

The Contribution of Pyrolysis of Water Hyacinth to South Africa's Low-carbon and Climate Resilient Economy Transition: A Mini Review

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Abstract – South Africa is a carbon-intensive country, with coal dominating the indigenous energy resource base; however, targets have been set to reduce the national carbon emissions. The transition from coal to cleaner sources of energy generation can be encouraged by the administration of new technologies. Hence, the study aims to review research progress on the pyrolysis of water hyacinth as a tool for the smooth transition to low carbon and climate-resilient economy. Water hyacinth is suitable for energy recovery due to its high carbon content and heating value. The outcome shows that pyrolytic products such as liquid, char and non-condensable gas fractions are beneficial. This paper contributes to policy and research deliberations on promoting and adopting pyrolysis technology in addressing South Africa's energy crisis and water hyacinth invasion.

Keywords – Bioenergy, water hyacinth; pyrolysis; South Africa; low-carbon economy.

1. INTRODUCTION

South Africa is the 12th top emitter of greenhouse gas (GHG) emissions globally, with coal dominating the indigenous energy resource base [1], [2]. At COP26, some partner countries (United States, United Kingdom, and European Union) pledged \$ 8.5 billion for South Africa to end its dependence on coal and transit to a greener economy [2]. The government set a target to decrease national carbon emissions to 350–420 CO₂-eq by 2030 [3]. According to the World Bank Group [4], the South African Country Climate and Development Report proposed three interrelated transitions: decarbonising, resilient and just. While decarbonising and resilient transitions necessitate the revamp of the energy sector and the development and deployment of renewable energy technologies, just transition ensures that jobs are created, poverty is relieved, and natural systems are resilient. Biomass is considered a renewable energy source with the utmost potential for sustainable development [5] because most nations have available biomass resources, and biomass can deliver all forms of energy in demand

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(biofuel, electricity and heat). According to IEA Bioenergy [6], biomass makes up 85 % of the renewable energy in South Africa; however, earlier in 2016/2017, biomass was not considered cost-effective to replace coal within the Biomass Action Plan for Electricity Production in South Africa (BAPEPSA). Nevertheless, with the pledge from the partner countries at COP26, exploring energy from biomass may be reconsidered.

Water hyacinth (*Eichhornia crassipes*) is a biomass source with terrific possibilities for energy recovery [7]. Its use as a bioenergy source is recommended as it does not compete with land use, food production and water resources [8]. *Eichhornia crassipes* is an aquatic invasive plant that is threatening the water-scarce country and affecting the pillars of sustainability. Several control measures have been implemented to mitigate the weed; however, the different control measures have not been entirely effective due to the plant's fast growth rate and high control cost. Therefore, its use as a biomass source is recommended because it does not compete with land use, food production and water. There are two significant conversion routes for water hyacinth biomass to bioenergy; the biochemical route, such as anaerobic digestion and the thermochemical route, such as pyrolysis, gasification and combustion [9], [10]. While anaerobic digestion has been considered because it adapts to an extensive spectrum of substrates, nutrient retrieval, and net energy output [11]–[13], pyrolysis is also reflected as one of the utmost suitable and sustainable thermal conversion processes utilised in converting biomass to bioenergy because of its simple operation and modest investment amount [14].

Pyrolysis is the thermal devolatilisation of materials in the absence of oxygen, resulting in the production of char residue and volatile products, condensable liquid fraction and non-condensable gas [15]–[17]. The pyrolytic product yield results from both the substrate's primary decomposition reactions and the consequent secondary reactions of the primary volatiles. The secondary reaction magnitude depends on the pyrolysis conditions and reactor type. Pyrolytic products are valuable; biochar is utilised as an agricultural soil amendment as it improves the properties of the soil, reduces GHG emissions and increases the crop yield [18]. It can also be used as activated carbon [19], building materials [20] and environmental detoxification. The liquid fraction and the non-condensable gases, which constitute various gases, methane (CH₄), carbon dioxide (CO₂), hydrogen (H₂) and carbon monoxide (CO), can be used as biofuels [21]. The liquid fraction comprises numerous chemicals with specific high-quality and added-value purposes.

