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Novel strategy in biohydrogen energy production from COVID-19 plastic waste: A critical review

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HIGHLIGHTS

- The abundance of plastic waste (medical, household, packaging) is generated during COVID-19.
- The incineration technique used for treating plastic waste releases harmful gases.
- Adoption of pyrolysis or gasification technique helps to reduce the harmful gases.
- Pyrolysis of plastic waste produces a high amount of biohydrogen and syngas.

GRAPHICAL ABSTRACT

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Introduction

COVID-19 pandemic has highlighted the importance of plastics in our everyday lives once again. During this situation, plastics made a significant contribution to the healthcare industry and public health safety. Other reasons that held for the vast usage of plastics during COVID-19 times were due to the implementation of lockdown in many countries, travel restrictions among different nations, social distancing in public, banning public meetings and gatherings, compulsory wearing of facemask and regular practice of hand sanitizers to control the spread of infections. Apart from those, the healthcare employees were mandatorily wearing personal protective equipment’s (PPE) which is mostly made from plastics to protect them from virus infections. Usage of plastics in making these PPEs such as surgical masks, aprons, gloves, face shields is due to the properties like high strength-to-weight ratio, as well as durability and adaptability [1]. Plastics are indispensable in the healthcare industry due to these qualities, having important uses in single-use medical tools, equipment, and packaging and use in several surgical procedures and transplants [2]. Plastics have also evolved as the ideal material for common packing due to their lightweight, flexibility and long-lasting properties. Plastics are used most extensively in packaging applications around the world during the COVID-19 pandemic times. People are primarily relied on online shopping nowadays which has led to enormous plastic packaging of their essential goods as home delivery. However, there has been a ban on their usage in many countries [3,4]. The fabrication of PPEs and packaging materials accounts for most of the increase in plastic demand during the COVID-19 pandemic. PPEs are mostly made up of non-degradable polymers in which polyethylene terephthalate, high-density polyethylene are commonly recycled whereas polystyrene, low-density polyethylene are hardly recycled. Other components present in PPEs like polyvinyl chloride and polypropylene cannot be recycled [5]. Plastic production also significantly affects petroleum resources because 99% of plastics are derived from petroleum resources [6]. In this pandemic period, the demands have been increased intensely, which has led to an increase in the volume of plastic waste generation. An increase in plastic waste has led to major problems for human health and environmental concerns, namely in causing groundwater contamination, increasing greenhouse gases (GHGs) emissions, risk of fire and explosion, etc. [7,8].

Plastic degradation may take up billions of years; thus, plastic materials’ continuous disposal would cause a major threat to the environment. Plastic waste management and its dumping in landfills have been given substantial importance in recent years. Various practices were carried out to dispose of plastic waste like reuse, recycling, and recovering energy. However, successful treatment strategies for plastic disposal are an urgent necessity to address the environmental crisis. Researchers have investigated several techniques to degrade plastic waste; and these techniques are categorized into two major plastic treatment processes such as conventional and advanced techniques. In the conventional method, plastic waste disposal has been carried out through two major techniques: incineration and landfills; however, these techniques face several bottleneck challenges. Generally, the incineration disposal process of plastic waste requires a large amount of energy. On the other hand, this disposal process generates several hazardous byproducts such as CO₂, acidic gases (oxides of sulfur), heavy metals, and particulate matter, which causes global warming. It is also associated with numerous health issues, including respiratory illness and cancer [9,10].

Landfilling is another standard method used for plastic waste disposal, and this process includes the highest amount
Plastic waste: a serious threat to human health and the environment

The rapid growth of the human population leads to an increase in the production of plastic materials. Plastics play a significant role in day-to-day human life; however, plastic waste is still considered a major source of environmental pollution. Earlier reports revealed that the world plastic production of 2018 was about 400 million tons every year (Fig. 2) [22]. Approximately, every year 13 million tons of plastics are dumped directly into the ocean, and from the remaining, 387 million tons, 79% of plastic materials are ended in landfills, 9% of plastics are recycled, and 12% of plastics are incinerated [23]. Besides, the COVID-19 emergency also increases in massive production of PPE (e.g., mask, glove, protective gown, etc.) which is made up of plastic materials. Plastic materials undergo slow degradation and can persist in the environment for hundreds of which brings various environmental issues [24].

Currently, several techniques are available to manage plastic pollution. The conventional methods for plastic waste disposal, including incineration and landfills, face many bottleneck challenges. Generally, the incineration process requires a large amount of energy and hazardous discharges. During this process, the major hazardous byproducts such as CO₂, heavy metals, persistent organic compounds (dioxins and furans), acidic gases (oxides of sulfur), and particulate matter. These hazardous substances directly affect our ecosystem, animals and human health [25].

Today, more than 5000 different types of plastic materials are available in the market, and a number of chemicals were used in plastic production. Studies show that food packing plastic materials alone contain more than 4000 chemicals [17]. The improper disposal of plastic waste persists in the environment, and these wastes are exposed to continuous processes such as photo-oxidation, biological decomposition, chemical weathering, and mechanical forces. These processes
directly affect the plastic materials' structural integrity, which results in fragmentation [26]. Increased production, improper disposal of plastic materials, and low biodegradation rates generate microplastics (plastics size <5 mm) which are considered as a high-risk contaminant. These microplastics are widely distributed in the environment, specifically in water, sediment and several organisms [27]. These plastic materials contained many chemical and hazardous substances like Bisphenol A (BPA), brominated flame retardants, antiminitroxide, thalates, and poly-fluorinated chemicals, etc. [28]. These substances are a severe risk factor for the environment and human health issues. Improper disposal of plastic materials may lead to several human health issues such as respiratory problems, lung diseases, liver dysfunction, high risk of cancers, eye diseases, skin diseases, birth effects, reproductive, cardiovascular, etc. [25]. Besides, plastics cause serious environmental pollution such as water pollution, soil pollution, and air pollution.

**Types of plastics and its significance during COVID-19**

There has been a drastic increase in the production and consumption of plastics during COVID times; however, the same pose as the major pollutant during the pandemic. The surge in the generation of plastic wastes during the COVID-19 pandemic is mainly due to the compulsory usage of personal protective equipment, single-use plastics in healthcare centers and hospitals, and common packaging materials. Polymers such as polyurethane (PU), polypropylene (PP), polycarbonate (PC), low-density polyethylene (LDPE), and polyvinyl chloride (PVC) make up the majority of PPEs. Packing materials are frequently made of high-density polyethylene (HDPE), LDPE, polystyrene (PS), polyethylene terephthalate (PET), and other polymers.

People wear masks and use hand sanitizer regularly as a protective measure to prevent the rapid spread of the COVID-19 virus. Disposable masks (surgical) are primarily intended to protect healthcare workers from potential hazards when performing medical procedures. However, during outbreaks of infectious diseases, the vast majority of citizens wore the medical face mask, as prescribed by authorities [29]. The face mask is thought to lower the danger of transmission from person to person. According to a recent study, face masks could minimize disease transmission rates, resulting in the avoidance of illness in healthy people and the inhibition of asymptomatic transmission [30]. An estimation of around 89 million masks are needed each month to combat the current severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic around the world.

Meanwhile, there are three types of protective face masks: homemade cloth masks, surgical/medical masks, and respirators. Generally, any medical mask (surgical) is of flat type, which gets hold to the head via straps that can wound/connected around the ear. They help in stable filtration, better

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Fig. 1 – Schematic representation of Production of Hydrogen Fuel from COVID-19 Plastic waste through Thermochemical process of Gasification and Pyrolysis.
breathing capability, highly resistant to any fluid entrance and have 3 μm droplet filtering capabilities. Basically, they have three layers, the external layer is normally non-woven and weather-proof, while the internal layer is composed of soft fibres. The most important layer being the middle one which consists of micro and nano-fibres that can act as an excellent filter [31,32]. They are typically constructed of polymer components like polypropylene, polyethylene and polystyrene. Polypropylene, which consists of propylene monomers, has been spun-woven in the middle layer as a mask filter. This layer is was prepared by extruding the melted polymer through small nozzles in the presence of high-speed blowing gas. Furthermore, the fibres become electrically charged, attracting the particles as the air passes through the filter. Polyethylene (PE), which is essentially a xylene derivative, is used to create a flexible and snug-fitting mask sheath. Moreover, PU, a toluene-based substance, is commonly used as the nose piece’s supporting material, ensuring a secure fit. The surgical mask’s inner and outer layers are made of cotton or other textiles.

