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A review on the sustainable energy generation from the pyrolysis of coconut biomass☆

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A B S T R A C T

The negative impacts of the extraction and exploration of fossil fuel on the environment and its depletion that has led to environmental degradation have encouraged researchers, stakeholders, and the government to explore alternative and renewable energy sources such as lignocellulosic biomass. Biomass pyrolysis has proven to be a viable energy conversion process over the last decade due to its low carbon footprint on the environment. Pyrolytic products that are bio-char, bio-oil, and bio-gas have several applications and contribute to our society's industrial, commercial, and economic growth. This paper reviews the different types of pyrolytic processes using coconut biomass as a feedstock while focusing on the biomass properties that make it useful for pyrolysis and the factors affecting the process.

Introduction

The 21st-century global community faces challenges resulting from a high population boom with increased industrial and commercial activities translating into high energy demand, which results in fossil fuel depletion, increased environmental pollution, global warming, and healthy lifestyle deterioration [1]. This energy crisis led to the search for alternative energy generation sources to sustainably cater to the global energy demand [2]. Researchers have identified biomass as a sustainable, renewable, and eco-friendly energy source like sunlight, wind, water, and biomass [3–5]. Agricultural wastes are regarded as a viable energy generation source to meet the growing demands of energy consumption and assuage fossil fuel depletion and environmental degradation [6].

Biomass constitutes about 12.83% of renewable energy stock for the environment, and it is expected that its utilization would span decades to come [7]. Large quantities of biomass are generated from the cultivation, harvesting, processing, and consumption of agricultural products [6]. These residues constitute waste, with landfill considered as the viable means of treatment. Plant residues from banana, plantain, fruit peels, coconut, etc., are suitable as feedstock for thermochemical processes [8].

Energy can be recovered from plant wastes using thermochemical methods such as pyrolysis, gasification, steam reforming, hydrolysis, and hydrothermal treatment [6]. Pyrolysis is a relatively inexpensive and straightforward thermochemical

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technology that sustainably converts biomass into a useful by-product (solid, liquid, or gas) in the absence of little oxygen [9]. It has been identified and proposed as a veritable strategy to improve the combustion performance and output of biomass and reduce the environmental impact of indiscriminate use of fossil fuels, thereby achieving a sustainable and efficient clean energy generation [7]. However, prior knowledge of the biomass thermal behavior is required to improve the pyrolytic process [1].

Coconut waste is one of the most abundant biomass found in over 90 countries globally and with a global production of 62.5 million tons per year [10,11]. Coconut (*Cocos nucifera*) is cultivated extensively in tropical countries such as Thailand, India, Nigeria, and a host of other African countries, thereby leading to a large coconut residue waste generation. [12]. The large cultivation and expansion of coconut contributes to the higher generation of coconut waste biomass such as coconut husk, shell, frond, fiber, and pulp [12–14].

This work reviews the pyrolytic process of energy generation from coconut biomass wastes.

Energy generating methods

Energy systems play a crucial role in obtaining energy and converting it to the other forms of energy required for applications in different sectors such as industry, utility, building, and transportation [15,16]. Energy can be extracted directly from the environment (primary energy) and then transformed into other energy forms (secondary energy). Primary energy sources (i.e., the energy obtained directly from the environment) include non-renewable energy/fossil fuels (such as crude oil, coal, nuclear power, and natural gas), renewable energy (such as biomass, wind, solar energy, geothermal, and hydropower) and waste. On the other hand, secondary sources of energy include hydrogen, fuel oil, ethanol, and methanol [17].

Traditionally, fossil fuels have been used as a significant source of obtaining energy. However, fossil fuel energy consumption comes with several drawbacks such as air pollution, greenhouse gas (GHG) emission, and global warming with detrimental effects on the people's environment and health conditions, thereby posing adverse social and economic impacts. About two-thirds of global GHG emissions are attributed to fossil fuel energy supply and utilization. Also, fossil fuel energy is not renewable, and as such, the sustainability and preservation of natural resources have become a significant concern [18]. This has led to the use of alternative sources of energy, commonly referred to as renewable energy.

The transition from fossil fuels to renewable energy is a core strategy for developing sustainable energy systems and has become an essential aspect of the sustainable development goals. These goals aim to reduce fossil fuel utilization and greenhouse gas emissions, thereby mitigating climate change [19]. According to the sustainable development goals to limit the average global surface temperature increase below 2 °C, renewable energy can contribute a major part of reducing GHG emission while supplying two-third of the worldwide energy demand [18]. As stated earlier, renewable energy sources include wind, solar, biomass, geothermal, hydropower, and ocean energy. Energy can be obtained from these sources using different mediums. Most of the renewable energy sources are used mainly to generate electricity or heat energy except biomass, which has other applications asides from electrical energy generation. Biomass applications include thermochemical conversion to products for water treatments, carbon sequestration, composites, etc. It is safe to say that energy generation from biomass has more extensive applications than other renewable energy sources [20,21].

Renewable energy sources are not without disadvantages, but some have more drawbacks than others. Solar and wind energy have a low energy density, resulting in high land area and material requirements that have quite a significant economic impact since some of the materials required are potentially scarce and expensive to mine. Wind energy transformation requires rare earth metals for wind turbines, while solar energy transformation requires Indium and Tellurium for photovoltaic cells [22,23]. The high economic requirement of solar and wind energy makes it unaffordable for rural environments except with government or elite intervention, leading to rural development [24].

