated solution occurred at an initial dye concentration of 25 mgL^{-1}: adsorbent dosage of 3 gL^{-1}, solution pH of 7.0, contact period of 90 minutes, and temperature of 30°C. The pseudo-second-order and Freundlich models reasonably described the adsorption isotherm.

Balintova et al. [146] examined low-cost natural sorbents as an alternative to expensive heavy metal removal technologies. Peat and wood sawdust (poplar, hornbeam, spruce, pine, cherry, ash, and oak) were used to remove copper, zinc, and iron cations from acidic solutions. Infrared spectroscopy was used to investigate the presence of hemicelluloses, cellulose, and lignin in the structure of natural sorbents. Metal cations were removed from aquatic model solutions with an efficiency of around 80 percent using peat and poplar wood sawdust. Cu, Zn, and Fe removal effectiveness in hornbeam and poplar wood sawdust was 45 percent at five times greater concentrations of these metal cations. Peat absorbed more than 50 percent of metal ions from higher concentration solutions. Bozic et al. [147] used beech sawdust to perform heavy metal ion adsorption from synthetic single-ion solutions. The highest sawdust adsorption capacity was obtained at pH > 4. Cu^{2+} and Ni^{2+} ions have comparable adsorption capacities (4 to 4.5 mg g^{-1}), but Zn^{2+} ions have a capacity of 2 mg g^{-1}, indicating that the first two have some selectivity towards zinc ions. This and other studies indicate that the adsorption of metals by sawdust is by an ion exchange mechanism and follows a pseudo-second-order kinetic model.

Most studies highlighted so far used raw sawdust. However, there are indications that sawdust performs better in adsorption when activated either by a chemical or physical process or a combination of both. Activation removes inactive constituents of the adsorbents, increases surface area, and makes surface functional groups more active. Essentially, it modifies the surface characteristics of the adsorbent to make it more favorable to adsorption. Acar et al. [148] reported that poplar wood sawdust activated by H_2SO_4 at 150°C for 24 hours outperformed unmodified sawdust in removing Cu(II) ions from aqueous solutions. The adsorption capacity of modified (13.495 mg/g) sawdust was more than twice that of unmodified sawdust (5.432 mg/g), with greatest removal efficiencies of 92.4% and 47.1% at pH of 4.0 and 5.0, respectively. According to Ahmad et al. [149], raising the pH, temperature, and amount of adsorbent improved the adsorption outcome of chemically treated sawdust. Shukla et al. [150] found that dye-loaded sawdust (specifically Reactive Orange 13) had a greater potential for the adsorption of Cu(II), Ni(II), and Zn(II) ions than unloaded sawdust. Dye-loaded sawdust was reported to have adsorption capacities of 8.07, 9.87, and 17.09 mg/g for Cu(II), Ni(II), and Zn(II), respectively as against the corresponding values of 4.94, 8.05, and 10.96 mg/g for unloaded sawdust. This was achieved because of the reaction between Reactive Orange dye and the hydroxyl and amino acid functional groups at the surface of the sawdust, thus making it have a higher affinity for cation. Setyono et al. [151] reported that arsenite and arsenate anions were effectively removed from sawdust impregnated with lanthanum and zirconium oxide nanoparticles. At pH 7, the maximum adsorption capacities of lanthanum oxide (La_2O_3) treated sawdust for arsenite and arsenate were 22 and 28 mg/g, respectively.

In contrast, maximum adsorption capacities of zirconium oxide (ZrO_2) treated sawdust were 29 and 12 mg/g for arsenite and arsenate, respectively. The most interesting aspect of the study is that the La_2O_3 modified sawdust can be fully regenerated without any loss of arsenic removal efficiency. Argun et al. [152] found that acid (HCl) treated oak sawdust was removing good adsorbent for Cu(II), Ni(II), and Cr(VI) ions from wastewater with maximum removal efficiencies of oak sawdust at pH of 4.0, 8.0 and 3.0 respectively and corresponding removal efficiencies of 93%, 82%, and 84%. Functionalization of sawdust using mineral acids results in an increase in the intensities of functional groups and changes in surface morphologies, as well as an increase in carbon content which causes an overall increase in the adsorption capacity of the material. Surface characteristics usually modified by functionalization include surface charges, porosity, surface roughness, and functional groups. Rabago et al. [153] reported activation of sawdust activated with citric, malonic, and tartaric acids increase in the proportion of the functional carboxylic group and a consequent increase in adsorption capacity (304 mg/g) for Pb(II) ions.

The efficiency of the adsorption process is highly dependent on certain critical physic-chemical parameters such as particle size, pH of adsorbate, initial adsorbate concentration, rate of agitation, temperature of the solution, and even the type of parent wood. While there seems to be a favorable result for smaller particle sizes, the effect of pH depends on a consortium of factors such as the method of activation, zero pint charge of pollutant, and valent state of the pollutant. However, even when all factors seem favorable, the adsorption capacity of the particular sawdust can constitute a limiting factor.

The studies discussed in the preceding paragraphs indicate that sawdust has been successfully applied in pollutant containment, specifically in the adsorption of pollutants from water. The most common application of sawdust in pollutant containment is heavy metals and colour adsorption from water and wastewater. The industrial revolution resulted in the massive emission of numerous environmental pollutants into the soil, water, and atmosphere. Industrial wastewater laden with heavy metals is usually discharged without proper treatment. The sawdust-based adsorbent is an affordable and reliable containment agent. This is in line with SDG 11.0 (Sustainable cities and communities).

4. Building Construction: Production of Ceiling Boards and Particle Boards

Urban slums form an integral part of the social ecosystem in many developing countries. These are characterized by the poorest and most dehumanizing living conditions and a loud absence of good shelter and basic amenities. Urban slum dwellers live in shanty houses rented out by owners of such buildings at unreasonable prices, which might still be affordable compared to the rent in the city centers. These urban slum dwellers are usually persons of the lowest social strata who cannot afford to build their own houses. Affordable and sustainable housing can be made possible through conserving resources and waste recycling. It is expected that housing components made from waste materials such as sawdust will go a long way in reducing the cost of building. The use of wood-based materials in civil construction is increasing dramatically. Using renewable resources such as wood aligns with the principle of sustainable development. Industrial lignocellulosic leftovers, such as wood sawdust, may be simply employed as substitutes for wood-based raw materials. Wood scraps can generate energy [154, 155] or as raw materials [156, 157]. Ceiling boards are lightweight structural parts commonly used to improve aesthetics and acoustics in industrial applications, commercial and residential buildings, etc. Ceiling-mounted smoke detectors, security cameras, electric lighting, and signs are widespread in modern structures [158].

Mineral fiber is the most often used material for ceiling boards. However, other materials, such as fiberglass, are also utilized [159, 160]. Because of its strength, low heat conductivity, and good fire resistance, the fiber found in rocks (asbestos) has been utilized to construct ceiling boards for many years. However, asbestos causes asbestosis in humans, which is carcinogenic [161-163]. As a result, academics and other stakeholders are becoming more interested in finding an appropriate alternative for asbestos in board manufacturing. Agro and industrial wastes are being used in green buildings since they are typically more cost-effective and more environmentally friendly in the long term. This resulted in the development of new sustainable technologies for converting agricultural residues such as rice husk, maize cob, groundnut shell [164, 165], durian peel [166, 167], coconut coir, chir pine needles, wheat straw, bamboo [168], bagasse, chili pepper stalks [169], woven cotton fabrics, rubber wood, red cedar [170], cotton stalks, banana stem, and sawdust, among others, into high-quality value-added.

As a substitute, sawdust, cellulose fiber, agricultural waste, and other materials can be utilized [171-177]. The wood industry uses sawmill planks strategically. The increased use of wood for furniture, building construction, and interior design globally has resulted in considerable growth in sawmills and the volume of sawdust generated daily [178]. Poor management of this increasing quantity of wood dust has an impact on both aquatic and terrestrial ecosystems. A large proportion of sawdust generated in developing countries is burnt off, disposed of on land, or dumped into nearby streams. Burning of sawdust generates ashes and gaseous emissions, which disrupt water eco-systems, cause environmental difficulties and health issues, particularly in the eyes and respiratory tract, cause water and air pollution, and contribute to climate change [179-181]. Converting sawdust into value-added products such as ceiling boards will drastically reduce the adverse environmental impacts of mismanagement and poor handling of sawdust. Some research has been conducted on the production of composite particle and ceiling boards using agricultural and industrial sources. The weight of sawdust, scrap paper, and starch was changed to create a ceiling board with good physical, mechanical, and thermal conductivity qualities [182].

