

Potential Routes and Innovative Technologies for Valorisation of Cassava Peels

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Abstract - The large-scale processing of Cassava (*Manihot esculenta* Crantz.) generates significant quantities of solid wastes annually. Cassava peels (CP) account for 5 wt.% - 30 wt.% of wastes from the processing of cassava tubers. The poor disposal and management of CP pose risks to human health, safety and the environment. Therefore, there is an urgent need to identify and examine low cost, socially acceptable and environmentally friendly strategies to mitigate the immediate and long terms disposal and management challenges. Lack of such measures results in the accumulation of CP wastes, which are currently buried, combusted, or dumped in open fields. Therefore, this paper reviewed the potential routes for the biochemical, thermochemical, and plasma valorisation of CP. The literature reviewed revealed that biochemical technologies such as anaerobic digestion (AD) and fermentation are the most widely utilised approaches currently adopted for CP valorisation. AD produces biogas (methane 50-72 vol. % and carbon dioxide 25-45 vol. %), whereas fermentation yields bioethanol. However, the numerous challenges such as substrate-induced inhibition associated with the biochemical processes hamper microbial degradation, methane formation, and process efficiency. Furthermore, the processes generate secondary wastes or digestate/sludge, which requires additional processing before disposal. Therefore, innovative thermal, thermochemical, and plasma technologies were proposed to valorise CP into syngas, biofuels, bioenergy, biochemicals, and fertilizers, among others. However, the waste products of fermentation cannot be effectively utilised as bio-fertilizers, whereas bioethanol causes corrosion in engines. Overall, the biochemical, thermal, thermochemical and plasma technologies can effectively valorise CP for effective net energy generation.

Keywords: Cassava peels, valorisation, thermal, thermo-chemical, biochemical, biogas.

1. Introduction

In today's global civilization, the pressure on fossil fuels has resulted in the attenuation of global reserves [1]. Likewise, the burning of fossil fuels for energy emits significant quantities of greenhouse gases (GHG) that jeopardize humans and the environment [2, 3]. Hence, there is an urgent need for long-term strategies for the exploitation of renewable energy technologies (RETs) and clean fuels that could complement or substitute fossil fuels in the short or long term [4, 5]. One of the most suitable approaches is the energy from biomass [6, 7]. Various studies have demonstrated the potential of RETs as innovative and prospective approaches for mitigating greenhouse gases, which could possibly address global warming and climate change [8, 9]. It is envisaged that the adoption of RETs could satisfy humanity's growing demand for energy and fortify local economies [10, 11].

Biogas is a colourless, combustible, and low-priced RET generated through various biochemical technologies such as anaerobic digestion (AD) of natural waste materials [12, 13]. Hence, the process is widely considered a practical solution that could satisfy the energy needs of rural populations [14, 15]. It is also clean, smokeless, and more suitable fuel to utilize than other solids fuel [16]. Typically, biogas (also known as digester gas) refers to the yield of methane from the fermentation of natural matter. Examples of such natural matter include wastewater, manure, municipal solid waste (MSW), sludge and other biodegradable feedstocks suitable for anaerobic digestion. Biogas produced under anaerobic conditions is a resource-efficient approach for managing a huge quantity of solid waste generated. Hence, it is a sustainable method of energy generation. The constituents of biogas include methane (50 - 72 vol. %), carbon dioxide (25 - 45 vol. %), nitrogen (>2 vol. %), hydrogen sulphide (> 1 vol. %), oxygen (>2 vol. %) and water (2 - 7 vol. %) [17, 18].

Similarly, biogas can be generated from raw materials such as agricultural wastes, which can vary from animal wastes to various crop residues. For example,

cassava peels (CP), obtained from cassava tubers, can be used as feedstock to produce biogas through anaerobic processes. The cassava (*Manihot esculenta*) tuber is cultivated mainly in the tropics and subtropical countries of the world. It is an essential source of food, which could stimulate socio-economic growth, sustainable development and offer food security [19]. The utilization of CP also offers immense prospects for the manufacture of bioenergy, particularly biogas, due to its chemical makeup. CP contains a high concentration of cyanogenic glucosides, which is inappropriate for animal feed [20]. Over the years, the haphazard dumping of CP has generated grave environmental concerns due to chemical contamination as well as potential risks to human health and safety [21, 22]. The breakdown of CP wastes produces poisonous leachates that pollute the environment. Furthermore, when the gases from the leachates are inhaled by humans, it could result in infectious diseases that could take effect within a short time. Similarly, plant life and soil within the region of degradation could be severely affected by biological processes or chemical reactions [23, 24].