Several biological and thermochemical methods in the utilization of biomass include biochemical conversion, combustion, gasification, and pyrolysis (Fig. 1). Biochemical conversion involves enzymatic hydrolysis coupled with microbial digestion to transform sugar in lignocellulosic biomass to ethanol [25]. However, this process involves several pretreatment steps; hence, it takes a longer time and generates a low yield of ethanol. Gasification and pyrolysis aim to convert solid biomass into different chemical products, while combustion aims to convert biomass to heat energy for other applications [26]. The biomass pyrolysis products include bio-oil, bio-char, and bio-gas, while the gasification mainly converts the solid biomass to gas.

Biomass conversion has several benefits, such as zero-emission of CO_2 low emissions of SO_x and NO_x compared to fossil fuels. However, combustion has high negative environmental impacts compared to gasification and pyrolysis. Particulate emissions (NO_x and SO_x) from biomass combustion contribute largely to air pollution and fouling problems in furnaces and boilers [27]. These emissions contain toxic compounds such as polycyclic aromatic hydrocarbons (PAHs), causing serious health and pollution problems. Although biomass is renewable, the thought of biomass conversion as a sustainable means of generating energy is only half-truth [28]. However, researchers have explored several techniques to reduce particulate emissions into the atmosphere from biomass combustion. Some of these techniques include: denitrification [29], application of additives such as aluminosilicate [27], catalytic action [30] and electrostatic precipitation [31]. Biomass gasification converts solid biomass materials to a high-caloric-value gas mixture combustible and preventing NO_x emission [26]. This process is used in obtaining products with more value than the biomass itself as it is used mainly in the production of syngas and hydrogen [32]. Syngas has capacity to be used as fuel to generate electricity, or as a basis for large petrochemical products

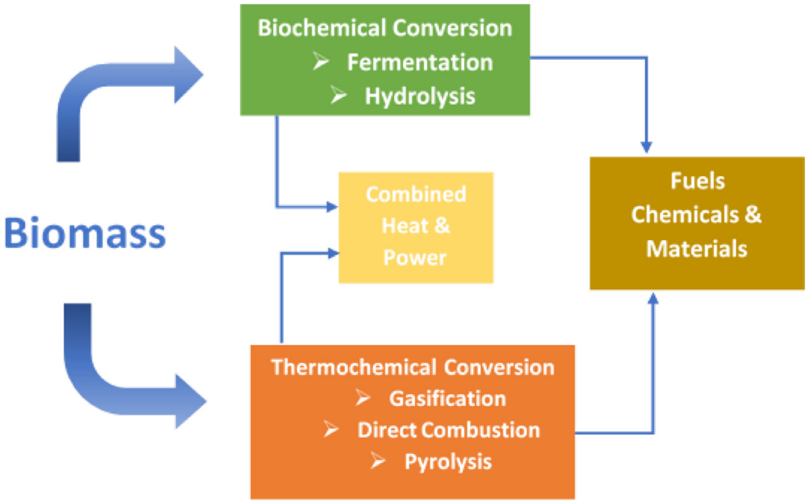

Fig. 1. Methods of biomass conversion to energy and chemicals [25].

such as ammonia, methanol, synthetic gasoline, etc. [33]. However, there are several challenges associated with gasification such as tar formation resulting in low quality gas, commercial utilization of the gaseous fuel for direct use domestically and industrially. Although there are several designs and implementation of small-scale gasifier reactors, an advanced gasification system with efficient gas conditioning technology can significantly combat these challenges [34]

Heat is supplied by partial oxidation in a gasification process but in pyrolysis, thermochemical conversion is achieved in the absence of oxygen using an indirect heat source [35]. Pyrolysis reactors are also operated at a lower temperature than gasification, which reduces the energy required for the process and hence improves energy efficiency [25]. Because pyrolysis has a low environmental impact, it takes a shorter process time and can be operated independently. In an evaluation study, Bridgwater *et al.* [36] noted that the fast pyrolysis process is proven to be a better method of power production than gasification and combustion. It was further highlighted that the fast pyrolysis step could be operated independently with the biofuel's intermediate storage, hence increasing the overall reliability of the process. An economic analysis of biomass pyrolysis, gasification, and biochemical conversion processes to produce transportation fuels by Anex *et al.* [37] also shows that biomass pyrolysis has a much lower capital cost biochemical conversion and gasification. An economic evaluation of the pyrolysis process for biofuel and electricity generation by Tursi [33] revealed that pyrolysis has higher conversion efficiency than other thermochemical processes but lower efficiency than biological processes. However, biological processes are not time efficient. Although biological conversion processes have these process reliability and efficiency, pyrolysis's economic and environmental benefits make it a preferable option for biomass conversion compared to other conversion technologies.

Biomass pyrolysis

In the last decade, pyrolysis has become one of the most promising thermochemical technologies for biomass conversion to energy-enhancing biofuels production to replace fossil fuels [38]. Biomass pyrolysis is a process by which a biomass feedstock is thermally degraded in the absence of oxygen [39]. Pyrolysis is not just an independent process; it is also the first step in the gasification or combustion process. Production of liquid fuel via pyrolysis has garnered a lot of interest due to its enormous advantages in transportation and versatility of application such as boilers, turbines, and combustion engines [40,41]. The thermochemical conversion of biomass at high temperatures in the absence of oxygen has proven feasible with relatively minimal challenges [38].