The pyrolysis of water hyacinth biomass has not been explored in South Africa; prior studies focused significantly on the pyrolysis of waste tyres [22], [23]. Therefore, this study which builds on previous reviews, aims to provide a comprehensive technical overview of pyrolysis and assess the role of the pyrolysis of water hyacinth in South Africa's low-carbon and climate-resilient economy transition. With the country's continuous struggle with frequent blackouts due to insufficient energy generation capacity, this review can address South Africa's energy crisis and water hyacinth invasion and add to socio-economic development. Furthermore, the study taps into the present socio-economic problems currently experienced in South Africa, such as unemployment and poverty, for a just transition. The rest of this paper is structured as follows: Section 2 describes the need for a low-carbon economy transition, and Section 3 explains how pyrolysis can aid South Africa in a smooth transition to a low economy. Section 4 provides background information on the classification of pyrolysis, different reactor types and process parameters to increase pyrolytic product yield, and Section 5 draws the main conclusions of this paper.

2. THE NEED FOR SOUTH AFRICA'S LOW CARBON ECONOMY TRANSITION

At the COP21, which took place in Paris in December 2015, some countries pledged to regulate global warming to less than 2 °C and follow through with the 1.5 °C targets. As such, energy transition has persistently been strengthened in numerous sectors of the economy with the assistance of technological changes, cost-efficient renewable energy and impressive public guidelines [24]. The International Renewable Energy Agency [25] established a Global Renewable Energy Roadmap (REmap 2030), which requests for the portion of renewable energy in the global energy mix by 2030 to be intensified. The purpose of REmap 2030 is to make biomass the most vital renewable resource by 2030, to account for 60 percent of universal renewable energy usage and dominate end-use sectors. Biomass is, therefore, considered a prospective source of carbon-based fuels and chemicals in the transition to a low-carbon economy. South Africa is considered to have significant biomass potential; however, most of the biomass is not fully exploited; they are not for lucrative purposes and are mainly utilised in cooking and heating [26], [27].

While South Africa's energy sector is accountable for over 80 percent of the country's greenhouse gas emissions, mainly due to the consumption of coal for generating power and the synthetic fuel industry [28], several policy mediations, such as Integrated Resource Plan 2019 (IRP2019) and introduction of a carbon tax have been recommended to mitigate emissions in this area. The IRP2019 is aimed at decommissioning over 35 GW out of 42 GW of the coal-fired power capacity by 2050, and the carbon tax aims to provide for the levying of a tax on the carbon dioxide equivalent of greenhouse gas emissions. However, according to PwC South Africa [28], carbon taxes are inappropriate to be charged on power generation in South Africa as consumers are already severely taxed on their energy use. Instead, other suitable mechanisms such as energy mix and energy efficiency regulation, incentives and subsidies, and sensitisation should be applied in mitigating carbon emissions in the energy sector. For South Africa to be compliant with the Paris Agreement goals, there would be a need to implement further progressive climate action beyond the IRP2019, such as further expanding renewable energy capacity by 2030, ending the intended commissioning of 1.5 GW of new coal capacity, complete discontinuation of coal-fired power generation by 2040, and circumventing investment in natural gas [29].

Pyrolysis technology can aid in South Africa's transition to a low-carbon economy. The technology is not a new concept; however, its application has been limited to inorganic feedstocks such as waste tyres [22], [23]. As such, the application of this technology on water hyacinth biomass has not been explored. Since the introduction of water hyacinths in South Africa, it has caused considerable damage to the pillars of sustainability. For instance, the infestation of Hartbeespoort Dam, the largest and most active dam in the country, has been a major concern. Numerous efforts have been made to control the spread of these invasive alien plants from the dam without much achievement. Utilising this aquatic weed for environmental and financial gains has received attention in recent times as a means of mitigation. *Eichhornia crassipes* have been applied in the production of bioenergy, phytoremediation, animal feed, enzyme and high-value chemicals [8]. Considering the need for a substantial change from conventional fuels to bioenergy, the use of water hyacinth in pyrolysis technology is suitable [14], [15].

