Waste Tyre Gasification Processes: A Bibliometric Analysis and Comprehensive Review

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Highlights

- A bibliometric analysis of all known works on waste tyre gasification was investigated.
- Models that could simulate carbon nanomaterials production from waste tyre gasification need to be investigated.
- Polygeneration of products from gasification would make the process more effective.
- The application of artificial intelligence in waste tyre gasification could be considered in future works.
- Bibliometric analysis of works on waste tyre gasification
- Simulation of carbon nanomaterials from this process needs investigation.
- Polygeneration of products would make the process more effective.
- AI application could be considered in future works.

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Abstract

Waste tyres are a significant environmental problem due to their large volume and the difficulty of disposing of them safely. Waste tyre gasification is one of the key thermochemical routes for converting waste tyres into valuable products such as gaseous fuels and/or solid fuels. In this review, a bibliometric analysis of all works on waste tyre gasification from its onset was investigated. We provide an overview of the current state of the art in waste tyre gasification processes, including the types of reactors, gasification modes, and gasification products. The modelling aspect of waste tyre gasification was also investigated as well as its shortcomings. We also discuss the challenges and opportunities associated with the co-production of gaseous products (syngas and hydrogen) and solid carbon products, polygeneration of multiple products, and identify areas for further research. Our review demonstrates that gasification of waste tyres is a viable option for the production of energy and valuable by-products, but more research is needed to optimize the process and improve its economic feasibility. More research is also required in modelling and optimization of other products such as carbon nanomaterials. In addition, the investigation of the life cycle assessment (LCA) of waste tyre gasification is vital as this can ease the adoption of waste tyre gasification technology in developing nations.

Keywords: *Waste Tyres; Hydrogen; Activated Carbon; Carbon Nanomaterials; Polygeneration.*

1.0. Introduction

Biomass wastes are considered to be an underutilized energy source that currently supplies around 10% of global energy and has the ability to supply well over 25% of global energy demand by 2035 [1-3]. This vast volume of biomass wastes combined with other solid wastes (including waste tyres) has enormous potential for conversion to energy [4-6]. By 2050, the population of the world is projected to exceed 9 billion while the number of automobiles is estimated to be around 2.4 billion [7]. Likewise, close to 17 million tons per annum of waste tyres—more than 1.4 billion in number—are produced by various sources related to transportation, meanwhile, only 10% of these waste tyres are being recycled globally [8-10]. With the current waste tyre recycling rate, these figures indicate that there will be a significant amount of waste tyres lying around if no proper action is taken. Tyres typically last between three and six years, and after that time they are either recycled or rethreaded, or they are disposed of in a landfill [11, 12]. Waste tyre management has been a major challenge because the dumping of these tyres in landfills is no longer permitted in most developing countries because of their chemical and biological resistance to degradation [12-15]. In the past, the common practice was to dispose of these tyres in landfills, where they would take up space and pose environmental risks [11, 16-18]. Tyres generally have a complex chemical makeup and are therefore difficult to decompose; it will take more than a century for them to decompose in a landfill [19]. The non-biodegradable and non-decomposable parts of waste tyres produce hazardous substances, solid waste, particulate matter, heavy metals, and pyrolytic oils that contain polycyclic aromatic hydrocarbons (PAHs) when they are disposed of in landfills or burned. These substances can also have a negative impact on the environment and human health [20]. An average passenger car tyre is known to weigh 7-10 kg with a calorific value between 30-45 MJ/kg which is greater than biomass and coal of equal weight [21, 22]. Over 40% of waste tyres are discarded worldwide without putting into considerable use hence, waste tyres must be disposed of properly to minimize their influence on the environment [23, 24]. However, as the awareness of the negative impact of landfill waste has grown, there has been a shift towards exploring alternative ways to manage waste tyres [25, 26]. As a compromise reached through the 2018 EU Landfill Directive, the European Environmental Agency set an aim to reduce the amount of solid waste being discarded (including waste tyres) to 10% of the total by 2035 [27].

One of the processes that is used in the recovery of energy from solid wastes such as biomass, waste tyres, and coal. is gasification. The capability of the gaseous products to be stored, transported, and supplied to boilers and combustors makes waste tyre gasification appealing [15]. The production of high-quality syngas from steam gasification is a possibility. Standard gasification systems, on the other hand, necessitate high temperatures to degrade the feedstock and to initiate reforming processes, both of which could reduce the efficiency of the process [28]. One of the main advantages of gasification is its versatility in terms of feedstock [29]. Unlike traditional incineration methods, which require a uniform and consistent fuel source, gasification can process a wide range of feedstocks, including solid waste (which includes waste tyres), biomass, and even coal as shown in **Fig. 1** [15, 30]. This flexibility allows gasification plants to operate in a more stable and reliable manner, as they can adjust their feedstock sources depending on availability and price [31, 32]. Waste tyres have been known to have a high sulphur content (1-5wt.%) when compared to other solid wastes which mostly come from vulcanization process [33-35]. This often leads to the formation of sulphur compounds, hence, proper cleaning must be carried out after the gasification process .

Authors such as Oboirien & North [36] and Labaki & Jeguirim [37] have published review articles on waste tyre gasification, however, no comprehensive review on waste tyre gasification works from 2018 till present has been made. In addition, to the best of the authors' knowledge, a bibliometric analysis that investigates all works on waste tyre gasification has not been made available. Hence, this work combined a detailed bibliometric analysis with a comprehensive review on the status of waste tyre gasification as well as recommendations for future works.

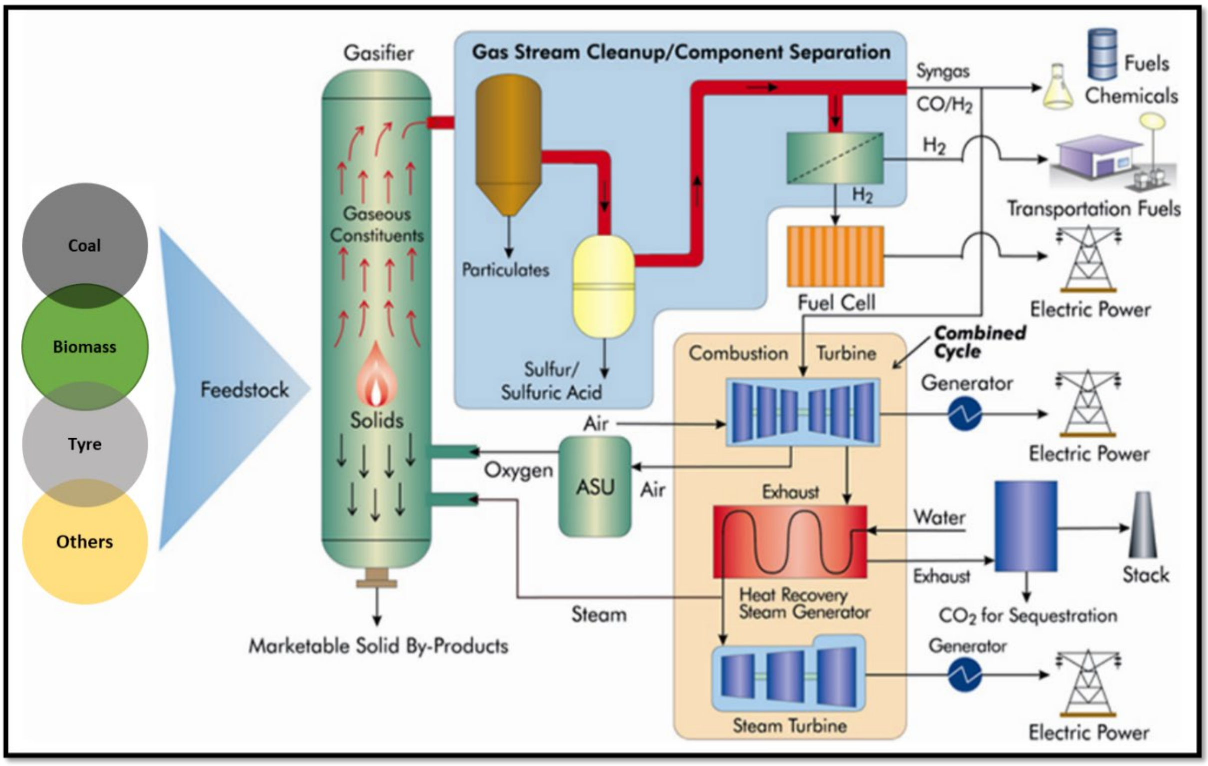

Fig. 1. A conceptual illustration of a gasification process showing the various kinds of products that can be produced as well as the feed flexibility (Image obtained with permission from National Energy Technology Laboratory [30]).

2.0. Bibliometric Analysis

The present study leveraged the bibliometric analysis technique to accomplish one of the goals of this review which is to quantitatively visualize data on waste tyre gasification. This approach is appropriate for reviews since it highlights and analyses waste tyre gasification research growth over the years using bibliographic data. The most commonly employed research article databases are Scopus, Google Scholar, and Web of Science, however, due to a wide literature coverage, and bibliometric data Scopus was employed in this study [38]. The search keywords for this analysis and review in the Scopus database were “Waste OR Scrap” “Tyre OR Tire” AND “Gasification”. The titles, abstracts and keywords of the articles containing these search terms were retrieved. The initial search contained 248 articles until those articles unrelated to waste tyre gasification such as waste tyre pyrolysis, combustion, and incineration were all excluded which narrowed the total number of articles to 163. These 163 articles included all articles from 1981 to date. These 163 articles were exported and using VOSviewer, the visualization of the keywords was illustrated as shown in **Fig. 2**. In addition, the bibliometric analysis of all the articles shows that the United States, China, United Kingdom, Canada and South Africa were the leading countries in waste tyre gasification research.

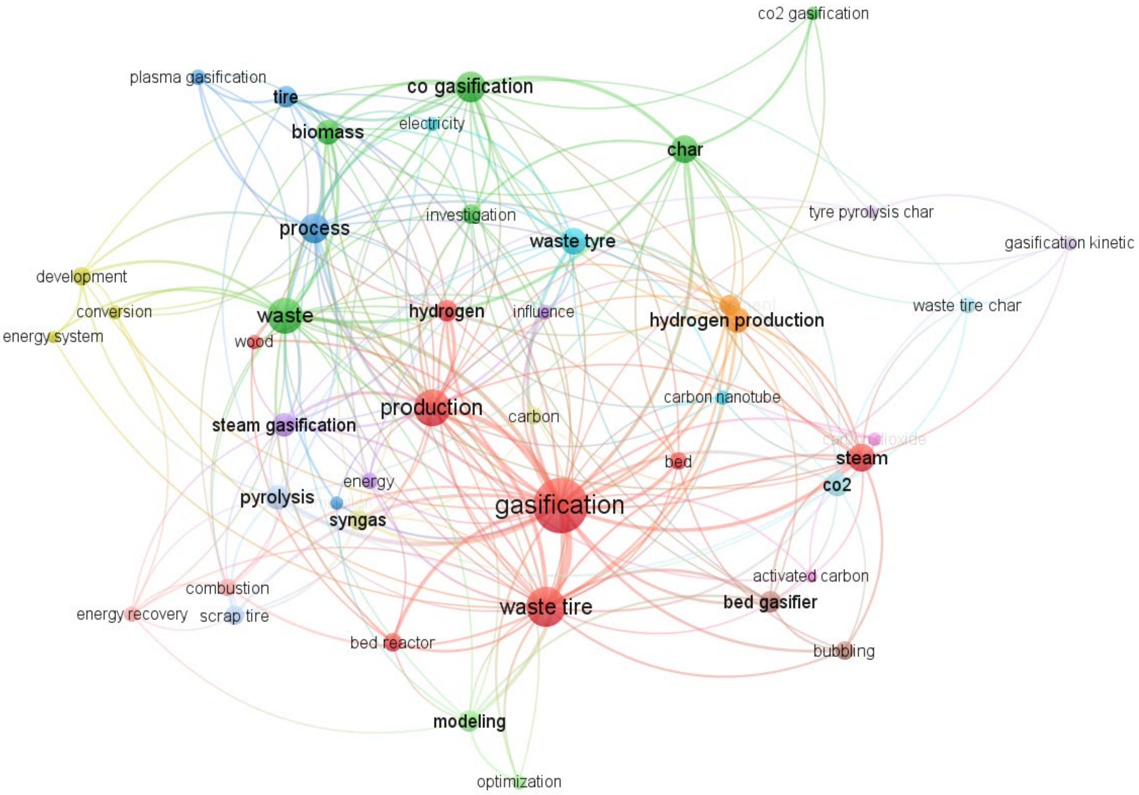

Fig. 2. VOSviewer visualization of keywords used in waste tyre gasification publications.

Fig. 3. shows the breakdown of waste tyre gasification publications in terms of metrics such as the document type, year of publication, publisher, main subject areas, and the publication source title. The document type breakdown shows 63% of the total articles were journal articles, 21% were conference papers, and 6% were review articles while the remaining 10% were book chapters, conference reviews, notes, data papers and erratum as shown in **Fig. 3a**. The breakdown of the waste tyre gasification also shows that 2018 to date has the highest number of researchers who have worked on the topic. A total of 73 articles representing 45% of all the works on waste tyre gasification fall within the last 5 years. From 2012-2017 represents 28% of all works on waste tyre gasification, while before 2011 only 22% of the total works on waste tyre gasification as shown in **Fig. 3b**. Considering the interest shown in waste tyre gasification in recent years shows that it is still a technology at its development stage worldwide. The top publishers for waste tyre gasification articles were Elsevier (55%), ACS (8%), Springer (6%), MDPI (3%) and IEEE (2%) as shown in **Fig.3c**. **Fig. 3d** shows that Energy (23%), Environmental science (17%), Chemical Engineering (16%), Engineering (14%), and Chemistry (10%) are the top subject areas in waste tyre gasification. Meanwhile, the top journal titles in waste tyre gasification were Energy & Fuels (10%), Fuel (10%), Waste Management (9%), Fuel Processing Technology (7%), Energy Conversion and Management (6%) and International Journal of Hydrogen Energy (6%).

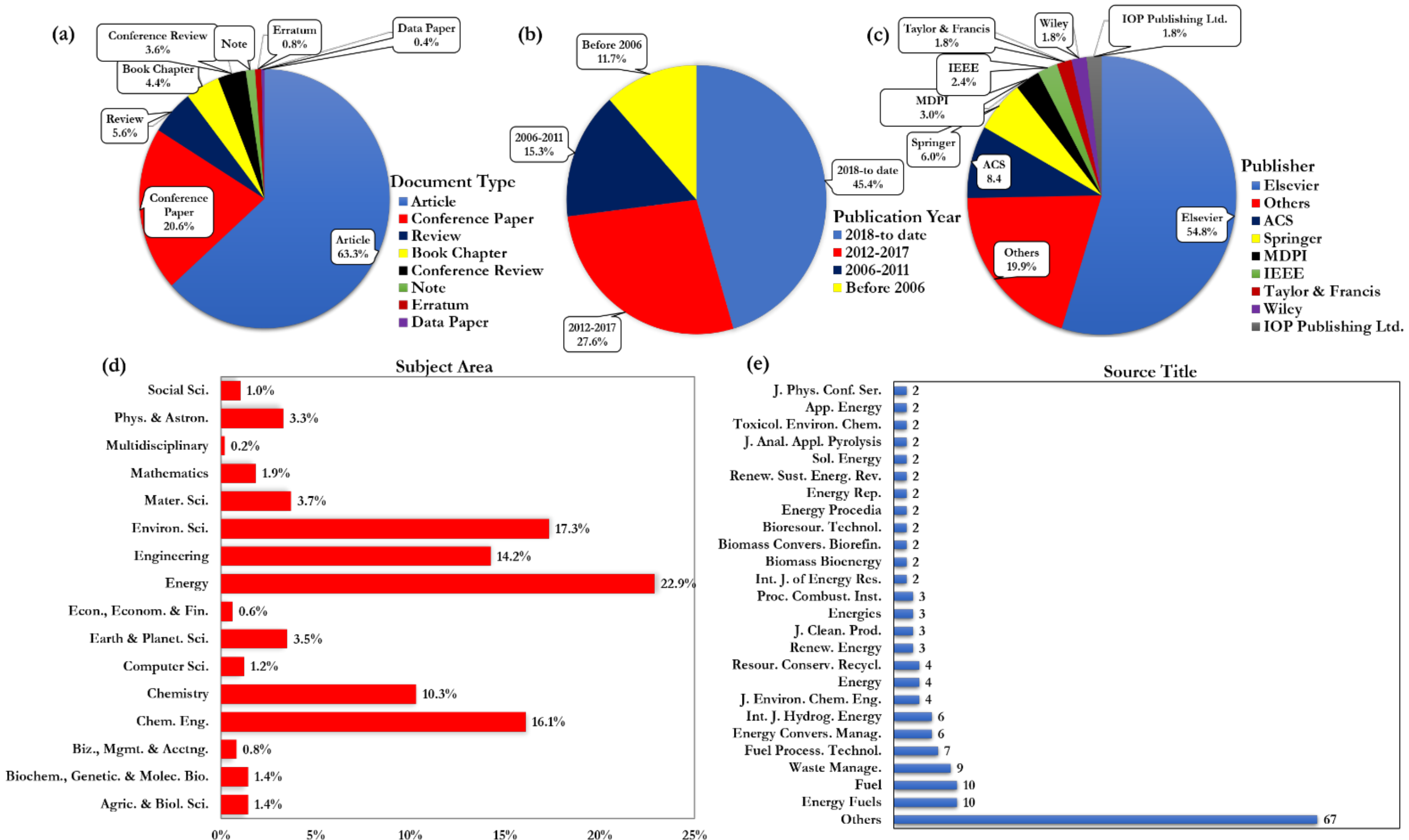

Fig. 3. Breakdown of waste tyre gasification publications in terms of (a) Document Type (b) Publication Year (c) Publisher (d) Subject Area (e) Source Title.

3.0. Literature Review

3.1. Waste Tyre Overview

Just like new tyre, waste/used/scrap tyres are made up of a variety of materials, including elastomers made of natural rubber (NR), synthetic rubber (SBR), cis-polyisoprene (SR), carbon black, zinc oxide (ZnO), sulphur, textiles and additives as shown in **Fig 4.** [23]. With ZnO acting as an activator and carbon black as a compound, raw rubber with a sulphur content of 1-3wt.% is vulcanized to create a cross-link for hardening, enhancing the rubber's elasticity, conductivity, support, as well as thermal and abrasion resistance [20]. During the production process, other components such as steel cables, sulphur, textiles, ZnO, rubber extender oils, and carbon black are combined [20]. Generally, tyres need an appropriate composition of carbon blacks with varying particle sizes to achieve the expected performance. The carbon black structure helps the rubber's continuous elongation stress and modulus. The more wear resistance and effective reinforcing there is, the smaller the carbon black particle size [39]. Waste tyre-derived fuel (WtDF) is produced by treating and removing the heavier components from it, followed by shredding, grinding, and sifting the waste tyres into various particle sizes. Compared to municipal solid wastes (MSW), coal, or biomass, the moisture content (MC) and ash content in waste tyres are low, while the fixed carbon content is higher [20]. This makes the calorific values (CV) of waste tyres (35-45MJ/kg) higher than those of various coal samples (13.5-33 MJ/kg) [40, 41], plastics (24-44MJ/kg) [42], refuse derived fuel (RDF) (30.42MJ/kg)[43] and a variety of biomass (15-22 MJ/kg) [44]. The high CV of waste tyre samples makes aids in for the potential energy recovery from waste into hydrogen, syngas, and liquid feedstock [45].

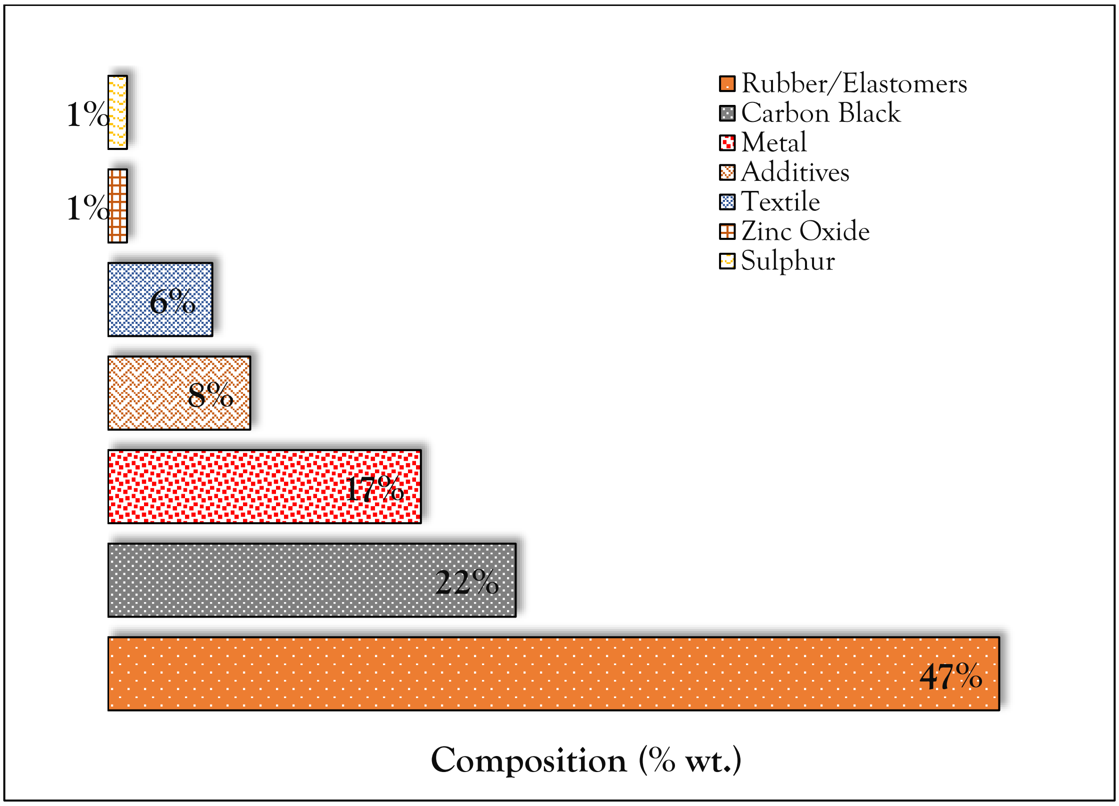

Fig. 4. Average tyre composition [46].