In the United States of America, a significant amount of sawdust and wood shavings are used to produce particleboards [183]. Between 2000 and 2017, the global output of wood-based panels such as particleboards, plywood, oriented strand boards (OSBs), and fiber boards surged by 125% [184]. Between 2012 and 2016, the Asia-Pacific area produced the most of these items (62%), followed by Europe (21%), North America (11%), Latin America and the Caribbean (5%), and Africa (1%). The low output for Africa and other developing continents in comparison to the large amount of sawdust generated suggests that there is a significant opportunity for increasing the production of sawdust-building composites from this waste in emerging nations. The loss of revenue that would have accrued from these value-added products, coupled with the environmental hazards resulting from the poor management of sawdust, represents a double minus in the value chain. Particleboards and associated items such as plywood and sawn lumber are in high demand globally, especially as the search for more cost-effective and cleaner production takes center stage in a world grappling with self-inflicted environmental catastrophe. Demand for these items is expected to rise by 39%, from 501,100 m^3 in 2010 to 698,700 m^3 in

2025 [185]. The integration of sawdust in fabricating these particleboards is expected to reduce the environmental damage caused by this waste. Particleboards and related wood products, such as low-density fiberboard (LDF) and chipboard, are made by combining different amounts of wood chips, sawmill shavings, or sawdust with a synthetic resin or any acceptable binder [186]. For instance, Abdulkareem et al. [187] demonstrated that particleboards manufactured from sawdust and plastic-based resin (PBR) synthesized from waste Styrofoam as a binder met the criteria of the American National Standard Institute (ANSI) A208.1 standard. This standard specifies the requisite dimensions and the physical and mechanical properties of various particleboard grades. Compared to urea-formaldehyde (UF) particleboards, sawdust-PBR particleboards demonstrated superior resistance to water penetration, dimensional stability, mechanical characteristics, and deformation resistance. As a result, they were more durable, harder, and more suited for use in most settings than UF particle boards. Dotun et al. [188] reported that combining sawdust and polyethylene terephthalate plastic waste yielded particle boards suitable for indoor applications. Similarly, Akinyemi et al. [189] noted that panels made from corncob and sawdust composites using urea-formaldehyde as a binder were appropriate for interior usage in buildings but not for load bearing. Erakhrumen et al. [190] demonstrated that the structural properties of particle boards made from sawdust could be improved by integrating coconut husk or coir and utilizing cement as a binder. Sawdust composites with high thermal conductivity have been developed by gluing sawdust or wood chips to expand polystyrene. These products have been certified in room dividers and suspended ceilings [191].

Olorunmaiye and Ohijeagbon [192] and [193] also enhanced the mechanical properties of sawdust particle board incorporating jatropha curcas seed cake and jatropha wood hulls. Akinyemi et al. [189] found that partial replacement of sawdust with 25 to 50% corn cob resulted in particle boards with favorable physical qualities suitable for interior usage in structures. Increasing the proportion of corn cob yielded particle boards with weak mechanical properties that failed to meet European Standard specifications. In response to the adverse health impacts of conventional asbestos ceiling boards, Obam [194] produced ceiling boards from sawdust, waste paper, and starch that have a thermal conductivity of 9.2×10^{-2} W/mK, flakiness of 6.86×10^{-3}, 8.6 percent water absorption and flexural strength of 0.05 N/mm^2. Thermal conductivity testing was performed on the composite sample boards.

Similarly, Drove et al. [195] used carpentry sawdust from African mahogany wood with binders from the tannin powder of Bridelia peels and African locust bean pod husk to make particleboards. The three-point bending test (TPB test), the traction test, and the thickness swelling test (TS test) were used to confirm the physical and mechanical fitness of the boards. The TS test demonstrate that the PB produced is only suitable for use indoors and in dry environments. The elasticity, rupture, and internal bond moduli are all well within the ranges specified by the ANSI A208.1-2016 standard. Atuanya and Obele [57] used Okhuen wood sawdust and recycled polyethylene (RLDPE) to manufacture sawdust/recycled polyethylene composite boards. The optimized composite board's average tensile strength was 13.991 MPa, which satisfied the standards for broad applications. Abu-Zarifa et al. [58] analyzed particleboards made from sawdust and various agricultural waste (banana stems, wheat bran, and orange peels). They reported mechanical and durability properties that outperformed commercially available products. The major issue with experimental particle boards is the lack of standardization and consumer feedback for measuring product performance. Another important factor is that economic analysis is hardly considered by researchers whose principal aim is feasibility rather than marketability and economic viability. Besides, the laboratory conditions where some resources might be free or heavily subsidized for the researcher do not always represent reality in an industrial setting with a cost associated with every service. No doubt, full or partial replacement of finite resources with sawdust in the production of ceiling and particle boards presents a very promising possibility both in terms of cost reduction and resource conservation. However, the yawning gap between laboratory idealization and commercialization still needs to be bridged.

SDG 11.1 focuses on adequate, safe, and affordable housing for all. Sawdust-derived particle boards and ceiling boards are cheap and environmentally-friendly alternatives to the conventional ceiling and partitioning materials. They are expensive and increase the overall cost of buildings because they significantly increase the design load of the building. Studies cited in the foregoing section present a very optimistic scenario and supportive argument for the beneficial use of sawdust in building construction. The cost of building materials is usually significantly influenced by the source. Imported materials are usually far more expensive than locally-made components. Developing countries that rely heavily on imported building materials can leverage locally made building components derived from sawdust as a cost-saving strategy for affordable housing. One of the notable benefits of recycling sawdust for building construction is that environmental impact is low, and the life cycle is reasonably long.

5. Water Treatment: Sawdust Clay Filter

In developing nations where access to clean drinking water has remained a mirage, water-related ailments are among the leading causes of mortality [196]. Many individuals in developing nations' rural and semi-urban areas lack access to municipal water systems; as a result, many turn to self-help water supply methods. This is also true of a significant section of the urban population where municipal services have partially or broken down. Most readily accessible water sources, including streams, rivers, and wells, have been harmed by human activity, making them unfit for human consumption. There has been a resurgence of rainwater harvesting in some places and heavy reliance on water vendors in other places, or a combination of both. These self-help methods of water supply are fraught with multiple weak links which might serve as contaminants' entry points into water. Obviously, there is not much the end users of such water can do about ingress contaminants into the water supply stream, but some remedial measures applied at the point of use will go a long way in minimizing adverse health issues that might arise from drinking contaminated water. Point-of-use (POU) treatment systems are components of water treatment equipment that treat water at the point of use, usually within a household. POU systems aim to significantly minimize transmission and conveyance-related pollution. Point-of-use systems are gaining prominence as solutions to water quality problems in developing countries [197]. Usually, the target is to eliminate pollutants introduced between the source and the point of use. There are also cases where water quality deteriorates during storage at the household level. When improper handling is the primary cause of contamination, safe storage is essential for some drinking water treatment systems. Safe storage containers may be a stand-alone solution to safeguard water quality [198]. POU systems can prevent the home's stored water from being polluted by improper water-handling procedures, which are considered to be the main determinant of deteriorating drinking water quality [199]. Traditionally, point-of-use treatment methods include porous clay filters, cloth or fiber filters, granular media, batch disinfection, boiling, and the use of coagulants. More technologically involved and recent methods include adsorption using activated carbon, ion exchange, redox filters, reverse osmosis membrane, and ultraviolet lamps. These devices/methods remove water contaminants using a mixture of physical, chemical, and biological processes such as physical straining, sedimentation, and adsorption. Some are particularly successful in lowering Vibrio cholera [200]. In a study that lasted over 35 months and comprised 65 villages in rural Bangladesh and around 133,000 participants, Colwell [200] found a 48% reduction in cholera related to the use of the filters. Filtration methods are increasingly used in third-world nations where chemical disinfection or boiling is not always feasible or efficient [200]. According to studies, these locally or commercially developed and manufactured filters efficiently remove microbiological pathogens in water [201].

The clay filter is one of the most basic and widely used POU water treatment methods. It involves using porous baked clay to filter microorganisms or other pollutants from drinking water. The underlying mechanism is particle exclusion bigger than the mean pore size. Pore diameters can occasionally be so narrow that they can catch anything bigger than a water molecule [202]. Burnout materials, which enhance flow velocity by generating a network of holes, and use bactericidal agents such as silver nanoparticles. Pathogen eradication has been used to considerably improve the performance of clay filters. Low-cost clay filters can vary widely in performance, depending on the production method, quality assurance and quality control, procedures, type of burnout material, firing temperatures and methods, and sometimes chemical amendments, and other characteristics [203]. Sawdust is one of the most commonly and abundantly available burn-out materials used to produce clay filters. Figure 8a shows a set of POU clay pots made from clay and sawdust as a burnout material, while Figure 8b shows a complete assembly of the POU filtration setup for domestic application. The use of sawdust as a burnout material in clay filters not only improves the filters' flow characteristics but also their purification efficiency through adsorption. Unlike chemical or thermal disinfection, Clay filters do not appreciably alter water taste or temperature while reducing turbidity [198, 204]. Filters are functionally stable since they only have one moving element (the tap) and do not require an external energy source [197]. The simplicity of design, low-level technology, and zero requirements of external energy sources make clay filters a cost-effective remedy for the increasing spate of domestic water contamination. With adequate care and maintenance, they have a potentially lengthy functional life of roughly five years or more [205]. The permeability properties of clay depend on the solution's pH, structure, particle size, shape, and surface features of the dispersed phase [206]. Controlling the rheological properties of clay is frequently required in industrial processes and practical applications requiring ceramics processing (melt-processing behavior such as injection molding) or paper coating [207].