Incorporating pyrolytic products into South Africa's energy sector will assist in diversifying the energy source for electricity production, providing a substitute for the tenacious dependence on crude oil import for transportation and increasing crop yield for food security. Biobased chemicals, which offer a substitute for conventional petroleum derivative products, are considered to increase the lucrativeness and environmental benefits of the technology. It

is, therefore, essential to develop and deploy biorefineries and develop and commercialise engineered char for environmental remediation. However, according to Ramokgopa [30], the unavailability of infrastructure and financing are some of South Africa's difficulties in a low-carbon economy transition. Although, through partnerships both nationally and globally and frameworks that make low-carbon productivity a priority, the transition could be effective. For instance, the Development Bank of Southern Africa [31], which adheres to agenda that confirms that the socio-economic transition from conventional fuel economies to low carbon economies is equitable and just, has performed a substantial part in funding the execution of the Renewable Energy Independent Power Producer Procurement Programme (REIPPP).

3. THE ROLE OF THE PYROLYTIC PRODUCTS

Pyrolysis has great prospects in converting biomass into energy and other valuable products for sustainable benefits. The products are solid (char), liquid (biofuel), and gaseous (syngas) fractions, and each yield depends on the operational conditions.

3.1. Char

Char is a carbon-rich biomaterial that is attained through pyrolysis. It is an emerging economy with a vast market prospect. Char offers an efficient means of eradicating carbon from the atmosphere; however, its suitable use necessitates a good understanding of its constituents and physical attributes. The following are the applications of char in industrial processes.

3.1.1. Activated carbon

Char, which has a high specific surface area, great macro porous make-up, and improved functional groups on its surface, in addition to a minor cost of substrates and production process, can also be an antecedent of valuable activated carbons [19], [32], [33]. Li, Chang [32] investigated the production of sludge-activated carbon (SAC) from pyrolysis char of sewage sludge and its adsorption performance for organic compounds in sewage; the resulting SAC is considered to be exploited as a low-cost adsorbent with good surface properties. Activated carbon is commonly relevant as an adsorbent in water treatment and air pollution control, and energy-storage technology; however, it has been revealed that biochar has potential sorption properties for several pollutants of water as well as polycyclic aromatic hydrocarbons and heavy metals [34]. The efficient application of biomass for activated carbon production will not only aid in mitigating environmental concerns, for instance, as a result of coal mining. However, it will also make the creation of sorbents utilised in water treatment and wastewater recovery to be cost-effective.

3.1.2. Soil conditioner

Char can be applied as a soil amendment to increase soil properties due to many interesting features; high pH, surface area, carbon content and porosity. Its porous characteristics permit it to adsorb other chemicals and minerals, averting these nutrients from leaching out of the soil and making them more accessible for plant use. Each biochar is unique and has different chemical and physical properties. For instance, Glazunova, Kuryntseva [35] assessed the potential of biochar as a soil conditioner using two biochar made from chicken manure (ChM) and sewage sludge (SS). The biochar samples were alkaline, signifying the ability to neutralise acidic soils. However, the germination index estimated for soil treated with SS

biochar was 97 percent, while soil treated with ChM biochar was lower at 78 percent. Char is considered to increase the valuable microorganisms' activity in the soil [36]. According to Dai, Xiong [37], soil microorganisms perform critical roles in soil nutrient cycling, carbon sequestration, fertility maintenance and crop health and production. Another characteristic of biochar that is vital for crop production is water retention for plants' usage, hence encouraging crop growth and reducing demand for irrigation. Char is often mixed with compost and other soil amendments before it is applied to the soil to improve food security.