3.2. Waste Tyre Gasification Overview

Waste tyre gasification as an alternate source of renewable energy has been regarded as a viable thermal conversion alternative process to pyrolysis as well as combustion. In comparison to biochemical routes, thermochemical gasification processes appear to be a better process for energy extraction from syngas [47, 48]. Waste tyre gasification is also a promising technology for converting waste tyres into other by-products such as chemicals and carbon products [23]. Depending on the gasification conditions, product gases from gasification process can yield as high as 40 MJ/Nm^3 [49]. The composition of the product gases as well as their heating values depend on the selected gasification agent. ~~Air gasification also produces large concentrations of nitrogen in the dry gas mixtures with lower heating values (LHV) between 4 MJ/Nm^3 and 5 MJ/Nm^3, whereas steam and steam-air mixture can yield more hydrogen with LHV ranging between 7 MJ/Nm^3 and 13 MJ/Nm^3 [50].~~Insights on the different waste tyre gasification agents as well as their ratios on waste tyre gasification are further explained in subsection 3.1.3.2. Waste tyre gasification process can be broken down into 5 stages which include: the collection stage, pre-processing stage, processing, post-processing and the application stage as shown in **Fig. 5**. The final stages show that waste tyres gasification has been employed in the production and co-production of several products. In order to improve syngas and hydrogen production, waste tyres have been co-gasified with other feedstocks such as coal, rubber, plastic and biomass such as acacia, pine, sawdust, and bamboo [34, 41, 43, 51, 52]. In waste tyre gasification processes, gasifier operating conditions (pressure and temperature) are very important. Any increase in the gasifier operating pressure will result in higher syngas (H_2 and CO) yield and higher lower heating value (LHV) [18]. Meanwhile, an increase in the operating temperature will increase the syngas production rate and reduce the char yield [53]. At temperatures above 1000°C, the production of hydrogen is favoured at the expense of methane [18, 54]. Waste tyre gasification can achieve a thermal efficiency of up to

$90\%_{LHV}$ [55, 56]. More insights on the operational parameters that can influence waste tyre gasification can be found in section 3.1.3. Some of the studies that employed waste tyre gasification and co-gasification ~~which produces key products and~~ are discussed in subsequent sections.

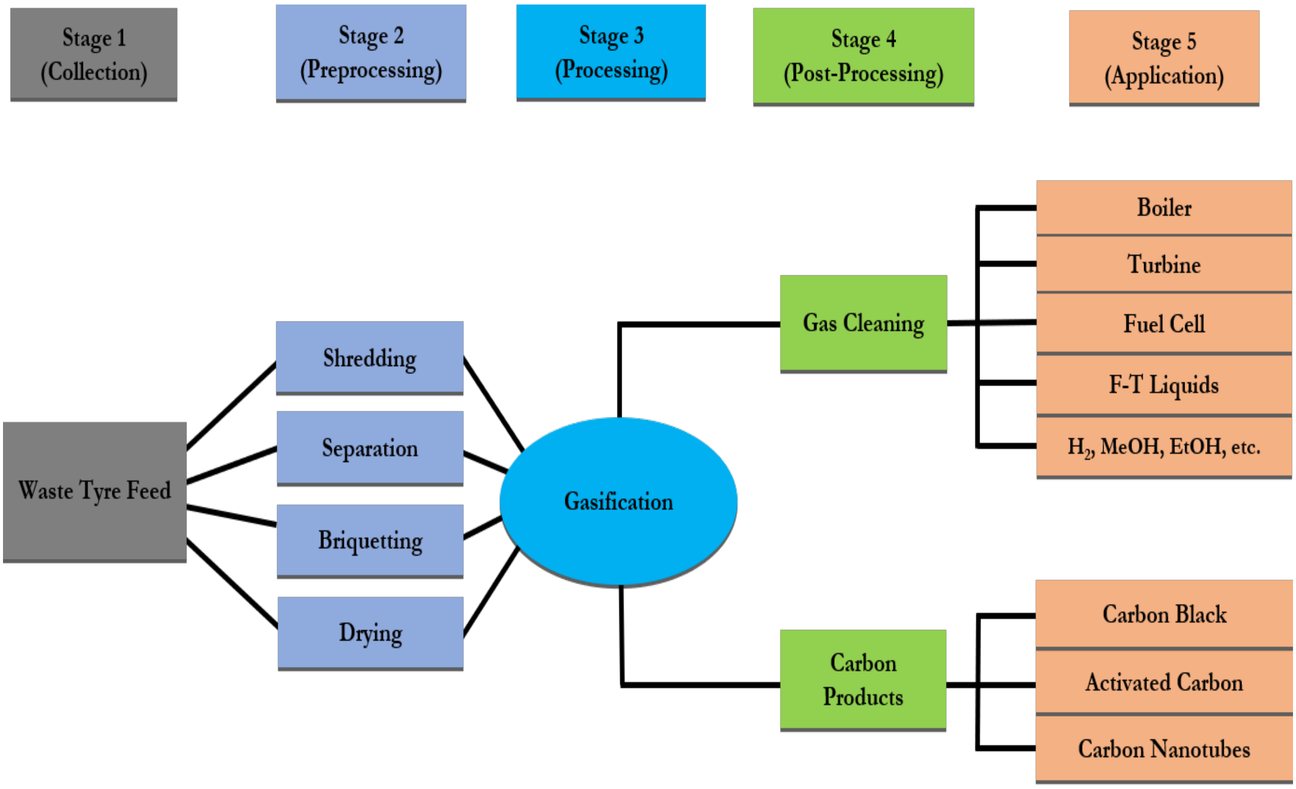

Fig. 5. Stages involved in a complete waste tyre gasification process [15].

3.2.1. Waste tyre Gasification Modes

Currently, there are four modes of waste tyre gasification processes that have been employed to date. They include common/conventional gasification [34, 51, 56-63], plasma gasification [64-70], hydrothermal gasification [8, 71], and solar-assisted gasification [72-75]. Each of the aforementioned waste tyre gasification modes is described in the subsequent section.

3.2.1.1. Conventional Gasification of Waste Tyres

Conventional gasification of waste tyres requires the use of gasifiers (fixed bed, fluidized bed, rotary kiln, and entrained flow gasifier) and gasifying agents to breakdown tyres into the desired products. The mode of operation of the conventional gasifiers is discussed in section 3.1.2. By using air or oxygen, the required heat needed to breakdown the organic portions of waste tyres is generated by the partial oxidation of the waste tyre feed [36].

3.2.1.2. Hydrothermal Gasification of Waste Tyres

Hydrothermal gasification of waste tyres is the gasification of tyres using supercritical or subcritical water [76]. This mode of waste tyre gasification process does not require any pre-drying, which results in significantly less tar and char being produced than typical gasification and pyrolysis procedures [8]. The complete miscibility of supercritical water with gas means that all reactions are carried out in homogeneous media which speeds up the heat and mass transfer process [77]. Hydrothermal gasification technology is also beneficial to the destruction of the polymer structures in waste tyres [8]. In addition, water serves as both a solvent and a reactant to improve the yield of hydrogen gas, which might considerably encourage the use of this gasification technology. This type of gasification is a promising technology recently employed to gasify waste tyres and this process can be environmentally-friendly for the conversion of waste tyres to hydrogen-rich syngas or hydrogen [8, 78].

3.2.1.3. Plasma Gasification of Waste Tyres

In this mode of waste tyre gasification, tyres are broken down into syngas and vitrified slag [36]. While conventional and hydrothermal are usually carried out in the common gasifiers (fixed bed, fluidized bed, rotary kiln, and entrained flow gasifier), plasma gasification is done in an electric arc or plasma torch furnace [65, 66]. A working gas must flow between the two electrodes in order to form the thermal plasma, which is done by transferring a strong electric current between them [79]. Plasma gasification of waste tyres requires higher temperatures than those used in conventional gasification. Regardless of the reactor architecture, the majority of studies on the conventional mode of gasification of tyres have been conducted below 1000°C while plasma can be carried out as high as 1800°C [36, 70, 79]. A major drawback of the plasma gasification process is the high concentration of N_2 in the syngas stream [67].

3.2.1.4. Solar-assisted Gasification of Waste Tyres

This mode of waste tyre gasification requires concentrated solar energy as the heat source [74]. Higher gasification temperatures (above 1100°C) are possible without the use of an oxygen-blown furnace, which leads to much faster reaction kinetics and better-quality syngas with low or no tar content [72]. The need for expensive downstream gas cleaning and separation is reduced because the contamination of syngas via combustion is prevented [72, 73]. Since, solar-assisted waste tyre gasification requires only steam, an upstream air separation unit (ASU) is not required and this also brings down the operating cost [80]. In addition, the process makes it possible to process virtually any kind of carbonaceous feedstock, maximizing the use of the available resources [73, 81].

3.2.2. Waste Tyre Gasification Reactors

Waste tyre gasification reactors (see **Fig. 6**) can be divided into three categories: fixed bed (which could be updraft, downdraft or cross draft), fluidized bed (which could be bubbling or circulation), and entrained flow reactor (which could be top-fed or side-fed) [6, 55, 82]. In addition to these three, rotary kilns and plasma reactors have also been employed to gasify waste tyres [79, 83]. The choice of reactor depends on the operation size, the properties of the waste tyre feed, and the intended application of the syngas [84]. All of these reactors have advantages and downsides as summarized in **Table 1.** Due to the relatively lower cost of a fixed bed gasifier, most recent studies [34, 35, 55, 58, 61, 85-89] have employed this reactor at all scales. In addition, rotary kilns have been explored mainly at pilot scale [83, 90, 91] while fluidized bed have been applied at lab scale [60, 90]. Ma *et al.* [65] and Larionov *et al.* [64]

explored plasma torches and electric arc approaches to gasify waste tyres. The Larionov *et al.* [64] result showed that hydrogen-rich syngas (with a composition of up to 54 vol.% H) were produced from this process. In addition, the CH_4, CO and CO_2 also ranged between 7-26 vol.%, 20-36 vol.% and 12-18 vol.% respectively. Ma *et al.* [65] also produced a hydrogen-rich syngas and also reported carbon conversion rate up to 99%, and $94\%_{HHV}$ energy recovery. Even though the electric arc system has not been commercialized, it has also been proven to co-produce carbon nanomaterials along with the syngas. Most studies of the commercial scale applications in recent years have been based on techno-economic analytical adaptation of these reactors. For example, a commercial scale fluidized bed gasifier system would cost over $10 million for a 5.4 ton/hr plant [86] while a rotary kiln system can cost as much as $279 million for a 90 ton/hr plant [92]. The intricate and complicated nature of the technology, together with the requirement for cutting-edge pollution control systems, contribute to the high capital cost of gasification plants. The majority of the time, these costs do not include the price of tar cracking, waste tyre pretreatment, ash handling, or syngas cleaning [92, 93]. Additionally, because of this cost, waste tyre gasification may find it challenging to compete with other waste management techniques (such pyrolysis), especially in areas with limited financial resources.

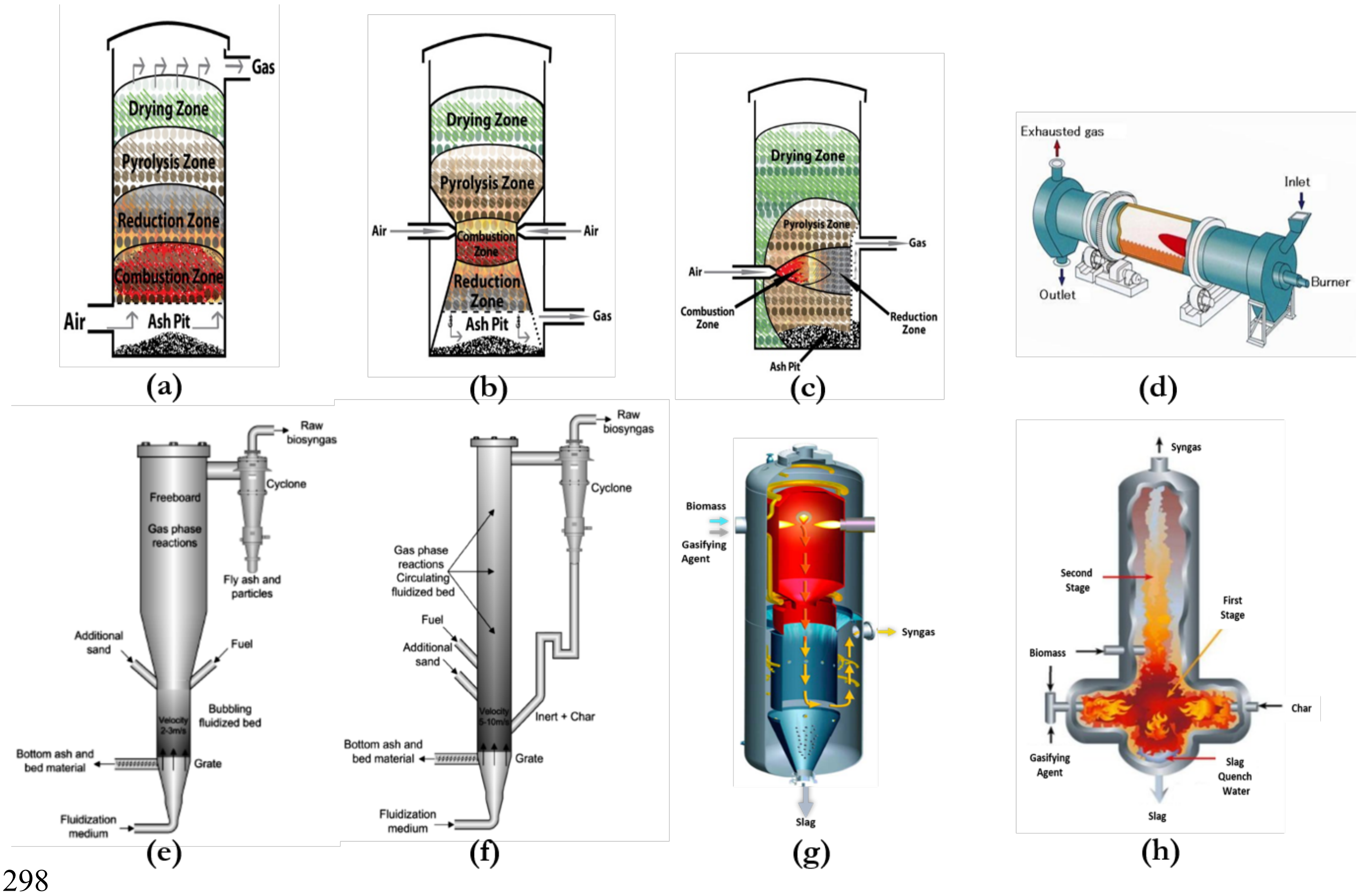

Fig. 6. Diagrammatic representation of different waste tyre gasification reactors (a) Updraft fixed bed (b) Downdraft fixed bed (c) Cross draft fixed bed (d) Rotary kiln (e) Bubbling fluidized bed (f) Circulation fluidized bed (g) Top-fed entrained flow reactor (h) Side-fed entrained flow reactor (Images reproduced with permission from [94-97]).

Table 1. Properties of different types of waste tyre gasifiers [98-100].

Gasifier	Pros	Cons
Updraft Fixed Bed Gasifier	1. Very Simple and less expensive. 2. Low exit gas temperature. 3. High carbon conversion ratio. 4. Clean gas. 5. High thermal efficiency. 6. Operates well under pressure. 7. Ability to handle high humidity materials. 8. Reduced ash and dust entrainment.	1. High tar production. 2. Potential channelling. 3. Clinkering. 4. Small feed size. 5. Bridging potential. 6. Low syngas production. 7. Low specific capacity.
Downdraft Fixed Bed Gasifier	1. Simple construction. 2. Low tar production. 3. High carbon conversion ratio. 4. Limited ash and dust entrainment. 5. High solid hold time. 6. Very reliable.	1. Minimum feed size. 2. Bridging and clinkering potential. 3. Requires feed with low moisture. 4. Limited scale up capacity.
Rotary Kiln Gasifier	1. Operates at very high temperature. 2. Not prone to overheating and chemical attacks. 3. Can resist high impact and thermal shocks. 4. Less tar formation. 5. Sensitivity to changes in feed size, composition and humidity is low. 6. High carbon conversion ratio. 7. Low cost of investment. 8. Simple construction and very reliable.	1. Difficult to operate under pressure. ~~2. High production of tar and dust.~~ 3. High cost of maintenance. 4. Low flexibility. 5. Low thermal efficiency. 6. Low heat exchange capacity. 7. High refractory consumption.
Bubbling Fluidized	1. Flexible feed rate and composition. 2. High ash fuel.	1. High product gas temperature. 2. Ash and dust dragging.

Bed Gasifier	3. Easy temperature control. 4. Ability to handle different kinds of feed. 5. Ideal for fuels with high reactivity. 6. Low level tar in syngas. 7. Good scalability. 8. Adaptable to catalyst usage. 9. High carbon conversion ratio. 10. High gas-solid contact and mixing. 11. High heat capacity.	3. High carbon content in fly ash. 4. High cost of maintenance. 5. High investment cost. 6. Pre-treatment is needed when used for co-gasification operation.
Circulating Fluidized Bed Gasifier	1. High operating temperature. 2. Flexible process. 3. Low tar production. 4. Low residence time. 5. Good scalability. 6. High carbon conversion.	1. Problems of corrosion and attrition. 2. Poor operational control. 3. High cost of operation. 4. Low solid-gas contact. 5. Require feed size reduction.
Entrained Flow Gasifiers	1. Very low in tar and CO_2. 2. Flexible to feedstock. 3. High exit tar temperature. 4. High temperature slagging operation. 5. Uniform reactor temperature. 6. No scale-up problem. 7. Excellent Process parameter control. 8. Short hold time. 9. High carbon conversion.	1. Low methane formation. 2. Requires very small feed size. 3. Ash slagging. 4. Complex control of operation. 5. High cost of maintenance. 6. Heat recovery is required to improve efficiency. 7. Requires large amount of oxidant. 8. Efficiency of the cold gas is low. 9. Components have short lifespan.

3.2.3. Waste Tyre Gasification Operational Parameters

The description of the operational requirements for gasifiers is a necessary step in the waste tyre gasification process. Research has been conducted on a number of parameters that impact several performance metrics such as product yield, energy efficiency, cold gas efficiency, syngas efficiency, and product gas quality [101]. These parameters are categorized into four categories: feed characteristics, gasifying agent, gasifer operating condition and catalyst. The following subsections provide insights on the parameters that can influence waste tyre gasification process.

3.2.3.1. Feed Characteristics

One of the feed characteristics that can affect the final composition of the produced gas during the waste tyre gasification process is its moisture content [55, 86]. The amount of water present in waste tyre sample, expressed as a percentage of its total mass, is known as its moisture content [102]. As a result, adding additional moisture will produce more water reactants, which will lower the GT and enhance the WGS reaction [102]. As energy is required for moisture vaporization and vapour superheating, moisture has a significant impact on recoverable energy [103]. In waste tyre gasification, the FMC was found to have no impact on other gasification parameters in the gasification reactors, however, the authors observed a rise in CO_2 and hydrocarbons and a decrease in other syngas components as the moisture level increased [86]. In addition, the FMC in waste tyres should not be confused with concept of hydrothermal gasification (see subection 3.1.1.2). Another key parameter influencing the rate and efficiency of char production during the waste tyre gasification process—which is mostly dependent on the gasifier diameter—is the size of the waste tyre particles [104, 105]. While Kandasamy & Gökalp [106] concluded that an FPS between 0.5-10mm does not have significant effect on the output of the tyre gasification process, some authors [104, 107] proved this does not apply to all scenarios. Straka & Bučko [107] studied the effect of FPS for particles sizes between 3-40 mm, the authors found that an FPS less than 20 mm is required to optimize waste tyre gasification and co-gasification processes. Leung & Wang [104] also explored how different gasification parameters in a fluidized bed reactor were affected by the FPS. FPS between 0.4 and 2.1 mm were examined by the authors and it was found that the smaller particles had higher reactivity because they dispersed more readily inside the reactor than the bigger ones. The authors concluded that when FPS above 1mm is employed, the gasification process becomes ineffective to the secondary reaction temperature and bed temperature. However, when FPS below 1mm was employed, the reaction temperature falls while the product gas yield, char yield, oil yield, volatile release ratio, energy recovery ratio, and gas heating value increase [104]. Song *et al.* [108] also concluded from their study that smaller FPS improved the syngas yield and syngas LHV. Furthermore, other characistics such as the volatile matter (VM), ash, fixed carbon (FC), heating value, sulphur, atomic (H/C), atomic O/C ratios, etc have also been established to influence waste tyre gasification process in their respective ways [11, 64, 108].

3.2.3.2. Gasification Agents (GAs) and their Ratios

Oxygen, air, steam, CO_2 as well as their combinations are the gasification agents that have been employed in previous studies [34, 58, 60, 61, 65, 85-87, 108] on waste tyre gasification on both lab-scale and commercial-scale. However, the choice of these agents is dependent upon the energy output and desired composition of the product gas stream. Through the exothermic process of gasification with air, hydrocarbons and minimal hydrogen gas are produced along with low heating value gas that is rich in CO [101]. Air gasification also produces large concentrations of nitrogen in the dry gas mixtures with LHV between 4 MJ/Nm^3 and 5 MJ/Nm^3, whereas steam and steam+air mixture can yield more hydrogen with LHV ranging between 7 MJ/Nm^3 and 13 MJ/Nm^3 [50]. In addition, gasification using steam is an endothermic process that yields a gas with a higher heating value with hydrogen composition

[101]. Gasifying waste tyres with steam+CO_2 have been observed to have a higher char reactivity and cold gas efficiency when compare with steam only process [87]. Karatas *et al.* [109] employed different GA combinations (steam, air+steam, and air+CO_2) in their study. The findings shows that steam>Air+CO_2>Air+steam have the highest syngas yield and LHV respectively. Gasification with steam and its combination with other GAs have been frequently chosen to improve the quality of producer gas because it increases the hydrogen concentration.

The equivalence ratio (ER) and steam to fuel ratio (SFR) are two most important parameters investigated in relation to the GA employed during waste tyre gasification. In the waste tyre gasification process where air or oxygen is used as the GA, the ER is defined as the ratio of the theoretical to the actual air requirement [86]. Given that gasification is predicated on attaining the partial combustion of the waste tyre samples, only a portion of this ratio is often employed. Theoretically, the oxygen demand needed to achieve the combustion of waste tyres depends on their contents [101]. The ER has been proven to have a significant effect on the performance of the gasification reactor. In addition, ER directly affects the thermal efficiency of the process, gas quality, as well as the bed temperature [86]. The SFR, which measures the amount of steam fed per mole of fuel, has a significant influence on the system's energy input as well as the composition of the final syngas stream [110]. Although the production of methane and solid carbon is encouraged by a lower SFR value, the carbon and methane present are ultimately converted to CO and hydrogen as more steam is delivered [101]. In addition, similar to the FMC, the introduction of more steam will also produce more water reactants, which will lower the GT and enhance the WGS reaction [55].