For these reasons, it is imperative to explore alternatives to manage the growing stockpiles of solid CP waste generated from processing cassava, which could potentially guarantee a hazard-free environment. Hence, the utilization of solid CP wastes as either standalone raw material or combined feedstock to produce bioenergy, biofuels, and biomaterials has been extensively examined in the literature. Cuzin *et al.* [25] investigated the use of solid CP waste as feedstock to produce biogas. Similarly, the use of poultry manure combined with solid CP waste for biogas production has been reported in the literature [26, 27]. Others have examined the combined utilization of CP and cow dung blends for biogas production [28, 29]. In a later study, Okudoh and Trois [30] explored the use of CP and Zebra droppings, while Ukpai and Nnabuchi [28] scrutinized the use of CP and Cowpea for biogas production. Bayitse *et al.* [31] explored the use of CP with manure blends to produce biogas and bio-fertilizer by optimizing the ratio of carbon to nitrogen. There are other comprehensive research works on the

valorisation of CP wastes into clean technologies, bioenergy, biofuels and biogas. The various approaches and technologies aim to effective and optimally recovery energy from CP as well as reduce the environmental burden of fossil-based fuels, energy and materials. Therefore, the primary focus of this review article is to abridge the conventional and more recent technologies utilised for energy, materials, and resources recovery from CP in literature.

2. Cassava Peels (CP)

CP is defined as the solid wastes generated from the processing of cassava (*Manihot esculenta*) tubers into essential products. It is also considered the significant portion of post-harvest losses obtained from the processing of cassava tubers for either industrial uses or domestic consumption. Typically, CP accounts for 8-15 wt% of the entire dry matter of the root [20]. Cassava tubers are rich in carbohydrates, proteins starch, and fats, which are typically used to produce staple foods [32]. It is a dependable source of energy, sweeteners and raw material for industry [33, 34]. When peeled mechanically, CP constitutes around 5% to 10% of the solid waste [35], but when peeled manually is 20% - 30% solid waste from cassava tubers [36, 37]. However, CP contains toxic cyanogenic glycosides [29]. The presence of toxic cyanogenic glycosides negatively affects biogas production, as such treatment is required to enhance the yield and onset of gas flammability [38]. CP consists of hemicellulose, cellulose, and lignin along with crude protein, organic matter and ash, as presented in Table 1 [20]. Chemical analysis of CP contains the following minerals; carbon (C), nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), sodium (Na), zinc (Zn), manganese (Mn), copper (Cu), and lead (Pb), as shown in Table 1 [27].

Table 1: Chemical properties of CP [20].

Analysis	Property	Symbol	Proportion
Lignocelluloses	Hemicellulose	H	20-31 wt.%
	Cellulose	C	16-42 wt.%
	Lignin	L	6-8 wt.%%
	Crude Protein	CP	4.1-6.5 wt.%%
	Organic matter	OM	81.9-93.9 wt.%
Chemical Elemental Composition	Carbon	C	48.7 wt.%
	Nitrogen	N	1% wt.%
	Carbon/Nitrogen ratio	C/N	48.7% wt.%
Metal Element Composition	Potassium	K	1.1 wt.%
	Phosphorus	P	1.6 wt.%
	Calcium	Ca	0.9 wt.%
	Sodium	Na	0.15 wt.%
	Zinc	Zn	125 mg/kg
	Manganese	Mn	180 mg/kg
	Copper	Cu	15 mg/kg
	Lead	Pb	16.7 mg/kg
	Nitrate	NO ₃	0.16 wt.%

Furthermore, Cassava has numerous merits when compared to other crops. It can be cultivated in every land, even in low soil fertility where most crops such as maize and other crops cannot thrive [39, 40]. It has a high yield of carbohydrates (4.742 kg/carb) per area of land besides sugarcane and sugar beet [30]. With an anticipated rise in cassava production globally, the generation of solid CP waste will rise continuously. Although drying solid CP waste can reduce toxic cyanogenic glycosides after utilization, large quantities are simply burned, buried or openly dumped and allowed

to decompose causing environmental challenges. Hence, various strategies have been proposed for the valorisation of CP into valuable products.

3. Cassava Peels Valorisation

This comprises all the processes utilised to convert solid CP waste into energy, fuels, materials, chemicals and other value-added products. The idea of waste valorisation revolves around the conversion of natural products or their residues into unexploited polymeric materials that could be utilised for various applications. For instance, CP could be converted via anaerobic digestion into biogas. This process is a complex process that occurs with the aid of microbial bacteria in the absence of oxygen. Ighalo and Adeniyi [41] proposed thermodynamic models to examine the valorisation potential of CP via pyrolysis and steam reforming. The authors found out that CP could be effectively valorised through thermochemical processes. Figure 1 depicts the various pathways, processes and products in which solid wastes such as CP could be valorised into various products such as high-value chemicals for sustainable environment and pollution abatement.