The surgical respirator masks labeled as “FFP1” in line with EN149 EU standards and popularly termed as N95 facemask, can filter 95% of particles up to 0.3 μm in size. A cellulose layer is typically placed between two layers of spun-bond polypropylene in N95 masks. Generally, N95 facemask is found to get contaminated within few hours, they must be discarded after a single usage. It has been predicted that using disposable surgical masks could result in the generation of about 128,000 tons of non-recyclable plastic waste every year. As a result, experts believe COVID-19’s waste plastic rise has the potential to prompt urgent and long-term transformations in global plastic waste management. Several ways have been used to meet waste disposal standards, including the incineration of the plastic waste, which exhibits mass destruction because the process involves high temperatures and also overcomes the low biodegradability issues associated with the N95 facemasks plastic waste. However, incineration may emit hazardous and harmful gases such as dioxins, furans, and polychlorinated biphenyls, resulting in negative environmental consequences. As a result, potential methods for plastic waste management must be researched in order to reduce the detrimental effects of plastics on the environment [33–35].

During the COVID-19 epidemic, various plastic-based PPE played a critical role in keeping people safe. Since the coronavirus epidemic began, there has been an unusual surge of single-use plastics such as gloves, protective medical suits, masks, hand-sanitizer bottles, takeaway food, package products and medical test kits. The management of plastic waste
generated by single-use plastics is a concerning result of the COVID-19 pandemic, which has wreaked havoc on worldwide healthcare systems and thrown economies into disarray. Essential municipal services like waste collection and treatment are in jeopardy, while medical and home plastic waste generation is at an extraordinary rise [36–38]. To combat the spread of the COVID-19 virus, most countries issued lockdown regulations as well as social and physical distancing measures. The COVID-19 epidemic, on the other hand, has exacerbated the plastic pollution problem by reviving consumer demand for single-use products and materials for health and safety concerns. Because of hygienic concerns, single-use plastic materials are commonly used to wrap vegetables and fruit in shops and supermarkets [39]. A lot of single-use PPE used by health workers and the general public gets discarded on a regular basis. Masks, gloves, protective aprons, face shields, safety glasses, sanitizer containers, plastic shoes, and medical gowns are examples of non-woven materials typically constructed of polymeric compounds like polypropylene. Medical professionals primarily utilize medical gloves to treat a variety of clinical disorders. They are not recommended for public use at this time since they provide no additional protection as long as the hand and face are not in contact [40]. Even though they are used mainly by healthcare personnel, their demand is exceptionally high and growing due to the COVID-19 pandemic. During this pandemic, the World Health Organization estimates that 67 million medical gloves will be needed each month. Natural rubber latex is used to make medical gloves because of its excellent line of defence against blood-borne infections. It is less priced after being penetrated and has the capacity to reseal and elasticity. Medical gloves can also be made of non-latex polymers such as polyvinyl chloride, neoprene, and nitrile rubber. On the other hand, most of these compounds are petroleum by-products and it is a great challenge to degrade, causing serious environmental concerns [41].

Medical protective gear is defined as the clothes worn by healthcare workers and people accessing specific health zones, such as infected areas and infectious disease patient rooms. Surgical gowns, isolation gowns, and coverall suits are the three forms of medical protective gear available, with each providing a different level of protection. The most frequent materials used in disposable medical protective gear include PP fabric, new PEs fiber, polymer-coated fabric, spunbond-meltblown spunbond (SMS) PP, and PE-breathable film. SMS PP is a non-woven fabric made up of three layers: spunbond PP, meltblown PP, and spunbond PP. As a result, a solid barrier against fluids and particles can be created [42]. Medical protective clothes, like other PPEs, is polluting the environment and as a result, appropriate treatment methods are required. Goggles and face shields are often used in hospitals and high-risk environments for infection control and protection from any fluids or particles in research and industrial activities. Protective goggles are worn to offer adequate eye protection, especially when performing healthcare tasks. It is mostly employed by healthcare staff while dealing with infectious disease patients. Apart from that, face shields have applications like they can act as mucous membrane protector of nose, mouth and eyes from the bodily fluid splashes, which can initiate the spreading of the diseases [43]. PVC, PC and rubber are used to make protective goggles. The clear visor is constructed of PET and PVC/acetate, the headband and bottom reinforcement bracket are made of polyactic acid, and the foam cushion is made of ethylene-vinyl acetate and PU [44].

Hand sanitizer and other disinfectant use have risen dramatically in healthcare facilities, home settings, offices, and public venues. Because of the high need for disinfection, the number of containers, bottles, sprayers, and dispensers is rapidly expanding as well. The principal materials utilized to create these containers were bottles, sprayers and dispensers are PET and PE, which would help in the buildup of the body, whereas PP is used to make the top of the container [15].

Due to improper disposal and treatment of COVID-19, plastic debris offers substantial risks of infectious agent exposures and secondary disease transmission among garbage pickers, sanitation workers, healthcare workers, patients, and the general public. Garbage workers and the surrounding community are exposed to harmful pollutants in air emissions and ash, when waste is burned or incinerated without proper pollution control system. Medical professionals and waste management specialists have cautioned sanitation employees and the rag pickers are in danger, while collecting the unmarked plastic waste like discarded masks and gloves, that the residences of isolated COVID-19 patients have dumped. In addition, contaminated waste is frequently mixed along with domestic, municipal waste, which provides greater risk to the sanitation employees and the environment [45].

The Central Pollution Control Board (CPCB) has issued a set of guidelines for waste management, treatment, and disposal, whichever produced from the COVID-19 quarantine patients. According to these regulations, hospital isolation wards must have separate color-coded bins for waste separation. In addition, only authorized personnel should handle a specialized container labeled “COVID-19” that was stockpiled at a different interim storage facility. It was also suggested that sanitation employees be stationed separately in these wards to deal with biological waste. The board also sought a record of the waste generated in isolation wards. The CPCB suggested putting biomedical waste in yellow bags and giving the bins containing them to authorized collectors from the quarantine camps as well as home quarantine patients [42].

During COVID-19, the Bio-medical Waste Management (BMWM) Rules were closely followed by most hospitals. However, waste disposed of by confined houses, where there is a lack of awareness about the problem, poses a greater risk to sanitation employees. COVID-19-related waste, such as masks, gloves, and hazmat suits, used in municipal, hazardous, and medical waste management, and food safety, must be managed. This waste could infect rag pickers, children, and the homeless living on the streets. It is crucial to make sure that this waste does not end up in common dumping grounds, where direct contact with these contaminated surfaces and objects poses the risk of coronavirus transmission. Cleaning staff who handle surfaces and linens on a regular basis are at moderate risk and must wear N-95 masks and gloves for protection. Basic waste segregation rules are still violated in many countries, in which the passing over of materials to approved waste pickers or collectors are not being done. The waste generators must segregate it at the source, however, there have
been cases in which households and civilizations have not adhere to these rules [42].

More explicit COVID-19-related standards will now be required in waste management systems. In several nations, healthcare personnel have contracted the virus as a result of their work scope involving contact with infected patients. Those who are in close touch with a suspected or confirmed COVID-19 patient or those who care for such patients are most at risk of contracting the virus. Sanitation employees, like medical professionals, police officers, and community health workers who interact with COVID-19 patients, are particularly vulnerable. Doctors, nurses, and other health care professionals are aware of the safeguards that must be taken, but sanitation employees are not, leaving them susceptible. Many sanitation personnel expressed concern about handling residential waste that included worn face masks dropped by residents. Rag pickers and waste collectors who rely on the informal recycling business for a living are also in danger. This is a key source of income for them, and as a result of their efforts, the entire waste management system has achieved extremely high collection rates [46].

The government has received complaints about biomedical trash being mixed with general waste, fears of “virus spreading,” illegal dumping of hospital waste on agricultural property, and the burning of expired pharmaceuticals, among other things. However, the majority of countries adhere to the CPCB’s applicable rules. COVID-19 waste is packaged in twin bags and delivered in separate licensed trucks before being burned in dual chambers running at 1050 °C in the presence of oxidizing agents or direct supply of oxygen. The product generated during this process is called as “syngas,” which is mainly composed of hydrogen gas and carbon monoxide. The other components that are carried by syngas include carbon dioxide, nitrogen and some hydrocarbons (methylene, ethylene, ethane, etc.). The gasification process also releases trace amounts of hydrogen sulfide, ammonia, tar, and char. Among the various components formed, tar and char are considered to be unwanted products. The factors mainly influence syngas production are such as reactor heating temperature, operating pressure, feedstock, oxidizing agents and catalyst. Mostly the gasifier is provided with the heat either directly or indirectly [49–51].

CO + 2H2 $\rightarrow$ [CH2] + H2O

Hydrocarbons

Syngas which is the end product produced during the gasification process has broad applications. Syngas thermal energy can be used in heat generation devices such as steam boilers, cement kilns, dryers, etc., by direct combustion of H2 and CO.[52]. Syngas, another application would be the clean synthetic liquid fuel (jet fuel) productions using the Fischer-Tropsch process. It is a surface polymerization reaction where H2 and CO act on the surface of the catalyst, such as iron or cobalt, in the range of pressure 40–80 bars, leading to the formation of long-chain paraffinic hydrocarbons. Syngas has been widely used to manufacture certain chemicals like methanol, ethylene glycol, ammonia, and dimethyl ether. Syngas has idealistic behavior so as it can be used for the production of electricity (Fig. 3). Its thermal energy has been used in heat-producing equipment like dryers, cement kilns, and steam boilers through direct combustion of hydrogen and carbon monoxide [53].