3.2.3.3. Gasification Conditions

The most significant impact on the overall efficiency of the waste tyre gasification process appears to be the temperature at which the gasifier is operated [101]. Reaction rate and product composition are impacted by gasification temperature (GT). The impact of the GT on the gasification of waste tyres has been investigated in various studies [34, 35, 60, 85-88, 106, 108]. Temperature changes in a gasifier have the ability to modify the equilibrium point of any gasification reaction, as these reactions are typically reversible [111]. Change in the GT during the gasification of have a notable impact on the shares of different fractions and the composition of the resulting syngas [33]. These changes also affect the quality of the gas produced and the parameters that describe the process' efficiency [33]. Raman *et al.* [112] observed that while the char yield remained constant, raising the GT increased the yield of product gas and decreased the yield of liquid. The process of gasifying waste tyres is also significantly influenced by the gasification pressure (GP). A few studies [58, 113] have looked into the significance of GP and found that as the pressure goes up, so do the syngas's HHV, composition, and yield. The number of active sites on the surface of the waste tire sample has been connected to an increase in the GP, which has also been found to promote heterogeneous gas-solid interactions. Furthermore, an increase in the GP has been found to boost the production rate and yield of CO. Due to the fact that homogeneous processes also occur in the gas phase, the impact of pressure on hydrogen was ambiguous [4, 33]. Another significant parameter influencing waste tyre gasification process is the heating rate (HR). Due to the limits of heat transfer, thermogravimetric curves move toward higher temperatures with increasing HR.When heating at a rate of 3K/min, Czerski *et al.* [114] found that the maximum conversion rate was around 1313K. However, when HR was increased to 15K/min, the conversion rate improved by ~5%. Song *et al.* [108] also observed that the HR employed in waste tyre gasification is proportional to the mass loss in the process. The residence time (RT) of the waste tyre char is another important component to take into account in waste tyre gasification in order to enhance syngas production. A study by Molino *et al.* [83] examined the impact of RT on waste tyre gasification. Investigated were six experimental studies with gasification residence periods ranging from 60 to 360 minutes. At the conclusion of the experiment, it was found that the waste tyre gasification process produced more syngas and a higher burn-off value the longer the char RT.

3.2.3.4. Catalyst

Catalyst action will expedite the waste tyre gasification process because it is imperative that the reaction rate be increased [52]. Waste tyre gasification procedures have been studied using catalysts such $MgCa(CO_3)_2$, NiO, CaO, Ni/Al_2O_3, Ni/SiO_2-Al_2O_3, Ni-Mg-Al, Ni/Ce, Co/Al_2O_3 amongst several others. Previous research [8] emphasized that syngas yield is increased by both homogeneous and heterogeneous catalysts by accelerating the WGS reaction and the cracking reaction. Some authors [8, 89, 115, 116] also came to the conclusion that catalysts were necessary in order to maximize the production of hydrogen gas from waste tyre gasification, after these Nickel-based catalysts were utilized to increase the production of hydrogen. Elbaba *et al.* [117] have investigated the viability of gasifying waste tyres in a steam atmosphere using a Ni–Mg–Al catalyst. The findings demonstrate that better solid and gas fraction yields were achieved at the price of lower liquid product yields when compared to the process performed without the inclusion of a catalyst. In addition, catalysts have also been reported to reduce the energy recovered from waste tyre gasification process [36]. Zhang *et al.* [89] also observed that the primary adverse reaction resulting from the application of catalyst is its deactivation from the char surface.

3.3. Waste Tyre Gasification Targeted at Gaseous Product Production

Waste tyre gasification can produce a variety of gases including syngas, hydrogen, methane and other volatile organic compounds (VOCs). Syngas (which comprise mainly carbon monoxide (CO) and hydrogen gas) have been used as fuel in internal combustion engines, gas turbines, and boilers [109, 118]. Methane and VOCs have been used as fuel in boilers and also as a feedstock for the production of other chemicals. Hydrogen has been used as a fuel in fuel cells or as a chemical feedstock [55]. Waste tyre gasification and co-gasification process(es) to produce syngas/hydrogen have been investigated using direct gasification [8, 34, 41, 51, 52, 55, 56, 59-61, 63, 71, 85, 86, 88, 91, 102, 108, 119-122], a combination of steam gasification and catalytic reforming [115] and catalytic pyrolysis–gasification [89, 117, 123]. This section will investigate recent studies on the use of gasification for the production of hydrogen and syngas production from waste tyres. These studies [8, 34, 41, 51, 52, 55, 56, 59-61, 63, 71, 85, 86, 88, 91, 102, 108, 119-122] have found that various gasification technologies, including catalytic, plasma-assisted, and entrained-flow gasification, are able to efficiently convert waste tyres into syngas/hydrogen with high yields. The use of catalysts in the process has also been found to improve the process efficiency and hydrogen yield [124]. However, more research is needed to optimize the process conditions and to investigate the longevity and stability of catalysts under prolonged use.

3.3.1. Waste Tyre Gasification Targeted at Syngas Production

As mentioned earlier, the syngas produced from waste tyre gasification process could be used to power gas turbines, and fuel cells [109, 118]. The quality of syngas produced in terms of the presence of tars, metals, sulphurous compounds, heating value (LHV), carbon conversion, and efficiency ($\%_{LHV}$) is a significant consideration in waste tyre gasification. Gas turbine and fuel cell applications for heat and electricity generation require a very high syngas quality [125]. Presently, varieties of technological alternatives have been put up as a way to trap corrosive gases that may hinder syngas quality [126]. Conventional technologies are largely multistep and complex so they need a very large land space with high capital cost [127, 128]. The process also suffers from a variety of operational challenges including equipment corrosion and fouling, solvent losses, liquid channelling, floods, and unusual foaming. The ash produced after gasification is quite different from that of incineration; while that of incinerator is considered safe for usage as substitute cover in dumping grounds, there have been concerns about its usage in commercial products [129]. However, in high-temperature gasification, the ash flows in molten form from the reactor where it is quenched and forms a glassy, non-leachable slag that could be used in industrial operations such as cement making, roofing shingles, asphalt filling, and sand blasting [129]. The findings of some authors who have worked on syngas production from waste tyre gasification in recent years are presented in **Table 2**.

Table 2. Summary of some recent studies on gasification of waste tyres targeted at syngas production.

Author(s)	Work	Gasifier Type & Scale	Waste Tyre Characteristics	GA(s), SFR & ER	Gasification Condition(s)	Catalyst	Deductions
1. Czerski *et al.* (2023) [34]	Study on steam co-gasification of waste tyre char and sewage sludge	Type: Fixed Bed Gasifier Scale: Lab Scale	Type: Waste Tyre Char FPS: NR *Proximate Analysis (wt.%)* MC: 1.1; FC: 75.4 VM: 2.2; Ash: 21.3 *Heating Value* HHV: 26.21 MJ/kg *Ultimate Analysis (wt.%)* C: 74.6; H: 0.77; N: NR S: 2.87; O: NR	GA: Steam SFR: 0.6 ER: NE	GT: 800-900°C GP: 1 MPa HR: NE RT: NR	SiO_2 and P_2O_5 from the sewage sludge ash	The authors employed steam gasification to evaluate the effect of feed ratio on syngas production. Two waste tyre char to sewage ratios (90:10 and 67:33)~~ were employed at different GTs (800-900°C) at 1 MPa~~. Their results show that at high temperatures (900°C), the 90:10 blend ratio improves both CO and CH_4 composition and reduces CO_2 and H_2 composition in the syngas stream. The authors concluded that the combination of waste tyre char and sewage sludge reduced both the activation energy and pre-exponential factor of waste tyre gasification process significantly.
2. Spiewak *et al.* (2023) [58]	Influence of pressure and sunflower husks ash as catalyst on tyre-char steam gasification	Type: Fixed Bed Gasifier Scale: Lab Scale	Type: Waste Tyre Char FPS: 100μm-2mm *Proximate Analysis (wt.%)* MC: 1.1; FC: 75.4 VM: 2.2; Ash: 21.3 *Heating Value* HHV: 26.21 MJ/kg *Ultimate Analysis (wt.%)* C: 74.64; H: 0.77; N: NR S: 2.87; O: NR	GA: Steam SFR: 0.6 ER: NE	GT: 800-1000°C GP: 0.5 MPa & 1 MPa HR: NE RT: NR	Sunflower husk ash (SHA)	The authors employed different SHA catalyst compositions (0-15 wt.%) in the production of syngas from waste tyre gasification. ~~In addition to this, the experiment was also performed at different GTs (800-1000°C) and pressures (0.5 MPa and 1 MPa).~~ Results from the study show that at low temperatures (<850°C) the effects of pressure and catalyst on the CO/H_2 ratios in the syngas stream were more pronounced. The carbon conversion reaction during steam gasification demonstrated that the catalyst addition decreased activation energy (Ea) and pre-exponential factor (A). In addition, the results indicated that steam gasification at low temperatures at 1 MPa, and 15 wt.% SHA is the best combination for obtaining hydrogen-rich syngas.

3. Larionov *et al.* (2023) [64]	Electric arc gasification of pyrolysis oil with the production of hydrogen-enriched synthesis gas and carbon nanomaterial	Type: Electric Arc Scale: Lab Scale	Type: Waste Tyre Oil FPS: NA *Proximate Analysis (wt.%)* MC: NR; FC: NR; VM: NR; Ash: Trace *Heating Value* HHV: 43.3 MJ/kg *Ultimate Analysis (wt.%)* C: 86.2; H: 11.0; N: 0.6 S: 0.8; O: 1.4	GA: Air SFR: NE ER: NR	GT: NA GP: 1 atm HR: 10°C/min RT: NR	NE	The authors employed waste tyre pyrolysis oil to produce syngas through waste tyre gasification using a 74-voltage laboratory-scale DC arc reactor. This process was validated by employing petroleum and pyrolysis oil from other samples such as sludge and wood. The result showed that hydrogen-rich syngas (with a composition of up to 54 vol.% H) were produced from this process. In addition, the CH_4, CO and CO_2 also ranged between 7-26 vol.%, 20-36 vol.% and 12-18 vol.% respectively.
4. Serrano *et al.* (2022) [60]	Waste tyres valorization through gasification in a bubbling fluidized bed: An exhaustive gas composition analysis	Type: Bubbling Fluidized Bed Gasifier Scale: Lab Scale	Type: Raw Waste Tyre FPS: 150-600µm *Proximate Analysis*^{db} *(wt.%)* MC: 1.19; FC^{a}: 25.19; VM: 64.76; Ash: 8.86 *Heating Value* HHV: 35.11 MJ/kg ^{ar} *Ultimate Analysis (wt.%)* C: 74.75; H: 5.46; N: 0.71 S: 1.15; O^{a}: 8.96	GA: Air & Air+Steam SFR: 0.39 ER: 0.13-0.33	GT: 700°C & 850°C GP:1 atm HR: NE RT: NR	NE	The authors investigated the effect of GT ~~(700°C and 800°C),~~ER ~~(0.13-0.33)~~ and SFR ~~(0.39)~~ on syngas production from waste tyre gasification. The results from the at high temperature and low ER, the production of H_2 and light hydrocarbons were favoured while cold gas efficiency (CGE), ~~lower heating value~~ LHV, and carbon conversion were not favoured. In addition, the authors concluded that the steam-gasified system produced higher H_2, lower CO, and higher syngas LHV than the air only-gasified system.
5. Song *et al.* (2021) [108]	Utilization of waste tyre powder for gaseous fuel generation via CO_2 gasification using waste	Type: Entrained Bed Gasifier Scale: Lab Scale	Type: Raw Waste Tyre FPS: 80-300 mesh *Proximate Analysis (wt.%)* MC: 0.95; FC^{a}: 30.66; VM: 62.17; Ash: 7.17 *Heating Value* HHV: 21.16 MJ/kg	GA: CO_2 SFR: NE ER: NE CO_2FR: NR	GT: 300-1400°C GP: 1 atm HR: 5-20°C/min RT: NR	NE	~~The authors employed furnace waste heat to gasify waste tyre powder in the presence of CO_2.~~ The gasification process was monitored in a thermogravimetry mass spectrometry (TGMS) system. In addition to the kinetic analysis investigated in the study, the effects of temperature, FPS, CO_2:CO ratio in the process were also studied. From the TGMS system, at temperatures from 300-500°C, the main syngas

	heat in converter vaporization cooling flue		*Ultimate Analysis (wt.%)* C: 79.41; H: 7.25; N: 0.77 S: 1.75; O^a: 3.65				components were CO, H_2, CH_4, H_2O, and C_2H_6. In addition, the activation energy from the process was found to be 144.5 kJ/mol while the LHV at 500°C was 10.27 MJ/Nm^3. The authors concluded that FPS and GT greatly affect syngas production and LHV.
6. Carmo-Calado *et al.* (2020) [35]	Co-combustion of waste tyres and plastic-rubber wastes with biomass technical and environmental analysis	Type: Fixed Bed Gasifier Scale: Pilot Scale	Type: Raw Waste Tyre FPS: 1-4cm *Proximate Analysis (wt.%)* MC: 0.8; FC: 29.6; VM: 64.5; Ash: 5.1 *Heating Value* HHV: 38.6 MJ/kg *Ultimate Analysis (wt.%)* C: 75.5; H: 0.7; N: 0 S: 5.6; O: 13.1	GA: Air SFR: NE ER: 0.28-0.41	GT: 790-900°C GP: NR HR: NE RT: NR	NE	The authors performed co-combustion and co-gasification tests using waste tyres with plastic, rubber and acacia, however, the key gasification test is waste tyre co-gasified with acacia. The experiment was performed in a downdraft fixed bed reactor at different GTs, ERs, and feed ratios. The obtained results indicate that the best syngas composition and LHV values were obtained at waste tyre/acacia blend ratios of 80:20 and 40:60 respectively. At these ratios, the syngas LHV were 3.64 MJ/m^3 and 3.14 MJ/m^3 respectively. In addition, the optimum GT and ER at these blend ratios were 800°C and ER of 0.31 respectively.
7. Wang *et al.* (2019) [85]	Co-gasification characteristics of waste tyre and pine bark mixtures in CO_2 atmosphere	Type: Semi-Batch Fixed Bed Gasifier Scale: Lab Scale	Type: Raw Waste Tyre FPS: 140 mesh *Proximate Analysis (wt.%)* MC: 0.69; FC: 27.88; VM: 62.58; Ash: 8.92 *Heating Value* HHV: NR *Ultimate Analysis (wt.%)* C: 74.75; H: 5.46; N: 0.71 S: 1.15; O:8.96	GA: CO_2 SFR: NE ER: NE CO_2FR: NR	GT: 800°C & 900°C GP: NR HR: NE RT: NE	NE	The authors co-gasified waste tyres and pine bark ~~in a fixed bed reactor~~ at different GTs ~~(800°C and 900°C)~~ and blend ratios in a CO_2 atmosphere. The results obtained from the co-gasification process showed that an increase in pine bark ratio increased the flowrate peak of H_2, CO, and total syngas, but decreased the flow rate peak of the hydrocarbon components (C_mH_n) at the two GTs. At the same blend ratios, the overall yield of the syngas was higher at 900°C than at 800°C. In addition, the authors concluded that co-gasification of waste tyres and pine bark with a blend ratio of 75:25 at 900°C has a higher energy recovery efficiency. At the same

							condition and different blend ratios, the reverse was the case.
8. Zang *et al.* (2019) [86]	Modeling and economic analysis of waste tyre gasification in fluidized and fixed bed gasifiers	Type: Downdraft Fixed Bed Gasifier and Fluidized Bed Gasifier Scale:^{fxb}Pilot Scale and ^{flb}Commercial Scale	Type: Raw Waste Tyre FPS: 2mm^{flb} & 20mm^{fxb} *Proximate Analysis (wt.%)* MC: 0.9; FC: 27.04; VM: 66.3; Ash: 6.66 *Heating Value* LHV: 37.1 MJ/kg *Ultimate Analysis (wt.%)* C: 81.74; H: 7.06; N: 0.30 S: 1.82; O: 2.42	GA: Air+Steam SFR: NR ER: 0.22-0.50	GT: 850°C GP: 1 atm HR: NE RT: NE	NE	~~The authors studied syngas production from waste tyre gasification and co-gasification (with wood) in two gasification reactors namely: fixed bed and fluidized bed.~~ The authors' objective was to find the most efficient and economic pathway to achieve the best production routes by comparing the performance of both gasifiers in a co-gasification process. To simulate the fixed bed and fluidized bed production routes, the authors employed a one-dimensional kinetic model and a semi-empirical model respectively. The effect of parameters such as waste tyre-to-wood ratio, ER, and MC (0.9-30%) were also investigated. The obtained result shows that waste tyre-wood mixture has higher syngas efficiency in both reactors however, the energy output from 100% waste tyre is greater. In addition, an ER of 0.3 produced the best gasification result. The authors also concluded that plant capacity is an important factor in determining the best reactor to employ in waste tyre gasification
9. Policella *et al.* (2019) [87]	Characteristics of syngas from pyrolysis and CO_2-assisted gasification of waste tyres	Type: Semi-Batch Fixed Bed Gasifier Scale: Lab Scale	Type: Raw Waste Tyre FPS:100µm *Proximate Analysis (wt.%)* MC: 0 ; FC: 26.2; VM: 66.5; Ash: 7.3 *Heating Value* LHV: 35.93 MJ/kg *Ultimate Analysis*^{daf} *(wt.%)*	GA: CO_2 SFR: NE ER: NE CO_2FR: NR	GT: 700-1000°C GP: 1 atm HR: NE RT: ^{v}21s	NE	The authors compared the quality of syngas produced from waste tyre gasification to syngas produced from waste tyre pyrolysis ~~in a lab-scale experiment~~. The pyrolysis experiment was performed from 400-900°C while the gasification was performed from 700-1000°C in the presence of CO_2. The result obtained shows that waste tyre gasification carried out at 800°C produced CO which is 3.3 times more than that produced by pyrolysis at 900°C. In addition, the CO produced from waste tyre gasification at

			C: 89.5; H: 7.3; N: 0.3 S: 1.9; O: 0.9				1000℃ is 150% higher than CO produced at 900℃. The authors concluded that the GT greatly influences the overall syngas yield, quality and energy content.
10. Škrbić *et al.* (2018) [90]	Differentiation of syngases produced by steam gasification of mono- and mixed sources feedstock: A chemometric approach	Type Bubbling Fluidized Bed Gasifier and Rotary kiln Scale: Lab Scale and Pilot Scale	Type: Raw Waste Tyre FPS: NR *Proximate Analysis (wt.%)* MC: NR; FC: NR; VM: NR; Ash: NR *Heating Value* HHV: NR *Ultimate Analysis (wt.%)* C: NR; H: NR; N: NR S: NR; O: NR	GA: Steam SFR:0.32-1.15 ER: NE	GT: 700-1000℃ GP: NR HR: NE RT: NE	NE	The authors employed principal component analysis (PCA) to select the best feedstock type, operation parameters, and gasifier type that would achieve the maximum syngas quality in waste tyre gasification and co-gasification process. The result from their experiment shows that the syngas quality in terms of CH_4, H_2/CO and H_2+CO, and CO_2 content from the co-gasification process were better than the single-fed process. In addition, they concluded that the coal+waste tyre mixtures produced the best result with higher H_2, H_2/CO and H_2+CO.

NE–Not Employed; NR–Not Reported; ^{ar}–As Received; ^{db}–Dry Basis; ^{daf}–Dry Ash-Free; ^{a}–By Difference; ^{fxb}–Fixed Bed; ^{flb}–Fluidized Bed; ^{v}–Vapour RT; CO_2FR–CO_2 to Fuel Ratio.

Collectively, the studies summarized in **Table 2** show that performance is significantly impacted by many parameters such as temperature, pressure, gasification agent (air/steam) and particle size. Furthermore, co-gasifying tyres with coal, biomass or other wastes like sewage sludge results in syngas blends that contain larger amounts of H_2 and CO than just waste tyre alone. In addition, co-gasification of waste tyres (at certain conditions) has been established to have higher efficiencies than tyres alone [34, 85]. Co-gasification of waste tyres with wood has been shown to have less syngas efficiency [86]. However, it has not yet been well-determined yet how co-gasification could affect the co-production of carbon products from waste tyre gasification process. Authors such as Czerski *et al.* [34] and Spiewak *et al*. [58] emphasized that catalyst play a vital role to achieve a high waste tyre char reactivity. Both authors also concluded that at temperatures below 850°C, the effect of pressure and catalyst on waste tyre gasification is more pronounced.

3.3.2. Waste Tyre Gasification Targeted at Hydrogen Production

The necessity for developing clean and renewable energy sources is enormous and growing as a result of current environmental pollution and its associated greenhouse impacts. It is consequently of great relevance that the hydrogen gas produced via waste tyre gasification has a high caloric value [91, 130]. Hydrogen has a higher heating value (HHV) of ~142 MJ/kg at 25°C and an LHV of ~120 MJ/kg at the same temperature [131, 132]. Compared to most fuels, which have a value of ~44 MJ/kg at 25°C, this number is substantially greater, however, it has one-quarter the energy density on a volumetric basis when compared to gasoline [132]. Hydrogen is a secondary energy source that could be produced from waste tyre gasification [133-136] in addition to more traditional routes such as the electrolysis of water, photolysis of water using solar energy, and thermochemical conversion of methane (such as steam reforming) amongst several others [130]. Hydrogen production through gasification process is also proven to be very fast and also has a high energy efficiency (47-69%$_{\mathrm{LHV}}$) [132, 137-139]. However, hydrogen production is largely influenced by the operational parameters, such as the gasification feedstock characteristics, reaction temperature, catalyst, steam-to-feed ratio, as well as ER [140, 141]. The findings of some authors who have worked on hydrogen production from waste tyre gasification in recent years are presented in **Table 3**.

Table 3. Summary of some recent studies on gasification of waste tyres targeted at hydrogen production.