Biomass is a biological material obtained from plants or plant-derived materials that contain cellulose, hemicellulose, and lignin. It is the most abundant and renewable material for biofuel production globally, with about 100billion tons of biomass production per year [42]. Biomass is carbon neutral and has low GHG emissions due to lower nitrogen and sulphur content than in coal or petroleum [43]. Sources of biomass that can be utilized for energy include wood and wood processing wastes, crops and residues, and municipal solid waste (Fig. SM1). Biomass potentially replaces fossil fuels substantially by limiting environmental impact and can be converted into electrical/heat energy or used as transportation fuels.

According to EN ISO 17225-1:2014, standard biomass can be classified into five different groups based on ecology and vegetation type. These classifications include wood and woody biomass, herbaceous biomass, aquatic biomass; animal and human waste biomass; and biomass mixtures [33]. Varieties of these classes of biomass are presented in Table SM1. Wood and woody biomass are considered the largest bioenergy feedstock source and have been used for heat production over thousands of years. Biomass mixtures combine materials of various origins from the first four categories to produce intentionally mixed biofuels (blends) [18].

Table 1
Properties of coconut biomass.

Sample	Lignin composition (%)	Hemicellulose composition (%)	Cellulose composition (%)	Ash content (%)	Extractive content	References
Shell	29.7-53.5	23.8-27.77	29.58-65.0	1.7-3.84	4.2	[5,45–47]
Leave	32.8-45.0	56.3-67.8	32.0-44.2	2.2-6.8	2.1-6.4	[46,48–49]
Frond	18.15-21.46	22.49-31.58	39.05-43.91	4.96	6.4	[14,50,51]
Husk	25.02-42.0	25.42-27.81	29.58-54	0.92-3.95	28.48	[5,52–54]
Coir	33.0-53.5	12	35.99-44	9.0	6.0	[55,56]

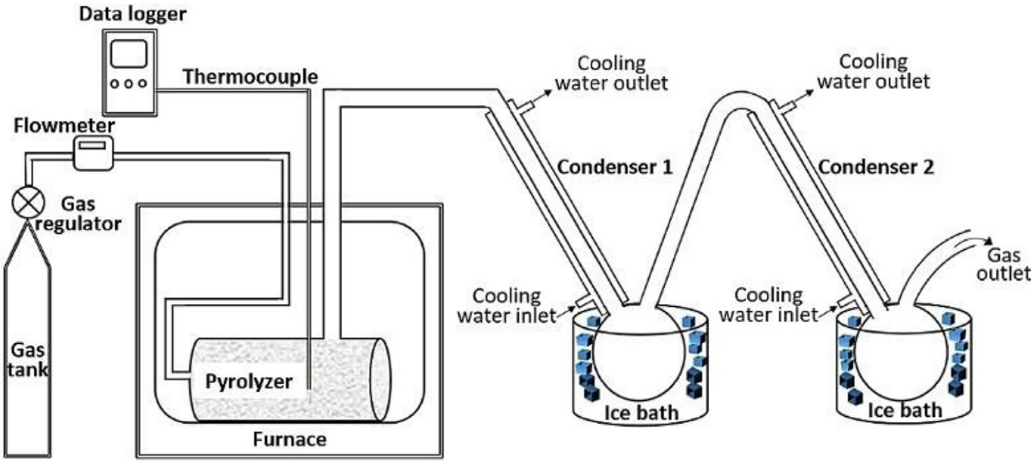

Fig. 2. Schematic diagram of the experimental set-up of slow pyrolysis [60].

Coconut biomass falls into the herbaceous biomass group. This group refers to agricultural and horticultural products and residues from the food and agricultural processing industry. Coconut waste, particularly shell and husk, is widely available since coconut is cultivated all year round, but they are mostly discarded inappropriately. With increased cultivation and coconut production over the years, the quantity of waste generated has increased dramatically since only about 40% of the plant is utilized. Coconut waste biomass is cheap, generates low carbon emissions, and consists of rigid polymers structures, including cellulose, lignin, and hemicellulose [44].

Coconut biomass has several advantages, such as high availability of waste to as low as cost, high lignin content, and low density. Due to its high lignin content, coconut shell has the highest biomass quality than other agricultural biomass such as bagasse, rice husk, coconut frond, and leaves. Properties of some coconut biomass are presented in Table 1. High amounts of lignin result in its high energy potential defined by its calorific value of averagely 20 MJ/kg, which is significantly higher than most biomass. The availability, high calorific value, low ash content, and low cost of coconut residue makes it a good potential for power plants [44].

Types of pyrolysis

The aim of biomass conversion through pyrolysis could be maximizing either the bio-oil or the bio-char yields, thereby adjusting operating parameters to achieve this. This justifies the three main biomass pyrolysis types, namely slow (conventional), fast, and flash pyrolysis [35,39,57]. They differ in heating rate, process temperature, residence time, biomass particle size, etc. The ranges of main operating parameters for the pyrolysis types are given in Table SM2 [11,39,58].

Slow (conventional) pyrolysis

Slow (conventional) pyrolysis, also known as carbonization, occurs at a relatively low temperature with a slow heating rate and long solids residence time, thereby favoring solid, liquid, and gaseous pyrolysis products significant proportions [39,57,59]. However, this process favours about 15% higher bio-char yield compared to bio-oil due to the longer retention time and relatively lower heating rates causing the formation of more carbonaceous solids [38].