3.1.3. Carbon sequestration

The growing reliance on conventional fuels has eventuated enormous CO₂, thereby causing global warming. There is substantial awareness of discovering reliable approaches to sequester carbon to reduce atmospheric greenhouse gas. Therefore, char is a possibly carbon-negative energy resource and a vital carbon sequestration product that could decrease atmospheric CO₂ levels [38], [39]. The possibility of using char for carbon sink has recently gained attention as a way of mitigating climate change whilst supplying energy and improving crop production through advanced climate-smart agriculture. According to Woolf, Amonette [39], sustainable global implementation of biochar can possibly balance up to 12 % of present anthropogenic CO₂-C equivalent (CO₂-Ce) emissions, and the total net offset from biochar would be 130 Pg CO₂-Ce over the course of a century. Substantial research has commenced to ensure that char sequestration pathways are adequately regulated.

3.1.4. Animal feeding

Biochar's use as feed additives for animal farming is a result of using activated charcoal to treat digestive illnesses in humans and animals. Livestock farmers are progressively exploiting biochar as a regular feed additive to enhance animal growth and health, boost nutrient intake efficacy and, subsequently, yield [40], [41]. The high adsorption rate of biochar reliably helps in the elimination of contaminants and toxins from the body of the animals and the surroundings. Eger, Graz [42] opined that biochar's high porosity offers an abode for gut microbes, such as methanogenic archaea, of cattle and goats, thereby reducing the generation of methane and consequently adding to the alleviation of greenhouse gas (GHG) emissions. Nevertheless, the World Health Organisation, Food and Agriculture Organisation of the United Nations and European Biochar Foundation have stringent guidelines to ensure feed-grade biochar is safe as feed supplements.

3.2. Liquid fraction

The pyrolytic product, liquid fraction, is a multifaceted mix of molecules such as water and organic compounds emanating after the depolymerisation of lignin, cellulose and hemicellulose [43], [44]. Its heating value is almost half of the fossil fuel and can function as an alternative to fuel oil or diesel for various heat and power purposes [45]. It also has insignificant SO_x and NO_x emissions and no CO₂ and greenhouse gas emissions [46]. The liquid fraction is an attractive source of bio-based chemicals, including acids, alcohols, aldehydes, ketones, esters, phenols, furans, alkene, aromatics, nitrogen compounds, and miscellaneous oxygenates, that meet significant market interest [47]. Sustainably produced bio-based chemicals present numerous advantages, not merely for reducing greenhouse gases but for enlivening rural areas and developing innovative biobased creation methods.

Although the liquid fraction is deemed more inefficient based on fuel combustion when likened to fossil fuels due to its high oxygen content that consequently results in excessive combustion complications, the improvement of its properties has become a major concern in

recent years. Nonetheless, the liquid fraction's quality is improved to substitute for crude oil by upgrading catalytic cracking, esterification or emulsification, co-pyrolysis, and pretreatment [46], [48], [49]. Attributes such as viscosity, pour point, density, flash point and diesel index are predominately used as indicators for the fuel quality of the liquid fraction.

3.2.1. Catalytic upgrade

The liquid fraction is relatively unstable, viscous, susceptible to ageing, corrosive and has high oxygen content; therefore, its direct application as conventional fuel is not generally accepted [44], [46]. Furthermore, liquid fraction polymerises when heated to relatively low temperatures and high-water content; however, it can be upgraded for stability and compatibility with machinery. Catalytic upgrade is considered the most auspicious method for enhancing the composition of the liquid fraction [50] and catalysts with the ability to alter the long chain and promote the formation of aromatic hydrocarbons are widely used. Catalysts enhance the thermal degradation of biomass into pyrolytic products by biomass cracking, hastening reaction and selection of products and upgrading of liquid fraction. The commonly utilised catalysts are metal, Ni-based, alkali metal and dolomite catalysts. Catalytic upgrade reduces the char fraction of the products, thereby resulting in relief of the ageing of the liquid fraction and considerably increasing the aromatic yields. In many cases, either the catalyst's cost or the catalyst's deactivation and poisoning make the process less attractive [51].