Figure 1: Green processing technologies for waste valorisation [42].

4. Conventional Technologies for CP Valorisation

The conventional route for the valorisation of solid wastes such as CP into biogas is through the biochemical route. The most common valorisation technologies or conversion systems for these conversion routes essentially utilize enzymes from microorganisms to strip off the energy, fuels and materials from biomass. Examples of these eco-friendly approaches are:

- Anaerobic digestion,
- Fermentation technology.

4.1 Anaerobic digestion (AD)

Anaerobic digestion (AD) is the biological disintegration of soluble complex organic matter by an intricate microbial ecosystem [43, 44]. The process occurs through a series of metabolic routes involving various synergistic microbial environments, which lead to the production of methane (CH₄) and carbon dioxide (CO₂). However,

Ekop *et al.* [45] define AD as the microbial decay or decomposition of organic matter (biomass) in the absence of oxygen. The process of AD is typically carried out in a well-designed reactor termed anaerobic bioreactors or digesters, as depicted in Figure 2. Bioreactors are especially instruments or devices developed to ensure the production of CH₄-rich biogas from solid wastes such as CP. An anaerobic bioreactor plant is made up of digester, feedstock, digestate reservoir, and biogas holder [46].

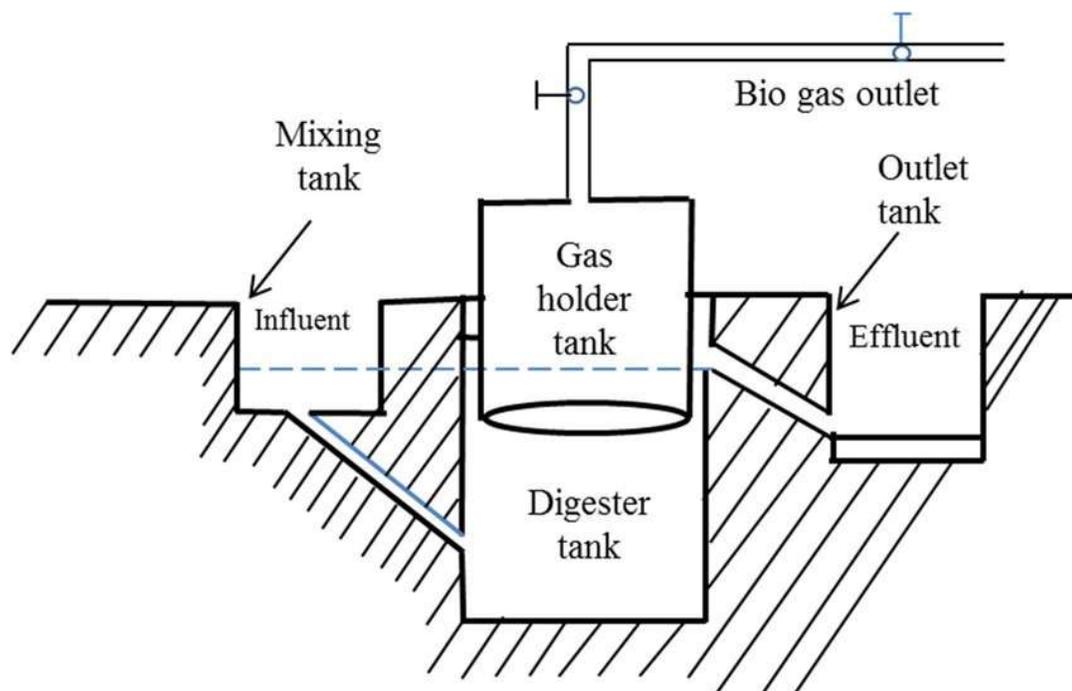


Figure 2: Schematic diagram of Biogas digester [46].