Noor *et al.* [60] used an experimental set-up for the slow pyrolysis of coconut shell waste (Fig. 2). The set up included pyrolyzing the condensing parts with an additional nitrogen gas system to maintain the pyrolyzer's inert atmosphere. The pyrolysis process was conducted at temperatures ranging from 350°C to 600 °C. Other parameters indicating slow pyrolysis were the heating rate of 5 °C/min and an hour's holding time [60].

Sarkar *et al.* [10] studied the slow pyrolysis of coconut shells under varying pyrolysis temperature conditions (400-800 °C) with a constant heating rate of 10 °C/min. The bio-char yield was found to decrease from 33.6% to 28.6% as the pyrolysis temperature was increased from 400-600 °C respectively, while the output of bio-oil increased from 15.4wt% to 18.3wt% as the temperature approached 800 °C. The temperature increase also favored a higher yield of biogas [10]. This implies that temperature significantly affects coconut biomass product yield during the pyrolysis process [50].

Fast pyrolysis

Fast pyrolysis is an attractive technology for biomass conversion with bio-oil as the preferred product having great potential in industrial fuel and transport fuel applications [61]. In this process development, technologies are employed to maximize the bio-oil yield of high quality and quantity [40]. The advantages of fast pyrolysis are greater combustion efficiency, the low cost associated with storage and transportation. Fast pyrolysis technologies include reactors with varying configurations such as ablative pyrolysis reactors, vacuum pyrolysis reactors, entrained flow reactors, circulating bed, fluidized bed, and fixed bed reactors. A fast pyrolysis process main features are very high heat transfer and heating rates that require a finely ground biomass feed, carefully controlled temperature (about 500 °C; and rapid cooling of the pyrolysis vapour to give bio-oil [61]. Fast pyrolysis produces high liquid yields at elevated temperatures (400–500 °C), vapor residence time less than 5 s, and an apparent heating rate (determined by the temperature of the heating unit) of 10–200 °C/s [11,61]. The feedstock used in fast pyrolysis ranges from wood, bark, agricultural wastes/residues such as nuts and seeds, algae, grasses, and forestry residues to energy crops such as sorghum and miscanthus [62].

Fardhyanti *et al.* [63] investigated the fast pyrolysis production of bio-oil from coconut shell using a fixed bed reactor at a temperature of 500 °C, a heating rate of 10 °C, and a holding time of 1 hour. The fast pyrolysis process is provided in Fig. SM2. The bio-oil obtained was found to have a density and viscosity of 0.961 g/cm^3 and 4.359 centipoise, respectively [63]. Siengchum *et al.* [11] also observed that the coconut shell's fast pyrolysis at temperatures ranging from 500-630 °C produced CO_2 as a major gaseous product. The highest liquid yield of 68.9 % was obtained at a temperature of 630 °C with a high heating rate. In comparison, the highest char yield (38.3%) was obtained at the lowest pyrolysis temperature of 500 °C and the highest gas yield (6.6) was obtained at the mid temperature of 615 °C. This shows that high temperature and high heating rate (fast pyrolysis) favour bio-oil production while a relatively low temperature (conventional pyrolysis) favours bio-char production [11].

Flash pyrolysis

Flash pyrolysis is carried out for small particle sizes of biomass at too high temperatures, high heating rates, and very short contact times. It gives off mostly gaseous products [35,39]. It is characterized by feed particle sizes of not more than 200 µm, higher heating rates of 1000–10000°C/s and shorter residence times (<0.5 s), resulting in very high bio-oil yields of up to 75–80 wt% [57].

Alias *et al.* [13] studied the characteristics and thermal degradation behaviour of coconut pulp alongside rice husk via flash pyrolysis. The effects of particle size, heating rate and biomass properties on the pyrolysis products were studied. It was observed that particle size has an insignificant effect on the pyrolysis of coconut pulp and rice husk. It was also observed that the bio-gas yield of coconut pulp was higher than that of rice husk at the same condition, thereby making coconut pulp a promising potential feedstock for biofuel production [13].

Kinetics of biomass pyrolysis

The decomposition kinetics of biomass during pyrolysis can be described using a single-step reaction model (isoconversional methods) and multi-step reaction models (independent parallel reaction schemes) [64].

A simplified single-step global reaction expression (Eq. (1)) was assumed by [1] and [64] to calculate the kinetic parameters of biomass pyrolysis. The expression shows that biomass pyrolysis yields volatiles (gases) and bio-char, which is a solid material. Other studies have shown, however that biomass decomposition also yields bio-oil during the fast pyrolysis process [62,63]

$$\text{Biomass}_{(s)} \overset{\text{pyrolysis}}{\rightarrow} \text{Volatiles}_{(g)} + \text{Bio} - \text{char}_{(s)} \quad (1)$$

Single-step reaction model kinetics of thermal decomposition of biomass are commonly described by Eq. (2) and the conversion rate defined by Arrhenius Equation (Eq. (3)) [7,65].

$$\frac{d\alpha}{dt} = k(T)\ f(\alpha) \quad (2)$$

where α denotes the extent of conversion, f(α) is the differential reaction model, dα/dt is the instantaneous rate of reaction, and k(T) is the rate constant expressed by the Eq. (3).

$$\boldsymbol{k(T) = A\ \exp\left(\frac{-E_a}{RT}\right)} \quad (3)$$

where A is the pre-exponential factor (1/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 J/K.mol), and T is the absolute temperature (K).

$$\boldsymbol{\frac{d\alpha}{dt} = A\ \exp\left(\frac{-E_a}{RT}\right).f(\alpha)} \quad (4)$$

The extent of conversion can be expressed by Eq. (5).

$$\alpha = \frac{m_o - m_i}{m_o - m_f} \tag{5}$$

where m_o is the initial mass, m_i is the instantaneous mass, and m_f is the final mass after pyrolysis [1].