3.2.2. Co-Pyrolysis

It is the process of utilising more than one substrate to enhance the quality and yield of pyrolytic products while curtailing energy use. According to Jarvik, Sulg [52], co-pyrolysis is a viable intermittent stride to attaining a carbon-neutral economy. Factors such as substrate type, heat rate, temperature and the blending ratio of the substrates affect the quantity and quality of pyrolytic product yield during co-pyrolysis. An increase in blending ratio is considered to reduce char production and increase the liquid and gas fractions, while the heating rate favours the synergy of substrates. Emdadul Hoque and Rashid [48] investigated the co-pyrolysis of rice straw with water hyacinth and found that the calorific value of the liquid and gas fraction in the co-pyrolysis process for rice straw and water hyacinth was greater than the calorific value of product yield from only water hyacinth or rice straw.

3.2.3. Pre-treatment

The liquid fraction comprises molecules rising from the disintegration of cellulose, hemicellulose and lignin. Feedstocks with higher cellulose content, higher heating value and lower lignin, ash, oxygen and sulphur content are regarded to increase liquid fraction yield [53]. However, employing new processing approaches and pre-treating the biomass before pyrolysis also enhances the liquid fraction quality, as pretreatment destroys the lignin and hemicellulose structures and increases the accessibility of cellulose [46]. Diverse pretreatment techniques have surfaced as auspicious substitutes with technical solutions to the poor characteristics of liquid fractions; they include physical, chemical, thermal, biological and integrated methods. According to Alvarez-Chavez, Godbout [46], while physical pretreatment is applied in altering the structure and size of the feedstock particles in order to increase heat transfer, thermal pretreatment is anticipated to decrease the hemicellulose content to generate liquid fraction with minor carboxylic acids and oxygenates contents; chemical pretreatment is employed in demineralising the biomass to evade secondary reactions of volatile cracking, and the biological pretreatment is utilised in liberating cellulose enclosed by the hemicellulose and lignin contents. Nonetheless, of all

pretreatment techniques, a biological method is considered sustainable due to its low energy utilisation and improved environmental footprint.

3.3. Non condensable gas

The non-condensable gas comprises primarily carbon dioxide (CO₂) and hydrocarbons such as methane (CH₄), carbon monoxide (CO) and hydrogen (H₂); other compositions are subject to feedstock type and operational conditions [45], [54]. As the gas has fundamental constituents of syngas, it could be a renewable substitute fuel for internal combustion engines and processes. It can be converted to synthetic natural gas (SNG) and liquid hydrocarbons through methanol [55]. Non-condensable gas is mainly utilised as a source of energy needed for the pyrolysis process [47]. However, for the gas to enhance quality and be economically feasible for commercialisation, the resulting gas mix necessities cleaning and processing to remove contaminants.