Author(s)	**Work**	**Gasifier Type & Scale**	**Waste Tyre Characteristics**	**GA(s), SFR & ER**	**Gasification Condition(s)**	**Catalyst**	**Deductions**
1. Ma *et al.* (2023) [65]	Thermodynamic analysis of a carbon capture hydrogen production process for end-of-life tyres using plasma gasification	Type: Plasma Torch Scale: Commercial Scale	Type: Raw Waste Tyre FPS: NR *Proximate Analysis*^{db} *(wt.%)* MC: 0.8 ; FC: 33.5; VM: 61.3; Ash: 5.2 *Heating Value* HHV: 38.6 MJ/kg *Ultimate Analysis*^{db}*(wt.%)* C: 84.1; H: 7.3; N: 0.3 S: 2.3; O: 0.8	GA: Oxygen+Air and Steam+Air SFR:0.1-1.1 ER: 0.1	GT: 1500-2500℃ GP: 1 atm HR: NE RT: NE	NE	The authors employed plasma gasification to produce H_2 from waste tyres. The effect of combinations of GAs ~~(Oxygen+Air and Steam+Air)~~ was studied to check for the best condition for H_2 production. The result from the experiment shows that the Steam+Air combination produced the highest H_2 (969 kmol/hr) along with the best carbon conversion rate (99%), energy recovery (94%$_{HHV}$), and exergy efficiency (80%$_{HHV}$).
2. Al-Qadri *et al.* (2022) [91]	Technoeconomic feasibility of hydrogen production from waste tyres with the control of CO_2 emissions	Type: Rotary Kiln Scale: Commercial Scale	Type: Raw Waste Tyre FPS: NR *Proximate Analysis (wt.%)* MC: 0 ; FC: 25.5; VM: 67.7; Ash: 6.8 *Heating Value* LHV: 33.96 MJ/kg *Ultimate Analysis (wt.%)* C: 77.3; H: 6.2; N: 0.6 S: 1.8; O: 7.3	GA: Steam SFR: 2 ER: NE	GT: 1000℃ GP: 1 bar HR: NE RT: NE	NE	The authors investigated H_2 production through two production routes. The first route involved three key processes (steam gasification, WGS and acid gas removal (AGR)). The second route used the first route but the integrated the gasification process with natural gas reforming. The result from their experiment shows that the second route has 28% higher H_2 production, 7% higher purity and 26% less CO_2 emission when compared to the first production route. However, the production cost of H_2 from the

							second route was more than the first production route.
3. Santasnachok & Nakyai (2022) [61]	Exergetic and environmental assessments of hydrogen production via waste tyre gasification with co-feeding of CO_2 recycled	Type: Downdraft Fixed Bed Gasifier Scale: Pilot Scale	Type: Raw Waste Tyre FPS: NR *Proximate Analysis*^{db}*(wt.%)* MC: 1.5; FC: 30; VM: 55; Ash: 13.5 *Heating Value* HHV: 36.5 MJ/kg *Ultimate Analysis*^{db}*(wt.%)* C: 75; H: 7.0; N: 0.3 S: 4.5; O: 2.7	GA: Air, Air+Steam, Air+Steam +CO_2 SFR:0.5-2.5 ER: 0.35 & 0.38 CO_2FR:0-3.5	GT: 500-1000°C GP: 1 atm HR: NE RT: NE	NE	The authors studied H_2 production from waste tyre gasification through a computer-aided simulation using different combinations of air, steam and CO_2 as the GAs at 800°C. Three experiments were carried out and all were done in the presence of air (i.e., Air+Tyre, Air+Steam+Tyre, and Air+Steam+CO_2+Tyre). The effect of gasification agent-to-fuel ratio on H_2 production as well as energy and exergy analysis were investigated in the process. The result from the experiment shows that the highest H_2 yield was obtained from the GA-to-waste tyre ratios of 2 and 0.1 for steam and CO_2 respectively. The energy and exergy efficiencies from the process with the highest H_2 yield were found to be 59.6%$_{HHV}$ and 49.4%$_{LHV}$, respectively. In addition, to estimate the greenhouse gas emission from the process, a CO_2 emission intensity test was also carried out and the authors established that the air+steam mixture has the lowest CO_2 emission when compared to the other two.

4. Marzoughi *et al.* (2021) [88]	Environmental and thermodynamic performance assessment of biomass gasification process for hydrogen production in a downdraft gasifier	Type: Downdraft Fixed Bed Gasifier Scale: Commercial Sclae	Type: Raw Waste Tyre FPS: NR *Proximate Analysis (wt.%)* MC: 0-40%; FC: 27.04; VM: 66.3; Ash: 6.66 *Heating Value* LHV: 38.65 MJ/kg *Ultimate Analysis (wt.%)* C: 81.74; H: 7.06; N: 0.3 S: 1.82; O: 2.42	GA: Air, Steam, Air+Steam SFR: 0-1.5 ER: 0-0.4	GT: 800-1500°C GP: 1 atm HR: NE RT: NE	NE	The authors investigated the effects of feed ratio, ER gasification inlet temperature, and MC (0-40%) in gasification experiments using different feedstock including waste tyres. Different combinations of gasification agents were employed in the process. The result from the experiment shows that steam gasification produced the highest H_2 yield and LHV when compared to air/steam and air-only GAs. The authors emphasized that the steam-feed ratio and gasification inlet temperature favours H_2 production. The authors emphasized from an environmental view, feed with high carbon such as plastic and waste tyre tend to emit more CO_2 (80-200 kg CO_2-e/hr) than other feeds (manure, MSW, paper, sawdust, wood and pine wood) investigated (< 94 kg CO_2-e/hr).
5. Hasan & Dincer *et al.* (2019a) [134]	Comparative assessment of various gasification fuels with waste tyres for hydrogen production	Type: Entrained flow Gasifier Scale: Lab Scale	Type: Raw Waste Tyre FPS: NR *Proximate Analysis (wt.%)* MC: 1.5; FC: 30; VM: 55; Ash: 13.5 *Heating Value* LHV: 36.5 MJ/kg	GA: Steam & Oxygen SFR: 0.17-1.7 ER: NR	GT: 1460°C GP: 2.4 MPa HR: NE RT: NE	NE	The authors investigated H_2 production through gasification in an integrated gasification combined cycle (IGCC) via computer-aided simulation using three different feeds including waste tyres. After the gasification process, the authors employed a WGS membrane reactor to simulate H_2 production to obtain

			Ultimate Analysis (wt.%) C: 75; H: 7; N: 0.3 S: 1.5; O: 2.7				a 98% H_2 conversion rate. From the result obtained from the process, the authors found that the H_2 production rate to waste tyre ratio was found to be 0.16 and better than coal with an average of 0.14. This rate was achieved at SFR of 0.25 and oxygen rates to feed ratio of 0.88. In addition, the waste tyre-to-H_2 production route has energy and exergy efficiencies of 55%$_{LHV}$ and 52%$_{LHV}$ respectively.
6. Nanda *et al.* (2019) [8]	Catalytic subcritical and supercritical water gasification as a resource recovery approach from waste tyres for hydrogen-rich syngas production	Type: Tubular Batch Reactor Scale: Lab Scale	Type: Raw Waste Tyre FPS: <2mm *Proximate Analysis (wt.%)* MC: 1.21; FC: 28.8; VM: 65.1; Ash: 4.9 *Heating Value* HHV: 29.5 MJ/kg *Ultimate Analysis (wt.%)* C: 67.9; H: 6.6; N: 1.9 S: 1.28; O: 17.4	GA: NE SFR: NE ER: NE	GT: 325-625°C GP: 21 MPa & 23 MPa HR: 15°C/min RT: NE	$Ni/SiO_2-Al_2O_3$, Ru/Al_2O_3, $Ba(OH)_2$, $Ca(OH)_2$, $Mg(OH)_2$	The authors studied hydrothermal waste tyre gasification in catalytic subcritical and supercritical conditions. Process parameters such as GT, reaction time and feed concentration and catalyst were optimized to achieve maximum syngas production. The result from their experiment shows that the best condition for H_2-rich syngas production was at 625°C, 60 mins and 5wt.% respectively. At this condition, a syngas and H_2 yield of 34 mmol/g and 14.4 mmol/g respectively with a 43% carbon conversion efficiency. In addition, the application of $Ni/SiO_2-Al_2O_3$ catalyst to the process improved H_2 production the most when compared

	to other calayst and no-catalyst scenarios.

NE – Not Employed; NR – Not Reported; ^{db} – Dry Basis; CO_2FR – CO_2 to Fuel Ratio.

The overall evaluation of the works presented in **Table 3** shows that waste tyre gasification for hydrogen production is a promising technology with various advantages, but still, a lot of work needs to be done to make the process more efficient, cost-effective and environmentally friendly. One suggestion includes a clear objective of the desired product (i.e., direct production of clean hydrogen fuel). Most of the hydrogen produced from previous studies is considered dirty until it is properly cleaned. The clean-up process could be expensive. As mentioned earlier, clean hydrogen production is largely influenced by the operational parameters such as properties of the waste tyre feed, gasification reaction temperature, catalyst, ER and gasification agents. In conclusion, the production of hydrogen from waste tyres is a complex process and the optimization of process conditions is vital to achieve the desired results which is an affordable alternative to fossil fuel.

3.4. Waste Tyre Gasification Targeted at High Valued Carbon Production

Since the beginning of waste tyre gasification, the formation of solid products has been dominated by the production of syngas/hydrogen as the primary goal of the process. Most authors who have worked on waste tyre gasification either presume a 100% carbon conversion, which is not always the case, or they discard the chars that are left over after gasification experiments [55]. Activated carbon (AC), carbon black, char, and carbon nanomaterials are some of the high-valued carbon products that could be produced through gasification of waste tyres. Some studies [55, 64, 83, 86, 89, 104, 142-145] have been able to report the production of these solid products obtained from waste tyre gasification. Some of these studies have also proposed that carbon products derived from waste tyre gasification carbon activation have a particle surface area of around 1000 m^2/g which is an equivalence of a medium-to-high quality AC which can be used for several applications [55, 83]. Some studies [86, 144, 145] show that char obtained from gasification could be utilized in direct carbon fuel cells, as catalyst, in soil amendment, or in water treatment. Raman *et al.* (1981) [49] were one of the first authors to investigate the gasification of waste tyres and were also the first to confirm the presence of solid product (char) in a waste tyre gasification experiment. The authors performed the experiment from 627-787°C and the resulting product had a gas composition between 20 wt.% to 52 wt.%, liquid composition from 51 wt.% to 17 wt.% and solid char yield 29 wt.% to 25 wt.%.

Leung & Wang [104] reported that after gasifying waste tyre powder from 350-900°C, the experiment yielded a char product within 24 wt.% to 37 wt.% from the process. The authors also highlighted the importance of parameters such as the ER, waste tyre feed rate and particle size in both solid char and syngas production. Gonzalez *et al.* [143] also reported the production of solid carbon (activated carbon) from waste tyre gasification in a two-stage activation procedure. In the first process, pyrolysis was carried out at 800°C in the presence of N_2 while the second process employed using steam and/or CO_2 as activation agents at different activation temperatures (750-900°C) and activation times (1-3 hrs). The authors employed carbon burn-off as the performance metrics of the experiment and the results from their experiment show that steam/N_2 and steam/CO_2 mixtures produced AC with a surface area of 1317 m^2/g and 496 m^2/g respectively. The authors conclude that the characteristics of AC depend on the degree of char activation, porosity of the char, surface area, the nature of the activating agent as well as the process temperature. Other authors that have worked on solid carbon production from waste tyre gasification in recent years are presented in **Table 4**.

Table 4. Summary of some recent studies on gasification of waste tyres targeted at carbon product production.

Author(s)	Work	Gasifier Type & Scale	Waste Tyre Characteristics	GA(s), SFR & ER	Gasification Condition(s)	Catalyst	Deductions
1. Larionov *et al.* (2023) [64]	Electric arc gasification of pyrolysis oil with the production of hydrogen-enriched synthesis gas and carbon nanomaterial	Type: Electric Arc Scale: Lab Scale	Type: Waste Tyre Oil FPS: NA *Proximate Analysis (wt.%)* MC: NR; FC: NR; VM: NR; Ash: Trace *Heating Value* HHV: 43.3 MJ/kg *Ultimate Analysis (wt.%)* C: 86.2; H: 11.0; N: 0.6 S: 0.8; O: 1.4	GA: Air SFR: NE ER: NR	GT: NA GP: 1 atm HR: 10°C/min RT: NR	NE	The authors co-produced CNT and syngas using a novel approach using different feedstock which are waste tyres, oil sludge, wood waste and petroleum. ~~The experiment was carried out in a 74V vacuum-free lab-scale DC arc reactor.~~ The carbon produced from the four samples was characterized and the result from the experiments shows that a graphite-like carbon nanomaterial (CNM) is very close to carbon black. In addition, the CNM produced from waste tyres has a specific surface area of 64.1 m^2/g and a porosity of 0.17 cm^3/g. The SEM analysis also confirmed that the structure of nanosized carbon particles was arranged in arrays in the forms of inhomogeneous agglomerated structures which differ from the typical spherical-shaped carbon black.
~~2. Semaan *et al.* (2022) [145]~~	~~Pilot scale pyro-gasification of biomass and waste: char characterization~~	~~Type: Fixed Bed Gasifier~~	~~Type: Waste Tyre Char~~ ~~FPS: <10mm~~ ~~*Proximate Analysis*^{db} *(wt.%)*~~	~~GA: Air~~ ~~SFR: NE~~ ~~ER: NR~~	~~GT: NA~~ ~~GP: 1 atm~~ ~~HR: 10°C/min~~ ~~RT: NR~~	~~NR~~	~~The authors performed pyro-gasification experiments with different feedstocks (sawdust, waste wood, grape pomace,~~

		~~Scale: Pilot Scale~~	~~MC: 0.575; FC: NR; VM: NR; Ash: 35~~ ~~*Heating Value*~~ ~~HHV: NR~~ ~~*Ultimate Analysis (wt.%)*~~ ~~C:62.4; H: 0.7; N: 0.11~~ ~~S: 2.0; O: 1.9~~				~~miscanthus wood, waste tyres, MSW, and industrial refuse-derived fuel (RDF)). The char produced from the process was characterized using different property domains which include physicochemical properties, texture and morphology, and surface chemistry and structure. The obtained results from the process show that waste tyre char has a surface area of 73 m^2/g and a skeletal density of 2.06 g/cm^3. The authors concluded that waste tyre char was the least reactive when compared to other feed samples.~~
2. Fajimi *et al.* (2021) [55]	Simulation studies on the co-production of syngas and activated carbon from waste tyre gasification using different reactor configurations	Type: Downdraft Fixed Bed Gasifier, Fluidized Bed Gasifier and Rotary kiln Scale: Pilot Scale and Commercial Scale	Type: Waste Tyre FPS: 2-20mm *Proximate Analysis (wt.%)* MC: 0.9; FC: 27.04; VM: 66.3; Ash: 6.66 *Heating Value* LHV: 37.1 MJ/kg *Ultimate Analysis (wt.%)* C: 81.74; H: 7.06; N: 0.30 S: 1.82; O: 2.42	GA: Air+Steam SFR: 0.1-0.25 ER: 0.18-0.38	GT: 850°C GP: 1 atm HR: NE RT: NE	NE	The authors employed three gasification reactors in the production of syngas along with activated carbon (AC) from waste tyre gasification via computer-aided simulation. The gasification reactors include fixed bed reactor, fluidized bed reactor, and rotary kiln reactor. In order to simulate these reactors a single-stage steam gasification (at 800°C) and char activation (at 900°C) was employed. In addition, an air-steam mixture was employed in the gasification process while N_2

							and steam were employed to activate the char. The effect of operational parameters such as ER and SFR were also investigated. The AC produced was characterized using the Brunauer-Emmett-Teller (BET) analysis. The result from this process shows that AC produced with a fixed bed gasifier had the highest BET surface area (698.6 m^2/g). The rotary kiln and the fluidized bed other the other had had AC with BET surface areas of 661.7 m^2/g and 432.5 m^2/g respectively. In addition, the authors concluded that the best condition to achieve maximum AC production is ER of 0.3 and SFR of 0.25.
3. Molino *et al.* (2018) [83]	Waste tyre recycling process for production of steam activated carbon in a pilot plant	Type: Rotary Kiln Scale: Pilot Scale	Type: Waste Tyre FPS: 1-2cm *Proximate Analysis*^{db} *(wt.%)* MC: 0.8; FC: 33.5; VM: 61.3; Ash: 5.2 *Heating Value* HHV: 38.6 MJ/kg *Ultimate Analysis*^{db}*(wt.%)* C: 84.1; H: 7.3; N: 0.3	GA: Steam SFR: 1 ER: NE	GT: 850°C GP: NR HR: NR RT: 0-6 hrs	NE	The authors performed a double-stage steam gasification (at 850°C) and steam activation (at 920°C) of waste tyre gasification in a pilot-scale rotary kiln reactor. The authors also investigated the best hold time for the char activation stage to ensure the production of the best AC quality. The authors employed~~ a steam-to-waste tyre ratio of 1,~~ an activation steam-to-char ratio of 2, a mean

			S: 2.3; ^{a}O: 0.8				residence time of 6mins and an activation N_2 flow rate of 1 Nm^3/hr. From the result obtained, the AC produced from the process has a surface area of 786 m^2/g and a carbon burn-off value of 78%. The authors concluded that the best hold time for producing high-quality AC is three hours.
4. Zhang *et al.* (2015) [89]	Pyrolysis-Catalytic Reforming/Gasification of Waste Tyres for Production of Carbon Nanotubes and Hydrogen	Type: Two-Stage Fixed Bed Gasifier Scale: Lab Scale	Type: Waste Tyre FPS: ~6mm *Proximate Analysis (wt.%)* MC: 0.82; FC: 32.31; VM: 62.7; Ash: 4.17 *Heating Value* HHV: NR *Ultimate Analysis (wt.%)* C: 81.2; H: 7.2; N: 0.8 S: 2.1; O^a: 8.7	GA: Steam SFR: NE ER: NE	GT: 800°C GP: NR HR: 40°C/min RT: NR	Co/Al_2O_3, Cu/Al_2O_3, Fe/Al_2O_3, and Ni/Al_2O_3	The authors co-produced carbon nanotubes (CNT) along with hydrogen in a two-stage waste tyre catalytic pyro-gasification process. Four different catalysts were employed to investigate the best for CNT production. An operating temperature of 600°C and 800°C were employed in the pyrolysis and gasification stages respectively. The CNT produced from the process was characterized by scanning electron microscopy (SEM), transmission electron microscopy (TEM) and Raman spectrometry. The obtained results from the Raman spectrometry showed that Ni/Al_2O_3 produced the highest hydrogen production along with a multi-walled CNT (MWCNT) formation. In addition, the SEM and TEM analysis conducted

	showed that the CNT formed replicates MWCNT in terms of its structure and the presence of filamentous carbon respectively.

NE–Not Employed; NR–Not Reported; ^{db}–Dry Basis; ^{a}–By Difference.

From the summary of previous works presented in **Table 4**, the production of value-added carbon products still has a long way to go. This process is largely stalled by the gasification process which hindered the quality and quantity of char produced in cases where activated carbon, carbon black and char are the target carbon products. In cases where CNMs are the target product, the process differs. In order to produce CNM such as CNT from waste tyre gasification, catalyst plays a big role. The nature of the catalyst determines the quality and structural properties of the CNT Zhang *et al.* [89]. This process is quite complex and only a few authors have explored CNT production from waste tyre gasification and gasification in general such as Larionov *et al.* [64] who used different gasification techniques to produce CNT from waste tyres. One gasification technique tried in that work was electric arc technology which is a very complex setup to develop on a large scale for continuous production. In addition, the environmental effect as well as the economics of this process have not been evaluated. In conclusion, a detailed techno-economic study on valuable carbon production from waste tyre gasification is required.

3.5. Waste Tyre Gasification Targeted at Other Products along with Energy Production

Most of the previous works focused on waste tyre-to-syngas or waste-tyre-to-hydrogen and/or carbon products. Only a few authors investigate the end use of these key products. Energy in the form of heat and electricity as well as valuable industrial chemicals (see **Fig. 5**), can be further produced from waste tyre gasification and co-gasification processes. Some of the works that focused on these areas are reviewed in this section

Zang *et al.* [57] designed a trigeneration system from waste tyre gasification as shown in **Fig. 7**. The trigeneration system includes cooling during summer, heating during winter and electricity production. Waste tyres and pine wood were combined in different ratios (0:100, 50:50 and 100:0) to generate power which was applied to an office building at the University of Iowa. The results from their experiment show that the average combined heat and power

(CHP) efficiency from the system is between $32\%_{LHV}$ for waste tyre only to $49\%_{LHV}$ when waste tyre is combined with pine wood. This result is based on the design options such as the gasifier type, period of the year, feed ratio, and gasifier operating condition among others. In addition, the authors also estimated the breakeven levelized cost of electricity (LCOE) from the process to be between \$0.009/kWh to \$0.12/kWh based on the design option.

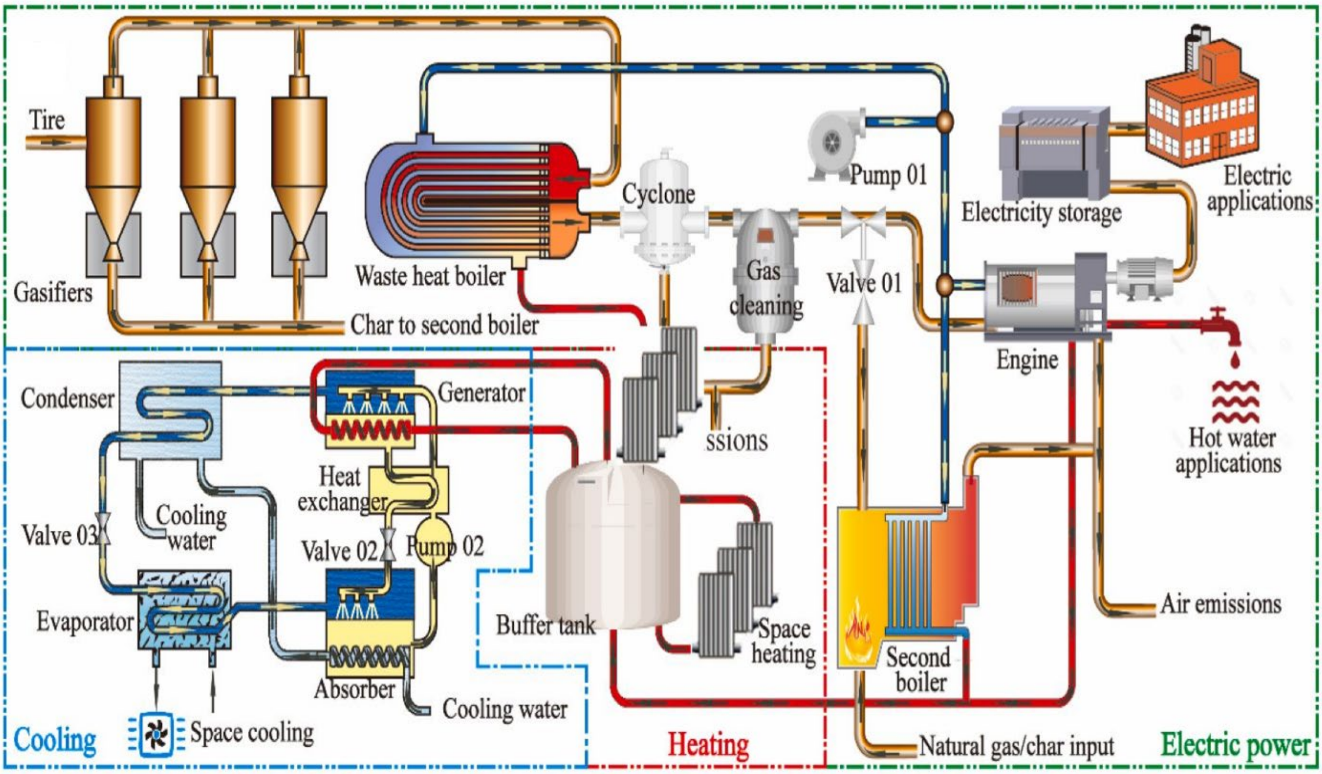

Fig. 7. Flow diagram of waste tyre gasification trigeneration system (Reprinted with permission from the original published in Zang *et al.* [57]).