The kinetics of the thermal decomposition of biomass can be analyzed by applying different iso-conversional methods such as differentials and integrals that can solve Eq. (4) under non-isothermal conditions [64]. The most commonly used differential method for the solution of Eq. (5) is Friedman Method [66], which has been applied by several authors [1].

Integral methods are further applied to the differential solution of Friedman to determine the kinetic parameters. Some of these integral methods include Coats-Redfern, Kissinger, Ozawa-Flynn-Wall, Starink, and Kissinger-Akahira-Sunose [67–71]. These iso-conversional methods can be applied without requiring the reaction model's prior knowledge and the reaction order [1,65].

Ali *et al.* [1] compared the model-fitting and model-free methods for coconut shell waste pyrolytic conversion. They observed that the apparent activation energy estimated from the integral and differential iso-conversional methods increased with an increase in pyrolytic conversion. The average activation energies of dehydration, decomposition of pseudo-cellulose and pseudo-hemicellulose estimated from the model-fitting method were found to be 21.9 kJ/mol, 106.4 kJ/mol, and 108.6 kJ/mol, respectively.

The kinetics study aimed to understand the conversion process and design of efficient pyrolyzers for coconut shell waste pyrolysis.

Pyrolysis products

Bio-char

Bio-char (also called charcoal) is the major solid product of biomass pyrolysis with slightly higher energy content than bio-oil [72], and it is a potential tool for climate change mitigation [60]. It contains unconverted organic solids and carbonaceous residues produced from the primary decomposition of biomass at temperatures between 200–400°C, which is the most important variable in biochar production [57,73]. Since biomass mostly undergoes partial decomposition to produce bio-char, bio-chars contain a range of plant nutrients, making them valuable as soil amendments and possessing the capacity to mitigate atmospheric carbon by sequestration [34,73]. Bio-chars can also be used as a low-cost adsorbent [74,75], as a bio-composite [76] in water treatment composting [77] and as solid fuels [78].

Coconut bio-char has been found to have a higher calorific value than its corresponding biomass, and it also contains hydroxyl, methyl, ethyl, and carbonyl groups making it suitable for use as an adsorbent. Priya *et al.* [80] produced biochar from the pyrolysis of coconut shells using a downdraft gasifier. This bio-char was noted to have a higher market value and suitable for use as fertilizer.

Bio-oil

Bio-oil (also referred to as bio crude, flash pyrolysis oil, fast pyrolysis oil, or pyrolysis liquid) is a dark-colored organic liquid fuel, with about 15-35 wt% water content, It is also referred to as pyrolysis liquid, pyrolysis oil, pyrolysis tar, bio-crude, wood oil, wood liquid or wood distillate [57]. Bio-oil is a mixture of about 200 types of major and minor organic compounds and can be used as a source of some pure chemicals such as phenol, organic acids, alcohol, aldehyde, etc. [81,82]. These characteristics make bio-oil an environmentally friendly fuel, with a potentially more excellent caloric value than other oxygen fuels such as methanol [63]. Bio-oil has tremendous potential and is a valuable liquid fuel for boilers.. However, its chemical composition (oxygenated organic compounds) and specific properties such as instability and low heating value significantly limit its application [59]. In the search to make bio-oil industrially and economically attractive, researchers have adopted hydrotreating and catalytic cracking processes to eliminate oxygen from the organic molecules [41,83]. Semi-continuous and continuous pyrolysis processes have also been adopted to produce bio-oil from biomass to tackle issues of product inconsistencies across batches, high residence time, high labour cost, and difficulty in industrial scale-up associated with batch pyrolysis [84].

Bio-oil has been reported to have properties comparable to that of diesel oil and can therefore run in diesel engines. The volumetric energy density of bio-oil, which is ten times larger than that of biomass, makes it suitable for use as vehicle oil [85,86]. It can also be used as boiler fuel for heat production and stationary power and chemical extraction and retrofitting [62].

Bio-gas

Biogas is a product of the thermochemical conversion of biomass consisting of non-condensable gases (methane, hydrogen, carbon monoxide, carbon dioxide) and can be utilized to produce syngas and energy recovery [38]. Biomass pyrolysis at higher temperatures produces gas rich in hydrogen that can be applicable for use in a fuel cell system to produce electrical energy with reduced environmental impact and significant energy recovery [87]. Biogas can be burnt with liquefied

Fig. 3. Coconut wastes generated after harvesting and utilization of coconut fruit [104,105].

petroleum gas, reducing fuel usage and environmental impact [70]. It is sometimes referred to as syngas (synthesis gas) and can be used as a replacement for natural gas or converted by chemical reaction using ethanol as a catalyst [57,88].