4. CLASSIFICATION OF PYROLYSIS

The rate of pyrolytic product yield is dependent on the classification of pyrolysis. Pyrolysis is categorised into conventional/slow, fast and flash processing, according to the operational parameters. *Slow pyrolysis* is the heating of organic material at a low temperature in the absence of oxygen. The operating conditions such as temperature, heating rate and residence time are less severe; 300–450 °C, <1 °C/s and >450 s, respectively [56]. This process takes several hours and results in ~60 % of char. The increased char residue results from the long residence time and low heating rate, encouraging the achievement of secondary reactions [57]. The long residence time and low heat transfer require more energy, which is one of the disadvantages of slow pyrolysis [45]. *Fast pyrolysis* is a high-temperature process where the substrate is quickly heated without oxygen, vaporises and condenses [58]. The temperature, heating rate and residence time are 550–1250 °C, 10–300 °C/s and 0.5–20 s, respectively [59]. It is the most widely used method and results in higher liquid fraction yield with the smallest char remains. It is estimated to generate 75 wt.% of liquid fraction in fast pyrolysis; however, several operating conditions such as feedstock type, reactor type, temperature and particle size significantly impact the performance and quality of the product. *Flash pyrolysis* is an extremely rapid thermal decomposition of organic materials with a high heating rate. The temperature, heating rate and residence time are 800–1300 °C, >1000 °C/s, and <0.5 s, respectively [59]. The process results in 60 % char and 40 % volatile products. However, some of its drawbacks include low thermal stability of the liquid fraction, creation of pyrolytic water and intensified viscosity through the catalytic action of char [45].

4.1. Pyrolysis Reactor Types

Comprehending the thermal behaviour of biomass systematically during devolatilisation is crucial to design appropriate reactor and temperature control systems and contributing to optimum pyrolytic products. In this respect, scientists commonly employ the thermogravimetric analysis (TGA) method. TGA is a process of heating the sample at a set temperature and examining the reduction in sample mass as a function of temperature or time [60]. Therefore, the complete TGA data attained are employed in predicting the devolatilisation mechanism and evaluating the reaction kinetics during the pyrolysis process. Sound knowledge of the kinetics of the devolatilisation of biomass and ensuing reactions is an important reason to design and model pyrolysis reactors. The type of reactor is essential

for the effective generation of the final target products and the vast quantity of heat transfer within the reactor wall to guarantee material devolatilisation. The common reactor types include fluidised bed, fixed bed, auger and rotary kiln reactors [61].

4.1.1. Fluidised bed reactor

The reactor involves the passing of high-velocity fluid/gas through a bed of solid particulate substance/catalyst under appropriate conditions enough to suspend the solid/fluid mixture and cause it to act as a fluid [62]. A fluidised bed reactor is preferably suitable for fast pyrolysis [63]. It is used in a broad range of industries, such as waste treatment, petrochemical, and chemical processes where adequate mixing and heat transfer are fundamental. A fluidised bed reactor is the most common reactor type because of its benefits; uniform temperature and suitable heat transfer, enormous liquid fraction yield, and scaling up easiness [63], [64]. However, its limitation includes high operating costs, low complexity in design, fabrication and operation, use of a large quantity of inert gases, attrition of catalysts particles, and erosion of the reactor internals [65]–[67]. According to Jahirul, Rasul [45], approximately 90 percent of heat transfer in fluidised bed reactors happens by conduction with a 10 percent minor influence by convection heat transfer, while other reactor types have heat transfer occurring by convection, conduction, and some radiation.

4.1.2. Fixed bed reactor

This consists of a tube, typically cylindrical, filled with solid catalyst particles stationed in a confined area of the reactor. The volatile products are released from the reactor throughout the pyrolysis process; char residue is acquired afterwards. A fixed bed reactor is easy to build, with low cost of construction, operation and maintenance, and further interaction between reactant and catalyst [47], [52], [68]. Its disadvantages are the low yield of pyrolytic liquid fraction, difficulty in heat transfer and the possibility of side reactions [67]. Biswas, Singh [69] studied the pyrolysis of *Azolla*, *Sargassum tenerrimum* and water hyacinth, respectively, in a fixed-bed reactor to comprehend the impact of compositional changes of the substrates on product distribution during slow pyrolysis. Results showed that a maximum liquid fraction yield of 38.5, 43.4 and 24.6 wt.% was obtained, respectively. Some other scholars have also explored the use of fixed-bed reactors to upgrade products obtained from primary pyrolysis [14], [15].