Kahraman and Dincer [120] proposed a geothermal-energy-supported integrated waste tyre gasification multigeneration system for a community setting as shown in **Fig. 8**. The system is designed for gasification products (hydrogen, electricity, cooling and heat) and by-products (ethanol and sulphuric acid). In order to achieve maximum production from the design, the authors investigated the effect of operational parameters to improve production rates as well as energy and exergy efficiencies while minimizing both greenhouse gas emissions and environmental wastes. The result obtained from the process simulation shows that the net electricity generation as well as the heating and cooling capacities were around 18 MW, 5 MW and 49 MW respectively for a 10 kg/s waste tyre feed at 1250°C. In addition, the production rates of hydrogen and ethanol from the process were found to be 3.02 kg/s and 0.13 kg/s respectively. The energy and exergy efficiencies of the overall system were around ~71.5%$_{LHV}$ and ~69.9%$_{LHV}$ respectively.

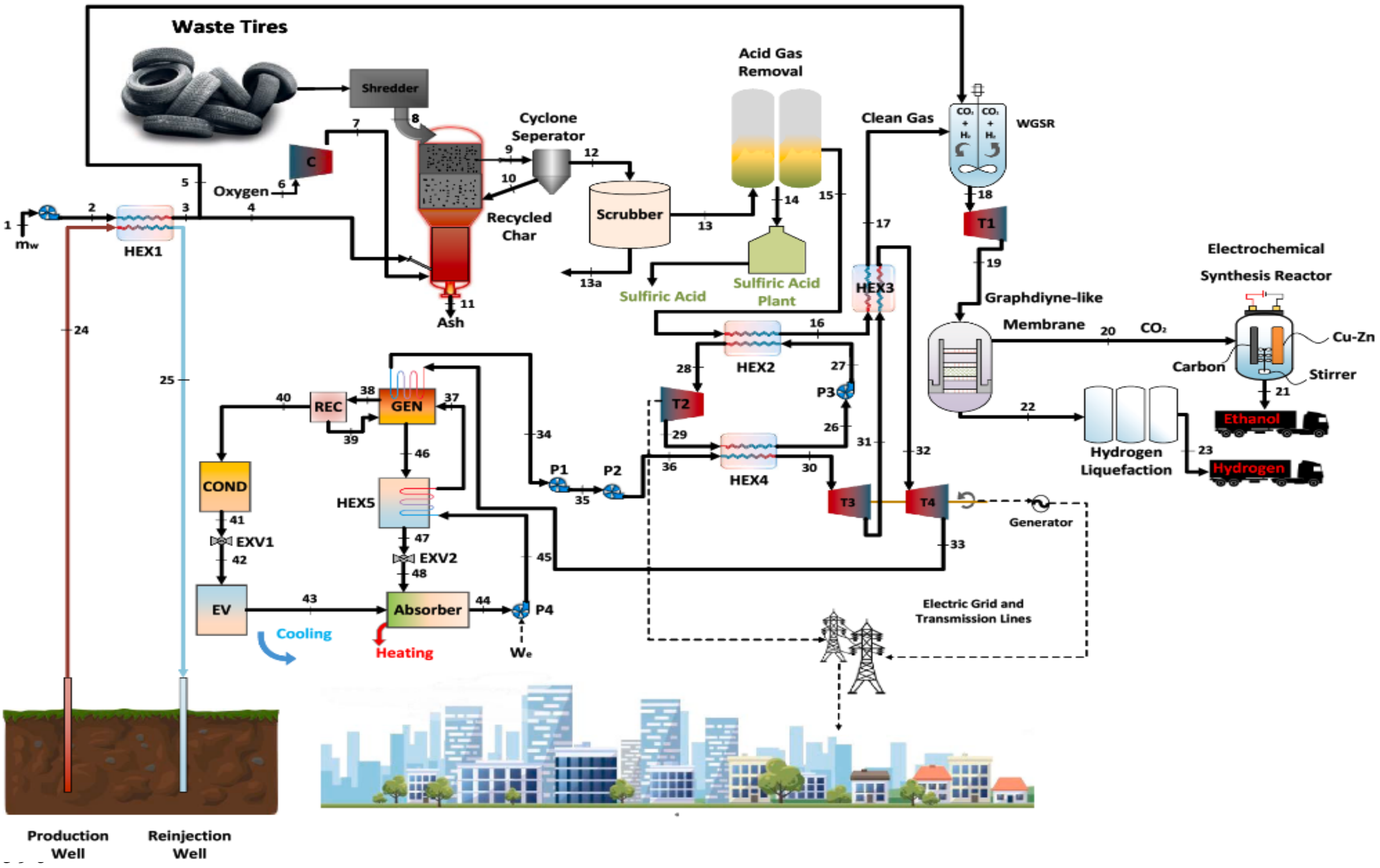

Fig. 8. Flow diagram of a geothermal-energy supported integrated waste tyre gasification multigeneration system for community setting (Reprinted with permission from the original published in Kahraman and Dincer [120]).

Gungor and Dincer [146] studied a solar energy-based integrated renewable waste-to-energy system for multiple production generation through waste tyre gasification. The authors employed waste tyre gasification combined with other processes to produce essential products such as hydrogen, biogas, freshwater, hot water, and power. The authors developed a waste tyre gasification system which produced hydrogen and syngas that were employed in the steam Rankine Cycle which was replaced with a forward multi-effect desalination unit for the production of other products. Other units combined with this system are shown in **Fig. 9**. The outcome of the proposed system shows that this integrated system is capable of producing up to 2.16 tonnes of freshwater and 163 MWh of electricity daily. A production rate of 309 m^3/hr of CH_4 was generated at the anaerobic digestion and a hydrogen-to-waste tyre ratio of 0.175 was produced from the gasifier on a mass basis. This proposed system has been found to have energy and exergy efficiencies of 74%$_{LHV}$ and 73%$_{LHV}$, respectively.

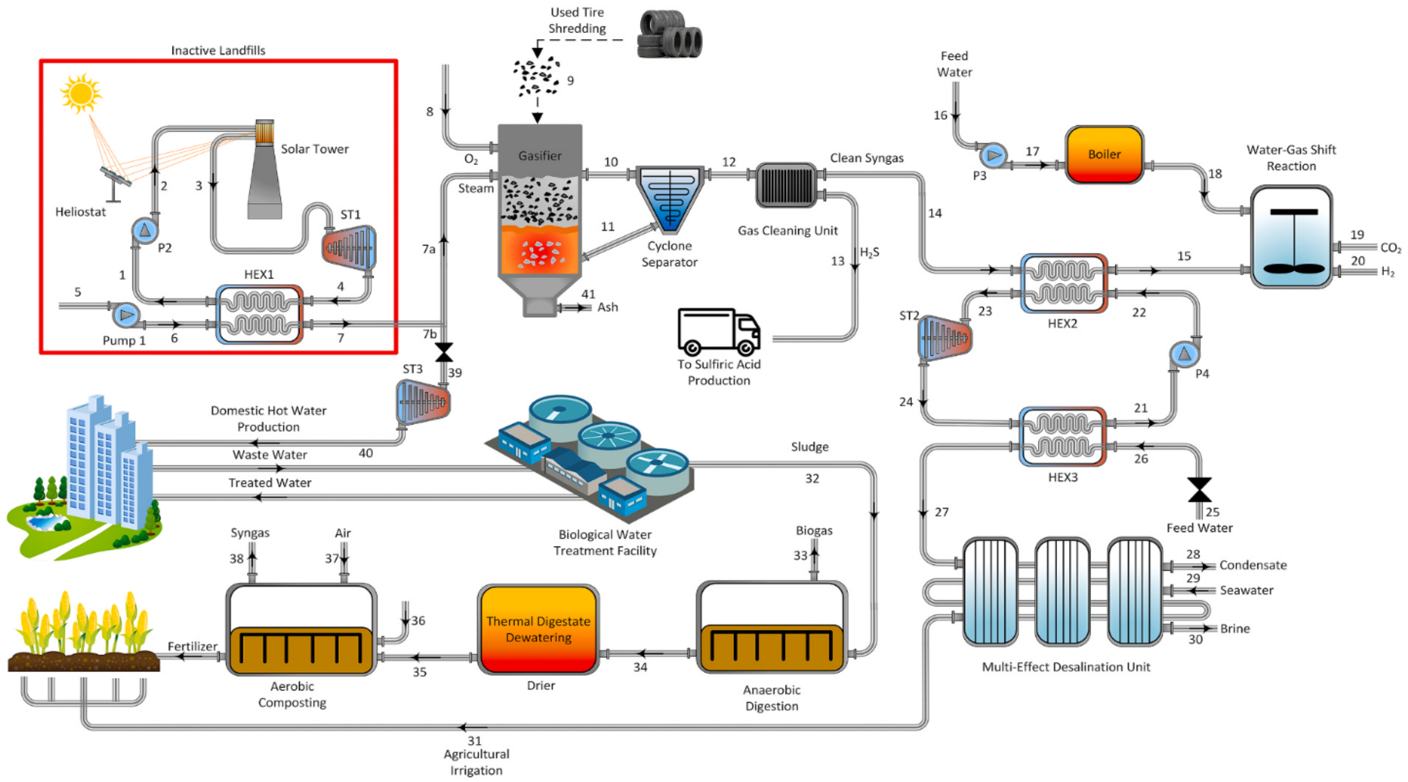

Fig. 9. Integrated waste-to-energy system through solar-assisted waste tyre gasification Reprinted with permission from the original published in Gungor and Dincer [146]).

Subramanian *et al.* [92] developed a model which combined the polygeneration of multiple products from waste tyre gasification process as shown in **Fig. 10**. The model was used to determine the optimal design and operation of a system that employs waste tyre gasification as the key operation to produce varieties of products which include a mixture of electricity, industrial chemicals and fuels. For process optimization, the authors used mixed-integer non-linear programming (MILP). The outcome of the experiment reveals that, while electricity generation is preferred in the base case with historically market pricing, methanol, liquefied synthetic natural gas (SNG), and dimethyl ether (DME) are preferred in more likely scenarios in which the relevant product fetches higher prices. The authors also came to the conclusion that pre-combustion CO_2 capture is favoured at lower CO_2 tax rates and post-combustion CO_2 capture is only optimal in scenarios with higher rates. The fact that the optimal product portfolio fluctuates dramatically with shifting market conditions encourages the construction of flexible polygeneration processes that are able to alter operational conditions in order to improve profitability by taking advantage of price peaks.

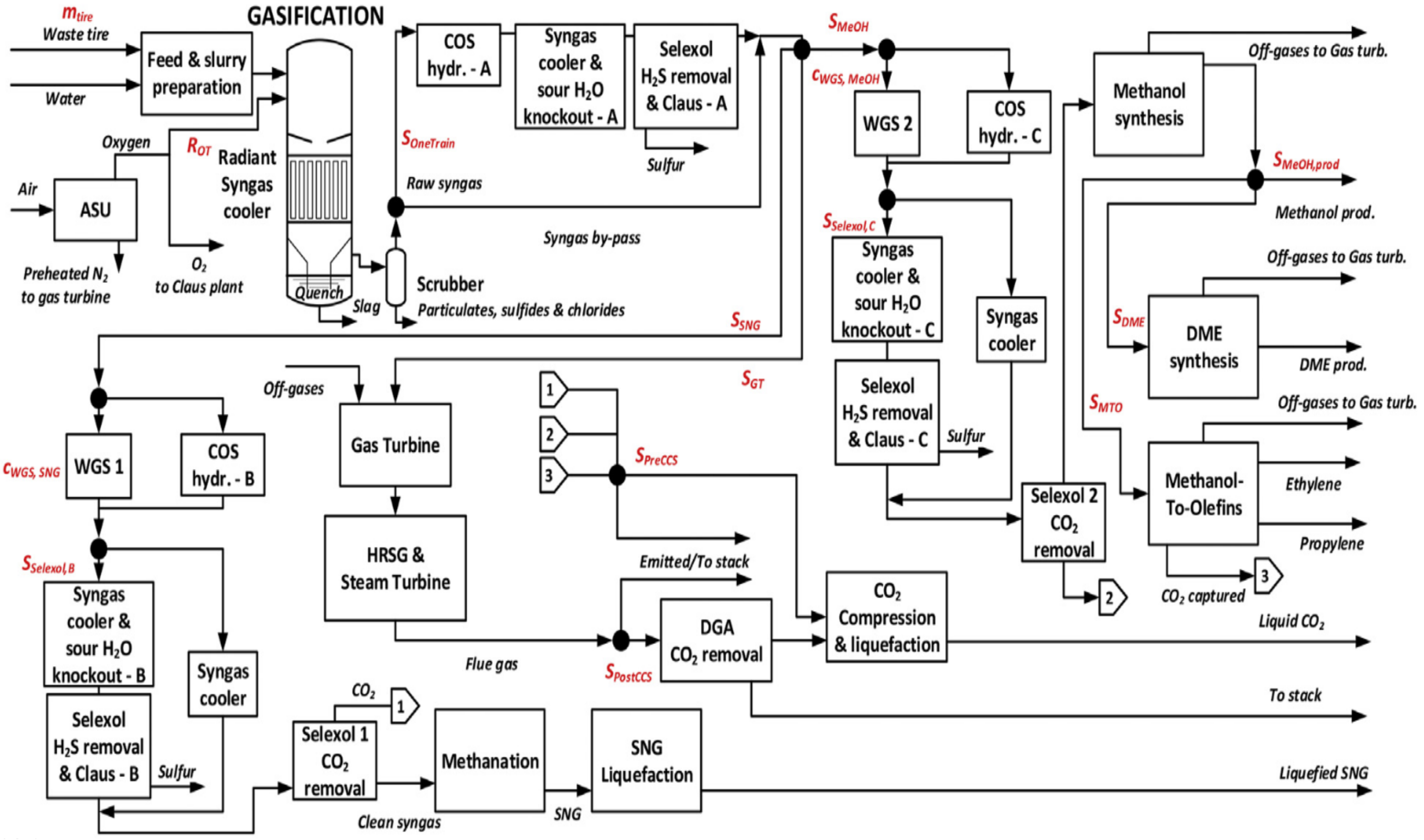

Fig. 10. Block diagram waste tyre gasification polygeneration system (Reprinted from the original published in Subramanian *et al.* [92]).

Subramanian *et al.* [147] proposed a production route for liquified synthetic natural gas (LSNG) from waste tyre gasification in Norway and the United States (see **Fig 11)**. The authors employed a combination of mathematical and empirical models along with experimental data in the process. Three design scenarios were investigated which include production without CO_2 capture and sequestration (CCS), production with precombustion CCS as well as production with both pre-combustion and post-combustion CCS. From the results obtained from process economics the production, the authors established a minimum selling price (MSP) for the LSNG produced from the process. For the process to be economically feasible in the United States, MSPs of \$16.7, \$17.5 and \$19.9 $GJ_{LHV,SNG}$ are required for the three design cases respectively. Meanwhile, the MSPs for the waste tyre-to-LSNG production process in Norway were estimated at \$20.9, \$21.8 and \$24.9 per $GJ_{LHV,SNG}$ respectively. The authors concluded that the process with pre-combustion and post-combustion CCS (scenario 3) is technologically feasible and environmentally feasible, especially in Norway where it was implemented for energy generation. In addition, the MSP is greatly influenced by plant scale and tipping fees, while other parameters have minimal effect on the production process.

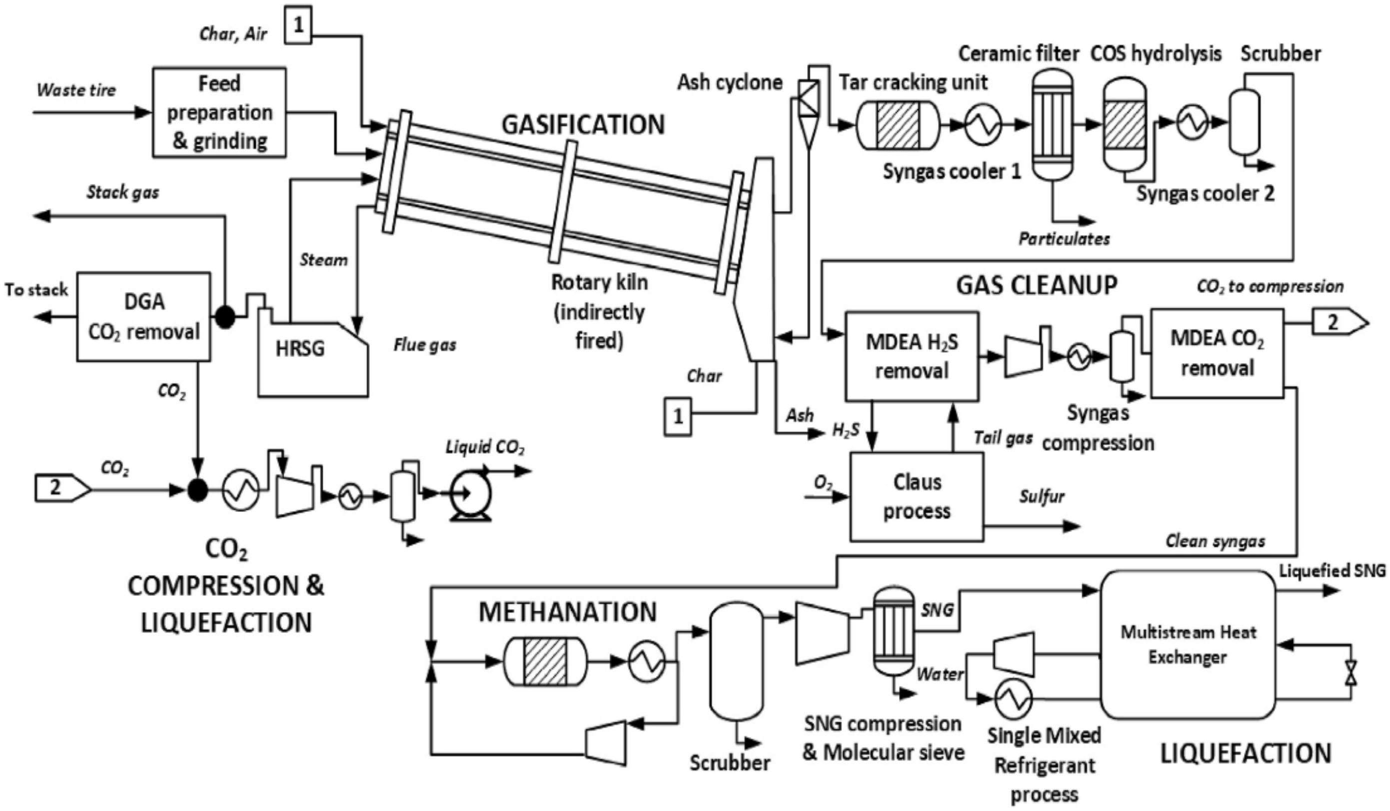

Fig. 11. Process flow diagram showing waste tyre to LSNG (Reprinted from the original published in Subramanian *et al.* [147]).

3.6. Modelling Waste Tyre Gasification Process

The modelling of physical, chemical, and biological processes is basically aimed at giving a full mathematical description of the processes. Modelling can be used to predict reactor operating conditions, product yield and composition. The most widely used gasification models are the thermodynamic equilibrium model and the kinetic model [148]. A deep survey on gasification modelling choices found that around 66% of authors who have worked on the simulation of gasification processes utilize some type of equilibrium model while others utilize some type of kinetic model [149]. ~~The optimization of gasification parameters such as the feedstock flow rate, GA ratio, ER, GT, and GP must be done in order to achieve a desirable syngas composition and yield. A change in any of these parameters can have a substantial impact on the product compositions and the gasifier performance [150].Veryg good~~ A great insight and economically efficient routes can be obtained by simply combining mathematical models and process simulation with physical experimentation. A good model can be used to predict the accurate representation of the chemical and physical phenomena occurring inside the gasifiers used in gasification processes [150]. A model that best fits experimental data can reveal to a great extent the major trends in a multivariate system and can also be employed by process engineers in scaling up a reactor to an industrial scale [148]. All possible reactions between the species would ensure the predictability of a model as well as the transport phenomena as realistic as possible. Before modelling waste tyre gasification processes, key gasification reactions such as the ones presented in **Table 5** have been used.

Table 5. Waste tyre gasification reactions ([86]).

Reaction Equation	**Reaction Name**	**Heat of Reaction (MJ/kmol)**	**Reaction Number**
$CO_{(g)} + H_2O_{(g)} \rightleftharpoons CO_{2(g)} + H_{2(g)}$	WGS/CO Shift	-41	R-1
$C_{(s)} + 2H_{2(g)} \rightleftharpoons CH_{4(g)}$	Methane Formation/Methanation	-75	R-2
$C_{(s)} + CO_{2(g)} \rightleftharpoons 2CO_{(g)}$	Boudouard Reaction	+172	R-3
$C_{(s)} + H_2O_{(g)} \rightleftharpoons CO_{(g)} + H_{2(g)}$	Water Gas Reaction	+131	R-4
$CH_{4(g)} + H_2O_{(g)} \rightleftharpoons CO_{(g)} + 3H_{2(g)}$	Steam Methane Reforming	+208	R-5
$C_{(s)} + \frac{1}{2}O_{2(g)} \rightleftharpoons CO_{(g)}$	Carbon Partial Combustion	-111	R-6
$CO_{(g)} + \frac{1}{2}O_{2(g)} \rightleftharpoons CO_{2(g)}$	CO Partial Combustion	-283	R-7
$H_{2_g} + \frac{1}{2}O_{2_g} \rightleftharpoons H_2O_g$	Hydrogen Partial Combustion	-242	R-8

3.5.1. Kinetic Model

Rate-based models attempt to predict product gas concentration with suitable kinetic structure for both homogenous and heterogenous processes occurring in the reactors. However, a large amount of unknown dynamic parameters makes product estimation difficult to measure for fluidized bed gasification [15]. Modelling the kinetics of the thermal degradation process of waste tyres can provide a detailed insight into the various mechanisms responsible for waste tyre gasification and predict potential difficulties in a gasification reactor. Previous investigations have created gasification models based on information gathered from thermogravimetric analysis (TGA), which quantify the sample weight loss with time and temperature [151-156]. Zang *et al.* [86] applied a kinetic model to simulate waste tyre gasification problem in a fixed bed reactor that assumes the simplified gasification process shown by Eq. 1. In addition, the authors broke down waste tyre gasification process into zones (Zone-A and Zone-B) to simplify each of the reactions and equations required to model the zone. A sub-stoichiometric environment is present in Zone-A, where the fuel sample is subjected to pyrolysis and oxidation. A full description of the model is given below. The products formed in Zone-A undergo reduction in Zone-B into the final product gases based on kinetically controlled chemical reactions.