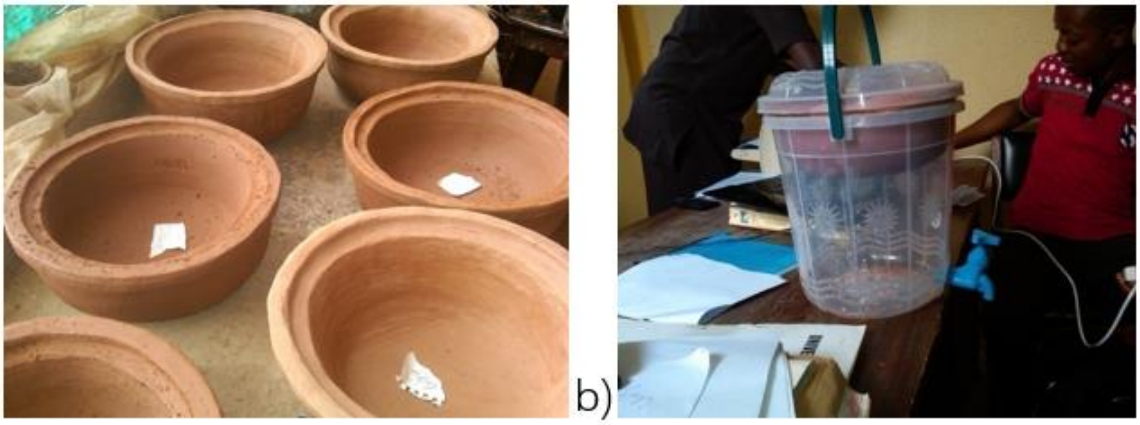

Figure 8 a) Clay filter pot; b) Assembled clay filter pot.

Furthermore, this feature has enabled the creation of clay-based composites and nano-composite materials. Clay water filters are typically compressed into cylindrical clay pots using a hydraulic or manual press, then left to dry in ambient temperatures before sintering (or burning) at high temperatures [201]. Chemical pollutants can also be removed from water via adsorption, while microorganisms are removed through particle size occlusion.

Researchers are constantly trying to find the most efficient and cost-effective burnout material for use in clay pot filters. In pursuit of this objective, attention has mostly been focused on agricultural waste products and other cheap or free resources. A mixture of sawdust, clay, and diatomite burned at 850°C has been used to produce a water filter whose performance satisfied WHO drinking water guidelines [208]. Wangrakdiskul and Kankaew [209] reported a combination of sawdust, bottom ash, and sediment soil in the ratio of 4:1:5 pressed at 40 bars and fired at 950 to 1050°C yielded a very promising product for domestic water purification. Efeovbokhan et al. [210] reported that filters made from sawdust and clay mixed in the ratios of 680, 5/80, and 4/80 produced filtrates that satisfied WHO guidelines for total dissolved solids, conductivity, turbidity, and several heavy metals when used to filter both industrial and kitchen wastewater. Nnaji et al. [197] developed a clay-sawdust composite filter with proportions of sawdust ranging between 5 and 50%. While the variation in the proportion of burnout materials resulted in a significant difference in filtration rates, there was no significant difference in the quality of filtrates. The flow rate increased from 0.0005 liters per hour for filters made with 5% of sawdust to 0.8 liters per hour for filters made with 50% of sawdust, representing 1600 folds improvement in flow rate. While the mean Log10 decrease in total count (TC) was 93.1%, the average removal of suspended solids (SS) and biochemical oxygen demand (BOD) was 98.6% and 33%, respectively. Akosile et al. [211] investigated the performance of ceramic filters made from variable proportions of clay and sawdust from a ratio of 40:60 to 60:40 and concluded that a mix ratio of 50:50 gave the most desirable result concerning the exclusion of microorganisms. Apart from improved flow characteristics and purification efficiency, using a higher proportion of burnout material also creates more space for the storage of entrapped contaminants, thus increasing the service time of the filter. This will also imply a longer contaminant breakout time.

Varkey and Dlamini [212] showed that ceramic filters of sawdust of particle sizes 600 µm and 900 µm performed better than those made of 300 µm and that bactericidal properties can be improved by placing a copper mesh in the filtrate receptacle. They proposed that cooper is a cheaper and more readily available bactericide than silver and should be used for point-of-use water treatment. Despite the beneficial use of metallic bactericides for microbial deactivation in point-of-use ceramic filters, there is a risk of filtrate contamination by the metals through leaching. Unfortunately, most researchers are so fixated on the bactericidal efficacy of these metals, mostly silver and copper, that they lose sight of the potential health risks inherent in the contamination of water by heavy metals. Hence, gains made concerning improvement in microbial quality are reversed by the addition of these metallic ions into the water. Besides, ceramic filters made from sawdust and other burnout materials are limited in application by drawbacks such as ease of breakage, low filtration rate (typically <3 liters per hour), limited capacity, quality control, and quality assurance issues as well as low virus removal efficiency. Notwithstanding, point-of-use ceramic filters remain a viable alternative for rural dwellers without conventional water treatment facilities.

The application of sawdust in the treatment of water for domestic use falls within the objectives of SDGs 3.0 and 6.0. While SDG 3.0 focuses on good health and well-being, SDG 6.0 concerns clean water and sanitation. The high association between contaminated water and some ailments has been strongly established in the literature. Several water-borne pathogens have been found to be highly detrimental to human health when ingested with water. The studies highlighted in the preceding sections have empirically established that a sawdust-clay water filter has been successfully applied in the inactivation of pathogens and the removal of other water contaminants. The use of sawdust-clay water filters for PoU water treatment has a greater impact in rural areas and urban slums of developing countries that do not have access to piped water. The filters can take care of native water contaminants and those introduced during fetching and transportation.

6. Conclusion

Timber processing and furniture production generate a significant volume of waste in the form of off-cuts, shavings, and sawdust, which presents hurdles and costs to manufacturing companies in terms of proper recovery and disposal. Sawdust is produced on a daily basis in developing countries because of the increasing demand for wood products for a range of applications. The environmental and health implications of these wood wastes are many. Thus, the reuse /recycling of these wood wastes will alleviate pressure on fast-decreasing forests, reduce pollution, and provide employment and income.

Based on many research articles published, this review examined sawdust as a waste product from the timber and furniture industry. Sawdust is a cheap energy source, an excellent adsorbent for removing heavy metals and other contaminants from water, affordable building material, and an alternative PoU water treatment in places where advanced water treatment technologies are beyond the reach of the people. A thorough review of the literature has revealed that sustainable management of wood waste (sawdust) for reuse, specifically as a sawdust-clay filter for water treatment, sawdust briquettes, heavy metal adsorbent, ceiling board production, sawdust cooking stoves, and fuel gas production, are highly achievable and efficient.

This study clearly showed that waste reuse in general and sawdust reuse in particular form a critical component of the sustainable development goals. The conversion of sawdust to energy by the various processes highlighted such as sawdust cook stove, briquetting, and pyrolysis squarely address SDG 7.0 (affordable and clean energy). The use of sawdust for heavy metals adsorption targets SDG 11.0 (sustainable cities and communities). With the development of efficient and cost-effective pollution containment techniques, the environment will be safer and more sustainable. The production of particle boards and ceiling boards also meets the objectives of SDG 11.0, while at the same time scratching SDG 9.0 (industry, innovation, and infrastructure) and SDG 12.0 (responsible consumption and production). Sawdust-clay PoU filters have been reported as an effective domestic water treatment method for water-stressed communities in line with SDG 6.0 (clean water and sanitation), a partial precursor for SGD 3.0 (good health and well-being). Figure 9 clearly shows the relationship between sawdust reuse and specific objectives of the sustainable development goals. In general, all re-use options discussed in this study are intricately woven into the objectives of SDG 9.0 (industry, innovation, and infrastructure) and SDG 12.0 (responsible consumption and production).

Figure 9 Sawdust reuse for SDGs.

The novelty of this work lies in developing new concepts embodied in Figures 1, 2, 3, 5, 6, and 9, which were used to drive home and further illustrate some salient points. Furthermore, this study linked sawdust reuse options to specific sustainable goals and objectives to further buttress beneficial environmental effects.