Bioreactors or digesters are typically designed with steel, gas or stainless-steel cylinder tanks with a capacity between 1 litre to over 50000 litres equipped with an agitator and integral heating or cooling system. Usually, bioreactors are more often designed and manufactured based on the growth prerequisite of the organisms (in this case, methanogens) involved. The purpose is to guarantee the successful conversion of biomass into the required by-products, which in this case is the biogas (methane and carbon dioxide). In principle, the molecule of the feedstock in the bioreactor is acted upon by an enzyme, which then diffuses through a biofilm before transforming into

CH₄ and volatile fatty acids, which subsequently diffuses out into the bulk liquid. The products and process of AD are significantly influenced by factors such as temperature, hydrogen-ion (pH) concentration, feedstock composition and nutrients. Likewise, the ratio of carbon/nitrogen (C/N) is also a critical parameter to produce biogas during AD. Furthermore, Tambone *et al.* [47] reported that anaerobic processes also partially eradicate the harmful organic content found in the waste, thereby making it less toxic and harmful when subsequently discharged into the environment or utilized as bio-fertilizer. The valorisation of CP through the process of AD has been examined in the literature. In this AD pathway, biogas is produced from CP via microorganisms. AD engross bacterial fermentation of organic solid waste in the absence of oxygen. During the process, CP undergoes four (4) stages in the presence of different microorganisms before biogas is obtained. The phases involved in the process include Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis.

Hydrolysis phase

The complex insoluble organic compounds (or polymers) in CP such as protein, cellulose, and hemicelluloses are broken down into simpler ones (soluble monomers). This process occurs due to the secretion of hydrolytic enzymes produced from the extracellular enzymes and cofactors [48]. Typically, these enhance the degradation of polymers in CP into various monomers, which is enhanced by higher temperatures.

Acidogenesis phase

The simpler compounds from the hydrolysis phase are further degraded into short-chain organic acids, alcohols, aldehydes, carbon dioxide, and hydrogen with the aid of acidifying bacteria. This stage is considered the fastest step in the AD process [49]. However, if CP has a low shock absorber capacity and the organic loading rate is high,

the build-up of unstable fatty acids can give rise to a drop in pH, which subsequently restrains the methanogens that produce methane in the final step.

Acetogenesis phase

In this phase, the acetate bacteria can enzymatically degrade the by-products from the acidogenesis phase into acetates and H_2 , which may be used by methanogenic bacteria in the final stage [50]. Likewise, the acetogenic bacteria in this stage can survive under low H concentrations. Hence, high yields of hydrogen from the acidogenesis step can hinder such bacteria [51].

Methanogenesis phase

This stage of the AD process results in the production of CH_4 and CO_2 , which make up the most significant proportion of the biogas product. It is termed the fourth and final stage of the process. Typically, this stage involves the microbial conversion of H_2 and acetic acid into the biogas product [52]. Figure 3 presents the entire process for the valorisation of CP through AD. Note however that it is essential that the organisms involved in each phase of the anaerobic oxidation reactions team up with the next.

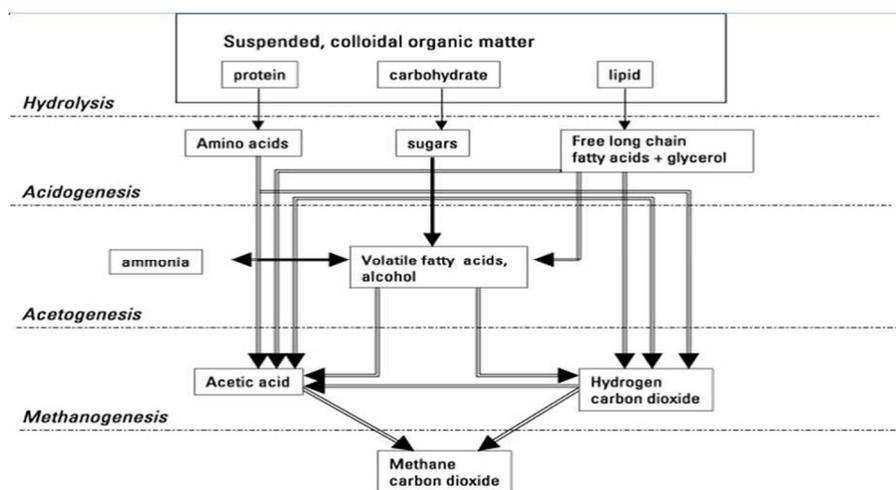
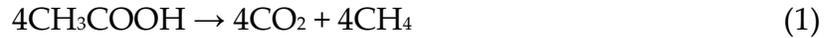


Figure 3: Schematic diagram of AD [53].