Advances in pyrolysis techniques

Biomass pyrolysis has proven to be a promising technology for generating energy, fuels, and chemicals due to its flexibility of technology and adaptability to a wide range of biomass feedstock [58,89]. The successful commercialization of renewable fuels and the technologies being used to produce them depend on yield, production costs, and scalability [90]. Over the last decades, several reactor designs that meet the rapid heat-transfer requirements have been explored. Modern reactor designs for pyrolysis include a fixed bed, fluidized bed, heated kiln, microwave, ablative, auger, rotating cone, circulating fluidized bed, vacuum pyrolysers [35,57]

Other technologies are being considered for industrial biomass pyrolysis but are currently in the research and development stage. They include hydrothermal pyrolysis [58], microwave-assisted pyrolysis [91–93], catalytic pyrolysis [83,94], bubbling fluid bed reactors [89], and integration of biomass pyrolysis with other processes such as NOx reduction systems [95,96] and iron ore reduction [97–99]. They have advantages such as time and energy savings, low carbon and greenhouse gas emission [92].

Although there has been rapid growth in biomass pyrolysis, there are still barriers and challenges to overcome in order to utilize the full potentials of the pyrolysis processes. Some of these challenges include poor product quality, low overall energy efficiency, the unreliability of reactors and processes, limitations in reactor scalability and process integration [57,92]. Recent technological improvements have shown that fast pyrolysis will become a more commercially viable pyrolysis technology since it addresses logistical and technical challenges [58].

Valorization of coconut biomass for energy generation

Biomass is the generic term for the plant (phytomass) and animal (zoomass) matter [100]. All biologically produced matter are described by the term biomass [39]. Plant residues have been recognized as renewable energy sources that serve as an alternative to depleting fuel resources [101]. Lignocellulosic biomass constitutes mainly of cellulose, hemicellulose, lignin, and other organics. The primary chemical elements of coconut biomass include holocellulose, lignin, and extractives such as oils, waxes, and resins [5,102]. Coconut biomass contains 45% cellulose, 35% hemicellulose, and 15% lignin, and each component is decomposed at different rates during pyrolysis [69]. As seen in Fig. 3, waste generated from harvesting and utilization of coconut fruit includes coconut shell [1,103], coconut skin, coconut husk [65], coconut pulp [13].

Physical and chemical properties of coconut biomass

Biomass samples are characterized to determine the elemental analysis, heating value, ash content, and moisture content [8]. Several researchers have performed the proximate and ultimate analysis of coconut biomass to determine the physico-chemical properties of different coconut residues (Table 2).

Biomass analysis is an essential process in biomass energy conversion. Proximate analysis is carried out to obtain the percentage of inorganic waste material (ash) and the percentage of the material that burns in gaseous state (volatile matter)

Table 2
Properties of Coconut Biomass.

Coconut Biomass	Proximate Analysis (wt %)				Ultimate Analysis (wt %)				Heating Value (MJ/kg)	Reference(s)
	Moisture	*Volatile matter*	*Fixed Carbon*	*Ash*	*C*	*H*	*N*	*O*		
Frond	0.37	89.96	5.37	4.67	42.81	7.23	-	49.19	-	[50]
Frond	7.08	78.03	17.01	4.96	34.01	7.71	0.46	59.92	17.77	[14]
Husk	11.28	91.81	5.88	2.31	44.83	6.16	0.79	48.22	18.15	[65]
Husk	0.18	84.13	15.54	0.33	47.36	1.43	7.02	44.16	-	[50]
Husk	9.96	72.60	15.21	2.23	48.95	5.40	0.40	43.10	-	[5]
Leaf	4.77	87.75	12.92	6.33	47.89	6.19	1.66	37.93	20.83	[4]
Pulp	9.55	67.83	22.30	0.45	39.44	6.14	0.50	-	17.03	[13]
Shell	3.29	73.8	19.40	6.78	46.77	5.61	0.79	46.83	18.64	[65]
Shell	10.70	79.18	20.26	0.56	47.94	6.41	0.10	45.56	17.35	[103]
Shell	7.82	79.91	12.04	0.23	39.22	4.46	0.22	56.10	9.62	[10]
Shell	10.70	68.20	21.60	0.60	48.60	6.00	0.10	44.20		[106]
Shell	3.65	44.47	48.81	2.77	73.92	5.60	3.0	-	-	[87]
Shell	10.10	75.50	11.20	3.20	64.23	6.89	0.77	27.61	20.15	[107]
Shell	4.42	91.03	7.92	1.05	58.33	14.33	1.32	24.65	28.85	[60]
Skin	13.19	87.99	11.51	0.50	47.43	6.16	0.62	45.79	18.98	[65]

in the solid state (fixed carbon). On the other hand, ultimate analysis is used to determine the elemental composition of the biomass [87]. Fixed carbon is the biomass component that does not constitute volatile matter, moisture, or ash, while ash content refers to the biomass minerals [3].

The data presented in Table 2 shows that coconut residues have varying analytical values attributed to varying cultivation and harvesting conditions of the coconut plant. It was noted that coconut residues have high volatile matter content, with coconut frond/leaf relatively having the highest range. High volatile matter favours the pyrolysis process. The low ash content of coconut residues prevents aggregation in experimental procedures and allows coconut char to serve as an excellent fuel for carbon fuel cells [10,11]. Although some of the residues have low moisture content and can be used directly, some others with moisture content above 5% still need to be dried before use as pyrolytic products to enhance the pyrolysis products' quality. High moisture content reduces bio-oil yield as it influences the outcome of pyrolysis liquid [107].

Studies also show that coconut shell is the most commonly used coconut biomass for pyrolysis. A researcher noted that coconut shell is more suitable for the pyrolysis process as it contains lower ash content, high volatile matter content and low carbon and methane emissions [88].