Author Contributions

Conceptualization, C.C.N. methodology, C.C.N. and U.U.U.; formal analysis, C.C.N. and U.U.U.; investigation, C.C.N. and U.U.U.; resources, C.C.N. and U.U.U.; writing-original draft preparation, C.C.N. and U.U.U.; writing-review and editing, C.C.N. and U.U.U. All authors have read and agreed to the published version of the manuscript.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

References

1. Nnaji CC, Udokpoh UU. Sawdust waste management in Enugu timber market. Proceedings of the 4th African International Conference on Industrial Engineering and Operations Management; 2022 April 5-7; Nsukka, Enugu State, Nigeria. Southfield: IEOM Society International.
2. Nnaji CC, Afangideh BC, Udokpoh UU, Nnam JP. Evaluation of solid waste storage and disposal practices in Nsukka, Enugu State. In: IOP Conference series: Materials science and engineering. Bristol: IOP Publishing Ltd.; 2021. pp. 012016.
3. Minghua Z, Xiumin F, Rovetta A, Qichang H, Vicentini F, Bingkai A, et al. Municipal solid waste management in Pudong New Area, China. Waste Manage. 2009; 29: 1227-1233.
4. Belgiorno V, Panza D. Solid waste management system: An impressive case study. WIT Trans Ecol Environ. 2008; 117: 715-724.
5. Abdel-Shafy HI, Mansour MS. Solid waste issue: Sources, composition, disposal, recycling, and valorization. Egypt J Pet. 2018; 27: 1275-1290.
6. Sujauddin M, Huda MS, Rafiqul AT. Household solid waste characteristics and management in Chittagong, Bangladesh. Waste Manage. 2008; 28: 1688-1695.
7. Burntley SJ. A review of municipal solid waste composition in the United Kingdom. Waste Manage. 2007; 27: 1274-1285.
8. Nabegu AB. An analysis of municipal solid waste in Kano metropolis, Nigeria. J Hum Ecol. 2010; 31: 111-119.
9. Owoyemi JM, Zakariya HO, Elegbede IO. Sustainable wood waste management in Nigeria. Environ Socio Econ Stud. 2016; 4: 1-9.
10. Oyedepo SO, Dunmade IS, Adekeye T, Attabo AA, Olawole OC, Babalola PO, et al. Bioenergy technology development in Nigeria-pathway to sustainable energy development. Int J Environ Sustain Dev. 2019; 18: 175-205.
11. Tilak LN, Santhosh Kumar MB, Manvendra SN. Use of sawdust as fine aggregate in concrete mixture. Int Res J Eng Technol. 2017; 5: 1249-1253.
12. Ogunwusi AA. Wood waste generation in the forest industry in Nigeria and prospects for its industrial utilization. Civ Environ Res. 2014; 6: 62-69.
13. Akhator P, Obanor A, Ugege A. Nigerian wood waste: A potential resource for economic development. J Appl Sci Environ Manage. 2017; 21: 246-251.
14. Nobre C, Vilarinho C, Alves O, Mendes B, Gonçalves M. Upgrading of refuse derived fuel through torrefaction and carbonization: Evaluation of RDF char fuel properties. Energy. 2019; 181: 66-76.
15. Rezaei H, Yazdanpanah F, Lim CJ, Sokhansanj S. Pelletization properties of refuse-derived fuel-effects of particle size and moisture content. Fuel Process Technol. 2020; 205: 106437.

16. Chalermcharoenrat S, Laohalidanond K, Kerdsuwan S. Optimization of combustion behavior and producer gas quality from reclaimed landfill through highly densify RDF-gasification. Energy Procedia. 2015; 79: 321-326.
17. Kara M. Environmental and economic advantages associated with the use of RDF in cement kilns. Resour Conserv Recycl. 2012; 68: 21-28.
18. Moussiopoulos N, Banias G, Douros J, Michailidou AV, Tsegas G. Emission estimates and air quality impacts from the use of alternative fuels by the titan cement factory in Thessaloniki. Glob Nest J. 2012; 14: 218-224.
19. Goshwe NY, Kureve TD, Okeleke A. Performance evaluation of power in GSM BTS in Nigeria using PV solar system. Int J Emerg Res Manag Technol. 2015; 4: 14-26.
20. Oghogho I, Sulaimon O, Adedayo BA, Egbune D, Kenechi AV. Solar energy potential and its development for sustainable energy generation in Nigeria: A road map to achieving this feat. Int J Eng Manage Sci. 2014; 5: 61-67.
21. Felix AA, Akinbulire TO, Abdulkareem A, Awosope CO. Wind energy potential in Nigeria. Int Electr Eng J. 2012; 3: 595-601.
22. Bourguignon D. Biomass for electricity and heating: Opportunities and challenges. London: European Parliament; 2015; PE 568.329.
23. Kehinde AL, Awoyemi TT, Omonona BT, Akande JA. Technical efficiency of sawdust production in Ondo and Osun state Nigeria. J For Econ. 2009; 16: 11-18.
24. Ohimain EI. The prospects and challenges of waste wood biomass conversion to bioelectricity in Nigeria. J Waste Convers Bioprod Biotechnol. 2012; 1: 3-8.
25. Singh K, Gautam NN, Singh B, Goel VL, Patra DD. Screening of environmentally less-hazardous fuelwood species. Ecol Eng. 2014; 64: 424-429.
26. Elehinafe FB, Okedere OB, Fakinle BS, Sonibare JA. Assessment of sawdust of different wood species in Southwestern Nigeria as source of energy. Energ Source Part A. 2017; 39: 1901-1905.
27. Uzoma CC, Nnaji CE, Nnaji M. The role of energy mix in sustainable development of Nigeria. Cont J Soc Sci. 2012; 5: 21-29.
28. Saint Akadiri S, Alola AA, Akadiri AC, Alola UV. Renewable energy consumption in EU-28 countries: Policy toward pollution mitigation and economic sustainability. Energy Policy. 2019; 132: 803-810.
29. Mboumboue E, Njomo D. Biomass resources assessment and bioenergy generation for a clean and sustainable development in Cameroon. Biomass Bioenergy. 2018; 118: 16-23.
30. Ackom EK, Alemagi D, Ackom NB, Minang PA. Modern bioenergy from agricultural and forestry residues in Cameroon: Potential, challenges and the way forward. Energy Policy. 2013; 63: 101-113.
31. Veeyee KF, Bup ND, Boldor D, Elambo NG. Potentials of sustainable electricity production from sawdust by small-scale wood transformation units: A case study in Cameroon. Int J Energy Environ Eng. 2021; 12: 101-114.
32. Lertsatitthanakorn C, Jamradloedluk J, Rungsiyopas M. Study of combined rice husk gasifier thermoelectric generator. Energy Procedia. 2014; 52: 159-166.
33. Forster-Carneiro T, Berni MD, Dorileo IL, Rostagno MA. Biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. Resour Conserv Recycl. 2013; 77: 78-88.

34. Tidze V, Ibrahim M, Issac T. Dynamics of household energy and cooking stoves in Maroua, far north region of Cameroon. J Sci Res Rep. 2016; 9: 1-13.
35. Rasoulkhani M, Ebrahimi-Nik M, Abbaspour-Fard MH, Rohani A. Comparative evaluation of the performance of an improved biomass cook stove and the traditional stoves of Iran. Sustain Environ Res. 2018; 28: 438-443.
36. Amutio M, Lopez G, Artetxe M, Elordi G, Olazar M, Bilbao J. Influence of temperature on biomass pyrolysis in a conical spouted bed reactor. Resour Conserv Recycl. 2012; 59: 23-31.
37. Arazo RO, Genuino DA, de Luna MD, Capareda SC. Bio-oil production from dry sewage sludge by fast pyrolysis in an electrically-heated fluidized bed reactor. Sustain Environ Res. 2017; 27: 7-14.
38. Bolaji BO. The use of sawdust as an alternative source of energy for domestic cooking and as a means of reducing deforestation. Glob J Environ Sci. 2005; 4: 73-76.
39. Sutar KB, Kohli S, Ravi MR, Ray A. Biomass cookstoves: A review of technical aspects. Renew Sust Energ Rev. 2015; 41: 1128-1166.
40. Banerjee M, Prasad R, Rehman IH, Gill B. Induction stoves as an option for clean cooking in rural India. Energy Policy. 2016; 88: 159-167.
41. Halder PK, Paul N, Beg MR. Assessment of biomass energy resources and related technologies practice in Bangladesh. Renew Sust Energ Rev. 2014; 39: 444-460.
42. Das BJ, Das S, Boro RN, Bishal PB, Ashim K. Study and fabrication on heat efficient stove of low smoke emission. J Inst Eng (India) Ser E. 2021; 103: 125-134.
43. Sime G, Tilahun G, Kebede M. Assessment of biomass energy use pattern and biogas technology domestication programme in Ethiopia. African J Sci Technol Innov Dev. 2020; 12: 747-757.
44. Raman P, Ram NK, Gupta R. Development, design and performance analysis of a forced draft clean combustion cookstove powered by a thermo electric generator with multi-utility options. Energy. 2014; 69: 813-825.
45. Getahun E, Tessema D, Gabbiye N. Design and development of household gasifier cooking stoves: Natural versus forced draft. In: Advances of science and technology. Cham: Springer; 2018. 274p.
46. Okino J, Komakech AJ, Wanyama J, Ssegane H, Olomo E, Omara T. Performance characteristics of a cooking stove improved with sawdust as an insulation material. J Renew Energy. 2021; 2021: 9969806.
47. Janssen R, Rutz D. Bioenergy for sustainable development in Africa. Berlin: Springer; 2012.
48. Bamwesigye D, Kupec P, Chekuimo G, Pavlis J, Asamoah O, Darkwah SA, et al. Charcoal and wood biomass utilization in Uganda: The socioeconomic and environmental dynamics and implications. Sustainability. 2020; 12: 8337.
49. Oyejide OJ, Okwu MO, Tartibu LK. Adaptive design and development of a modular water hyacinth briquette stove. Energ Source Part A. 2019. Doi: 10.1080/15567036.2019.1675808.
50. Shanono A, Diso I, Garba I. Performance and emission characteristics of liquid biofuels cooking stoves. Athens J Technol Eng. 2020; 7: 219-238.
51. Darlami HB, Ale BB, Pokharel GR. Experimental analysis of thermal efficiency of mud improved cookstove with variation of different parameters and economic analysis. J Inst Eng. 2019; 15: 385-392.