The three (3) biochemical reactions through which the process of methanogens functions is given as:



4.2 Fermentation

Fermentation is a biochemical conversion technological process instigated by microbes under anaerobic surroundings. Under such processes, cellulose, sugar and starch found in biomass are transformed into ethanol and carbon dioxide as metabolic waste products [54]. The fermentation process involves the removal of contaminants that accompany the feedstock (CP) at the source before the digestion process. In addition, the feedstock is resized to enhance the surface areas for easy access by bacteria for the hydrolyzation process. Before the fermentation of CP, organic compounds (i.e. starch, cellulose and hemicellulose) found in the peels are pre-treated. In other words, the CP experiences the principle of co-metabolism where saccharolytic microorganism breaks down the complex compound. For instance, starches are first and foremost hydrolysed into fermentable sugars by enzymes from moulds before the fermentation process. Cellulosic biomass either undergoes acidic hydrolysis, enzymatic hydrolysis or gasification pre-treatment before fermentation. Gasification pre-treatment before fermentation of cellulose produces synthesis gas (i.e. CO, CO₂, and H₂). Figure 4 shows the pathway for the fermentation and digestion of biomass feedstocks for the microbial production of biogas [55]. However, the use of fermentation technology to obtain energy from biomass has limits. For example, bioethanol generated from highly polluting wastes cannot be used directly in fields as biofertilizers. Likewise, bioethanol in the engine as fuels affects electric fuel pumps through internal wearing and

unwanted flash generation. Lastly, the ethanol is hygroscopic which causes corrosion in engines [56].

Biogas production through the processes of anaerobic digestion and fermentation of biomass of any kind has come a long way. However, these processes are prone to numerous challenges. For example, the study by Fagbohunge *et al.* [57] observed that one of the significant challenges of AD is substrate-induced inhibition. The phenomenon is known to hamper the constant operation of the process of AD by slowing down the microbial degradation of the organic waste and methane formation. As a result, the overall energy output and process efficiency are reduced considerably. In addition, the process results in the production of secondary waste or digested by-product sludge, which requires additional costs, energy and processing for disposal, management or valorisation. In recent times, production biogas has taken new novel turns since the AD method was first to embrace technologies that are environmentally friendly and optimize biogas production.

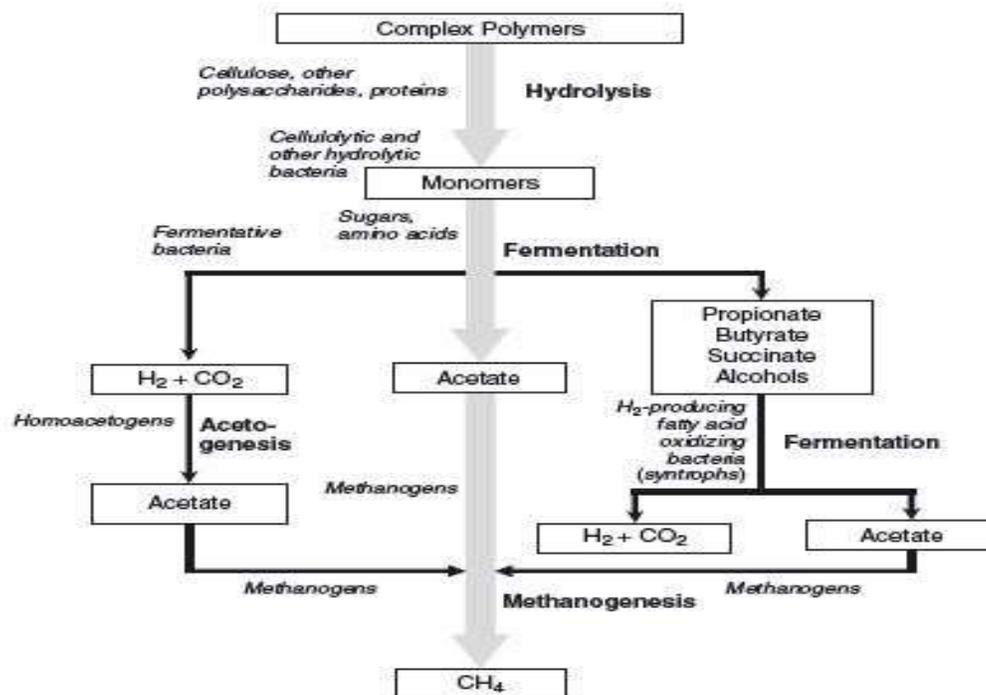


Figure 4: Schematic of anaerobic decomposition and fermentation processes [55].

5. Innovative Technologies for Valorisation of CP

Over the years, numerous innovative technologies have been proposed to valorise CP. In general, some of the novel technologies for valorisation of CP into biogas are diverse but can roughly be categorised into three (3) groups, including;

- Thermal conversion,
- Thermochemical conversion,
- Plasma technologies.