Gasification process

Generally, the gasification process involves four phases for any kind of feedstock or biomass, including 1) Feedstock drying, 2) Pyrolysis or Combustion, 3) Oxidation and 4) Reduction. In the feedstock drying process, feedstock with variable moisture content are dried at a temperature range of 100–150 °C. No chemical reactions have occurred at this stage, and the heat given is expended among liquid water and water vapor in the phase change. Plastics possess very low moisture content, unlike biomass or coal, due to their external humidity, difficulty in drying, and cannot be forced to diffusion processes.

Complex chemical reactions of an endothermic form takes place during the pyrolysis or combustion process. There is the
formation of volatile compounds and a solid or carbonized residue. Process parameters like the heating rate (°C/s) and the temperature will influence these product amounts. In addition, the distribution of products is influenced by feedstock size and composition. Pyrolysis is a delicate process where the plastic particles are melted, which binds together and triggers agglomeration and de-fluidization in fluidized bed reactors. Interestingly during fast pyrolysis process, certain polymers like PS, PE, and PP will be mostly transformed into their respective volatile substances [54].

In the presence of sub-stoichiometric oxygen, a heterogeneous reaction occurs at high temperatures among the oxidant and raw materials leading to the evolvement of carbon monoxide and water vapor. The feedstock’s chemical composition, the quality of the oxidant used, and the operating conditions are the factors that influence the oxidation in the gasification process. This stage is basically an exothermic process where the released thermal energy provides the heat energy required for the process [55].

The reduction is an endothermic reaction that takes place at high temperatures in the absence of oxygen. Two reactions are encouraged by steam: 1) Char and tar steam reforming (endothermic), 2) Water-gas shift reaction (exothermic), which causes hydrogen production. The most efficient method in increasing hydrogen production is reducing water usage in the steam gasification process. As carbon dioxide reacts with char that settles down in the reactor, which leads to the formation of carbon monoxide. It’s called the Boudouard reaction, and it’s primarily an endothermic process. Inside oxy-fuel combustion/gasification, carbon dioxide can also be recirculated with oxygen [56,57].

Gasification of plastic waste

Plastic waste gasification primarily seeks the efficient conversion to syngas or gas products, while char and tar are produced as the only undesirable by-products. Gasification occurs in multiple phases and complex chemical reactions. The whole process is explained briefly in four steps, namely 1) Drying, 2) Pyrolysis, 3) Gas-phase cracking and reforming reactions, and 4) Heterogeneous gasification of char. The role of these phases in the efficiency of the process and their kinetics depends on the feedstock’s characteristics and conditions of gasification [58].

a) Drying

This process plays a minor role in the conversion, since the waste plastics moisture content is typically much lower than that of other feedstock that are usually gasified into coal and biomass. In addition, the external moisture of waste plastics can be dried rapidly as it is not under diffusion restrictions [59].

b) Pyrolysis:

A series of complex chemical reactions of an endothermic nature include the pyrolysis process, which leads to the
evolution of volatiles such as gases, tars, and some solid residues of chars. Plastic waste's physical and chemical properties make pyrolysis a vital phase in the process of gasification. Because of its low heat conductivity and the sticky character of fused plastics, its thermal breakdown kinetics are slowed, especially if the gasifier is unable to deliver high heat transfer rates and prevent fused plastic agglomerates from developing. Their high volatile content is another characteristic of plastic waste. Indeed, when pyrolysis is performed under rapid heating conditions, polymers like PS or polyolefin are completely transformed into their respective volatiles, which is the case with most conventional gasification technologies [60]. Likewise, the other polymers like PVC or PET can lead to less char in their degradation process. Significant char formation only occurs when different materials are present in the plastic waste, biomass, fibers, or cardboards. Therefore, the low yield of char reduces the significance of plastic pyrolysis during the heterogeneous conversion to the kinetics of the gasification system. In contrast to coal and biomass gasification, the design of the gasifier is intensely conditioned as the char gasification is the control stage, involving a remarkable difference [61].

c) Gas-phase cracking and reforming reactions:

During gaseous degradation of plastics, the volatiles composition that were formed by the subsequent cracking and reforming reactions will play a major role during the process. Random scission contributes to a wide distribution of products, which is considered an important thermal degradative process of polyolefin. However, it should be remembered that the dominant degradative process is occurring at the end chain scission of above 800 °C temperatures, with the possible paths being either the direct scission of 1,5-radical transfer or by several steps of radical transfer scissions. Also, the polyolefin degradation by the latter process mainly produces the formation of light olefins. However, the cracking should be carried out at high temperatures with short residence periods would be considered as the viable path in separating the light olefins from polyolefin selectively. Other polymers like PS were mainly degraded by random breaking, leading to the formation of oligomers of different lengths. The oligomers may transform into styrene or other monoaromatic and polyaromatic species in their respective gaseous phase depending on the influence of certain parameters such as temperature or residence time. A random scission degradation process forms the compounds with vinyl and carboxyl functional groups when considering the PET. This leads to the extensive distribution of products like carbon monoxide, carbon dioxide, and oxygenated compounds. A wide range of reactions is used in homogeneous gasification reactions. These reactions balance and magnitude mostly depend on the various types of gasifying agents used, its feed ratio and temperature. During gasification reactions, oxygen helps in combustion and partial oxidation reactions producing carbon monoxide, carbon dioxide and water. Moreover, the oxidation reaction's exothermic nature provides the energy needed for highly endothermic steam, reforming carbon dioxide and the Boudouard reactions. The supply of steam in the gasifier enhances the hydrogen production through its reforming reactions and water-gas shift (WGS) equilibrium. In particular, high temperatures, particularly carbon dioxide gasification, whose kinetics are between 2 and 5 times slower than in the steam atmosphere and do not occur below 730 °C, are needed to promote char gasification. The most significant disadvantage of high temperatures in gasification processes is the thermodynamic limitation of the WGS reaction. During gasification processes, certain reforming catalysts were in practice and the most common catalyst that is being used was Nickel (Ni) based ones. These kinds of catalysts help to form tars and other vital hydrocarbons, leading to a wide increase of hydrogen production, thereby encouraging the WGS reactions [62].

d) Heterogeneous gasification of char:

The tar formation and its evolution depends primarily on the compositions of the plastic waste's. Primary aromatic tar is produced upon degradation of plastic waste until the polymers possess aromatic ring structures like in PS and PET. In addition, alkanes and alkenes of varying chain length are the volatiles or primary tar produced from polyolefin degradation. Additionally, the primary tar and volatiles are formed from the degradation of polyolefin and alkenes; alkenes were the products formed. These hydrocarbons have a limited thermal stability and are quickly broken down into lighter compounds at gasification temperatures; in fact, linear hydrocarbons are not found in tar produced by polyolefin gasification. Among the various hydrocarbon compounds formed during the thermal degradation of plastic waste, the light olefins occurring plays a crucial role in tar formations. Therefore, tar precursors are C2–C4 olefins, and especially acetylene, with hydrogen abstraction, acetylene addition, dehydrogenation reactions and Diels-Alder condensation being the possible tar forming methods. Certainly, in plastic waste gasification, the higher concentration of light olefin produces higher tar yields when compared with those that are derived from coal or biomass gasification. Hence, the rise in tar yield spotted in plastic waste gasification is attributed to the higher light hydrocarbon content. Although the initial degradation of PS results in styrene and styrene oligomers in plastic waste, the instabilities of these compounds promote more stable structures such as secondary and tertiary tars, which are not commonly seen in the tar formed during gasification. Similarly, PET decomposition in plastic waste produces primary tars such as benzoic acid and benzoic formic acid, which are often stabilized in the gasifiers into a spectrum of secondary and tertiary tars. It is challenging to convert into secondary and tertiary tars because residence times >0.5 s and around 1250 °C reaction temperature are needed for efficient thermal cracking [63]. Table 1 explains the chemical reactions that take place during the treatment of plastic waste through the gasification process.