52. Comsawang P, Nanetoe S, Soponpongpipat N. Co-firing of sawdust and liquid petroleum gas in the application of a modified rocket stove. Processes. 2020; 8: 112.
53. Njenga M, Gitau JK, Iiyama M, Jamnadassa R, Mahmoud Y, Karanja N. Innovative biomass cooking approaches for sub-Saharan Africa. African J Food Agric Nutr Dev. 2019; 19: 14066-14087.
54. Bhanap IJ, Deshmukh RD. Development of an improved sawdust gasifier stove for industrial applications. J Renew Sustain Energy. 2012; 4: 063113.
55. Peša I. Sawdust pellets, micro gasifying cook stoves and charcoal in urban Zambia: Understanding the value chain dynamics of improved cookstove initiatives. Sustain Energy Technol Assess. 2017; 22: 171-176.
56. Aliyu S, Buba B. Evaluation of thermal efficiency of double-hole sawdust stove using different biomass residues in Sokoto, Nigeria. Int J Eng Sci Invent. 2019; 8: 43-46.
57. Atuanya CU, Obele CM. Optimization of process parameter for sawdust/recycled polyethylene composites. J Miner Mater Charact Eng. 2016; 4: 270.
58. Zarifa AA, Shammala MA, Sheikh AA. Sustainable manufacturing of particleboards from sawdust and agricultural waste mixed with recycled plastics. Am J Environ Eng. 2018; 8: 174-180.
59. Ajimotokan HA, Sher I. Thermodynamic performance simulation and design optimisation of trilateral-cycle engines for waste heat recovery-to-power generation. Appl Energy. 2015; 154: 26-34.
60. Khennich M, Galanis N. Thermodynamic analysis and optimization of power cycles using a finite low-temperature heat source. Int J Energy Res. 2012; 36: 871-885.
61. Obi OF, Okongwu KC. Characterization of fuel briquettes made from a blend of rice husk and palm oil mill sludge. Biomass Convers Biorefin. 2016; 6: 449-456.
62. Amoo OM, Fagbenle RL. Renewable municipal solid waste pathways for energy generation and sustainable development in the Nigerian context. Int J Energy Environ Eng. 2013; 4: 42.
63. Eddine BT, Salah MM. Solid waste as renewable source of energy: Current and future possibility in Algeria. Int J Energy Environ Eng. 2012; 3: 17.
64. Akolgo GA, Awafo EA, Essandoh EO, Owusu PA, Uba F, Adu-Poku KA. Assessment of the potential of charred briquettes of sawdust, rice and coconut husks: Using water boiling and user acceptability tests. Sci Afr. 2021; 12: e00789.
65. WHO. Household air pollution and health [Internet]. Genève: WHO; 2022 [cited date 2022 June 18]. Available from: https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health.
66. Obeng GY, Amoah DY, Opoku R, Sekyere CK, Adjei EA, Mensah E. Coconut wastes as bioresource for sustainable energy: Quantifying wastes, calorific values and emissions in Ghana. Energies. 2020; 13: 2178.
67. Morales-Máximo M, Rutiaga-Quiñones JG, Masera O, Ruiz-García VM. Briquettes from Pinus spp. residues: Energy savings and emissions mitigation in the rural sector. Energies. 2022; 15: 3419.
68. Soponpongpipat N, Sae-Ueng U. The effect of biomass bulk arrangements on the decomposition pathways in the torrefaction process. Renew Energ. 2015; 81: 679-684.
69. Kuti OA, Adegoke CO. Comparative performance of composite sawdust briquette with kerosene fuel under domestic cooking conditions. AU J T. 2008; 12: 57-61.

70. Suarez JA, Luengo CA, Fonseca FF, Bezzon G, Beaton PA. Thermochemical properties of Cuban biomass. Energy Sources. 2000; 22: 851-867.
71. Wilaipon P. Physical characteristics of maize cob briquettes and quantity of maize cob under moderate die pressure. Am J Appl Sci. 2007; 4: 995-998.
72. Rabiu AB, Lasode OA, Ajimotokan HA, Afolayan VA. Combustion characteristics of selected tropical wood residues in relation to particle size. Proceedings of the 33rd International Conference on Solid Waste Technology and Management; 2018 March 11-14; Anapolis, MD, USA. Mumbai: NSWAI. 2018. pp. 320-330.
73. Wakchaure GC, Mani I. Effect of binders and pressures on physical quality of some biomass briquettes. J Agric Eng. 2009; 46: 24-30.
74. Akowuah JO, Kemausuor F, Mitchual SJ. Physico-chemical characteristics and market potential of sawdust charcoal briquette. Int J Energy Environ Eng. 2012; 3: 20.
75. Obidzinski S. Pelletization of biomass waste with potato pulp content. Int Agrophys. 2014; 28: 85-91.
76. Mitchual SJ, Frimpong-Mensah K, Darkwa NA, Akowuah JO. Briquettes from combination of maize cobs and ceiba pentandra at room temperature and low compacting pressure without a binder. Int J Energy Environ Eng. 2013; 4: 38.
77. Raslavicius L. Characterization of the woody cutting waste briquettes containing absorbed glycerol. Biomass Bioenergy. 2012; 45: 144-151.
78. Stelte W, Holm JK, Sanadi AR, Barsberg S, Ahrenfeldt J, Henriksen UB. A study of bonding and failure mechanisms in fuel pellets from different biomass resources. Biomass Bioenergy. 2011; 35: 910-918.
79. Xiao X, Li C, Ya P, He J, He Y, Bi XT. Industrial experiments of biomass briquettes as fuels for bulk curing barns. Int J Green Energy. 2015; 12: 1061-1065.
80. Azasi VD, Offei F, Kemausuor F, Akpalu L. Bioenergy from crop residues: A regional analysis for heat and electricity applications in Ghana. Biomass Bioenergy. 2020; 140: 105640.
81. Kpelou P, Kongnine DM, Kombate S, Mouzou E, Napo K. Energy efficiency of briquettes derived from three agricultural waste's charcoal using two organic binders. J Sustain Bioenergy Syst. 2019; 9: 79-89.
82. Bonsu BO, Takase M, Mantey J. Preparation of charcoal briquette from palm kernel shells: Case study in Ghana. Heliyon. 2020; 6: e05266.
83. Emerhi EA. Physical and combustion properties of briquettes produced from sawdust of three hardwood species and different organic binders. Adv Appl Sci Res. 2011; 2: 236-246.
84. Kuti OA. Performance of composite sawdust briquette fuel in biomass stove under simulated condition. AU J T. 2009; 12: 284-288.
85. Mitchual SJ, Frimpong-Mensah K, Darkwa NA. Relationship between physico-mechanical properties, compacting pressure and mixing proportion of briquettes produced from maize cobs and sawdust. J Sustain Bioeng Syst. 2014; 4: 44248.
86. Ajimotokan HA, Ehindero AO, Ajao KS, Adeleke AA, Ikubanni PP, Shuaib-Babata YL. Combustion characteristics of fuel briquettes made from charcoal particles and sawdust agglomerates. Sci Afr. 2019; 6: e00202.
87. Anggraeni S, Girsang GC, Nandiyanto AB, Bilad MR. Effects of particle size and composition of sawdust/carbon from rice husk on the briquette performance. J Eng Sci Technol. 2021; 16: 2298-2311.