5.1 Thermal Conversion

The process involves the conversion of thermally degradable materials such as biomass through the application of heat at low to high temperatures. During the thermal processing of biomass, the intrinsic chemical energy is harvested through direct burning. As a result, the feedstock's chemical energy is converted into heat, steam, and electricity. Typically, thermal conversion equipment such as boilers is used to convert biomass such as CP into heat energy which is subsequently utilised to produce steam in the industry. The pressure of the steam generated is then channelled to a spin turbine attached to a DC electrical generator that generates electrical current [58]. However, the prospects of directly utilising or combusting any biomass feedstock for energy generation largely depends on its physicochemical and calorific fuel properties [59]. Nevertheless, the open combustion of waste emits compounds like acid gases, furans, and dioxins that are harmful and at the same time, cause air pollution. As such direct burning is discouraged [60]. Kemausuor *et al.* [61] investigated the techno-economic and socio-economic prospects of utilising CP as feedstock for biogas production. The findings showed that 225 tonnes of CP can generate 75 million litres of gas with a methane content of 60 vol.%. Furthermore, the analyses showed that CP is a potentially suitable feedstock for establishing biogas plants with capacities ranging from 300 m³ –

500 m³ and replace 300 tonnes of fuel wood utilised in the regions under study and prevent. Lastly, the valorisation of CP as fuel for biogas production dramatically reduces the emission of toxic and greenhouse gases generated annually from the open burning (Figure 5) of CP in the country.

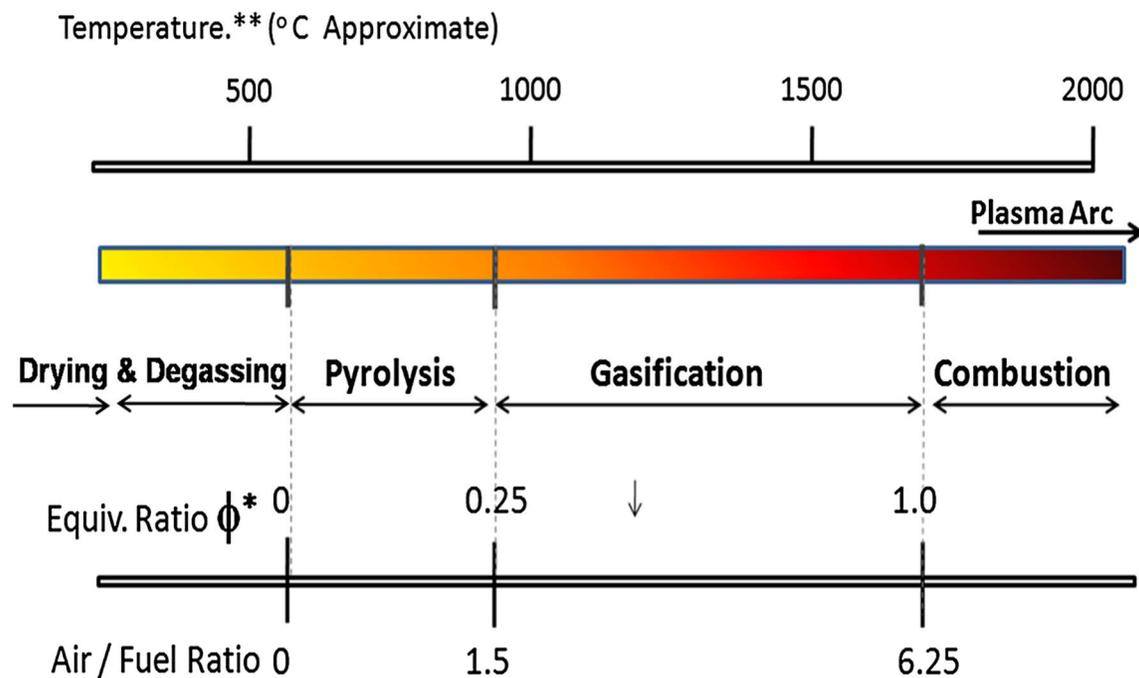
Another important thermal technology for the valorisation of CP is waste incineration. In principle, the process involves the burning of waste in the presence of oxygen (oxidation) under emission control in an incinerator. The heat energy generated from the process simultaneously converts waste into various products whilst destroying pathogens present in the waste. Hence, CP could be incinerated in an incinerator. Nonetheless, CP could be directly transformed into CO₂ and water vapour or indirectly to char, H₂, and CO during this incineration process. Note, however, that the determining factor is the concentration of oxygen supplied. High moisture affects both incineration and combustion. Many researchers have employed technological incineration methods in the valorisation of CP and findings have shown tremendous efficiency [62].