Types of gasifier used in gasification of plastic waste

The technologies for plastic waste gasification are those already adopted to gasify other feedstock like biomass or coal. However, in conventional gasification processes, unique features of plastic waste such as low thermal conductivity, prominent tar formation, high volatile content and sticky composition restrain the treatment and pose a significant
challenge in applying these methods. Therefore, an effective gasifier configuration for plastic waste handling must be combined with its features, such as 1) Capable of delivering high heat transfer rates to encourage rapid depolymerization reactions, 2) Preventing operational issues associated to the sticky existence of plastic waste by following the conditional operating regulations, 3) Facilitating tar cracking through sufficient residence time distribution, and 4) Allow in situ use of the primary catalyst to ensure good interaction with them. Certain gasifiers like fixed beds, fluidized beds, supercritical water reactors, microwave reactors, spouted beds and plasma reactors can be applied for the gasification of plastic waste.

a) Fluidized bed gasifier

The highly dense fuel components are gasified into minute fragments or particles using some gasifying agents (air, steam, oxygen, carbon dioxide) in this system. The gasifier is a thermochemical process where the fluidizing gas transforms the bed into a fluid. In this gasification method, two kinds of fluidized beds have been classically used, namely, circulating and bubbling fluidized beds [64]. Despite the fascinating features of rotating fluidized beds for gasification processes, plastic waste gasification can be conducted exclusively in bubbling reactors because of its high conversion rates and low tar yields. The key benefits of using this technique are their capability of high heating and mass conversion rates, remarkable gas-solid contacts, solid temperature control, excellent mixing regime and versatility. Their major disadvantages are their high cost of investment, bed and feed particle size limits, defluidization problems and unreacted material retention [65]. These reactors run in a continuous scheme and have a generally high degree of scale and growth, with many studies being carried out in pilot plant scale units. When plastic waste is gasified or co-gasified with coal or biomass in these gasifiers, the air is used as the gasification agent. The usage of this technique entails advantages such as lower tar formation in gaseous products and the operational advantages associated with the autothermal process regarding the production of low heating value gas. Because, the steam gasification is an extremely endothermic process, it has a high energy demand, which is fulfilled in feedstock gasification by using twin fluidized bed reactors, i.e., a steam-blown fluidized bed combined with an air-blown rapid fluid bed. This operational technique was applied to plastic waste gasification. Nevertheless, difficulties will emerge because of the difficulty in maintaining the heat equilibrium between combustion and gasification as well as the low char yield obtained [66].

b) Fixed/moving bed gasifier

In applying these gasifiers, the gasifying agent runs along the set bed of the fuels. Gasifiers are categorized according to the travel routes of the gasifying agent along the bed as (1) updraft, (2) downdraft, and (3) cross-draft [55]. While using a downdraft gasifier, the crude fuel or feedstock moves along with the gasifying agent, while the formed product gas will flow in the path downwards in the reactor and the gas that were released is withdrawn from the rim. The sequence of steps that were carried out while using this type of reactor includes drying, pyrolysis, combustion, and gasification. Reducing tar formation is a significant benefit of downdraft over updraft. This is because, unlike updraft, the downdraft gasifier is modeled so that the tar which is formed will be cracked when they are transient over the incinerator areas of the gasifier, while the gas will go through the combustion zone upon pyrolysis. In the updraft gasifier, the feedstock will be carried to the stream of the gasifying agent and undergoes the process of drying, pyrolysis, gasification, and combustions. The benefits of this type of gasifier are elevated cracking of char, admirable heat transfer, less temperature discharge, and optimal heat energy usage. When considering the cross-draft reactor, the flow of feedstock was driven from the upper part of the reactor. The gas administration site, areas of combustion, reduction and departure of syngas are all at the same horizontal phase in all forms of fixed style gasifier. The main drawbacks of employing fixed bed reactors for plastic waste gasification were their simple design, operations, low investment costs, product scaling up, continuous process, sluggish heat transfer rate, and little gas-solid interaction. Many models of fixed bed reactors are available, which bears common points used in a number of small-scale units. Generally, few experiments have been used in fixed-bed reactors for the plastic waste gasification or their co-processing with coal/biomass [67].

c) Supercritical water gasification

It is a type of hydrothermal gasification that uses a significant amount of water to create hydrogen and methane gas. Normally the output of this process is extremely high, but the temperature, the ratio of feedstock to water, and the catalyst are all variables that affect the production [68]. The ability to process wet feedstock with up to 70% humidity, which is necessary for typical thermal gasification, is the most advantageous characteristic of hydrothermal gasification and this saves significant drying expenses. Supercritical
gasification is usually carried out with or without a catalyst either at low-temperature range from 374 to 550 °C or high-temperature range of 550–700 °C. Hydrothermal gasification of high-moisture-content feedstock has been documented under non-catalytic circumstances and the results showed the production of methane at lower temperatures, while higher temperatures favored the evolution of hydrogen gas, but the performance of both was achieved at an optimum temperature of around 600 °C. Low-temperature supercritical gasification requires the use of transition metal-based catalysts because their reaction rate is too low. Still, high-temperature supercritical gasification can reach maximal gasification at 700 °C without the use of any catalyst [69,70]. Water can be used as a non-polar solvent in supercritical conditions to alleviate problems like poor heat transmission and high plastic content viscosity by dissolving plastic pieces like those found in the garbage. Water can also operate as a hydrogen donor that aids in the cracking of plastic wastes as well as the gasification process. This technology may be applied for gasification for various types of plastic materials like complex polyethylene, flame retardant plastics, and other plastic pollutants. Eliminating microplastics from the marine environment is one of the excellent applications of supercritical water gasification. There is no suitable alternative for other types of processes, such as pyrolysis or gasification, because the high-water content of plastics retrieved from the ocean will necessitate a drying period, which will significantly impact the recycling cost [71]. Currently, very few studies have been recorded on CPW treatment with supercritical water gasification, mostly at the experimental level [72].

d) Microwave gasification

An efficient method for converting feedstock into fuel through microwave-assisted pyrolysis and gasification. The capacity to treat large feedstock particles, uniform temperature profile, cost-effectiveness and cleaner product production with high heating value are the benefits of microwave pyrolysis/gasification over traditional gasification [73]. However, microwave radiation, especially its non-thermal effects in chemical reactions, is not well understood. Latest studies on microwave gasification of feedstock with laboratory-scale using Co, Fe, and Ni-based catalysts have been conducted. The findings revealed that Ni is the most effective catalyst for increasing syngas output and lowering tar levels. With a syngas yield of 80%, the ideal catalyst to feedstock ratio was calculated to be 1:5–1:3. The presence of steam in the reaction was discovered to be critical. Although microwaves have long-term potential for feedstock and CPW gasification, the approach has only been used in the laboratory so far [74].

e) Plasma gasification

The gasifier works at over 2500 °C in plasma gasification and is capable of treating unprocessed general waste, hazardous waste, and medical waste, as well as achieve complete carbon conversion despite the form of feedstock [75]. Air and/or oxygen are injected through tubes from the top or side of a huge refractory lined vessel, and the waste feedstock is reacted. The plasma torches attempt to heat and melt the trash to generate a molten liquid at 1600 °C. High-temperature syngas is obtained at ~950 °C from the upper part of the gasifier. The tars are broken down and turned into smaller molecules like carbon monoxide, hydrogen, methane and CO₂. Before passing through gas cleaning processes, the hot syngas is cooled and used for power production, chemicals, or biofuel production. Because of the high temperature, any inorganic substance in the waste that is tapped from the bottom of the gasifier as molten slag can be melted. However, because of the high-temperature use, the capital cost is extremely high, and the design is extremely intricate. Plasma gasifiers will also consume up to 50% of the electrical power generated to keep the operation running [76]. There are also high maintenance and operating expenses for the technology. The oxidant systems of plasma gasification procedures convert plastic waste chemicals into gaseous products. Plasma reactors for plastic waste gasification have the benefit of achieving high temperatures for the process. Increasing the removal of harmful and toxic compounds facilitates almost complete cracking of tar compounds and thus high gas yields. According to plasma discharge techniques, they are classified into three groups, namely, direct current, radiofrequency, and microwave [77,78].

The gasification characteristics of COVID-19 medical waste in a novel updraft plasma gasifier were evaluated using numerical simulations in a recent study's using plasma processes. Three different medical waste samples with varying carbon content and five different equivalence ratios (ER) ranging from 0.1 to 0.5 were employed in the simulations to investigate the effects of diverse chemical compositions and waste feeding rates on hydrogen and syngas production. The plasma intake in the numerical model is defined using the outlet parameters of a 10 kW microwave air plasma generator, and the airflow rate is kept constant in all situations. The findings of the study revealed that an ER value of 0.1 delivers the greatest results for COVID-19 medical wastes (CMW) gasification, with up to 32.78% H₂ generation, 25.37% CO, and 78.61% cold gas efficiency. The impacts of moisture content on gasification features and H₂ production capacities were more effective than the effects of carbon and hydrogen in the CMW feedstock. In addition, the factors like temperature and CO₂ distributions are also compared to see if there is a correlation. The region of gasification and syngas production for this gasifier can be altered according to the gasification characteristics of CMW. During the process, the maximum H₂S mole fraction was found to be 0.6%. According to the findings, plasma gasification technology could be used for both CMW treatment and H₂ synthesis. Gasification features can be improved by controlling the syngas production position, increasing the moisture content, and reducing ER values. As a result, the gasifier’s exhaust pipe height should be modified for more efficient use in CMW gasification, even though the generation of hazardous compounds were found to be within the limits of standards and regulations [79].