4.1.3. Rotary kiln reactor

A rotary kiln reactor comprises a long rotating tube that is slightly inclined at a horizontal angle, and gas is passed through the counter currently to the solid particles [70]. This reactor type has been effectively employed as an applied industrial solution at several scales [68]. The rotary kiln's benefit includes handling diverse feedstocks, high operating temperatures, and continuous mixing of incoming substrates. In contrast, the detriment includes difficulty to use and high capital, operating and maintenance costs. Jefferson, Alberto [71] investigated the thermal conversion of acerola industrial waste in a continuous rotary kiln reactor. The experiment was conducted at 300–600 °C temperatures; the biochar yield decreased from 86.2 % at 300 °C to 28.6 % at 600 °C, and the highest liquid fraction yield of 7.6 % was at 500 °C.

4.1.4. Auger reactors

Auger reactor, also known as screw reactor, is considered for its flexibility in the thermal conversion of various substrates and is a reactor type that can be used in slow, fast, or intermediate pyrolysis [43]. It entails a helical screw spinning in an enclosed shell. The merits include less usage of inert gas, flexible operation, and minor solid fraction attrition. At the same time, the demerits are poor mixing in the radial direction, higher residence time resulting in the possibility of secondary reactions, mechanical wear and tears as a result of its moving parts and difficulty in heat transfer [43]. In the study of Puy, Murillo [72] on the valorisation of forestry waste by pyrolysis in an auger reactor at 773–1073 °K and residence time of 1.5–5 min, the experimental results demonstrated the highest liquid fraction yield of 59 wt.% and optimal product characterisation at the lowest temperature signifying that complete reaction of forest woodchips can be achieved in an auger reactor. Other studies that have utilised auger reactors include Rego, Xiang [73], Veses, Aznar [74].

4.2. Pyrolysis Process Parameters

Pyrolytic yield is dependent on process factors such as temperature, particle size, heating rate, residence time, pretreatment and catalysts [33], [61]. Some factors are considered more significant than others. For instance, the study of Rahman [14] on the effect of operational factors on product distribution for the transformation of water hyacinth into high-value products revealed that the product yield is intensely affected by temperature change and blandly impacted by the heating rate.

4.2.1. Temperature

This is the most significant parameter that affects the pyrolytic product yields and compositions. The fundamental function of temperature is to deliver essential heat of devolatilisation to fragment biomass linkages [69]. At a low temperature, a small quantity of volatiles is generated, which could be ascribed to incomplete pyrolysis, where the biomass was not thermally cracked to cleave into smaller fragments. However, increased temperature triggers condensable hot volatiles' secondary reactions, resulting in more non-condensable gas [14], [15], [47]. Primary reactions occur at lesser temperatures, and as temperature rises, there is increased vapour generation. Subsequently, the condensed vapour increases, leading to more liquid fraction yield. Nevertheless, the secondary reaction increases as temperature increases, but after a specific temperature, the liquid fraction yield reduces [75]. The structural and physicochemical characteristics of char, such as pore structures, surface area, elemental compositions and functional groups, are affected by pyrolysis temperature [76]. The char yield decreases as temperature increases [77], [78] due to considerable volatile matter loss or secondary devolatilisation. Also, the char composition is influenced by temperature change; rising temperature results in higher carbon contents and the carbon structure of the char changing from amorphous to aromatic ring structures [76].

4.2.2. Particle size

This parameter has a direct influence on heat and mass transfer rates and, eventually, on the pyrolytic product yield and composition [61], [79], [80]. Wauton and Ogbeide [15] studied the effect of particle size (0.15, 0.3, 0.6, 1.0, 1.4, 1.7 and 2.0 mm) on pyrolytic product yield and reported an increase in liquid fraction yield (41–43 wt.%) as particle size increased from 0.15 to 0.6 mm; subsequently, a drop in liquid fraction (36 wt.%) was noted as particle size increased further. On the other hand, an increase in char (32–46 wt.%) was stated as particle

size increased (0.15–2 mm). The heat transfer rate in small particle sizes is high because of the distance from the particle's surface to the internal radius resulting in an exhaustive devolatilisation of the substrate and consequently producing low liquid fraction and high char yield. While the heat transfer rate in large particle sizes is to a certain depth due to the core of the particles, thus resulting in the increased liquid fraction. Also, in the smaller particle size, the reaction rate is fast so is the rate of the production of the hot volatiles; thus, more hot volatiles in the hot reaction zones. Small particle sizes cause high gaseous yield during pyrolysis [15], [49].