88. Mitchual SJ, Frimpong-Mensah K, Darkwa NK. Effect of species, particle size and compacting pressure on relaxed density and compressive strength of fuel briquettes. Int J Energy Environ Eng. 2013; 4: 30.
89. Zepeda-Cepeda CO, Goche-Télles JR, Palacios-Mendoza C, Moreno-Anguiano O, Núñez-Retana VD, Heya MN, et al. Effect of sawdust particle size on physical, mechanical, and energetic properties of pinus durangensis briquettes. Appl Sci. 2021; 11: 3805.
90. Araque O, Arzola N, Gallego L. Mechanical behavior of briquettes made from a mixture of sawdust and rice husks for commercialization. Resources. 2022; 11: 32.
91. Cordero T, Marquez F, Rodriguez-Mirasol J, Rodriguez J. Predicting heating values of lignocellulosics and carbonaceous materials from proximate analysis. Fuel. 2001; 80: 1567-1571.
92. Abdelouahed L, Authier O, Mauviel G, Corriou JP, Verdier G, Dufour A. Detailed modeling of biomass gasification in dual fluidized bed reactors under Aspen Plus. Energy Fuels. 2012; 26: 3840-3855.
93. Gani A, Naruse I. Effect of cellulose and lignin content on pyrolysis and combustion characteristics for several types of biomass. Renew Energ. 2007; 32: 649-661.
94. Goyal H, Seal D, Saxena R. Bio-fuels from thermochemical conversion of renewable resources: A review. Renew Sust Energ Rev. 2008; 12: 504-517.
95. Sulaiman S. Biomassa Gasifikasi. Surabaya: Baristand Industri Surabaya; 2009.
96. Rominiyi OL, Adaramola BA, Ikumapayi OM, Oginni OT, Akinola SA. Potential utilization of sawdust in energy, manufacturing and agricultural industry; waste to wealth. World J Eng Technol. 2017; 5: 526-539.
97. Higman C, van der Burgt M. Thermodynamics of gasification. In: Gasification. 2nd ed. Amsterdam: Gulf Professional Publishing; 2003. pp. 11-31.
98. French R, Czernik S. Catalytic pyroly sis of biomass for biofuels production. Fuel Process Technol. 2010; 91: 25-32.
99. Heo HS, Park HJ, Park YK, Ryu C, Suh DJ, Suh YW, et al. Bio-oil production from fast pyrolysis of waste furniture sawdust in a fluidized bed. Bioresour Technol. 2010; 101: S91-S96.
100. Park DK, Kim SD, Lee SH, Lee JG. Co-pyrolysis characteristics of sawdust and coal blend in TGA and a fixed bed reactor. Bioresour Technol. 2010; 101: 6151-6156.
101. Carlson TR, Cheng YT, Jae J, Huber GW. Production of green aromatics and olefins by catalytic fast pyrolysis of wood sawdust. Energy Environ Sci. 2011; 4: 145-161.
102. Ren S, Lei H, Wang L, Bu Q, Chen S, Wu J, et al. Biofuel production and kinetics analysis for microwave pyrolysis of Douglas fir sawdust pellet. J Anal Appl Pyrolysis. 2012; 94: 163-169.
103. Chaula Z, Said M, John G. Thermal characterization of pine sawdust as energy source feedstock. J Energy Technol Policy. 2014; 4: 57-64.
104. Mansur FZ, Faizal CK, Samad NA, Atnaw SM, Sulaiman SA. Gasification performance of sawdust, pelletized sawdust and sub‑bituminous coal in a downdraft gasifier. SN Appl Sci. 2020; 2: 1543.
105. Manzoor Q, Nadeem R, Iqbal M, Saeed R, Ansari TM. Organic acids pretreatment effect on Rosa bourboniaphytobiomass for removal of Pb(II) and Cu(II) from aqueous media. Bioresour Technol. 2013; 132: 446-452.
106. Ahluwalia SS, Goyal D. Microbial and plant derived biomass for removal of heavy metals from wastewater. Bioresour Technol. 2007; 98: 2243-2257.

107. El-Eswed B, Yousef RI, Alshaaer M, Hamadneh I, Khalili F. Adsorption of Cu(II), Ni(II), Zn(II), Cd(II) and Pb(II) onto kaolin/zeolite based-geopolymers. Adv Mater Phys Chem. 2013; 2: 119-125.
108. Kumar PS, Ramalingam S, Sathyaselvabala V, Kirupha SD, Murugesan A, Sivanesan S. Removal of cadmium (II) from aqueous solution by agricultural waste cashew nut shell. Korean J Chem Eng. 2012; 29: 756-768.
109. Politi D, Sidiras D. Wastewater treatment for dyes and heavy metals using modified pine sawdust as adsorbent. Procedia Eng. 2012; 42:1969-1982.
110. Udokpoh UU, Ndem UA, Abubakar ZS, Yakasi AB, Saleh D. Comparative assessment of groundwater and surface water quality for domestic water supply in rural areas surrounding crude oil exploration facilities. J Environ Pollut Hum Health. 2021; 9: 80-90.
111. Guerra DJ, Mello I, Resende R, Silva R. Application as absorbents of natural and functionalized Brazilian bentonite in Pb^{2+} adsorption: Equilibrium, kinetic, pH, and thermodynamic effects. Water Resour Ind. 2013; 4: 32-50.
112. Farghali AA, Bahyat M, Allah AE, Khedr MH. Adsorption of Pb(II) ions from aqueous solution using copper oxide nano structures. Beni Suef Univ J Basic Appl Sci. 2013; 2: 61-71.
113. Ogbu IC, Akpomie KG, Osunkunle AA, Eze SI. Sawdust-kaolinite composite as efficient sorbent for heavy metal ions. Bangladesh J Sci Ind Res. 2019; 54: 99-110.
114. Sari A, Tuzen M. Kinetic and equilibrium studies of biosorption of Pb(II) and Cd(II) from aqueous solution by macrofungus (Amanita rubescens) biomass. J Hazard Mater. 2009; 164: 1004-1011.
115. Gorgievski M, Bozic D, Stankovic V, Bogdanovic G. Copper electrowinning from acid mine drainage: A case study from the closed mine Cerovo. J Hazard Mater. 2009; 170: 716-721.
116. Bhatnagar A, Sillanpää M, Witek-Krowiak A. Agricultural waste peels as versatile biomass for water purification-A review. Chem Eng J. 2015; 270: 244-271.
117. Ahmad A, Rafatullah M, Sulaiman O, Ibrahim MH, Chii YY, Siddique BM. Removal of Cu(II) and Pb(II) ions from aqueous solutions by adsorption onto sawdust of Meranti wood. Desalination. 2009; 247: 636-646.
118. Kristanti RA, Hadibarata T, Al Qahtani HM. Adsorption of bisphenol A on oil palm biomass activated carbon: Characterization, isotherm, kinetic and thermodynamic studies. Biointerface Res Appl Chem. 2019; 9: 4217-4224.
119. Babel S, Kurniawan TA. Various treatment technologies to remove arsenic and mercury from contaminated groundwater: An overview. Southeast Asian Water Environ. 2005; 1: 214-222.
120. Gupta VK, Agarwal S, Saleh TA. Synthesis and characterization of alumina-coated carbon nanotubes and their application for lead removal. J Hazard Mater. 2011; 185: 17-23.
121. Gopalakrishnan A, Krishnan R, Thangavel S, Venugopal G, Kim SJ. Removal of heavy metal ions from pharma-effluents using graphene-oxide nanosorbents and study of their adsorption kinetics. J Ind Eng Chem. 2015; 30: 14-19.
122. Anirudhan TS, Sreekumari SS. Adsorptive removal of heavy metal ions from industrial effluents using activated carbon derived from waste coconut buttons. J Environ Sci. 2011; 23: 1989-1998.
123. Mubarak NM, Sahu JN, Abdullah EC, Jayakumar NS, Ganesan P. Microwave assisted multiwall carbon nanotubes enhancing Cd(II) adsorption capacity in aqueous media. J Ind Eng Chem. 2015; 24: 24-33.