First, the combustible part of waste tyre is represented by CH_mO_n with the assumption that waste tyre contains only Carbon, Hydrogen, and Oxygen [157].

$$\text{(Waste Tyre)} + \text{(Moisture)} + \text{(Air)} \longrightarrow \text{(Syngas)} + \text{(Char)}$$

$$(CH_mO_n)_{(s)} + wH_2O_{(g)} + a(O_2 + 3.76N_2)_{(g)} \rightarrow \left(x_1H_{2_g} + x_2CO_g + x_3CO_{2_g} + x_4H_2O_g + x_5CH_{4_g} + x_6N_{2_g}\right) + x_7C_{(s)} \quad (1)$$

The values of m and n can be estimated from Eqs. 2-3.

$$m = \frac{\%H \times MW_C}{\%C \times MW_H} \quad (2)$$

$$n = \frac{\%O \times MW_C}{\%C \times MW_O} \quad (3)$$

where $\%C$, $\%H$ and $\%O$ are the compositions (wt.%) of C, H, and O in the waste tyre while MW_C, MW_H, and MW_O are their respective molecular weights. The moisture content present in the sample was accounted for separately as shown in Eq. 1. The quantity of air required in the process is determined from the ER. w indicates the number of moles of the moisture content (*MC*) in the waste tyre and can obtained from Eq. 4.

$$w = \frac{MC}{(100 - MC) \times (100 - ASH)} \times \frac{MW_F}{MW_W} \quad (4)$$

where ASH represent the ash content in the waste tyre as obtained from the proximate analysis. MW_W and MW_f represents the molecular weights of H_2O and CH_mO_n respectively.

a represents the number of moles of O_2 from the air per mole of CH_mO_n and can be obtained from Eq. 5.

$$a = \frac{1+\frac{m}{4}-\frac{n}{2}}{ER} \tag{5}$$

where ER is the defined by Eq. 6.

$$ER = \frac{\frac{\dot{m}_{O_a}}{\dot{m}_{wt}}}{\frac{\dot{m}_{O_{st}}}{\dot{m}_{wt}}} = \frac{\dot{m}_{O_{st}}}{\dot{m}_{O_a}} \tag{6}$$

where $\dot{m}_{O_a}$, $\dot{m}_{o_{st}}$, and $\dot{m}_{wt}$ represents the mass flow of actual O_2, stoichiometric O_2 and waste tyre respectively. The seven unknown variables $(x_1 - x_7)$ requires seven different equations to estimate their values. From the atomic balance of the key elements (C, H, O, N), four equations can be expressed as shown in Eqs. 7-10 [157].

Carbon (C) Balance: $1 = x_2 + x_3 + x_5 + x_7$ (7)

Hydrogen (H) Balance: $m + 2w = 2x_1 + 2x_4 + 4x_5$ (8)

Oxygen (O) Balance: $n + w + 2a = x_2 + 2x_3 + x_4$ (9)

Nitrogen (N) Balance: $3.76a = x_6$ (10)

Zone-A follows that the reaction R-1 (i.e., WGS) (see **Table 5**) $CO_{(g)}$, $H_2O_{(g)}$, $CO_{2_{(g)}}$ and $H_{2_{(g)}}$ are in chemical equilibrium. The equilibrium constant (k_1) of R-1 is a function of the temperature of the zone (i.e., $k_1 = f(T_{Zone-A})$) and can be associated to the number of moles $(x_1 - x_4)$ of the reacting species in as:

$$k_1 = \frac{x_1 x_3}{x_2 x_4} \tag{11}$$

Also, $CH_{4_{(g)}}$ is assumed to be produced from the methanation reaction (R-2) in the zone

Hence,

$$k_2 = \frac{x_5}{x_1^2} \tag{12}$$

where k_2 is the equilibrium constant of R-2. The values of the equilibrium constant (k_1, k_2) are estimated from the change in Gibbs functions ($\bar{g}_i^0$) between the gaseous species ($CO_{(g)}$, $H_2O_{(g)}$, $CO_{2_{(g)}}$, $H_{2_{(g)}}$and $CH_{4_{(g)}}$) in the products and reactants at T_{Zone-A} as shown in Eqs, 13-14.

$$k_1 = exp\left(-\frac{\bar{g}_{CO_2}^0}{RT_{Zone-A}} - \frac{\bar{g}_{H_2}^0}{RT_{Zone-A}} + \frac{\bar{g}_{CO}^0}{RT_{Zone-A}} + \frac{\bar{g}_{H_2O}^0}{RT_{Zone-A}}\right) \tag{13}$$

$$k_2 = exp\left(-\frac{\bar{g}_{CH_4}^0}{RT_{Zone-A}} + 2\frac{\bar{g}_{H_2}^0}{RT_{Zone-A}}\right) \tag{14}$$

where R represents the universal gas constant which is ~8.314 kJ/kmol K, T_{Zone-A} represent Zone-A temperature and can be estimated from the energy balance across the zone by factoring the gasification reactor heat loss (Q_{loss}). The yield of the solid char from the process is evaluated as the fixed carbon (FC) from waste tyre proximate analysis (on dry basis) which is divided into carbon solid (C) and the CH_4 formed on the char surface from methanation reaction (R-2). Therefore,

$$x_5 + x_7 = \frac{FC}{C} \tag{15}$$

where C is the carbon content from the ultimate analysis of the waste tyre sample (wt.%). The authors also made the assumption that changes in both the kinetic energy and potential energy were not considered in all the streams, hence, the energy equation applied across Zone-A in steady-state as:

$$H_{in} + Q_{loss} = H_{out} \tag{16}$$

where H_{in} and H_{out} are the enthalpies entering and leaving Zone-A. In addition, one mole of CH_mO_n, in Eq. 16 can be expressed as:

$$\bar{h}^0_{f_{wt}} + a\int_{T_o}^{T_a} \bar{c}_{p,O_2} dT + 3.76a\int_{T_o}^{T_a} \bar{c}_{p,N_2}\, dT + w\bar{h}_{f_{H_20}} + Q_{loss} =$$

$$= \sum_{i=1}^{6} x_i \left[\bar{h}^0_{f_i} + \int_{T_0}^{T} \bar{c}_{p,i} dT\right] + x_7\bar{c}_{p,C}(T - T_0) + m_{ash}c_{p,ash}(T - T_0)$$

$$(17)$$

where $i = 1 - 6$ represents the gaseous species ($H_{2_{(g)}}CO_{(g)}$, $CO_{2_{(g)}}$,$H_2O_{(g)}$,$CH_{4_{(g)}}$, and $N_{2_{(g)}}$) respectively, the ash and char leaving zone energy streams were also accounted for. In Eq. 17 above, $\bar{h}^0_{f_i}$ and $\bar{c}_{p,i}$ represent the formation enthalpies and the specific heat capacities of the gaseous and carbon species respectively, T_a is the temperature of the air that is fed into the gasification reactor, T_0 is the waste tyre feed temperature (25°C). The disparities in the $\bar{c}_{p,i}$ of the gaseous with temperature have been accounted as:

$$\bar{c}_{p,i} = a_i + b_iT + c_iT^2 + d_iT^3 \qquad (18)$$

where the values of a_i, b_i, c_i and d_i of each species can be obtained from Perry [158], however, the values of the $c_{p,char}$ and $c_{p,ash}$ are given as 1 kJkg^{-1}K^{-1} and 0.84 kJkg^{-1}K^{-1} respectively [15, 159].

In Zone-B, reactions R-2 to R-5 from **Table 5** were the reduction reactions considered in modelling the zone. The net reaction rates in this zone are expressed by Arrhenius type kinetic rate equation (Eqs. 19-22):

$$r_{R2} = C_{RF}A_{R2}\, exp\left(-\frac{E_{R2}}{RT}\right)\left(y_{CO_2} - \frac{y^2_{CO}}{K_{R2}}\right) \qquad (19)$$

$$r_{R3} = C_{RF}A_{R3}\, exp\left(-\frac{E_{R3}}{RT}\right)\left(y_{H_2O} - \frac{y_{CO}y_{H_2}}{K_{R3}}\right) \qquad (20)$$

$$r_{R4} = C_{RF}A_{R4}\, exp\left(-\frac{E_{R4}}{RT}\right)\left(y^2_{H_2} - \frac{y_{CH_4}}{K_{R4}}\right) \qquad (21)$$

$$r_{R5} = C_{RF} A_{R5}\, exp\left(-\frac{E_{R5}}{RT}\right)\left(y_{H_2O}y_{CH_4} - \frac{y_{H_2}^3 y_{CO}}{K_{R5}}\right) \quad (22)$$

where C_{RF} is the chat reactivity factor, (A_R) and (E_R) are the activation energy and pre-exponential factor for each of the reactions. The A_R and $E_R$of the forward reactions can be found in Wang and Kinoshita (1993) [160]. The equilibrium constants $(K_{R2} - K_{R5})$ as well as the specific rates of reactions $(r_{R2} - r_{R5})$ and of the backward reactions can be evaluated from the forward reactions as expressed in Eqs. 23-26. The active sites on the char surface are taken into account by C_{RF}.

$$K_{R2} = exp\left(-2\frac{\bar{g}_{CO}^0}{RT} + \frac{\bar{g}_{CO_2}^0}{RT}\right) \quad (23)$$

$$K_{R3} = exp\left(-\frac{\bar{g}_{CO}^0}{RT} - \frac{\bar{g}_{H_2}^0}{RT} + \frac{\bar{g}_{H_2O}^0}{RT}\right) \quad (24)$$

$$K_{R4} = exp\left(-\frac{\bar{g}_{CH_4}^0}{RT} - 2\frac{\bar{g}_{H_2}^0}{RT}\right) \quad (25)$$

$$K_{R5} = exp\left(-\frac{\bar{g}_{CO}^0}{RT} - 3\frac{\bar{g}_{H_2}^0}{RT} - \frac{\bar{g}_{CH_4}^0}{RT} + \frac{\bar{g}_{H_2O}^0}{RT}\right) \quad (26)$$

Following the exit from the pyro-oxidation zone, the product gases move into Zone-B (also known as the reduction zone). Based on the flow rate of the dry waste tyre sample delivered to the gasifier (m_F), the flowrate of each species at Zone-B entrance was determined as follows:

$$X_i^0 = \frac{m_F(1 - ASH/100)}{MW_F} x_i. \quad i = 1 \text{ to } 7 \quad (27)$$

where x_i represent the number of moles of species formed per mole of CH_m0_n in Zone-A. The mass flow rate of the ash flowing with the product is given by Eq. 28.

$$m_{ash} = \frac{m_F ASH}{100} \quad (28)$$

The geometry of Zone-B is thought to be divergent in nature, with the entire zone divided into a number of elemental control volumes (k) that have constant temperatures and concentrations [86, 161]. The energy and mass balances of each specie were calculated for each of the control volumes, taking into account the rate of species creation and/or consumption according to various reaction equations, such as the heat loss equation from the gasification reactor [86]. Eq. 29 provides the balance across the control volume for any species.

$$X_i^{\mathrm{k}} = X_i^{\mathrm{k}+1} + R_i^{\mathrm{k}} \Delta V_{\mathrm{k}} \tag{29}$$

where R_i^{k} is the net formation rate of species (i) and $\Delta \mathrm{V_k}$ is the volume of the respective k. The R_i^{k} of each specie is presented in **Table 6**.

Table 6. Net rate of formation of different species according to Eqs.23-26 ([86])

Species	**R*i* (mol m^{-3} s^{-1})**
H_2	$r_{R-2} - 2r_{R-4} + 3r_{R-5}$
CO	$2r_{R-2} + r_{R-3} + r_{R-5}$
CO_2	$-r_{R-2}$
H_2O	$-r_{R-2} - r_{R-5}$
CH_4	$r_{R-4} - r_{R-5}$
N_2	0
C	$-r_{R-2} - r_{R-3} - r_{R-4}$

Zone-B temperature was estimated from Eq. 30, the temperature and concentration of each species exiting the final k determines their values in the product gases leaving the gasification reactor.

$$\sum_{i=1}^{6} X_i^{\mathrm{k}-1}\left(\bar{h}_{f_i}^{0} + \int_{T_o}^{T^{\mathrm{k}-1}} \bar{c}_{p.i} dT\right) + X_7^{\mathrm{k}-1}\, \bar{c}_{p.C}\left(T^{\mathrm{k}-1} - T_0\right) + m_{ash} c_{p.ash}\left(T^{\mathrm{k}-1} - T_0\right) + \dot{Q}_{loss}^{\mathrm{k}}$$

$$= \sum_{i=1}^{6} X_i^{\mathrm{k}}\left(\bar{h}_{f_i}^{0} + \int_{T_o}^{T^{\mathrm{k}}} \bar{c}_{p.i} dT\right) + X_7^{\mathrm{k}}\, \bar{c}_{p.C}\left(T^{\mathrm{k}} - T_0\right) + m_{ash} c_{p.ash}\left(T^{\mathrm{k}} - T_0\right)$$

(30)

where $\dot{Q}_{loss}^{k}$ indicates the rate at which heat dissipates from the final k. Since hot gases in this zone tend to migrate up toward the area around the exhaust, it was presumed that heat loss from the gasification reactor was not taken into account.

In addition, Isaac *et al.* [119] also applied kinetic models in the isothermal gasification of waste tyres. Two kinetic models namely the random pore model (RPM) and grain model were employed; however, this model does not describe the entire gasification process as they were both targeted at the char product. The same applies to Molino *et al.* [83] who also employed RPM to model and predict the surface areas and burn-off of the activated carbon produced from waste tyre gasification.

In conclusion, Eqs. 1-30 sums up the kinetic model that has been frequently employed for modelling waste tyre gasification in a downdraft fixed bed reactor. Even though the model combines some thermodynamics principles to estimate some of the variables, the model relies on kinetic parameters determined from gasification experiments. ~~In addition,~~ Another disputed assumption is that kinetic models also assume the gasification process to be one-dimensional (in space). In addition, one of the assumptions made is the waste tyre comprises mainly of C, H, and O, in most cases, sulphur is one of the components of waste tyre and the formation of sulphorous compounds could mean a great problem in real-life application when it is ignored. Even though the main pollutants in the waste tyre gasification process that contain sulphur are SO_2 and H_2S, the primary source of SO_x emissions is the high-temperature oxidation of waste tyres [162]. Janajreh *et al.* [70] investigated the different products from waste tyre gasification and concluded that up to 44 different species (including all sulphur compounds) can be obtained from waste tyre gasification.

3.5.2. Thermodynamic Equilibrium Model (TEM)

Thermodynamic equilibrium models (TEMs) have proven to be much more convenient because they are independent of the type of gasifier adopted and can also use thermodynamic properties of the variables to guide the design, evaluation and improvement [163]. TEMs also have their limitations. For example, they cannot be used for spatial designs, sub-equilibrium operations or process dynamics and control. ~~Some of the studies that have employed TEMs in waste tyre gasification are examined below.~~ Jarungthammachote and Dutta [164] developed a TEM to predict the composition of producer gas in a downdraft solid waste gasifier. The model applies the second law to analyze the gasification system on municipal solid waste. In order to improve the model, WGS reaction and methane reaction were adopted to correct the equilibrium constant. While varying the moisture content of the feedstock, the authors reported a high yield of H_2 and CO_2 while other products have a lower yield when compared with lower moisture content value. This method has been employed by other authors in waste tyre gasification [55, 86]. Janajreh *et al.* [70] applied TEM to simulate waste tyre gasification in two different gasification reactors (plasma and conventional). ~~A comparison between plasma gasification process and conventional air gasification model was performed via simulation using Aspen Plus software.~~ The approach does not require chemical reactions nor does it require the selection of intermediate reactions using equilibrium constant. In the work, the authors used a non-stoichiometric Gibbs energy minimization approach to model waste tyre gasification process. This approach minimizes the total Gibbs energy ($\bar{g}^{t}_{T,P}$) of a system by employing the constrained atomic mass balance equation which provides room for the formation of other species produced during waste tyre gasification experiment [70]. The description of the process is given in Eqs. 31-40.

$$\bar{g}^{t}_{T,P} = g(n_1, n_2, n_3, \dots n_i) \tag{31}$$

where $\bar{g}_{T,P}^{t}$, and n_i represent the total Gibbs free energy, and mole fraction of each of the species respectively. To compute the n_i, several steps are required, the first includes the definition of the material balance for each element present within the system.

$$\sum_{i} n_i a_{ij} = A_j \; (j = 1, 2 \ldots w)$$

(32)

where a_{ij} represents the number of atoms of the j^{th}element in each molecule of the chemical species (i), A_j represents the total number of atomic masses of the j^{th}element inside the system while w represents the total number of atoms present inside the system. Lagrange principles were applied to Eq. 32 to give:

$$\sum_{j} \lambda_j \left(\sum_{i} n_i a_{ij} - A_j\right) = 0$$

(33)

A new function, F is formed by adding Eqs. (31) and (33)

$$F = \bar{g}_{T,P}^{t} + \sum_{j} \lambda_j \left(\sum_{i} n_i a_{ij} - A_j\right)$$

(34)

The minimum value of F is obtained when the partial derivative of F with respect to n_i at specified conditions (temperature and pressure) approaches 0 as shown in Eq. 35.

$$\frac{\partial F}{\partial n_i} = \frac{\partial \bar{g}^{\,t}}{\partial n_i} + \sum_{j} n_i a_{ij} = 0 \qquad (i = 1, 2, \ldots n)$$

(35)

The equation can be re-written as:

$$\mu_i + \sum_{j} n_i a_{ij} = 0$$

(36)

where μ_i is known as chemical potential which is defined as:

$$\mu_i = \bar{g}_i^{\,0} + RT\, ln\left(\frac{f_i}{f_i^o}\right) \tag{37}$$

where $\bar{g}_i^{\,0} = \Delta\bar{g}_{fi}^0$ is the standard state Gibbs energy of formation, T is the temperature of the system, R is the universal gas constant, $\frac{f_i}{f_i^o}$ is the fugacity ratio of the species. For ideal gases at the standard pressure. The $\frac{f_i}{f_i^o}$ term can be replaced by the mole fraction of the species as given by Eq. 38.

$$\mu_i = \bar{g}_{fi}^0 + RT\, ln\left(\frac{n_i}{n_{total}}\right) \tag{38}$$

By substituting, Eq. 36 in Eq. 39, we have,

$$\bar{g}_{fi}^0 + RT\, ln\left(\frac{n_i}{n_{total}}\right) + \sum\nolimits_j n_i a_{ij} = 0 \qquad (i = 1, 2, \dots n) \tag{39}$$

Eq. 39 represents *n* equilibrium equations which refers to each specie present within the system. In addition, all the participating specie are a combination of the basic elements present in the waste tyre sample (CHNOS), therefore, the energy balance is given as:

$$h_{f^o_{CHONS}} + m\Delta h_{o_2} + p\Delta h_{H_2O} = \sum\nolimits_{i=product} n_i \Delta h_i \tag{40}$$

where $h_{f^o_{CHONS}}$ represent the enthalpy of formation of waste tyre and Δh is the relative enthalpy of each species within the system.

The proposed TEM model by Janajreh *et al.* [70] took into account several feedstocks (which also included waste tyres) and two gasification modes (plasma and conventional). ~~The results of both plasma and conventional gasification methods were evaluated on the basis of~~

~~efficiency of the gasification process.~~ The result obtained from the process shows that the ~~waste tyre~~ gasification efficiency ~~(the LHV of the syngas divided by the LHV of the feed)~~ of plasma reactor was estimated to be around 43%$_{LHV}$, while that of conventional reactor is approximately 74% $_{LHV}$. Janajreh *et al.* [165] in another study combined the equilibrium constant method (ECM) with the element potential method (EPM) to model waste tyre gasification process. The ECM was used to determine the concentration of the species at equilibrium as well as the temperature and pressure of the products exiting the gasifier. The EPM on the other hand was employed to detect the presence of graphite in the product stream. The basic assumptions made in the implementation of these models include the assumption of infinite residence time, the system is in both chemical and thermodynamic equilibrium, no spatial distribution of species as well and no account for the kinetics of the reactions. Mozarafi *et al.* [166] also applied TEM ~~to model waste tyre gasification, the authors also applied the minimization of Gibbs energy~~ similar to Janajreh *et al.* [70]. The authors employed penalty method to account for mass balance constraints in the objective function. The authors validated their model based on the prediction of thermal parameters of adiabatic combustion of propane at stoichiometric air to fuel ratio. ~~The goal of the validation was to assess the reliability of their model in predicting adiabatic temperature.~~ The authors concluded that the proposed TEM could be used as a reference simulator to forecast adiabatic temperature and product distribution in the thermolysis and air gasification of waste tyres.

In conclusion, TEM only forecasts the performance bounds of a specific gasifier under a specific set of operating parameters. Syngas and other product composition measurements frequently deviate from the equilibrium's ideal [149]. The two most frequently mentioned and notable differences between ideal equilibrium forecasts and experimental findings are first, higher CH_4 concentrations in the final syngas relative to the equilibrium CH_4 concentration, and second, higher levels of unreacted char in some instances [149]. The cons of using this method include non-consideration of tars and heat losses, limited to fluidized bed reactors, assumes zero-dimensionality of the reactor, and it is not ideal for low temperature operations.

3.5.3. Other Models Employed in Waste Gasification

Generally, the modelling of waste tyre gasification process over the years has based their simulation on the kinetic model and TEM [55, 70, 86, 165-168]. However, due to the simplified assumptions and errors involved in TEM and also the uncertainty in kinetic parameters of tyre gasification for predicting the presence of hydrocarbon products, neither method may be best suited for fluidized bed simulation [86, 169]. Hannula and Kurkela [148] proposed a semi-empirical model (SEM) to model fluidized bed gasification reactors. The authors however did not apply this model to waste tyre gasification. Zang *et al.* [86] and Fajimi *et al.* [55] have applied SEM to model waste tyre gasification in a fluidized bed reactor in the Aspen Plus environment. SEM was basically used to account for ammonia, hydrocarbon formation and carbon conversion by using ER as the key parameter.

4.0. ~~Research Gaps~~ Waste Tyre Gasification Challenges and Limitations

Waste tyre gasification has its challenges and limitations that need to be addressed. One of the main issues is the cost of building and operating gasification plants, which can be relatively high compared to traditional waste management methods [93]. For instance, the total plant cost of the fluidized bed gasifier is more than $10 million for a commercial scale plant [86, 93]. The high capital cost of gasification plants is partly due to the complex and sophisticated nature of the technology, as well as the need for advanced pollution control systems. Most times, these cost do not include the cost of syngas cleaning operation, ash handling, waste tyre preteatement operations, tar cracking etc [93]. This cost factor also can make it difficult for waste tyre gasification to compete with other waste management options (such as pyrolysis), particularly in regions with limited financial resources. Another issue with waste tyre gasification is the potential for emissions of harmful pollutants, such as dioxins and furans. These pollutants can be produced during the gasification process, particularly if the plant is not equipped with adequate pollution control systems. To address this issue, many waste tyre gasification plants employ advanced scrubbing and filtration technologies to remove these harmful pollutants from the gas stream.