Biomass conversion processes

Various biomasses such as agricultural residues, city wastes, and forestry products are abundantly available globally. They can be used for energy production, from old direct burning to modern gasification and pyrolysis [1]. The conversion technologies for utilizing biomass can be separated into direct-combustion, thermochemical and biochemical processes [39,88].

Direct combustion process

Direct combustion is one of the oldest and most used processes through which heat energy can be obtained. It can be used in the drying of agricultural products and heat and steam generation [64]. In this process, oxygen is used as an oxidizing agent while the temperature is being increased. Biomass can be utilized by direct combustion process to produce heat energy or power generation. However, this process has several drawbacks: low efficiency, undesirable ash buildup, and high CO_2 emission [100]. Another disadvantage is that biomass combustion cannot be used as a high-temperature heat source as required by specific applications [108].

Biochemical process

Biochemical processing of biomass utilizes enzymes and microorganisms to decompose and transform lignocellulosic biomass into biofuels and other useful chemicals. This process however, takes days to complete and, as such, gives a low process efficiency [25,100].

Thermochemical process

This process involves the conversion of biomass by the action of heat [5]. These processes have shown great potential as an alternative for fossil materials in many energy applications [62,109]. The most current techniques include gasification, pyrolysis, and combustion according to operating conditions. However, further research is required to improve the quality of the products obtained both at intermediate and final points of the processes.

Table 3
Coconut biomass pyrolysis parameters.

Biomass	Temp(°C)	Heating Rate(°C/min)	Retention time (min)	Yield (wt %)			Reference(s)
				Char	Oil	Gas	
Coconut Fiber	700	30	15	29.89	13.20	28.50	[73]
Coconut Husk	900	10	-	34.60	17.30	26.90	[5]
Coconut Pulp	700	50	14	19.57	-	80.43	[13]
Coconut Pulp	700	80	9	16.56	-	83.44	[13]
Coconut Shell	500	10	60	-	-	-	[63]
Coconut Shell	500	75	20	38.3	55.9	5.8	[11]
Coconut Shell	630	75	20	25.4	68.9	5.4	[11]
Coconut Shell	615	175	20	32.4	61.0	6.6	[11]
Coconut Shell	900	10	-	24.30	25.50	26.30	[5]
Coconut Shell	575	20	-	26.50	49.50	24.00	[107]

The gasification of biomass for power generation has some disadvantages. It needs coupling between gasification and power generation units and the difficulty of storage, transportation, and handling of gaseous fuels [2].

Factors affecting coconut biomass pyrolysis

There are quite many parameters that influence the biomass pyrolysis process, product yield, and properties. These factors include the biomass type, temperature, biomass pretreatment (physical, chemical, and biological), heating rate, reactor type, reaction atmosphere, co-reactant, and vapour residence time [13,57]. Before pyrolysis, coconut biomass samples are mainly washed with distilled water, dried in an oven, crushed or ground using a hammer mill [63] or rotary grinder [11] then sieved into the desired sizes. The heating rate of pyrolysis could range from 10-200 °C/min.

Bhad *et al.* [6] conducted the slow pyrolysis of coconut shells to determine the effect of heating rate, pyrolysis temperature, and particle size on the product yield. It was noted that the pyrolysis temperature and particle size had a more significant effect on the product yield than the heating rate and residence time.

Table 3 shows the yield of pyrolytic products obtained from the conventional, fast, and flash pyrolysis of coconut biomass as conducted by selected researchers. It can be observed from the table that the pyrolysis of coconut biomass is performed at a temperature range from 500 °C to 900 °C. The data also shows that higher temperature (700 °C and above) with correspondingly high heating rate results in a high yield of biogas with low bio-oil yield and an intermediate yield of biochar.

Biomass pretreatment

The feedstock biomass preparation facilitates the required heat transfer rates and is determined by the preferred product. Biomass pretreatment methods include thermal (drying, torrefaction, hot water treatment); physical (crushing and grinding); biological (fungal, enzymatic, and microbial); chemical (acid/base treatment), and a combination of any of the above pretreatment methods [57,84].

Coconut biomass particle size significantly influences the heating rate, making it an essential parameter in the biomass pyrolysis process. Smaller particles enhance heat and mass transfer, allowing for uniform temperature within particles during pyrolysis, thereby strengthening the bio-oil production and limiting the char formation. However, excessively smaller or larger feed size negatively affects bio-oil production [57,61,101]. Studies have shown that coconut biomass is crushed [110], blended [4], ground [107], and then sieved before pyrolysis. However, the biomass size used depends on the type of pyrolysis to be utilized, which in turn depends on the desired pyrolysis product (Table 2).

Coconut biomass is dried to increase the efficiency of the pyrolysis process and improve the quality of the products. This involves reducing the moisture content as high moisture content can lead to phase separation in the products obtained, especially bio-oil [57,111,112]. However, the extremely dry biomass feedstock can lead to high carbon deposition during pyrolysis [87]. Therefore, moisture content ranging from 10-12 wt% is recommended for quality biomass pyrolysis [84].

Drying methods to reduce coconut biomass moisture content include solar drying, waste heat drying, sun drying, and oven drying. Studies have shown that coconut biomass is either sun-dried [106], oven-dried [4,60], or both sun and oven-dried [107] before being fed into the pyrolysis reactor. Other pretreatment processes are also carried out on coconut biomass before pyrolysis to remove the inorganic materials present, including hot water treatment [106].