The global catastrophe caused by the current COVID-19 outbreak has resulted in a large increase in the volume of used personal protective equipment (PPE) trash, with a special focus on waste N95 facemask. As a result, innovative solutions are needed to address the growing facemask waste...
disposal in a cost-effective and environmentally sustainable manner. In an effort to address the evolving global waste challenge, another study looked at the economic and environmental performance of converting N95 facemasks to steam and electricity via a combined heat and power plant, to ethanol via a syngas fermentation process, and to an energy-dense gasoline-like oil product via a hydrothermal liquefaction process. The ASPEN plus (Advanced System for Process Engineering) plus® V10 process simulator was used to examine these processes using “conceptual” process models (Aspen Technology Inc., Cambridge, MA, USA). This is owing to its ability to generate realistic, albeit simplified, models for energy and mass balances that can be solved using fundamental process in engineering approaches [80,81].

Based on literature reported proximal and final results, established methodologies in modelling the properties of components such as enthalpy and density were employed to simulate the waste N95 facemask, ash, and char components using the in-built models. Other chemical inputs, such as ethanol, water, and air, were taken from the chemical property library’s databank. All models were created to simulate continuous processes in a steady-state situation. It should be emphasized that in this simulation procedure, conceptual models for generating the specified target materials from waste N95 facemask were built using publicly available reaction conditions, conversions, and product yields with generic processes. There is currently no experimental data indicating the yields of the product fractions from the conversion of waste N95 facemasks to valuable products via thermochemical methods due to the novelty of the N95 feedstock waste. Waste N95 facemasks are widely employed in management processes that create steam electricity from syngas through a gasification process, energy-dense oils by hydrothermal liquefaction, and ethanol-based liquid fuel from gasification of plastic waste with enhanced oxygen is also expensive and energy-intensive [91]. Yet, the gasification process is the air [90]. However, due to nitrogen’s dilution effect, there will be an evolution of gases with a lower heating value, which would be a major disadvantage of using air. Consequently, handling higher calorific value cleaner gas without nitrogen is an important benefit of oxygen over the air. However, the fundamental difficulty is that producing pure oxygen is both expensive and energy-intensive [91]. Yet, the gasification of plastic waste with enhanced oxygen is also

f) Spouted bed gasifier

It is a modified version of a fluidization bed reactor. Solid particles dynamic behavior in the gasifier would be the main alteration among the sputtered bed and the fluidized bed [85]. In a fluidized bed reactor, gases were passed through a multi-orifice provider, while in the spouted bed reactor, it was provided with only one orifice present at the central bottom of the reactor. Therefore, the central spout formation will have occurred which runs the constituents upwards. The key benefit of using the spouted bed reactor instead of the fluidized bed reactor is their ability to agitate the gluey and the rough nature of plastics and maintain the uniform size and heat-sensitive feedstock [86]. The plastic waste valorization procedures use sputtered beds as an alternative to fluidized beds because of their unique features. High heat and mass transfer rates, effective solid mixing, and appropriate gas-solid contact define these reactors [87]. Additionally, their cyclic solid circulation prevents de-fluidization issues and aids in handling a variety of irregular particles and those with bigger size and sticky material distribution. The main disadvantages of their use in gasification operations are the volatile compounds short residence period, which interferes with the tar cracking reaction. This technology has been extensively used in bench-scale units [88]. For coal as feed, the original use of sputtered beds in gasification processes was introduced and more recently, this technology has been adapted for gasification to other feedstock like biomass or plastic waste. In situ, different primary catalysts were explored, or secondary catalysts were used in a second reactor to improve process performance and minimize the tar content of the gaseous substance [89].

Factors influencing the syngas production in the gasification process of plastic waste

Various factors that influence syngas production during the plastic waste gasification process were feedstock composition, gas flow rate, gasifying agents, temperature, pressure, equivalence ratio, types of gasifiers and feed flow rate. Based on the contents of the gases as their primary end products and their applications, these factors were selected for the gasification process. Hence, it is very important to carefully select the factors for the gasification process of plastic waste to optimize the gasifier and quality improvements of gases as products for particular applications.

a) Gasification agents

Air gasification benefits are flexibility and low cost compared to oxygen supply. The most popular gas medium for the gasification process is the air [90]. However, due to nitrogen’s dilution effects, there will be an evolution of gases with a lower heating value, which would be a major disadvantage of using air. Consequently, handling higher calorific value cleaner gas without nitrogen is an important benefit of oxygen over the air. However, the fundamental difficulty is that producing pure oxygen is both expensive and energy-intensive [91]. Yet, the gasification of plastic waste with enhanced oxygen is also
possible. The decreases in the nitrogen dilution effects and nitrogen oxide during syngas production immensely improve the amounts of other gases like hydrogen, carbon monoxide, carbon dioxide, methane; and eventually, raise the heating value and cold gas efficiency. Enhancement of oxygen also increases the gasification's burning capability, which liberates high heat, raising the bed temperature and decreasing the expense of preheating the reactor [92].

Furthermore, steam and CO₂ were the gasifying agents that are particularly used to produce hydrogen and carbon monoxide enriched gas. The usage of carbon-dioxide as a gasifying agent increases the concentration of carbon-monoxide [93]. This is especially important when it comes to generating liquid fuel through the synthesis of Fischer-Tropsch reactions. Endothermic reactions are both steam and carbon dioxide reforming, making their products evolution at higher temperatures. Steam gasification vastly encourages the char and hydrocarbon compounds formation through steam reformation. Therefore, steam gasification achieves an increase in the concentration of hydrogen and carbon monoxide. Likewise, steam gasification increases the reactor's efficiency and beneficial heating [94]. The use of steam in the gasification of a plastic waste two-stage pyrolysis improves the yield of gases and decreases the yields of solids and oils. The increase in thermal cracking of large molecules in the presence of steam is thought to be the cause. Steam gasification has also been shown to minimize methane, ethylene, and ethane concentrations, which helps to improve hydrogen and carbon-monoxide advancement. This is significant due to the steam reaction generating tar and char. Carbon-dioxide was found to be not a suitable medium for plastic waste when compared with other gasifying agents. The Boudouard response is the only reaction in such systems that are significantly impacted. Therefore, running the gasification reaction with the plastic waste using pure Carbon-dioxide gas enhances the formation of carbon-monoxide in this reaction. However, such processes gas yield can be increased by using oxygen in the gasifying medium, improving oxidation reactions, and thus encouraging the yield of the gases. Despite its benefits, steam gasification of plastic waste has numerous drawbacks, most notably the lack of a direct oxygen carrier and the need for an extra heating source. As a result, a steam generation facility is required to make the process even more energy-intensive. On the other hand, steam is produced using recycled heat from within the process, the energy cost of manufacturing steam is reduced [95]. For example, it is possible to generate steam by cooling the syngas prior to tar recovery/cleaning. The gasification process using a combination of steam/air/oxygen does not require any additional heating, and steam improves syngas efficiency. Another option to reduce tar forming and promote the water-gas change reaction and hydrocarbon reform is a direct steam injection into an air gasifier.

b) Pressure

The influence of pressure on the gasifier are not as significant as other considerations. Increasing the reactor throughput and enriching the methane content in the product gas are merits of high-pressure gasification. High-pressure usage in power generation gas turbines would find the applications of syngas to the gasifier more supportive because of the production of high degree syngas released via pressurized gasifiers. The gasification processes tested mostly on a laboratory level on the plastic waste are carried out under ambient conditions. This may be attributed to some of the harmful consequences of pressurized conditions, such as the promotion of tar formation. At high pressures, a range of industrial grade gasifiers are operated for treating the plastic waste. Of all the gasification reactions, the only reactions which are greatly influenced by an increase in pressure are methanation and methane reforming [96]. Rising pressure makes the output gas methane-rich, and amounts of hydrogen and carbon monoxide are reduced [97]. The development of tar is another effect of working at elevated pressure. This is especially essential in the gasification of plastic waste, which is due to its volatility, frequently results in the formation of tar. It has been clearly understood that a rise in gas pressure will totally shift the equilibrium to fewer molecules in order to reduce the impact of the increase in pressure. This mostly eliminates tar reforming and cracking, which results in the formation of tar and significant hydrocarbons in the stream as products [98].