4.2.3. Residence time

The residence time of the substrate in the reactor is an essential process factor as it ascertains the energy obtained by the charge at a certain heating rate [47]. Residence time aids in the techno-economic feasibility of the pyrolysis process by evading excessive energy consumption. The low liquid fraction at long residence time is a result of cracking and polymerisation reactions of vapours to gases and solids, while low residence time impacts the biomass devolatilisation process by causing incomplete depolymerisation of lignin because of unsystematic bond cleavage and inter-reaction of lignin macromolecule [80]. The impact of residence time is controlled by temperature and other process factors, making it difficult to determine its role in char yield [81].

4.2.4. Heating rate

The function of the heating rate in the pyrolysis of biomass is essential as the heat change rate influences the type and make-up of the end product up to a certain level [81]. Rahman [14] determined the effect of different heating rates; 10 to 50 °C/min with 10 °C/min increase at 350 °C temperature, 0.5–1 mm particle sizes and inert gas flow rate of 4 lpm (litre per minute) and reported a decrease in liquid fraction (43.1–35.2 wt.%) and char (29.95–26 wt.%) and increased in gas (25.2–33.15 wt.%) as the heating rate increased. At a comparatively lower heating rate, the likelihood of secondary reactions is reduced, and thermal cracking is prevented, thereby resulting in high char yield, while at a quick heating rate, the chance of the biomass devolatilising into gaseous yield is increased, repolymerisation is avoided thereby increasing liquid fraction yield [82].

4.2.5. Inert gas flow rate

Nitrogen and argon are predominately utilised as carrier gas because they are readily obtainable and more economical than other inert gases. Rahman [14] investigated the influence of Nitrogen gas flow rate (0–12 lpm) on the pyrolysis of water hyacinth at 350 °C temperature, 30 °C/min heating rate, and 0.5 mm particle size. The liquid fraction improved (27–44.9 wt.%) as the flow rate reached 6 lpm and later reduced to 22.5 wt.%, the char yield decreased from 40.07 to 22.5 wt.%, and gas increased from 25.24 to 35.1 wt.%. The inert gas flow rate influences the level of secondary char creation and removes the pyrolysis products from the hot zone to reduce the secondary cracking reactions. According to Wauton and Ogbeide [15], the gas flow rate is directly connected to vapour residence time. A low gas flow rate results in high vapour residence time, thereby producing low liquid fraction and high char yield, while a high gas flow rate decreases the gas yield by lessening the cracking reaction [14].

5. CONCLUSION

The utilisation of invasive alien plants, like water hyacinth, for pyrolysis, is gaining attention. Water hyacinth is an economical biomass source for the generation of bioenergy; nonetheless, its thermal conversion demands comprehending its pyrolytic characteristics. Pyrolytic product yields such as liquid, char and non-condensable gas fractions are dependent on the reactor types and process parameters such as temperature, particle size, residence time and heating rate. Pyrolytic products are beneficial and could play a fundamental role in South Africa's low-carbon economy transition. For instance, the liquid fraction contains valuable bio-based chemicals and is considered an alternative energy source to conventional fuels; the char is considered suitable as a soil conditioner, activated carbon and animal feed, while the non-condensable gas could be applied in restoring power or producing syngas. Since SA's electricity public utility is considering to repurpose aged coal-fired power stations into renewable energy stations, the adoption of pyrolysis technology is recommended.

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