Another general problem encountered in waste tyre gasification is the existence of tar in syngas. These tars are made up of heavier aromatic hydrocarbons, and present major difficulties for the usage of syngas downstream. Tar-designated compounds have the ability to damage downstream equipment and applications through a variety of mechanisms, from as simple as blocking flow channels in internal combustion engines and turbines to as serious as contaminating catalytic layers in fuel cells and alcohol synthesis processes [170]. As such, in order to achieve the maximum permitted limits, syngas must be cleaned to the degree required by certain uses [171]. It is critical to have a solid understanding of the chemistry and design of gasifiers, the formation of tar during waste tyre gasification, the composition-based classification of tar, the necessary level of tar removal from syngas, and the science behind tar removal technology. It is abundantly clear that the current secondary tar removal technologies cannot produce the required syngas purity without multistage cleaning in addition to in situ mitigation of tar production. Since most other solutions involve the use of syngas cooling for tar removal, catalytic tar removal techniques have demonstrated tremendous promise for removing tar with high thermal stability without sacrificing cold gas efficiency [170]. For successful application, it is necessary to address catalyst deactivation caused by coke, fouling, and sintering, as well as other syngas contaminants. In modelling waste tyre gasification process, the difficulty in determining the effect of hydrodynamic variables on gasification when using TEMs is a big disadvantage. A kinetic model would be necessary if the aim was to understand or optimize the impact of variables like feed density, reactivity, and particle size distributions on the final syngas composition, carbon conversion, as well as system performance. However, the kinetic and transport parameters typically required in kinetic models are hard to find. Even if these variables are measured, the final model will still be somewhat constrained to the particular gasifier type, design, feedstock, agent, and operating range combination for which the rate expression form and parameter values are appropriate.

5.0. Conclusion and Recommendations for Future Works

~~In conclusion, waste tyre gasification is a promising technology for managing waste tyres by converting them into energy-rich gases and other valuable industrial products.~~

The possibility of producing valuable products while lowering carbon footprints and producing energy carrier fuels like syngas and hydrogen are the key areas of attention for current waste tyre processing research. Typically, elevated temperatures are necessary to carry out the process of extracting valuable materials from waste tyres. It is therefore practical to employ the gasification process to meet the requirements and obtain hydrogen and/or syngas in addition to valuable carbon products. In addition, Considering the enormous waste generated globally on an annual basis, the high-energy fuel produced from gasification technology could be used to replace fossil fuels. However, there are still challenges and limitations that need to be addressed, particularly with regard to cost and emissions control. Further research and development are needed to improve waste tyre gasification technology and make it more economically viable for widespread adoption in both developed and developing countries. In addition, after taking a big-picture view of the literature, the following areas are recommended for careful investigation.

1. *Tar Consideration:* Controlling the composition of the final product and increasing the hydrogen-rich syngas production depend heavily on understanding the processes involved in waste tyre gasification, including tar formation and conversion. Currently,

the majority of research on tar formation and conversion having only one model compound in use. However, the various components in tar interact with one another, making it a complex mixture. Therefore, to comprehend the mechanism of tar reformation under actual conditions, the catalytic reformation of a combination of several model compounds should be investigated. Furthermore, the majority of tar research has concentrated on light components; however, more has to be done to further the study of heavy tar conversion.

2. *Waste tyre Gasification and Carbon Nanomaterials*: Few studies have proven that carbon nanomaterial such as carbon nanotube (CNT) can be produced from waste tyre gasification. Zhang *et al.* [89] were the last authors who attempted this and proved CNT could be produced from waste tyre gasification. In addition, are limited research on modelling CNT production from waste tyre gasification.
3. *Environmental Impact of Waste Tyre Gasification*: The investigation of the environmental impact of waste tyre gasification emission through a detailed life cycle assessment (LCA) is vital as this can ease the adoption of waste tyre gasification technology. Investigating the LCA of the process is required to ensure that we actually do have a net environmental benefit. In addition, LCA is required to determine and understand the best processes and routes for using waste tyres considering both environmental and economic trade-offs. To the best of our knowledge, only Santasnachok and Nakyai [61] and Batuecas *et al.* [172] have researched this area, however, a more detailed approach is required.
4. *Waste tyre Gasification and Artificial Intelligence (AI):* The application of artificial intelligence (AI) in waste tyre gasification processes is still in its infancy with limited work available in this area. With the aid of experimental and literature data, AI algorithms could be used to predict critical waste tyre gasification parameters such as

the heating value, syngas composition, and thermal efficiency amongst others. Authors such as Pandey *et al.* [173], Mutlu & Yucel [174], and Han *et al.* [175] have all applied AI techniques to predict biomass gasification parameters. However, besides Ozonoh *et al.* [176] who employed AI in predicting waste tyre gasification emissions, critical works in AI applications in waste tyre gasification are currently unavailable to the best of our knowledge.

5. *Hydrothermal Gasification of Waste Tyres*: The gasification of waste tyres at supercritical conditions is an interesting area that is still lacking detailed research. As discussed earlier in section 3.1.1.2, this is a promising gasification technology and very limited works are available in this area.
6. *Solar-assisted Waste Tyre Gasification*: Solar-assisted gasification has a number of advantages over traditional gasification, as was previously mentioned. Sideways solar concentrator integrated gasifiers offer a workable alternative for lowering emissions from the gasification process and helping to increase the calorific value of syngas [80]. Only a few authors [72-75] have research in this area. In the last decade, no work on solar-assisted gasification has been available.

Declaration of Conflict of Interest

The authors declare no conflicts of interest

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References

1. Kopetz, H., *Build a biomass energy market: governments must offer incentives to drive a switch to biofuels and other renewables.* Nature, 2013. **494**(7435): p. 29-31.
2. Fajimi, L.I., J. Chrisostomou, and B.O. Oboirien, *A techno-economic analysis (TEA) of a combined process of torrefaction and gasification of lignocellulose biomass*

(bagasse) for electricity production and methanol production. Biomass Conversion and Biorefinery, 2022.

3. Popp, J., S. Kovács, J. Oláh, Z. Divéki, and E. Balázs, *Bioeconomy: Biomass and biomass-based energy supply and demand.* New Biotechnology, 2021. **60**: p. 76-84.
4. Xu, F. and Y. Li, *Biomass for renewable energy production*, in *Biomass Digestion*. 2017, Elsevier: Sustainable Energy Technologies & Sustainable Chemical Processes. p. 197-204.
5. Alsaleh, A. and M.L. Sattler, *Waste tire pyrolysis: influential parameters and product properties.* Current Sustainable/Renewable Energy Reports, 2014. **1**: p. 129-135.
6. Ramos, A., E. Monteiro, V. Silva, and A. Rouboa, *Co-gasification and recent developments on waste-to-energy conversion: A review.* Renewable Sustainable Energy Reviews, 2018. **81**: p. 380-398.
7. Okafor, C., C. Ajaero, C. Madu, K. Agomuo, and E. Abu, *Implementation of circular economy principles in management of end-of-life tyres in a developing country (Nigeria).* AIMS Environmental Science, 2020. **7**: p. 406-433.
8. Nanda, S., S.N. Reddy, H.N. Hunter, D.-V.N. Vo, J.A. Kozinski, and I. Gökalp, *Catalytic subcritical and supercritical water gasification as a resource recovery approach from waste tires for hydrogen-rich syngas production.* The Journal of Supercritical Fluids, 2019. **154**: p. 104627.
9. Zhang, L., B. Zhou, P. Duan, F. Wang, and Y. Xu, *Hydrothermal conversion of scrap tire to liquid fuel.* Chemical Engineering Journal, 2016. **285**: p. 157-163.
10. Ferdous, W., A. Manalo, R. Siddique, P. Mendis, Y. Zhuge, H.S. Wong, W. Lokuge, T. Aravinthan, and P. Schubel, *Recycling of landfill wastes (tyres, plastics and glass) in construction–A review on global waste generation, performance, application and future opportunities.* Resources, Conservation and Recycling, 2021. **173**: p. 105745.
11. Rogachuk, B.E. and J.A. Okolie, *Waste tires based biorefinery for biofuels and value-added materials production.* Chemical Engineering Journal Advances, 2023: p. 100476.
12. Pathak, P. and S. Sinha, *Valorisation of waste tires into fuel and energy*, in *Advanced Technology for the Conversion of Waste Into Fuels and Chemicals*. 2021, Elsevier. p. 109-122.
13. US Environmental Protection Agency, *Wastes-resource conservation-common wastes & materials-scrap tires*. 2012, United States Environmental Protection Agency: Washington, D.C.
14. Botes, A., *South african waste management tyre fee to generate R700 million per year to promote tyre recycling*. 2017.
15. Fajimi, L.I., *Modelling and simulation studies on syngas and activated carbon production from waste tyre gasification*, in *Chemical Engineering*. 2020, University of Johannesburg: South Africa. p. 162.
16. Mohajerani, A., L. Burnett, J.V. Smith, S. Markovski, G. Rodwell, M.T. Rahman, H. Kurmus, M. Mirzababaei, A. Arulrajah, and S. Horpibulsuk, *Recycling waste rubber tyres in construction materials and associated environmental considerations: A review.* Resources, Conservation and Recycling, 2020. **155**: p. 104679.
17. Tran, T.Q., B.S. Thomas, W. Zhang, B. Ji, S. Li, and A.S. Brand, *A comprehensive review on treatment methods for end-of-life tire rubber used for rubberized cementitious materials.* Construction Building Materials, 2022. **359**: p. 129365.
18. Grammelis, P., N. Margaritis, P. Dallas, D. Rakopoulos, and G. Mavrias, *A review on management of end of life tires (ELTs) and alternative uses of textile Fibers.* Energies, 2021. **14**(3): p. 571.

19. Jahirul, M.I., F.M. Hossain, M.G. Rasul, and A.A. Chowdhury, *A review on the thermochemical recycling of waste tyres to oil for automobile engine application.* Energies, 2021. **14**(13): p. 3837.
20. Rauch, R., Y. Kiros, K. Engvall, E. Kantarelis, P. Brito, C. Nobre, S.M. Santos, and P.A. Graefe, *Hydrogen from Waste Gasification.* Hydrogen, 2024. **5**(1): p. 70-101.
21. Oponeo, *Tyre Articles*, in *How much does a tyre weigh?* 2019: United Kingdom. p. https://www.oponeo.co.uk/tyre-article/how-much-does-a-tyre-weigh.
22. Ruwona, W., G. Danha, and E. Muzenda, *A review on material and energy recovery from waste tyres.* Procedia Manufacturing, 2019. **35**: p. 216-222.
23. Machin, E.B., D.T. Pedroso, and J.A. de Carvalho Jr, *Technical assessment of discarded tires gasification as alternative technology for electricity generation.* Waste Management, 2017. **68**: p. 412-420.
24. Valentini, F. and A. Pegoretti, *End-of-life options of tyres. A review.* Advanced Industrial Engineering Polymer Research, 2022.
25. Bianco, I., D. Panepinto, and M. Zanetti, *End-of-life tyres: Comparative life cycle assessment of treatment scenarios.* Applied Sciences, 2021. **11**(8): p. 3599.
26. Palos, R., A. Gutierrez, F.J. Vela, M. Olazar, J.M. Arandes, and J. Bilbao, *Waste refinery: the valorization of waste plastics and end-of-life tires in refinery units. A review.* Energy & Fuels, 2021. **35**(5): p. 3529-3557.
27. European Union, *Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste*. 2018. p. 100-108.
28. Muzenda, E. *A comparative review of waste tyre pyrolysis, gasification and liquefaction (PGL) processes*. in *Proceedings of the International Conference on Chemical Engineering & Advanced Computational Technologies (ICCEACT'2014)*. 2014. Pretoria, South Africa.
29. Danso-Boateng, E. and O.-W. Achaw, *Bioenergy and biofuel production from biomass using thermochemical conversions technologies—A review.* AIMS Energy, 2022. **10**(4): p. 585-647.
30. National Energy Technology Laboratory *Gasification Introduction*.
31. Ahlström, J.M., V. Walter, L. Göransson, and S. Papadokonstantakis, *The role of biomass gasification in the future flexible power system–BECCS or CCU?* Renewable Energy, 2022. **190**: p. 596-605.
32. Blanco-Sanchez, P., D. Taylor, and S. Cooper, *IEA Bioenergy Task 33*, in *UK Country Report*. 2021: International Energy Agency: Paris, France. p. 1-20.
33. Soprych, P., G. Czerski, and P. Grzywacz *Studies on the thermochemical conversion of waste tyre rubber—A review*. Energies, 2024. **17**, DOI: 10.3390/en17010014.
34. Czerski, G., K. Śpiewak, D. Makowska, and B. Grycova, *Study on steam co-gasification of waste tire char and sewage sludge.* Energies, 2023. **16**(5).
35. Carmo-Calado, L., M.J. Hermoso-Orzáez, R. Mota-Panizio, B. Guilherme-Garcia, and P. Brito, *Co-combustion of waste tires and plastic-rubber wastes with biomass technical and environmental analysis.* Sustainability (Switzerland), 2020. **12**(3): p. 1036.
36. Oboirien, B.O. and B.C. North, *A review of waste tyre gasification.* Journal of Environmental Chemical Engineering, 2017. **5**(5): p. 5169-5178.
37. Labaki, M. and M. Jeguirim, *Thermochemical conversion of waste tyres—a review.* Environmental Science Pollution Research, 2017. **24**(11): p. 9962-9992.
38. Meho, L.I., *Using Scopus's CiteScore for assessing the quality of computer science conferences.* Journal of Informetrics, 2019. **13**(1): p. 419-433.

39. Gao, N., F. Wang, C. Quan, L. Santamaria, G. Lopez, and P.T. Williams, *Tire pyrolysis char: Processes, properties, upgrading and applications.* Progress in Energy and Combustion Science, 2022. **93**: p. 101022.
40. Tan, P., C. Zhang, J. Xia, Q.-Y. Fang, and G. Chen, *Estimation of higher heating value of coal based on proximate analysis using support vector regression.* Fuel Processing Technology, 2015. **138**: p. 298-304.
41. Ozonoh, M., T.C. Aniokete, B.O. Oboirien, and M.O. Daramola, *Techno-economic analysis of electricity and heat production by co-gasification of coal, biomass and waste tyre in South Africa.* Journal of Cleaner Production, 2018. **201**: p. 192-206.
42. Barbarias, I., G. Lopez, M. Artetxe, A. Arregi, J. Bilbao, and M. Olazar, *Valorisation of different waste plastics by pyrolysis and in-line catalytic steam reforming for hydrogen production.* Energy Conversion and Management, 2018. **156**: p. 575-584.
43. Oboirien, B.O. and S. Bada. *Co-gasification of waste tyres, bamboo and refuse derived fuel (RDF) using carbon dioxide*. in *12th ECCRIA Conference, (The European Conference on Fuel and Energy Research and its Applications)*. 2018. Cardiff University, UK.
44. Yin, C.-Y., *Prediction of higher heating values of biomass from proximate and ultimate analyses.* Fuel, 2011. **90**(3): p. 1128-1132.
45. Nkosi, N., E. Muzenda, J. Gorimbo, and M. Belaid, *Developments in waste tyre thermochemical conversion processes: gasification, pyrolysis and liquefaction.* RSC advances, 2021. **11**(20): p. 11844-11871.
46. Machin, E.B., D.T. Pedroso, and J.A. de Carvalho Júnior, *Technical assessment of discarded tires gasification as alternative technology for electricity generation.* Waste management, 2017b. **68**: p. 412-420.
47. Dincer, I., *Green methods for hydrogen production.* International Journal of Hydrogen Energy, 2012. **37**(2): p. 1954-1971.
48. Rupesh, S., C. Muraleedharan, and P. Arun, *Aspen plus modelling of air–steam gasification of biomass with sorbent enabled* CO_2 *capture.* Resource-efficient Technologies, 2016. **2**(2): p. 94-103.
49. Raman, K.P., W. Walawender, and L. Fan, *Gasification of waste tires in a fluid bed reactor.* Conservation Recycling, 1981. **4**(2): p. 79-88.
50. Jarungthammachote, S. and A. Dutta, *Experimental investigation of a multi-stage air-steam gasification process for hydrogen enriched gas production.* International Journal of Energy Research, 2012. **36**(3): p. 335-345.
51. Kartal, F. and U. Özveren, *Energy and exergy analysis of entrained bed gasifier/GT/Kalina cycle model for* CO_2 *co-gasification of waste tyre and biochar.* Fuel, 2023. **331**.
52. Lahijani, P., M. Mohammadi, and A.R. Mohamed, *Investigation of synergy and inhibition effects during co-gasification of tire char and biomass in* CO_2 *environment.* Biomass Conversion and Biorefinery, 2022. **12**(6): p. 2229-2241.
53. Portofino, S., A. Donatelli, P. Iovane, C. Innella, R. Civita, M. Martino, D.A. Matera, A. Russo, G. Cornacchia, and S. Galvagno, *Steam gasification of waste tyre: Influence of process temperature on yield and product composition.* Waste Management, 2013. **33**(3): p. 672-678.
54. Xiao, G., M. Ni, Y. Chi, and K. Cen, *Low-temperature gasification of waste tire in a fluidized bed.* Energy Conversion and Management, 2008. **49**(8): p. 2078-2082.
55. Fajimi, L.I., B.O. Oboirien, and T.A. Adams II, *Simulation studies on the co-production of syngas and activated carbon from waste tyre gasification using different reactor configurations.* Energy Conversion and Management: X, 2021: p. 100105.

56. Subramanian, A.S.R., T. Gundersen, P.I. Barton, and T.A. Adams, *Global optimization of a hybrid waste tire and natural gas feedstock polygeneration system.* Energy, 2022. **250**.

57. Zang, G., J. Zhang, A. Ratner, and Y. Shi, *Techno-economic analysis of a cooling, heating, and electricity trigeneration system based on downdraft fixed bed wood and tire gasification: Case study of a campus office building.* Sustainable Energy Technologies and Assessments, 2023. **55**.

58. Śpiewak, K., P. Soprych, and G. Czerski, *Influence of pressure and sunflower husks ash as catalyst on tire-char steam gasification*, in *4th International Conference on Sustainable Energy and Environmental Development, Institute of Sustainable Energy, 2021*. 2023, Energy Reports: Cracow, Poland. p. 1-15.

59. Varank, G., A. Ongen, S.Y. Guvenc, H.K. Ozcan, E.E. Ozbas, and E. Can-Güven, *Modeling and optimization of syngas production from biomass gasification.* International Journal of Environmental Science and Technology, 2022. **19**(4): p. 3345-3358.

60. Serrano, D., A. Horvat, E. Batuecas, and P. Abelha, *Waste tyres valorisation through gasification in a bubbling fluidised bed: An exhaustive gas composition analysis.* Renewable Energy, 2022. **200**: p. 1438-1446.

61. Santasnachok, M. and T. Nakyai, *Exergetic and environmental assessments of hydrogen production via waste tire gasification with co-feeding of CO_2 recycled.* Energy Reports, 2022. **8**: p. 859-867.

62. Jansen, A.A., I.J. van der Walt, and P.L. Crouse, *Waste-tyre pyrolysis and gasification via the reverse boudouard reaction: derivation of empirical kinetics from TGA data.* Thermochimica Acta, 2022. **708**.

63. Grzywacz, P., G. Czerski, and W. Gańczarczyk, *Effect of pyrolysis atmosphere on the gasification of waste tire char.* Energies, 2022. **15**(1).

64. Larionov, K.B., P.V. Povalyaev, A.Z. Kaltaev, K.V. Slysarsky, A.S. Gorshkov, V.E. Gubin, V.O. Stoyanovskii, and A.Y. Pak, *Electric arc gasification of pyrolysis oil with the production of hydrogen-enriched synthesis gas and carbon nanomaterial.* Fuel Processing Technology, 2023. **245**.

65. Ma, Y., H. Qi, J. Zhang, P. Cui, Z. Zhu, and Y. Wang, *Thermodynamic analysis of a carbon capture hydrogen production process for end-of-life tires using plasma gasification.* Journal of Cleaner Production, 2023. **384**.

66. Galaly, A.R. and G. Van Oost, *Environmental and economic aspects of the plasma treatment of scrap tires to produce syngas and synthetic fuels in Saudi Arabia.* IEEE Transactions on Plasma Science, 2020. **49**(2): p. 522-534.

67. Popov, V.E., D.I. Subbotin, A.V. Surov, S.D. Popov, E.O. Serba, E.P. Godina, and A.A. Kiselev. *Co-gasification of lignite and used car tires by H_2O/air thermal plasma*. in *Journal of Physics: Conference Series*. 2019.

68. Liavonchyk, A., D. Morozov, V. Sauchyn, and H. Dalholenka, *Numerical modeling of processes in a plasma reactor for conversion of hydrocarbons.* High Temperature Material Processes, 2017. **21**(4): p. 359-375.

69. Hrabovsky, M. *Thermal plasma gasification of organic waste and biomass*. in *20th Symposium on Physics of Switching Arc 2013, FSO 2013*. 2013.

70. Janajreh, I., S.S. Raza, and A.S. Valmundsson, *Plasma gasification process: Modeling, simulation and comparison with conventional air gasification.* Energy Conversion and Management, 2013. **65**: p. 801-809.

71. Nie, S.Q., M.Q. Chen, and Q.H. Li, *Evaluation on hydrothermal gasification of waste tires based on chemical equilibrium analysis.* International Journal of Hydrogen Energy, 2022. **47**(3): p. 1435-1448.