c) Feedstock

Generally Plastic wastes have elevated gasification rate, because they are highly reactive and volatilize very fast. Because of the fast carbon conversion property, a low-temperature gasifier is more than enough to gasify the plastic waste completely. The feedstock properties are crucial in designing gasifiers for plastic waste in proximate and elemental analysis. These properties indicate the quality of the fuel [99]. Simultaneously, plastic waste has different properties, like mostly they possess less moisture as well as ash content, but they exhibit high volatile components. Therefore, plastic waste compound analysis has a major impact on the purity and constituents of the syngas generated by that waste's gasification. Suppose the plastic waste carries the major component being polyethylene terephthalate (PET), rich in oxygen naturally, upon gasification process. In that case, they undergo a partial oxidation reaction, causing more carbon-monoxide and an increase in the flue gas temperature. Hydrogen enhancement was also identified with more PET by water-gas shift reaction. Another plastic waste that could be utilized to explore the role of feedstock in product delivery is propylene. It is one of the kinds of polyolefin compounds that would be an excellent hydrogen source [100]. Therefore, its use in the co-gasification process elevates the yield of gases as well as the hydrogen contents in the syngas. The H/C ratio is enhanced when there is an increase in the amount of polypropylene in plastic waste, thereby improving hydrogen evolution. Another plastic waste component being polyvinyl chloride (PVC), which has high chlorine content in them and this would be the difficult aspect for the gasification process [101]. During the gasification process, such feedstock produces HCl, and this restricts the immediate usage of the gases formed since it needs more cleaning process before its use. The cleaning of HCl is quite difficult because they are highly corrosive, toxic agents for acid rain formation and generate huge numbers of halogenated hydrocarbons.
d) **Temperature**

It is one of the most important working parameters for plastic waste treatment, using steam gasification for a yield of gas as well most gasification processes are endothermic in nature. Increasing the gasification temperature greatly improves the gas-solid reaction, which can enhance the process efficiency by raising the gas yield as well as reducing the yield of methane, some of the heavier hydrocarbons, tar and char \[^{102}\]. It is noteworthy in operating high-temperature gasifiers, which stimulate Boudouard and reforms reactions, thus improving hydrogen and carbon monoxide evolution during the gasification of plastic waste. It's also important to remember that the temperature of the bed or reactor is mainly determined by the amount of air or energy supplied by the furnace for direct heating or indirect heating. In the gasification process, the product yield's sensitivity to the operating temperature depends on a catalyst's presence. Noncatalytic steam pyrolysis/gasification processes have been recorded for plastic waste of polypropylene/polystyrene and shown product delivery to be more susceptible to temperatures of the gasification process rather than the catalytic processes. It could be essential to recovering appropriate energy in the product gas for the effective conversion of heat. The heating benefit of the producer gas is also diminished by gasification at high temperatures due to the increased conversion of heavy hydrocarbons.

e) **Equivalence ratio**

It is one of the important parameters which helps in improving the quality yield of the gas in plastic waste air gasification. ER is defined as the actual ratio of air: fuel to the stoichiometric ratio of air: fuel for combustion. In the case of plastic waste gasification, ER was shown to have a more significant impact on gas yield and reactor temperature than bed height and fluidization velocity, and it must not be increased. As the ER rises, more air is introduced into the gasifier, increasing the oxidation process rather than reformation and cracking, resulting in increased generation of carbon dioxide, water, and nitrogen. On the other hand, carbon monoxide and hydrogen concentrations have decreased. However, in CPW gasification, as opposed to other feedstock, the decrease in hydrogen concentration with a high ER may not be increased. This is because CPW has a more volatile compound, which can lead to more tar formation than other feedstock, so tar cracking and adsorption at elevated ER upholds high operational temperature and can form an extra amount of hydrogen. The amount of methane and other substantial hydrocarbons were found to decrease with a rise in ER due to enhanced oxidation reactions. On the other hand, reducing the equivalence ratio increases the evolution of hydrogen, carbon monoxide, methane, and other hydrocarbons \[^{102}\].

Aside from the nitrogen dilution effects, raising ER reduces the heating value of the gas by removing high heat-value gases like hydrogen and methane and heavier hydrocarbons. Therefore, an increase of ER reduces the evolution of hydrogen and carbon monoxide, which raises the amounts of gases and decreases the contents of char and tar. This is because an increase in ER boosts the bed temperature, resulting in more gas being emitted during the pyrolysis phase of gasification \[^{104}\]. The enhanced bed temperature additionally promotes tar splitting, creates light hydrocarbons, and increases char reactions through the water-gas shift and Boudouard reactions. Overall, the plastic waste gasification process could not be too high to avoid producing syngas with less hydrogen and carbon monoxide than the equivalence ratio requires. Tar elimination can also be accomplished by including bed additives and thermal cracking in the gasification process \[^{105}\].

Other parameters that may influence the distribution of products in plastic waste gasification are fluidization velocity, residence time, the height of the bed in the reactor, and interrelated effects. The reaction residence time would be increased by raising the bed height and would thus be an enhanced conversion of tar cracking, char, and hydrocarbons \[^{106}\]. However, to prevent the detrimental impact of poor contact, there is a need to provide an optimal bed height. The development of larger bubbles may occur with a high bed, contributing to the reduction time of gas-solid interaction. Because of an increased rate of an exothermic reaction, the fluidization velocity raises the bed temperature and thus, the cracking of tar is enhanced. The speed must be regulated; otherwise, too high speed allows the char to pass rapidly into the cyclone through the product formed and thereby limits the conversion of the char. Functioning at high speed will lead to lowering the residence time, which can shorten the length of tar cracking and lead to the further output of tar.

**Thermochemical conversion process (pyrolysis) and its impact on biohydrogen synthesis**

**Pyrolysis of COVID-19 plastic waste**

Pyrolysis is a thermochemical process, a high temperatures and anaerobic conditions are used to disintegrate the solid and liquid organic materials present in plastic waste. The macromolecular compounds that exist in the waste get disintegrated into simpler compounds such as carbonaceous materials (char and tar), crude synthetic gases, and liquid fuels depend on the process condition \[^{107,108}\]. Further, the products so formed can be refined into pure chemicals or fuels. However, collected CPW carries mostly a mixture of various types of plastics and, therefore, yields a mixture of products including different hydrocarbons of various chain lengths. Besides, this technique is more efficient and cost-effective as less landfill space is required, hence reducing pollution. The end products of this process have high commercial value as they are the alternative energy replacement for non-renewable feedstock, fossil fuels \[^{109}\].

In comparison to gasification, pyrolysis occurs in an inert environment and thus involves no gasifying agent. For several purposes, pyrolysis is regarded as one of the competitive technologies for the gasification process for plastic waste management. From environmental degradation, it is better because the process occurring in an inert environment will be free from oxygen where no dioxin formation until the products are encountered with the oxygen. In order to attain a specific product distribution, the pyrolysis process methods
can also be altered, which makes it more versatile. The chief pyrolysis product would be the liquid oil used for combustion purposes, while the rest of the byproducts obtained include char, tar, and gas [110]. A sequence of thermochemical events inside the reactor depolymerizes plastics’ long-chain polymer compounds in an oxygen-free environment. Like fossil fuels, it also results in the products like char, oils and gas. The recovered product’s yield and composition depend on several variables, including the various forms of plastic waste, temperature, different reactor systems, pressure, catalyst, and residence time, just like the gasification process. It has been of great interest to use plastic wastes as feedstock for pyrolysis because they can yield cleaner distillates when compared to the other feedstock [111].

During the COVID-19 outbreak, extensive use, production, and disposal of personal protective equipment resulted in an increase in plastic waste and posing environmental risks. Around the world, 129 billion face masks and 65 billion plastic gloves are used and discarded every month. A recent study employed the pyrolysis process to establish the type of polymer used in face masks and gloves and sustainable plastic waste disposal solutions. Characterization studies validated the polymers identification in PPE, which can further aid in fuel conversion alternatives. The medical face mask, glove, upcycling technologies and environmental concerns were also highlighted. According to the acquired endothermic peaks, the melting point of PVC and polypropylene polymers of medical gloves was around 431 °C and 175 °C for surgical masks. The face mask and glove were pyrolyzed for 1 h at 400 °C in a closed reactor. Approximately 75% liquid and wax fuel, 10% char, and non-condensable gases were obtained using lab-scale processes. Because of their thermoplastic nature, which contains a large proportion of oil, medical plastics might be recycled into oil, and waste to energy conversion could potentially reduce the capacity of PPE plastic waste [112].

**Pyrolysis of plastic waste and its valuable products**

Slow pyrolysis is the process by which the least important component products like char are generated and they are maximally accomplished by the use of low temperatures, slow heating and long residence periods. Production of char occurs by the slow pyrolysis process at a temperature of a maximum of 600 °C with a less heating rate of 100 °C/min, which guarantees residence time of 10 min. Char mostly contains carbon with less constituents of humidity and residues. For example, the char attained by pyrolysis of high-density plastic waste holds carbon of 97% and a trace of sulfur. The high carbon composition of char led to usage in numerous applications like solid fuel or as adsorbent [113]. In addition, relatively lesser volatile components are attained by slow pyrolysis, and they are converted by condensation of the gases into highly valuable bio-oils. The volatile products of the plastic waste pyrolysis process, which uses high reaction temperatures and heating rates of more than 10,000 °C/min with low residence time, resulting in numerous forms of liquid oils and gases. The liquid oils achieved through plastic waste pyrolysis methods were thick and greasy dark colored and typically had a strong odor due to its high aromatic contents. The characteristics of pyrolysis oil mainly hang on the kinds of plastic wastes present in the plastic waste which are fed into the reactor/process [114,115].