Temperature

Temperature is the parameter that mainly influences the amount of heat available for biomass decomposition during pyrolysis. It affects the yield variations in the different pyrolysis products (oil, gas, and char) [4,84].

Noor *et al.* [60] investigated the effect of temperature on the yield and properties of biochar obtained from coconut shell waste's slow pyrolysis. The pyrolysis temperature varied from 350 °C to 600 °C with a heating rate of 5°C/min. It was observed that an increase in temperature from 350 °C to 600 °C reduced the bio-char yield from 23.54 wt% to 13.97 wt% with a significant effect on biochar properties and composition. An increase in pyrolysis temperature produced significantly reduced the volatile matter content in the bio-char and lower hydrogen and oxygen content [60].

Joardder *et al.* [114] observed the effect of temperature on the product yields during the coconut shell pyrolysis over a temperature range of 400-600 °C. It was observed that liquid yield increased and attained a maximum value of 35 wt% at 450°C, after which it decreases until it reaches the minimum yield value (25 wt%) at 600 °C. On the other hand, the char yield decreased with an increase in temperature while the gas yield increased over the temperature range. Similar observations were also noted by [79].

Heating rate

The fundamental parameter that defines the biomass pyrolysis type (flash, fast, and slow pyrolysis) is the heating rate [57]. An increase in biomass heating rate during pyrolysis improves the maximum rate of decomposition of biomass [111]. Fast pyrolysis is characterized by high heating rates (10-200 °C) with short vapour residence times, while the slow pyrolysis process has low heating rates (5-20 °C) with longer vapour residence time. Flash pyrolysis is described by higher heating rates ($>$1000 °C) and short vapour residence time, which may result in maximum oil yield [84]. Higher heating rate promotes the evolution of pore structures in the bio-char, thereby enhancing its capacity for adsorption [115].

Pranoto *et al.* [79] investigated the effect of heating rates and final temperatures on coconut biomass pyrolysis to determine their influence on biochar physical and chemical properties. It was noted that the heating rate during pyrolysis does not have any significant effect on the chemical composition of biochar, but the final temperature affects it. However, both the heating rate and temperature of the biochar product's calorific value and activation energy were affected. It can be noted that a change in heating rate and final temperature of pyrolysis will, in turn lead to a change in the quantitative ratios between the solid, liquid, and gas pyrolysis products [116].

Vapour residence time

Shorter residence time enhances quick removal of organic vapours from the reactor, minimizing secondary reaction and favouring bio-oil production [57]. The lower the vapour residence time, the higher the liquid (bio-oil) yield. Fast pyrolysis process with concise vapour residence time produces higher bio-oil followed by immediate pyrolysis process. In contrast, a slow pyrolysis process with a longer vapour residence time gives a low bio-oil yield [84].

Reactor type

In the pyrolysis process, the reactor used is determined by the type of pyrolysis to be employed for use in the process. Drum, rotary, screw feed/auger reactors are commonly used for slow pyrolysis processes [5,58,101]. A fast pyrolysis process, on the other hand, requires the use of various types of the reactor such as fluidized bed reactor [61,112], tandem micro-reactor [8,113], ablative [117], and sometimes fixed bed reactors [87]. Other rector types used in pyrolysis include circulating fluidized bed, microwave, ablative, auger, rotating cone, vacuum, and solar reactor, which has the advantage of using renewable energy sources in heating [35].

Applications of coconut biomass pyrolysis

The pyrolysis of coconut biomass has been used to produce several pyrolytic products that have great potential industrially, commercially, and economically. Pyrolytic products obtained from coconut biomass pyrolysis and some of their respective applications include biochar from coconut shells used as carbon sorbents [116]; bio-oil from coconut fiber and shell used as diesel fuel [86]; coconut shell to produce crude oil [106]; extraction of phenol from coconut shell bio-oil [81]; coconut pith bio-chars for mercury adsorption [75]; syngas production from coconut shell pyrolysis [80].

Knowledge gap

An overview of this paper shows that coconut shells are used more often as a feedstock for biomass pyrolysis than other residues from the coconut plant. The use of other residues such as coconut husk, coconut leaf/frond, and coconut pulp is not adequately studied (within the authors' search scope). Also, little attention is paid to the economic/financial feasibility studies of coconut biomass use as pyrolysis feedstock. These perspectives represent potential areas for future research.

Conclusion

This work gives a summary of the processes involved in the pyrolysis of coconut biomass. The methods of energy conversion from biomass were evaluated, and it was noted that pyrolysis is more suitable due to high conversion efficiency, energy efficiency, and low cost. The properties of coconut biomass were discussed. It was observed that coconut shell is more commonly used as a feedstock for biomass pyrolysis than other coconut residues such as coconut husk, frond, leaf, and pulp. This may be attributed to the abundance of coconut shell since it constitutes a larger part of the coconut fruit, and the shell's balanced properties as moisture content, volatile matter, fixed carbon, and ash content making it a suitable feedstock for biomass pyrolysis. The utilization of coconut biomass as an alternative energy resource provides an economically viable means of safe disposal. The kinetic parameters of pyrolysis as well as factors affecting pyrolysis parameters such as heating rate, temperature, particle size, and moisture content on the pyrolysis process and product quality, were also examined. Knowledge gaps and possible future research perspectives were also highlighted.

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The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Supplementary materials

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