124. Kikuchi Y, Qian Q, Machida M, Tatsumoto H. Effect of ZnO loading to activated carbon on Pb(II) adsorption from aqueous solution. Carbon. 2006; 44: 195-202.
125. Akhouairi S, Ouachtak H, Addi AA, Jada A, Douch J. Natural sawdust as adsorbent for the eriochrome black T dye removal from aqueous solution. Water Air Soil Pollut. 2019; 230: 181.
126. Karthik R, Muthezhilan R, Jaffar Hussain A, Ramalingam K, Rekha V. Effective removal of methylene blue dye from water using three different low-cost adsorbents. Desalination Water Treat. 2016; 57: 10626-10631.
127. Hebeish A, Ramadan MA, Abdel-Halim E, Abo-Okeil A. An effective adsorbent based on sawdust for removal of direct dye from aqueous solutions. Clean Technol Environ Policy. 2011; 13: 713-718.
128. Khattri SD, Singh MK. Use of Sagaun sawdust as an adsorbent for the removal of crystal violet dye from simulated wastewater. Environ Prog Sustain Energy. 2012; 31: 435-442.
129. Yang J, Liang X, Jiang N, Huang Z, Mou F, Zu Y, et al. Adsorption characteristics of modified eucalyptus sawdust for cadmium and arsenic and its potential for soil remediation. Bull Environ Contam Toxicol. 2022; 108: 1056-1063.
130. Manyuchi MM, Sukdeo N, Stinner W, Mutusva TN. Influence of sawdust based biochar on gold tailings wastewater heavy metal contaminants removal. S Afr J Chem Eng. 2021; 37: 81-91.
131. Patil C, Ratnamala GM, Channamallayya ST, Belagavi K. Adsorption studies for removal of acid yellow 17 using activated rice husk. Int Res J Eng Technol. 2015; 2: 769-774.
132. Darabi SS, Bahramifar N, Khalilzadeh MA. Equilibrium, thermodynamic and kinetics studies on adsorption of eosin Y and red X-GRL from aqueous solution by treated rice husk. J Appl Res Water Wastewater. 2018; 5: 392-398.
133. Sivakumar VM, Thirumarimurugan M, Xavier AM, Sivalingam A, Kannadasan T. Colour removal of direct red dye effluent by adsorption process using rice husk. Int J Biosci Biochem Bioinforma. 2012; 2: 377-380.
134. Abbas FS. Dyes removal from wastewater using agricultural waste. Adv Environ Biol. 2013; 7: 1019-1026.
135. Asiagwu AK. Removal of tartrazine yellow dye from aqueous solution using groundnut shell as biomass: Kinetic approach. Int J Eng Res. 2018; 7: 404-411.
136. Ibrahim MB, Ibrahim AM, Haruna MA, Yaro MS. Removal of Congo red dye from aqueous solution using sugarcane bagasse and Bambara groundnut shell. ChemSearch J. 2013; 4: 22-28.
137. Ata S, Imran Din M, Rasool A, Qasim I, Ul Mohsin I. Equilibrium, thermodynamics, and kinetic sorption studies for the removal of Coomassie brilliant blue on wheat bran as a low-cost adsorbent. J Anal Methods Chem. 2012; 2012: 405980.
138. Akpomie GK, Ogbu IC, Osunkunle AA, Abuh MA, Abonyi MN. Equilibrium isotherm studies on the sorption of Pb(II) from solution by Ehandiagu clay. J Emerg Trends Eng Appl Sci. 2012; 3: 354-358.
139. Biserka B, Boris S. Kinetic analysis of the exchange process between sodium ions from zeolite A and cadmium, copper and nickel ions from solution. Sep Purif Technol. 2004; 37: 17-31.
140. Echeverria JC, Zarranz I, Estella J, Garrido JJ. Simultaneous effect of pH, temperature, ionic strength and initial concentration on the retention of lead on illite. Appl Clay Sci. 2005; 30: 103-115.

141. Das B, Mondal NK. Calcareous soil as a new adsorbent to remove lead from aqueous solution: Equilibrium, kinetic and thermodynamic study. Univers J Environ Res Technol. 2011; 1: 515-530.
142. Akpomie KG, Dawodu FA. Efficient abstraction of nickel (II) and manganese (II) from solution unto an alkaline-modified montmorillonite. J Taibah Univ Sci. 2014; 8: 134-147.
143. Nnaji CC, Emefu SC. Effect of particle size on the sorption of lead from water by different species of sawdust: Equilibrium and kinetic study. BioResources. 2017; 12: 4123-4145.
144. Alam MS. Removal of Congo Red Dye from industrial wastewater by untreated sawdust. Am J Environ Prot. 2015; 4: 207-213.
145. Suganya S, Kumar PS, Saravanan A, Rajan PS, Ravikumar C. Computation of adsorption parameters for the removal of dye from wastewater by microwave assisted sawdust: Theoretical and experimental analysis. Environ Toxicol Pharmacol. 2017; 50: 45-57.
146. Balintova M, Demcak S, Pagacova B. A study of sorption heavy metals by natural organic sorbents. Int J Energy Environ. 2016; 10: 189-194.
147. Bozic D, Gorgievski M, Stankovic V, Strbac N, Serbula S, Petrovic N. Adsorption of heavy metal ions by beech sawdust-Kinetics, mechanism and equilibrium of the process. Ecol Eng. 2013; 58: 202-206.
148. Acar FN, Eren Z. Removal of Cu(II) ions by activated poplar sawdust (Samsun Clone) from aqueous solutions. J Hazard Mater. 2006; 137: 909-914.
149. Ahmad A, Rafatullah M, Danish M. Sorption studies of Zn(II)-and Cd(II) ions from aqueous solution on treated sawdust of sissoo wood. Eur J Wood Wood Prod. 2007; 65: 429-436.
150. Shukla SR, Pai RS. Adsorption of Cu(II), Ni(II) and Zn(II) on dye loaded groundnut shells and sawdust. Sep Purif Technol. 2005; 43: 1-8.
151. Setyono D, Valiyaveettil S. Chemically modified sawdust as renewable adsorbent for arsenic removal from water. ACS Sustain Chem Eng. 2014; 2: 2722-2729.
152. Argun ME, Dursun S, Ozdemir C, Karatas M. Heavy metal adsorption by modified oak sawdust: Thermodynamics and kinetics. J Hazard Mater. 2007; 141: 77-85.
153. Salazar-Rabago JJ, Leyva-Ramos R. Novel biosorbent with high adsorption capacity prepared by chemical modification of white pine (*Pinusdurangensis*) sawdust. Adsorption of Pb(II) from aqueous solutions. J Environ Manage. 2016; 169: 303-312.
154. Hansted AL, Cacuro TA, Nakashima GT, Costa VE, Yamamoto H, Yamaji FM. Use of a lignocellulosic residue as solid fuel: The effect of ash content in the energy potential. Ind Crops Prod. 2018; 116: 209-214.
155. Shafie SM, Othman Z, Hami N. Potential utilisation of wood residue in Kedah: A preliminary study. J Technol Oper Manag. 2017. Doi: 10.32890/jtom0.0.0.9489.
156. Zhang Q, Khan MU, Lin X, Yi W, Lei H. Green-composites produced from waste residue in pulp and paper industry: A sustainable way to manage industrial wastes. J Clean Prod. 2020; 262: 121251.
157. Barbos JD, Azevedo JB, Pollyana da Silva MC, da Costa Garcia Filho F, del Rio TG. Development and characterization of WPCs produced with high amount of wood residue. J Mater Res Technol. 2020; 9: 9684-9690.
158. Meyers-Levy J, Zhu R. The influence of ceiling height: The effect of priming on the type of processing that people use. J Consum Res. 2007; 34: 174-186.

159. Oladele IO, Akinwekomi AD, Aribo S, Aladenika AK. Development of fibre reinforced cementitious composite for ceiling application. J Miner Mater Charact Eng. 2009; 8: 583-590.
160. Sanjay MR, Yogesha B. Studies on mechanical properties of jute/E-glass fiber reinforced epoxy hybrid composites. J Miner Mater Charact Eng. 2016; 4: 15-25.
161. Ichetaonye SI, Ajekwene KK, Ulaeto SB, Yibowei ME, Alosaimi AM, Hussein MA, et al. Sustainable alternative ceiling boards using palm kernel shell (PKS) and balanite shell (BS). J Polym Environ. 2021; 29: 3878-3886.
162. Martias C, Joliff Y, Favotto C. Effects of the addition of glass fibers, mica and vermiculite on the mechanical properties of a gypsum-based composite at room temperature and during a fire test. Compos B Eng. 2014; 62: 37-53.
163. Kyeongmin K, Kyung EZ, Domyung P. Incidence of cancer and asbestos-related diseases among residents living near abandoned asbestos mines in South Korea: A retrospective cohort study using national health insurance database. Int J Environ Res Public Health. 2021; 18: 2-15.
164. Mgbemene C, Rosenkranz A, Pichelin F, Lehmann M, Job C, Kimeng H, et al. Feasibility study on the production of particleboard from maize cobs, rice husks, and groundnut shells using acacia mimosa tannin extract as the bonding adhesive. J Archit Eng. 2014; 20: 04013006.
165. Sekaluvu L, Tumutegyereize P, Kiggundu N. Investigation of factors affecting the production and properties of maize cob-particleboards. Waste Biomass Valorization. 2014; 5: 27-32.
166. Khedari J, Nankongnab N, Hirunlabh J, Teekasap S. New low-cost insulation particleboards from mixture of durian peel and coconut coir. Build Environ. 2004; 39: 59-65.
167. Khedari J, Charoenvai S, Hirunlabh J. New insulating particleboards from durian peel and coconut coir. Build Environ. 2003; 38: 435-441.
168. Melo RR, Stangerlin DM, Santana RR, Pedrosa TD. Physical and mechanical properties of particleboard manufactured from wood, bamboo and rice husk. Mater Res. 2014; 17: 682-686.
169. Oh YS, Yoo JY. Properties of particleboard made from chili pepper stalks. J Trop For Sci. 2011; 23: 473-477.
170. Hiziroglu S, Holcomb R. Some of the properties of three-layer particleboard made from eastern redcedar. Build Environ. 2005; 40: 719-723.
171. Amellie J, Brochard P, Letourneux M, Paris C, Pairon JC. Asbestos-related cancer risk in the presence of asbestosis or pleural plaques. Rev des Mal Respir. 2011; 28: 11-17.
172. Hua LS, Chen LW, Geng BJ, Kristak L, Antov P, Pędzik M, et al. Particleboard from agricultural biomass and recycled wood waste: A review. J Mater Res Technol. 2022; 20: 4630-4658.
173. Dagwa IM, Builders PF, Achebo J. Characterization of palm kernel shell powder for use in polymer matrix composites. Int J Mech Mechatron Eng. 2012; 12: 88-93.
174. Edmund CO, Saffron CM, Kamdem PD. Characterization of palm kernel shell for materials reinforcement and water treatment. J Chem Eng Mater Sci. 2014; 5: 1-6.
175. Odeyemi SO, Abdulwahab R, Adeniyi AG, Atoyebi OD. Physical and mechanical properties of cement-bonded particle board produced from African balsam tree (Populous Balsamifera) and periwinkle shell residues. Result Eng. 2020; 6: 100126.
176. Isheni Y, Yahaya BS, Mbishida MA, Achema F, Karfe GS. Production of agro waste composite ceiling board (a case study of the mechanical properties). J Sci Eng Res. 2017; 4: 208-212.