Overall pyrolysis process described above would be an equally important technique like the Gasification process. Because pyrolysis occurs in an inert atmosphere within the chamber, no further agents are required to start the process. The non-release of hazardous gases and products similar to fossil fuels is an advantage of the pyrolysis process. Like any plastic waste handled through the pyrolysis process produces energy-yielding products. Similarly, the same technique can be adopted for CPW. Though the procedure of treating CPW with pyrolysis is still new, it appears to be a better technique than other currently available technologies. Pyrolysis units require less area for installation, yet they are more expensive than other technologies.

**Various factors that influence the pyrolysis of plastic waste**

**Constituents of plastic waste**

The types of plastics contained in the CPW determine the compositions of products formed during the pyrolysis process. The main plastic components of plastic trash are polyethylene, polypropylene, polystyrene, polyethylene terephthalate and nylon. The plastic waste is mostly composed of repeating components of monomers, and they are well connected among themselves, which greatly influences their thermal degradation. Straight chained polymers have certain monomers aligned linearly, while side chains are linked to the normal ones in the branched-chain polymers. During pyrolysis, the plastic waste components present in plastic waste start losing its stability rapidly under high thermal conductivity. The plastic waste becomes soft when the attractive forces between the bonds in each polymer are broken. Some cross-linked polymers exist in addition to the polymers found in plastic waste, and they have long chains of molecules with strong covalent bond properties. These cross-linked polymers start to crack and produce valuable energy-rich products like liquid oil, syngas, hydrogen gas, hydrocarbons, char at high-temperature pyrolysis [115].

**Reactors used in pyrolysis**

The types of reactors that are mainly applied in treating plastic waste using pyrolysis include batch, semi-batch, and continuous reactors. The reactors used in plastic waste pyrolysis greatly affect the parameters such as the product formed, catalysts applied in the reactions, product distribution, mixture of plastic, residence time and heat transfer rate. In batch reactors, the raw-materials feeding for the pyrolysis process have to be provided in batches and even the product like liquid fuel or gas is also collected as such [116]. However, in a continuous reactor, the feeding of the plastic waste and the product formed is carried out simultaneously. The feedstock is applied batch-wise in a semi-batch reactor, but the synthesized products are extracted continuously. For research or laboratory scale, the most preferable were the batch or semi-batch reactors while considering the continuous industries ones were more suited for rapid production of the products [117].

Likewise, the gasifiers in gasification technology, the pyrolysis reactors too exhibit the mechanisms of heat transfer...
and flow movements of the feedstock as well as the materials. For the operating technique of the pyrolysis process number of reactors like fixed bed, fluidized bed and screw kiln are used [118]. Fixed-bed reactor usage in the pyrolysis process can be made easy to build and operate.

Because of the low thermal conductivity and irregular geometries of plastic waste feedstock, which can result in low-temperature gradients and feeding issues in batch or continuous pyrolysis processes, this factor makes these reactors a less feasible approach for industrial usage [119]. Compared to a fixed-bed reactor, the fluidized-bed reactor would be the greatest solution for industrial-scale since they can constantly run with better heat and transfer of mass. One of the most recent approaches was using the screw-kiln reactor, which has expressed much popularity in plastic waste pyrolysis. There is an extruder in the screw-kiln reactor for which heat is provided externally and the feedstock plastic waste were screwed before passing the reactor. Altering the extruder rotational movement can regulate the feeding rate and, eventually, the residence time [120].

Effect of pressure on the pyrolysis process
Operating pressure might have a significant effect on pyrolytic reactions and the yield of the products, but mainly other factors might be majorly influencing the pyrolysis process. The rise in boiling point and an increase in pressure on a particular temperature can cause more cracking reactions rather than the effects of vaporization, but considering the degree of pressure can only exhibit a significant impact only at specific temperatures. It was stated that pyrolysis of some particular types of plastics in a continuously stirred tank reactor has less evident pressure effect at temperatures above 430 °C. Gaseous product yield was increased over 100% at 410 °C while it was just 50% at 440 °C; on referring to these facts, it can be concluded that pressure at higher temperatures has a significant effect since the reactants are below their boiling point at lower temperatures, which makes the pressure unaffected. The rate of the breaking of carbon-to-carbon bonds is significantly affected by high pressures and thereby decreases the yield of the gaseous end product [121]. Meanwhile, pressure is least recorded at elevated temperatures, which leads to reduced focus on the pressure outcomes rather than the temperature. Additional components like compressors and sensors for pressure control were needed for high-pressure pyrolysis which can raise operating costs vastly, and thus, this form of pyrolysis may not be an acceptable option from an economic point of view.

Vacuum pyrolysis
This process becomes functional in the presence of inert diluents and their primary products, once formed, get rapidly exited from the reactor, thereby preventing the secondary reactions from occurring. This kind of pyrolysis can occur at vacuum conditions while pressures fall below 0.2 atm. There has been increased diesel fraction of the char’s oil, porosity, and surface area has been observed under vacuum conditions. The vacuum creates an increase in the removal of certain particles, leading to a block of pores in the carbon structure. Another benefit of vacuum pyrolysis is the larger particle sizes will be processed easily than the fast pyrolysis reactors. Large pipes and vessels are needed for the high vacuum formation in the reactor, which is quite expensive as well as a complicated process. Vacuum pyrolysis can only be possible when there is excess demand for bio-oil.

Role of catalysts in the pyrolysis process
Catalysts usually speed up the reactions, which greatly impact product creation in the pyrolysis reactor. When compared to thermal cracking, catalytic cracking is a faster process that uses less energy and lower temperatures. Additionally, the use of catalysts like zeolites aids in the production of high-energy-yielding molecules. Long hydrocarbons are formed as a result of the thermal pyrolysis of plastic waste. Short carbon chain products can be generated by using certain catalysts. Specific catalysts were used to decrease the degree of unsaturation of several hydrocarbons, rise in dienes and aromatics yield, ultimately increasing the firmness and product, cetane count. The activation energy was found to be decreased during the pyrolysis of the plastic waste upon the usage of certain catalysts like HY, HZSM-5, and MCM-41. Thus, the application of catalysts during the pyrolysis process was beneficial as they greatly reduce the operating expenses by minimizing the heat duty, leading to the production of liquid fuels of high demand [116].

Heterogeneous and homogenous catalysts used in the pyrolysis are categorized as per their involvement in the reactions. Homogeneous catalyst will be in a similar state with the medium of reactions, whereas it will be of a different phase when the heterogeneous catalyst is present. Lewis acids, such as aluminum chloride, are the most frequent homogenous catalysts. Nanostructured zeolites, basic oxides, carbon-supported metals, mesostructured catalysts, and super acid solids are examples of heterogeneous catalysts. Solid catalysts are commonly used to improve liquid and gaseous fractions selectively. It is possible to catalytically copyrolyze biomass and plastics without having to separate the feedstock prior to pyrolysis. The ratio of plastic and biomass can be varied to accomplish varying ratios of the anticipated liquid as well as gaseous products [117].

Effect of temperature on the pyrolysis process
In the pyrolysis of plastic waste, the temperature has been one of the most important operating parameters since it controls the polymers cracking reactions. At the time of cracking, the reaction temperature increase will weaken the van der Waals forces which will be holding the molecular bonding. However, increasing the temperature does not lead to the cracking of all the molecules exclusively. Molecular vibrations can be large enough to evaporate from the feeding surface due to a higher temperature. Cracking occurs when van der Waals forces present in the plastic waste polymers carbon chains producing larger energy compared with the enthalpy of individual C–C bonds in the carbon chains. So, the plastic waste polymers possess a higher molecular weight which will decompose instead of volatilizing after being exposed to high heat. Hypothetically, for any given plastic, the decomposition temperature should be constant, but studies from various researchers have not revealed the same. In order to prove the principle, two parallel experiments were conducted, each using batch and thermogravimetric methods for pyrolysis of plastic waste. The cracking, by contrast, took place at different temperatures, one
at 380 °C and the other at 650 °C. The most likely explanation for the temperature difference is observing their experimental setup and scheme at which sensors for temperature measurement were placed. In different studies, temperature measurement devices location is one of the various factors that influence the temperature variation. It was noted that during the completion of the pyrolysis process in the reactor and its core, there is a substantial alteration in temperature was found, which may be due to the heat loss at the end of the reactions in the reactor.

The temperature influences the distribution of products directly. The reaction temperatures above 600 °C produce certain products and they were mainly combinations of hydrogen and light hydrocarbons. Increased temperature produces mainly light hydrocarbons (C3−C4), whereas heavy hydrocarbons (C21−C30) production is lowered. At a temperature of 400 and 600 °C in the reactor encouraged the wax formation and liquid fuel products. Moreover, below 400 °C has produced extremely sticky liquid, leads to dehydrogenation condition, and had more chances to form secondary products.