Figure 5: Open combustion of CP heap [61].

5.2 Thermochemical conversion technologies

These technologies utilize a chain of chemical reactions that occur at diverse temperatures. The processes are known to proceed in the partial presence of oxygen (gasification) or in a total absence of oxygen (pyrolysis) to form its various by-products [63]. However, the temperatures required for such processes could extend beyond or overlap the spatial and temporal stages of aeration and degassing, pyrolysis and gasification [64]. Lastly, the complete or oxidative burning of materials, which results in the conversion of organic waste into ash, is also considered a thermochemical process [65, 66]. Figure 6 shows the overlapping technologies that make up thermochemical conversion, whereas Figure 7 shows the various thermo-conversion routes and their by-products.



* Φ = the actual air fuel ratio/the air fuel ratio for complete combustion for biomass: $\text{CH}_{1.4}\text{O}_{0.6}$

** Combustion temperatures shown are adiabatic flame temperatures.

Figure 6: Temperature overlapping of thermo-chemical conversion technology.

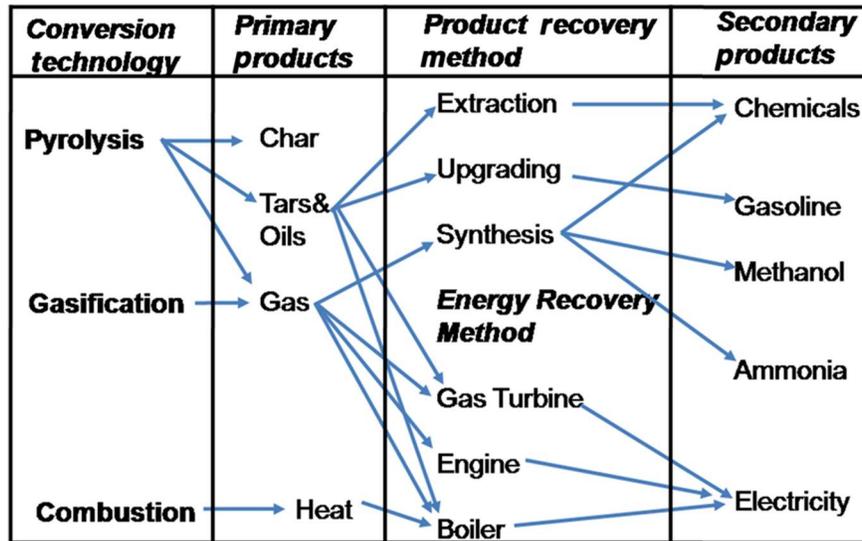


Figure 7: Thermo-conversion route and by-products [66]

Pyrolysis and gasification vary from incineration in that the former may be used for recuperating the chemical worth of the waste, whereas the latter is used to recuperate its energy worth. The chemical products produced from pyrolysis and gasification may be used as fuel or as secondary feedstock (char) for further fuel generations, which are later used to generate heat energy. However, the process of incineration does not generate fuels [62, 67, 68].

5.2.1 Pyrolysis

Pyrolysis is a thermo-chemical process that involves the thermal breakdown of natural material at relatively low temperatures between 300 °C and 600 °C in the absence of oxygen [63, 65]. The process typically results in the production of gases (non-condensable), liquid, and solid char products depending on the heating rates, gas medium, residence time, particle size and selected reactor [69]. Other products of pyrolysis include chemicals, pyrolysis oils, water, fuel gas mixtures (H₂, CO₂, CH₄, CO), and solid (coke and char) products [70, 71]. Due to its numerous advantages, the

process is currently explored as a valorisation technique for the recycling or size lessening of waste streams. Ighalo and Adeniyi [41] examined the valorisation of cassava peel using pyrolysis. According to the study, when CP is exposed to heat, larger molecules undergo primary breakdown to yield condensable gases and solid char as by-products. Next, these condensable gasses undergo further secondary decomposition to produce the non-condensable gases which include H₂, CO, CO₂, and CH₄, liquid and char. These disintegration processes travel partially through gas-phase reactions and to some degree through gas–solid-phase thermal reactions. In the gas phase, the condensable vapour is cracked into tiny molecules of non-condensable stable gases which are CO and CO₂, thus, these gases are of less concern in pyrolysis. The basic stoichiometry for pyrolysis of biomass is given as [63]:



In the process of CP valorisation into biogas, the CP are first and foremost ground to increase the surface area of the participating particles to increase the rate of heat transfer during the reaction. Secondly, these tiny ground particles of CP are dried to boost the competence of the reaction within the reactor. Further, the thermal breakdown of organic molecules (i.e. cellulose, hemicellulose and lignin) in CP produces pyrolysis products and eventual and secondary curing of the by-products. The leading gases produced from pyrolysis are methane, carbon monoxide, and hydrogen and are revealed by reaction Eqn 4. Pyrolysis has great intrinsic worth in waste management. This is because it presents a flexible and striking way of changing solid wastes in our environment into a quickly stocked up and movable fuel, which is further used to produce heat, power, and chemicals [63, 72, 73]. Pyrolysis gas can be used to power gas engines and gas turbines, which are used to generate electricity [74, 75]. With regards to operational parameters, pyrolysis can be classified into fast, slow,

and flash pyrolysis. In other publications, vacuum, microwave, hydro and catalytic pyrolysis are also reported [76, 77].

5.2.2 Gasification

Gasification is a thermo-chemical reaction process whereby fuel reacts with gasification agents to yield synthetic gas [63, 69]. It is a thermal conversion process whereby syngas is produced in the temperature range 600 °C – 1000 °C through gasifiers in the partial presence of air/oxygen from carbonaceous materials. The synthetic gases include H₂, CO, CO₂, N₂ and other hydrocarbons such as C₂H₄, CH₄, C₂H₆, along with small quantities of NH₃, tars, and H₂S may also be found [78]. The gasification process is an endothermic reaction, and as such, external heating is needed for the process [70]. In theory, gasification occurs when water vapour (steam) and carbon dioxide reacts with char in gasifiers to yield H₂ and CO. Further, within the temperature of the gasifier, both the products and reactants balanced speedily through equilibrium reaction. Synthetic gases are used as fuel for electricity production [79]. However, a combination of these gases can be used as gasification agents. Typically, the techniques used during gasification are grouped based on oxidizing medium. For instance, steam and plasma melting gasification, which is are novel gasification technologies [80]. Zhang *et al.* [78] reported that a gasifier is a crucial device that affects the entire process of gasification. It is classified into fixed bed, fluidized, and entrained flow gasifiers. The gasification of CP is a thermal conversation process that involves its thermal decomposition into principally synthetic gases. The resulting syngas is subsequently utilised for power generation, lighting, and heating [71]. Hence, the process is considered a proficient and cost-efficient system for the valorisation of solid wastes such as CP.

5.2.3 Plasma technology

Plasma technology is a high-temperature thermal process that involves the change in the state of matter. For example, matter can be converted from solid-state to liquid to gases state) when heat is applied, which is the fundamental working principle of the plasma process. According to Nandkumar [81] in plasma technology, when extra heat is applied to a gaseous state. It thus further ionized into a fourth state called energy-rich plasma state. Nevertheless, the source of high thermal energy for plasma state could either come from electric current or thermal or electromagnetic radiation. Therefore, the entire process is expensive. Nonetheless, one of the merits of this technology is it tolerates low energy biomass that is not fit for other technologies such as gasification Note, however, that the high heat energy needed in plasma technology aid in the complete disintegration of organic compounds into their components and eventually yielding high-energy synthesis gas [70].

6. Conclusion

The paper presented an overview of the current routes and future technologies for the valorisation of CP. The large-scale generation of CP wastes annually creates significant disposal and management problems, which could pose risks to human health, safety and the environment annually. Therefore, it has become imperative to identify and examine sustainable measures to address the disposal and management challenges posed by the growing problem of CP waste accumulation in the environment. Therefore, this paper reviewed the potential valorisation technologies used for CP wastes in the literature. The review of the literature showed that biochemical routes, including anaerobic digestion and fermentation, are the most widely current routes for the valorisation of CP. The AD process results in the production of biogas comprising methane and carbon dioxide, whereas fermentation

results in the production of bioethanol. However, the conventional techniques are prone to numerous challenges such as substrate-induced inhibition, which hamper the process of AD by reducing microbial degradation, methane formation, energy output and process efficiency. Furthermore, the AD and fermentation processes generate secondary waste or digested by-product sludge, which requires additional costs, energy and processing for disposal, management or valorisation. Therefore, innovative approaches such as thermal, thermochemical, and plasma technologies have been proposed to produce various products such as syngas, biofuels, bioenergy, biochemicals, and fertilizers, among others. However, the process of the fermentation process is plagued by the inability to reuse fermentation waste residues in fields as biofertilizers, whereas bioethanol causes corrosion in engines. Overall, the review of the literature revealed that the biochemical (particularly AD), thermal, thermochemical and plasma technologies do not only valorise waste into various products but also generate net energy.

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