177. Idris UD, Aigbodion VS, Abubakar IJ, Nwoye CI. Eco-friendly asbestos free brake-pad using banana peels. J King Saud Univ Eng Sci. 2015; 27: 185-192.
178. Kumar PR, Sreelekshmi KS, Babu Anjana S, Harikrishnan S, Nath Santhanu G, Leena VP. Role of agricultural wastes in construction industry. Int J Eng Res. 2020; 9: 66-69.
179. Sambe LN, Origbo B, Gbande S, Ande PU. Assessment of wood waste generation and utilization in Makurdi metropolis: Implication for sustainable management of forest resources. J Res For Wildl Environ. 2021; 13: 188-196.
180. Idise O, Okoko F, Aire P, Ogor O, Egbah A. The effects of solid wood waste discharge on the physico-chemical and microbial characteristics of the Warri river. Afr J Microbiol Res. 2012; 6: 4302-4314.
181. Anselm EO, Stephen NO. Mitigating the impact of climate change through waste recycling. Res J Environ Earth Sci. 2012; 4: 776-781.
182. Dukarska D, Walkiewicz J, Derkowski A, Mirski R. Properties of rigid polyurethane foam filled with sawdust from primary wood processing. Materials. 2022; 15: 5361.
183. Meyer C. Concrete and sustainable development. Farmington Hills: ACI Special Publications; 2002. pp. 501-512.
184. Mwango A, Kambole C. Engineering characteristics and potential increased utilisation of sawdust composites in construction-A review. J Build Constr Plan Res. 2019; 7: 59-88.
185. Ngandwe P, Chungu D, Ratnasingam J, Ramananantoandro, T, Donfack P, Mwitwa J. Forestry industry development in Zambia: An opportunity for public private partnership for small and medium enterprises. Int For Rev. 2017; 19: 467-477.
186. Mamza PA, Ezeh EC, Gimba E, Arthur DE. Comparative study of phenol formaldehyde and urea formaldehyde particleboards from wood waste for sustainable environment. Int J Sci Technol Res. 2014; 3: 53-61.
187. Abdulkareem S, Raji S, Adeniyi A. Development of particleboard from waste styrofoam and sawdust. Niger J Technol Dev. 2017; 14: 18-22.
188. Atoyebi OD, Adediran AA, Oluwatimilehin AC. Physical and mechanical properties evaluation of particle board produced from saw dust and plastic waste. In: International journal of engineering research in Africa. Stafa-Zurich: Trans Tech Publications Ltd.; 2018. pp. 1-8.
189. Akinyemi AB, Afolayan J, Oluwatobi EO. Some properties of composite corn cob and sawdust particle boards. Constr Build Mater. 2016; 127: 436-441.
190. Erakhrumen A, Areghan S, Ogunleye M, Larinde S, Odeyale O. Selected physico-mechanical properties of cement-bonded particleboard made from pine (pinuscaribaea m.) sawdust-coir (cocosnucifera l.) mixture. Sci Res Essay. 2008; 3: 197-203.
191. Agoua E, Allognon-Houessou E, Adjovi E, Togbedji B. Thermal conductivity of composites made of wastes of wood and expanded polystyrene. Constr Build Mater. 2013; 41: 557-562.
192. Olorunmaiye JA, Ohijeagbon IO. Retrofitting composite ceiling boards with Jatropha curcas seedcake material. J Prod Eng. 2015; 18: 96-102.
193. Iswanto AH, Febrianto F, Hadi YS, Ruhendi S, Hermawan D. Physical and mechanical properties of particleboard made from jatropha (Jatropha curcas) fruit hulls reinforced with wood particle. Jurnal Ilmu dan Teknologi Kayu Tropis. 2012; 10: 103-111.
194. Obam SO. Properties of saw-dust, paper and starch composite ceiling board. Am J Sci Ind Res. 2012; 3: 300-304.

195. Drovou S, Attipou K, Kadja K, Kassegne KA, Sanda K. Characterization of particleboards of African mahogany sawdust made with tannic powders of Bridelia and African locust bean pods. Eur J Wood Wood Prod. 2022; 80: 1175-1183.
196. Afangideh CB, Udokpoh UU. Spatiotemporal variability assessment of rainwater quality in oil and gas exploration region of Nigeria. J Hum Earth Future. 2021; 2: 355-370.
197. Nnaji CC, Afangideh BC, Ezeh C. Performance evaluation of clay-sawdust composite filter for point of use water treatment. Niger J Technol. 2016; 35: 949-956.
198. Clasen T, Brown J, Collin S, Suntura O, Cairncross S. Reducing diarrhea through the use of household-based ceramic water filters: A randomized, controlled trial in rural Bolivia. Am J Trop Med Hyg. 2004; 70: 651-657.
199. Clasen TF, Bastable A. Faecal contamination of drinking water during collection and household storage: The need to extend protection to the point of use. J Water Health. 2003; 1: 109-115.
200. Colwell RR, Huq A, Islam MS, Aziz KM, Yunus M, Khan NH, et al. Reduction of cholera in Bangladeshi villages by simple filtration. Proc Natl Acad Sci USA. 2003; 100: 1051-1055.
201. Yakub I, Plappally A, Leftwich M, Malatesta K, Friedman KC, Obwoya S, et al. Porosity, flow, and filtration characteristics of frustum-shaped ceramic water filters. J Environ Eng. 2013; 139: 986-994.
202. Erhuanga E, Kashim IB, Akinbogun L. Development of ceramic filters for household water treatment in Nigeria. Art Des Rev. 2014; 2: 6-10.
203. Cheesman SL. A feasibility study to assess the potential for red clay ceramic water filters to be reproduced by skilled artisans and an evaluation of the filters' ability to remove protozoa, bateria, and virus pathogens. Cranfield: Cranfield University; 2003.
204. Brown J. Evaluation of point-of-use microfiltration for drinking water treatment in rural Bolivia. University of Cambridge: Department of Geography, University of Cambridge; 2003.
205. Campbell E. Study of life span of ceramic filter colloidal silver pot shaped model. Managua: Agua Solutions, Inc.; 2005.
206. Ramos-Tejada M, Ontiveros A, Viota J, Duran J. Interfacial and rheological properties of humic acid/hematite suspensions. J Colloid Interface Sci. 2003; 268: 85-95.
207. Penner D, Lagaly G. Influence of anions on the rheological properties of clay mineral dispersion. Appl Clay Sci. 2001; 19: 131-142.
208. Ekpunobi UE, Agbo SU, Ajiwe VI. Evaluation of the mixtures of clay, diatomite, and sawdust for production of ceramic pot filters for water treatment interventions using locally sourced materials. J Environ Chem Eng. 2019; 7: 102791.
209. Wangrakdiskul U, Kankaew P. Utilizing sawdust and bottom ash for ecological water purifying materials produced. IOP Conf Ser Earth Environ Sci. 2021; 837: 012009.
210. Efeovbokhan VE, Olurotimi OO, Yusuf EO, Abatan OG, Alagbe EE. Production of clay filters for waste water treatment. J Phys Conf Ser. 2019; 1378: 032028.
211. Akosile SI, Ajibade FO, Lasisi KH, Ajibade TF, Adewumi JR, Babatola JO, et al. Performance evaluation of locally produced ceramic filters for household water treatment in Nigeria. Sci Afr. 2020; 7: e00218
212. Varkey AJ, Dlamini MD. Point-of-use water purification using clay pot water filters and copper mesh. Water SA. 2012; 38: 721-726.