72. Wieckert, C., A. Obrist, P.V. Zedtwitz, G. Maag, and A. Steinfeld, *Syngas production by thermochemical gasification of carbonaceous waste materials in a 150* kW_{th} *packed-bed solar reactor.* Energy & Fuels, 2013. **27**(8): p. 4770-4776.
73. Piatkowski, N. and A. Steinfeld, *Solar gasification of carbonaceous waste feedstocks in a packed-bed reactor-Dynamic modeling and experimental validation.* AIChE Journal, 2011. **57**(12): p. 3522-3533.
74. Piatkowski, N., C. Wieckert, and A. Steinfeld, *Experimental investigation of a packed-bed solar reactor for the steam-gasification of carbonaceous feedstocks.* Fuel Processing Technology, 2009. **90**(3): p. 360-366.
75. Matsunami, J., S. Yoshida, O. Yokota, M. Nezuka, M. Tsuji, and Y. Tamaura, *Gasification of waste tyre and plastic (PET) by solar thermochemical process for solar energy utilization.* Solar Energy, 1999. **65**(1): p. 21-23.
76. Nanda, S., S.N. Reddy, D.V.N. Vo, B.N. Sahoo, and J.A. Kozinski, *Catalytic gasification of wheat straw in hot compressed (subcritical and supercritical) water for hydrogen production.* Energy Science Engineering Structures, 2018. **6**(5): p. 448-459.
77. Okolie, J.A., S. Nanda, A.K. Dalai, F. Berruti, and J.A. Kozinski, *A review on subcritical and supercritical water gasification of biogenic, polymeric and petroleum wastes to hydrogen-rich synthesis gas.* Renewable sustainable energy reviews, 2020. **119**: p. 109546.
78. Nanda, S., M. Gong, H.N. Hunter, A.K. Dalai, I. Gökalp, and J.A. Kozinski, *An assessment of pinecone gasification in subcritical, near-critical and supercritical water.* Fuel Processing Technology, 2017. **168**: p. 84-96.
79. Lerner, A.S., A.N. Bratsev, V.E. Popov, V.A. Kuznetsov, A.A. Ufimtsev, and D.I. Subbotin, *Production of hydrogen-containing gas using the process of steam-plasma gasification of used tires.* Glass Physics Chemistry, 2012. **38**(6): p. 511-516.
80. Singh, A., A. Kaundal, R.K. Jha, S. Powar, and A. Dhar, *Solar assisted gasification.* Advances in solar energy research, 2019: p. 551-575.
81. Xu, D., X. Gu, and Y. Dai, *Concentrating solar assisted biomass-to-fuel conversion through gasification: A review.* Frontiers in Energy Research, 2023. **10**: p. 1029477.
82. Mazaheri, N., A. Akbarzadeh, E. Madadian, and M. Lefsrud, *Systematic review of research guidelines for numerical simulation of biomass gasification for bioenergy production.* Energy Conversion Management, 2019. **183**: p. 671-688.
83. Molino, A., A. Donatelli, T. Marino, A. Aloise, J. Rimauro, and P. Iovane, *Waste tire recycling process for production of steam activated carbon in a pilot plant.* Resources, Conservation and Recycling, 2018. **129**: p. 102-111.
84. Pio, D. and L. Tarelho, *Industrial gasification systems* $(>3\ MW_{th})$ *for bioenergy in Europe: Current status and future perspectives.* Renewable & Sustainable Energy Reviews, 2021. **145**: p. 111108.
85. Wang, Z., K.G. Burra, T. Lei, and A.K. Gupta, *Co-gasification characteristics of waste tire and pine bark mixtures in* CO_2 *atmosphere.* Fuel, 2019. **257**: p. 116025.
86. Zang, G., J. Jia, Y. Shi, T. Sharma, and A. Ratner, *Modeling and economic analysis of waste tire gasification in fluidized and fixed bed gasifiers.* Waste Management, 2019. **89**: p. 201-211.
87. Policella, M., Z. Wang, K.G. Burra, and A.K. Gupta, *Characteristics of syngas from pyrolysis and* CO_2*-assisted gasification of waste tires.* Applied Energy, 2019. **254**: p. 113678.
88. Marzoughi, T., F. Samimi, and M.R. Rahimpour, *Environmental and thermodynamic performance assessment of biomass gasification process for hydrogen production in a downdraft gasifier.* Chemical Product and Process Modeling, 2021. **17**(6): p. 637-654.

89. Zhang, Y., C. Wu, M.A. Nahil, and P. Williams, *Pyrolysis–catalytic reforming/gasification of waste tires for production of carbon nanotubes and hydrogen.* Energy & Fuels, 2015. **29**(5): p. 3328-3334.
90. Škrbić, B.D., N. Đurišić-Mladenović, and J. Cvejanov, *Differentiation of syngases produced by steam gasification of mono- and mixed sources feedstock: A chemometric approach.* Energy Conversion and Management, 2018. **171**: p. 1193-1201.
91. Al-Qadri, A.A., U. Ahmed, A.G. Abdul Jameel, U. Zahid, N. Ahmad, M. Shahbaz, and M.A. Nemitallah, *Technoeconomic feasibility of hydrogen production from waste tires with the control of CO_2 emissions.* ACS Omega, 2022. **7**(51): p. 48075-48086.
92. Subramanian, A.S.R., T. Gundersen, and T.A. Adams, *Optimal design and operation of a waste tire feedstock polygeneration system.* Energy, 2021. **223**.
93. Fajimi, L.I. and B.O. Oboirien, *A techno-economic study on the co-production of syngas and activated carbon from waste tyre gasification process.* Journal of Material Cycles and Waste Management, 2023.
94. All Power Labs. *Gasifier Types*. 2018 [cited 2023 June 11]; Available from: http://www.allpowerlabs.com/gasification-basics/gasifier-types.
95. Olofsson, I., A. Nordin, and U. Söderlind, *Initial review and evaluation of process technologies and systems suitable for cost-efficient medium-scale gasification for biomass to liquid fuels*. 2005: Umeå Universitet.
96. NHI Co Ltd. *Rotary Kiln*. 2006 [cited 2023 July 11]; Available from: https://snhi.co.jp/en/snhi_product_s/rotary-kiln/.
97. National Energy Technology Laboratory *UHDE – PRENFLO*.
98. Rampling, T.W.A. and P.J. Gill, *Fundamental research on the thermal treatment of wastes and biomass: thermal treatment characteristics of biomass*. Vol. 208. 1993: Harwell Laboratory, Energy Technology Support Unit.
99. McKendry, P., *Energy Production from Biomass (Part 2): Conversion Technologies.* Bioresource technology, 2002. **83**(1): p. 47-54.
100. Molino, A., S. Chianese, and D. Musmarra, *Biomass gasification technology: The state of the art overview.* Journal of Energy Chemistry, 2016. **25**(1): p. 10-25.
101. Radwan, A.M., *An overview on gasification of biomass for production of hydrogen rich gas.* Der Chemica Sinica, 2012. **3**(2): p. 323-335.
102. Powell, K., *Gasification based waste tire integrated energy conversion systems*, in *Dept. of Mechanical Engineering*. 2021, University of Tennessee at Chattanooga. p. 38.
103. Graboski, M. and R. Bain, *Properties of biomass relevant to gasification.* A Survey of Biomass Gasification, 1979. **2**: p. 21-65.
104. Leung, D.Y.C. and C.L. Wang, *Fluidized-bed gasification of waste tire powders.* Fuel Processing Technology, 2003. **84**(1-3): p. 175-196.
105. Donatelli, A., P. Iovane, and A. Molino, *High energy syngas production by waste tyres steam gasification in a rotary kiln pilot plant. Experimental and numerical investigations.* Fuel, 2010. **89**(10): p. 2721-2728.
106. Kandasamy, J. and I. Gökalp, *Pyrolysis, combustion, and steam gasification of various types of scrap tires for energy recovery.* Energy Fuels, 2015. **29**(1): p. 346-354.
107. Straka, P. and Z. Bučko, *Co-gasification of a lignite/waste-tyre mixture in a moving bed.* Fuel processing technology, 2009. **90**(10): p. 1202-1206.
108. Song, W., J. Zhou, Y. Li, S. Li, and J. Yang, *Utilization of waste tire powder for gaseous fuel generation via CO_2 gasification using waste heat in converter vaporization cooling flue.* Renewable Energy, 2021. **173**: p. 283-296.

109. Karatas, H., H. Olgun, and F. Akgun, *Experimental results of gasification of waste tire with air&CO_2, air&steam and steam in a bubbling fluidized bed gasifier.* Fuel Processing Technology, 2012. **102**: p. 166-174.
110. Molino, A., A. Erto, F.D. Natale, A. Donatelli, P. Iovane, and D. Musmarra, *Gasification of granulated scrap tires for the production of syngas and a low-cost adsorbent for Cd (II) removal from wastewaters.* Industrial Engineering Chemistry Research, 2013. **52**(34): p. 12154-12160.
111. Gumz, W., *Gas producers and blast furnaces: theory and methods of calculation*. 1950: Wiley.
112. Raman, K.P., W.P. Walawender, and L.T. Fan, *Gasification of waste tires in a fluid bed reactor.* Conservation Recycling, 1981. **4**(2): p. 79-88.
113. López, F.A., T.A. Centeno, F.J. Alguacil, B. Lobato, A. López-Delgado, and J. Fermoso, *Gasification of the char derived from distillation of granulated scrap tyres.* Waste management, 2012. **32**(4): p. 743-752.
114. Czerski, G., K. Śpiewak, P. Grzywacz, and F. Wierońska-Wiśniewska, *Assessment of the catalytic effect of various biomass ashes on CO_2 gasification of tire char.* Journal of the Energy Institute, 2021. **99**: p. 170-177.
115. Portofino, S., S. Casu, P. Iovane, A. Russo, M. Martino, A. Donatelli, and S. Galvagno, *Optimizing H_2 production from waste tires via combined steam gasification and catalytic reforming.* Energy & Fuels, 2011. **25**(5): p. 2232-2241.
116. Elbaba, I.F. and P.T. Williams, *Hydrogen from waste tyres.* International Journal of Environmental Ecological Engineering, 2012. **6**(6): p. 321-323.
117. Elbaba, I.F., C. Wu, and P.T. Williams, *Catalytic pyrolysis-gasification of waste tire and tire elastomers for hydrogen production.* Energy & Fuels, 2010. **24**(7): p. 3928-3935.
118. Karatas, H., H. Olgun, B. Engin, and F. Akgun, *Experimental results of gasification of waste tire with air in a bubbling fluidized bed gasifier.* Fuel, 2013. **105**: p. 566-571.
119. Issac, M., B. Dai, and L. Zhang, *Kinetics underpinning the C-CO_2 gasification of waste tyre char and its interaction with coal char upon co-gasification.* Fuel, 2019. **256**: p. 115991.
120. Kahraman, U. and I. Dincer, *Development of a waste tires-based integrated energy system for multiple useful outputs in sustainable communities.* Energy Conversion and Management, 2022. **271**.
121. Jamro, I.A., W. Ma, M. Ali, S.A.R. Shah, M.S. Korai, H.A. Baloch, and G. Chen, *Parametric study of waste tires through CO_2–aided gasification: An investigation of enhanced H_2-production using artificial neural network model.* Research Square, 2022.
122. Mavukwana, A.E., N. Stacey, J.A. Fox, and B.C. Sempuga, *Thermodynamic comparison of pyrolysis and gasification of waste tyres.* Journal of Environmental Chemical Engineering, 2021. **9**(2).
123. Elbaba, I.F., C. Wu, and P.T. Williams, *Hydrogen production from the pyrolysis–gasification of waste tyres with a nickel/cerium catalyst.* International Journal of Hydrogen Energy, 2011. **36**(11): p. 6628-6637.
124. Mavukwana, A., K.G. Burra, C. Sempuga, M. Castaldi, and A.K. Gupta, *Effect of spent fluid catalytic cracking (FCC) catalyst on syngas production from pyrolysis and CO_2-assisted gasification of waste tires.* Fuel, 2024. **355**: p. 129446.
125. Lanzini, A., H. Madi, V. Chiodo, D. Papurello, S. Maisano, and M. Santarelli, *Dealing with fuel contaminants in biogas-fed solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) plants: Degradation of catalytic and electro-catalytic*

active surfaces and related gas purification methods. Progress in Energy Combustion Science, 2017. **61**: p. 150-188.

126. Mathieu, Y., L. Tzanis, M. Soulard, J. Patarin, M. Vierling, and M. Molière, *Adsorption of SO_x by oxide materials: A review.* Fuel Processing Technology, 2013. **114**: p. 81-100.
127. Ortiz, M.I., A. Garea, A. Irabien, and F. Cortabitarte, *Flue gas desulfurization at low temperatures. Characterization of the structural changes in the solid sorbent.* Powder Technology, 1993. **75**(2): p. 167-172.
128. Pandey, R.A., R. Biswas, T. Chakrabarti, and S. Devotta, *Flue gas desulfurization: physicochemical and biotechnological approaches.* Critical Reviews in Environmental Science Technology, 2005. **35**(6): p. 571-622.
129. Global Syngas Technologies Council (GSTC). *Waste to energy gasification*. Syngas Production [cited 2020 November 20, 2022]; Available from: https://www.globalsyngas.org/syngas-production/waste-to-energy-gasification/.
130. Song, H., G. Yang, P. Xue, Y. Li, J. Zou, S. Wang, H. Yang, and H. Chen, *Recent development of biomass gasification for H_2 rich gas production.* Applications in Energy Combustion Science, 2022. **10**: p. 100059.
131. Ocko, I.B. and S.P. Hamburg, *Climate consequences of hydrogen emissions.* Atmospheric Chemistry and Physics, 2022. **22**(14): p. 9349-9368.
132. Osman, A.I., N. Mehta, A.M. Elgarahy, M. Hefny, A. Al-Hinai, A.a.H. Al-Muhtaseb, and D.W. Rooney, *Hydrogen production, storage, utilisation and environmental impacts: a review.* Environmental Chemistry Letters, 2022: p. 1-36.
133. Baykara, S.Z., *Hydrogen: A brief overview on its sources, production and environmental impact.* International Journal of Hydrogen Energy, 2018. **43**(23): p. 10605-10614.
134. Hasan, A. and I. Dincer, *Comparative assessment of various gasification fuels with waste tires for hydrogen production.* International Journal of Hydrogen Energy, 2019a. **44**(34): p. 18818-18826.
135. Hasan, A. and I. Dincer, *Assessment of an Integrated Gasification Combined Cycle using waste tires for hydrogen and fresh water production.* International Journal of Hydrogen Energy, 2019b. **44**(36): p. 19730-19741.
136. Yusup, S., R.A. Moghadam, A.A. Shoaibi, M. Melati, Z. Khan, L.M. Tzeng, and A.K.G.H. Wan Azlina, *Hydrogen production from catalytic steam co-gasification of waste tyre and palm kernel shell in pilot scale fluidized bed gasifier*, in *Biomass Processing, Conversion and Biorefinery*. 2013. p. 181-191.
137. Zhang, Y., P. Xu, S. Liang, B. Liu, Y. Shuai, and B. Li, *Exergy analysis of hydrogen production from steam gasification of biomass: A review.* International Journal of Hydrogen Energy, 2019. **44**(28): p. 14290-14302.
138. Cohce, M.K., M.A. Rosen, and I. Dincer, *Efficiency evaluation of a biomass gasification-based hydrogen production.* International Journal of Hydrogen Energy, 2011. **36**(17): p. 11388-11398.
139. Binder, M., M. Kraussler, M. Kuba, and M. Luisser. *Hydrogen from biomass gasification: IEA Bioenergy Task 33*. 2018 [cited 2023 June 25]; Available from: https://www.ieabioenergy.com/wp-content/uploads/2019/01/Wasserstoffstudie_IEA-final.pdf.
140. Arregi, A., M. Amutio, G. Lopez, J. Bilbao, and M. Olazar, *Evaluation of thermochemical routes for hydrogen production from biomass: A review.* Energy Conversion and Management, 2018. **165**: p. 696-719.

141. Abdus Salam, M., K. Ahmed, N. Akter, T. Hossain, and B. Abdullah, *A review of hydrogen production via biomass gasification and its prospect in Bangladesh.* International Journal of Hydrogen Energy, 2018. **43**(32): p. 14944-14973.
142. Ko, D.C.K., E.L.K. Mui, K.S.T. Lau, and G. McKay, *Production of activated carbons from waste tire–process design and economical analysis.* Waste Management, 2004. **24**(9): p. 875-888.
143. González, J.F., J.M. Encinar, C.M. González-García, E. Sabio, A. Ramiro, J.L. Canito, and J. Gañán, *Preparation of activated carbons from used tyres by gasification with steam and carbon dioxide.* Applied Surface Science, 2006. **252**(17): p. 5999-6004.
144. Qian, K., A. Kumar, H. Zhang, D. Bellmer, and R. Huhnke, *Recent advances in utilization of biochar.* Renewable and Sustainable Energy Reviews, 2015. **42**: p. 1055-1064.
145. Semaan, J.N., M. Huron, and E. Daouk, *Pilot scale pyro-gasification of biomass and waste: char characterization.* Biomass Conversion and Biorefinery, 2022. **12**(12): p. 5751-5765.
146. Gungor, B. and I. Dincer, *Development of a sustainable community with an integrated renewable and waste to energy system for multiple useful outputs.* Journal of Cleaner Production, 2021. **312**.
147. Subramanian, A.S.R., T. Gundersen, and T.A. Adams II, *Technoeconomic Analysis of a Waste Tire to Liquefied Synthetic Natural Gas (SNG) Energy System.* Energy, 2020: p. 117830.
148. Hannula, I. and E. Kurkela, *A semi-empirical model for pressurised air-blown fluidised-bed gasification of biomass.* Bioresource Technology, 2010. **101**(12): p. 4608-4615.
149. Safarian, S., R. Unnþórsson, and C. Richter, *A review of biomass gasification modelling.* Renewable and Sustainable Energy Reviews, 2019. **110**: p. 378-391.
150. Baruah, D. and D.C. Baruah, *Modeling of biomass gasification: A review.* Renewable and Sustainable Energy Reviews, 2014. **39**: p. 806-815.
151. Kovacik, G., M. Oğuztöreli, A. Chambers, and B. Özüm, *Equilibrium calculations in coal gasification.* International Journal of Hydrogen Energy, 1990. **15**(2): p. 125-131.
152. Chen, J.H., K.S. Chen, and L.Y. Tong, *On the pyrolysis kinetics of scrap automotive tires.* Journal of Hazardous Materials, 2001. **84**(1): p. 43-55.
153. Aguado, R., M. Olazar, D. Vélez, M. Arabiourrutia, J. Bilbao, and A. Pyrolysis, *Kinetics of scrap tyre pyrolysis under fast heating conditions.* Journal of Analytical and Applied Pyrolysis, 2005. **73**(2): p. 290-298.
154. Unapumnuk, K., T.C. Keener, M. Lu, and S. Khang, *Pyrolysis behavior of tire-derived fuels at different temperatures and heating rates.* Journal of the Air & Waste Management Association, 2006. **56**(5): p. 618-627.
155. Koreňová, Z., M. Juma, J. Annus, and J. Markoš, *Kinetics of pyrolysis and properties of carbon black from a scrap tire.* Chemical Papers, 2006. **60**(6): p. 422-426.
156. Quek, A. and R. Balasubramanian, *An algorithm for the kinetics of tire pyrolysis under different heating rates.* Journal of Hazardous Materials, 2009. **166**(1): p. 126-132.
157. Roy, P.C., A. Datta, and N. Chakraborty, *Modelling of a downdraft biomass gasifier with finite rate kinetics in the reduction zone.* International Journal of Energy Research, 2009. **33**(9): p. 833-851.
158. Perry, J.H., *Chemical engineers' handbook.* 1950, ACS Publications.

159. The Engineering Toolbox. *Solids - Specific Heats*. 2003 [cited 2023 June 15]; Available from: https://www.engineeringtoolbox.com/specific-heat-solids-d_154.html.

160. Wang, Y. and C.M. Kinoshita, *Kinetic model of biomass gasification.* Solar energy, 1993. **51**(1): p. 19-25.

161. Jayah, T.H., L. Aye, R.J. Fuller, and D.F. Stewart, *Computer simulation of a downdraft wood gasifier for tea drying.* Biomass bioenergy, 2003. **25**(4): p. 459-469.

162. Cheng, S., X. Ding, X. Dong, M. Zhang, X. Tian, Y. Liu, Y. Huang, and B. Jin, *Immigration, transformation, and emission control of sulfur and nitrogen during gasification of MSW: Fundamental and engineering review.* Carbon Resources Conversion, 2023. **6**(3): p. 184-204.

163. Chen, C., Y. Jin, J. Yan, and Y. Chi, *Simulation of municipal solid waste gasification in two different types of fixed bed reactors.* Fuel, 2013. **103**: p. 58-63.

164. Jarungthammachote, S. and A. Dutta, *Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier.* Energy, 2007. **32**(9): p. 1660-1669.

165. Janajreh, I., T. Arink, and A. Al Shehhi. *Alternative treatment of petroleum waste via thermochemical conversion*. in *Proceedings of 2014 International Renewable and Sustainable Energy Conference, IRSEC 2014*. 2014.

166. Mozafari, A., F. Farshchi Tabrizi, M. Farsi, and S.A.H. Seyed Mousavi, *Thermodynamic modeling and optimization of thermolysis and air gasification of waste tire.* Journal of Analytical and Applied Pyrolysis, 2017. **126**: p. 415-422.

167. Hejazi, B., J.R. Grace, X. Bi, and A. Mahecha-Botero, *Kinetic model of steam gasification of biomass in a bubbling fluidized bed reactor.* Energy & Fuels, 2017. **31**(2): p. 1702-1711.

168. Janajreh, I. and S.S. Raza, *Numerical simulation of waste tyres gasification.* Waste Management Research, 2015. **33**(5): p. 460-468.

169. Puig-Arnavat, M., J.C. Bruno, and A. Coronas, *Review and analysis of biomass gasification models.* Renewable and Sustainable Energy Reviews, 2010. **14**(9): p. 2841-2851.

170. Jayanarasimhan, A., R.M. Pathak, A.M. Shivapuji, and L. Rao, *Tar Formation in Gasification Systems: A Holistic Review of Remediation Approaches and Removal Methods.* ACS Omega, 2024. **9**(2): p. 2060-2079.

171. Asadullah, M., *Barriers of commercial power generation using biomass gasification gas: A review.* Renewable and Sustainable Energy Reviews, 2014. **29**: p. 201-215.

172. Batuecas, E., D. Serrano, A. Horvat, and P. Abelha, *Sustainable conditions for waste tires recycling through gasification in a bubbling fluidized bed.* Journal of Cleaner Production, 2023: p. 137839.

173. Pandey, D.S., S. Das, I. Pan, J.J. Leahy, and W. Kwapinski, *Artificial neural network based modelling approach for municipal solid waste gasification in a fluidized bed reactor.* Waste Management, 2016. **58**: p. 202-213.

174. Mutlu, A.Y. and O. Yucel, *An artificial intelligence based approach to predicting syngas composition for downdraft biomass gasification.* Energy, 2018. **165**: p. 895-901.

175. Wang, H., D. Chaffart, and L.A. Ricardez-Sandoval, *Modelling and optimization of a pilot-scale entrained-flow gasifier using artificial neural networks.* Energy, 2019. **188**: p. 116076.

176. Ozonoh, M., T.C. Aniokete, B.O. Oboirien, B.C. Udeh, K.O. Yoro, and M.O. Daramola. *Prediction of Emissions and Profits from a Biomass, Tyre, and Coal Fired Co-Gasification CHP Plant Using Artificial Neural Network: Nigerian and South African Perspectives*. in *Journal of Physics: Conference Series*. 2019.

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