**Effect of the residence time of the feeding stock in the reactor**

Residence time (RT) has been classified as vapor residence time (VRT) and solids residence time (SRT). SRT refers to the time it takes for the feedstock to be totally degraded in solid feed reactions, whereas VRT refers to the time it takes for the created vapor to leave the reactor. RT is regulated by either changing the amounts of the feedstock or the product gas formed. Long SRT will lead to more lateral reactions, which favor the char formations and additional stable compounds. Likewise, at 500 °C, temperature enhances the long VRT, which greatly encourages the alteration of chief vapor products into less unstable compounds like non-condensable petroleum gases and aromatics. In addition, fewer fractions of liquid oils and higher contents of char occurred during the longer vapor residency periods and these findings have been reported in multiple studies.

Residence time would have a major impact on products formed at these temperatures. However, end products gas and oil composition did not exhibit any changes in temperatures above 685 °C. As the effect at high temperatures became less evident, plastic waste pyrolysis experiments were formulated by giving the least importance to the influence of residence time. Nevertheless, residence time effects will be a vital factor to be considered at below 450 °C [122].

Several factors influence the formation of energy-producing products during the pyrolysis of plastic waste, as detailed above. The plastic waste feedstock, temperature, different reactor systems, pressure, catalyst, and residence time all impacted the yield compositions of the final product. Therefore, each factor stated above should be optimized for efficient product yield before scaling up and commercializing the product acquired through the pyrolysis process.

**Challenges and future outlook of biohydrogen production from CPW**

One of the most important disadvantages of thermochemical processing of plastic waste is the agglomeration as well as the tar formations. These may affect the particles’ fluidization in a fluidized bed gasifier which prevent the gasifier from running smoothly, and the products were subjected to costly gas cleaning facilities. Generally, tars were organic compounds that after gasification, break their molecular bonds and the smaller components develop as gases, while the main tars are the bigger ones. In addition, the pyrolysis phase of the gasification process leads to the formation of tars upon depolymerization, which can also undergo certain chemical reactions resulting in the formation of secondary and tertiary tars [106].

Because of the higher volatility property of plastic waste gasification, their tar output was in higher proportions when compared with biomass and coal gasification process. Meanwhile, during the applications of internal combustion engines and gas turbines, the tar contents that are present in the product gas should not exceed 10–50 mg/Nm3. Tar formation leads to certain issues like condensation, formation of more complex polymer compounds, tar aerosol formation and because of these reasons, removal of tar would be significant steps in the plastic waste gasification process. Possession of aromatic rings in the tar, they are classified as mono, di and poly, because of the highly volatile nature of monoaromatics that can prevent the condensation in the gasification process, which could ultimately affect the syngas formation leading to less problems on comparison with the di or polyaromatics [91]. Usage of catalysts like dolomite or nickel-derived can help to destroy the tar formation during plastic waste gasification.

**Removal of tar from the reactor during plastic waste gasification**

Two techniques, namely physical and chemical methods, can be used to extract tar. Physical removal of tar is carried out using scrubbers and filters, while thermal cracking is done for the chemical method. For elevated temperature cracking, the usage of calcined limestone or dolomite or nickel-containing catalysts can be used. Tar removal can be divided into two groups in the gasification process: the primary method involving treatment within the gasifier and the secondary method outside the gasifier by hot gas cleaning. Mechanical approaches such as cyclones, electrostatic filters, cloth filters, ceramic filters, and water scrubbers may also be used to remove tar. Tar removal can be more effectively carried out using secondary methods, but their investment and operational cost are too high as well as they possess a complex mechanism. In the plastic waste gasification process, the primary methods play a more effective part, and they can be accomplished with bed materials like olivine, activated carbon, dolomite, calcium oxide and nickel-containing catalysts at increased gasification temperatures. The primary approach needs no downstream treatment, so the process is more economical and simpler. An efficient tar cleaning and production of clean syngas can be made possible until it requires the combination of both methods [103].

Olivine encompasses a larger ability to eliminate tar and its elimination capability because of the chemical change (catalytic) tar decomposition of the iron associated with silicon dioxide sand as bed material. Mixing of silica bed material with 1% olivine and 100% olivine in the reactor has
vastly reduced the tar deposition in the plastic waste gasification process. In another investigation, dolomite was found to exhibit more tar extraction than olivine. In an experiment of the plastic waste gasification process, dolomite of 30 wt percent exhibited 1.5 g tar/Nm³. In contrast, olivine showed 10 g of tar/Nm³ with the same percentage of dolomite, but their gas productions of both catalysts were the same [104]. Activated carbon has been showing improved adsorption and removal of tar when compared with dolomite. But when prolonged exposure to activated carbon on tar formation causes pore block and decreased removal ability of tar, similarly like the dolomite. Dolomite and olivine usage as bed materials can boost the calcination process in gasification reactions when the temperature reaches at around 800 °C. Upon olivine calcination occurring at 850 °C leads to surface area improvement which separates the iron (II) contents in the surface and ultimately removes the tar by calcined olivine.

Nickel-containing catalyst has been used to crack tar and high yield of gases because of its lower cost, increased bond-breaking reactions, high hydrogen production via water-gas shift process and steam methane reforming. Nickel-containing catalyst exhibited gasification proficiency increment, fastens the reactions, progressed in gas formation, and reduced unnecessary solid-liquid production. Decay of catalyst occurring in bed materials because of sintering and deposition of carbon can be stabilized using aluminum oxide during the gasification processing of plastic waste (Table 2). Similarly, in the pyrolysis-gasification of plastic waste, the nickel-magnesium-aluminum catalyst was used, which decrease the solid yield, facilitate hydrocarbon reforming, and ultimately increase the formation of hydrogen carbon monoxide and carbon dioxide [94].

Harmful gas removal during plastic waste gasification

Apart from tar elimination, hydrochloric acid (HCl) removal from the chlorinated feedstock product (PVC in plastic waste) is highly important due to its harmful effects and can be absorbed by dolomite by reacting with calcium oxide or magnesium oxide that leads to calcium chloride or magnesium chloride formation [123]. Animal shells that are also rich in calcium oxide exhibited a significant role like dolomite in the effective elimination of tar and hydrochloric acid during plastic waste treatment in the gasification process. Sodium carbonate is another chlorine-removal compound that has proven to be more effective than calcium oxide and calcium hydroxide of animal sources [102].

Agglomeration removal using specific reactors

Spouted bed reactors help solve the agglomeration and defluidization in pyrolysis/gasification of plastic waste, and they can also effectively treat the sticky materials of plastic waste [124]. Spouted beds are relatively simple to set up, which needs less quantity of sand as well as they can operate with less pressure when compared with the fluidized bed and it also does not need any special distributor plate. Spouted bed reactors also exhibit less tar formation and solid deposits but result in higher heat transfer rates. In addition, the conical spouted bed often avoids little physical phase restrictions in gas-solid contacts, such as sand particle coating, plastic melting, and pre-gasification volatilization of pyrolysis materials, and improves char conversion [85].

Co-gasification

There were problems with plastic waste gasification, such as the accumulation of thin layers of black powder deposited in the reactor and feeding problems [125]. Due to softening of the plastic wastes during the feeding, which would stick to the wall of the feeding tube of the reactor. The problem of plastic gasification, such as feeding difficulties, can be reduced by co-gasification, mixing plastic waste and biomass/coal [126]. Upon mixing of biomass/coal with plastic waste led to an increase in the heating value of the product gas formed. Compared with the biomass/coal reactivity, the plastic waste cracking occurred quickly due to its fast melting. It was found that plastic waste mixing with biomass (pine) during the co-gasification process has resulted in a 50% higher gas yield when compared to gasification of them individual, which yields only 10% percent of gas. Quite a contradictory result was obtained when similar co-gasification was adopted with the mixture of lignite and plastic waste (10–20 wt%), which has not gained much heating value (11 MJ/m³) as well as hydrogen production. They exhibited very similar results of pure lignite gasification. But plastic waste, along with biomass/coal in the co-gasification process, has exhibited increased higher heating value as well as gas production [67].

Advancement in two-stage gasifier used for plastic-waste gasification process

Two-stage gasifier utilization will be more effective for tar evacuation, improved gas yield, and high calorific value has been recorded. Typically, when considering about the two-stage gasifiers in which the reactors were separately heated and individually isolated by the supplier [127]. Plastic feedstock and the bed are positioned in the lower reactor while with the help of certain agents like activated carbon, dolomite, olivine, etc. The tar cracking zone has been established in the upper reactor. Thus, it can lead to the removal of the tars from the lower reactor can be achieved. Tars that are absorbed can react among themselves, triggering the dehydrogenation process leading to coke formation. This undergoes further cracking on reacting with carbon dioxide, oxygen, and steam at elevated temperatures [128]. Two-stage plastic waste management techniques can operate with thermal degradation processes like pyrolysis and gasification in separate reactors. The plastic waste feedstock undergo pyrolysis in the first reactor at about 500 °C and the resulting gaseous product progress with the gasification process at 850 °C. Enriched hydrogen gas has been produced from the plastic waste feedstock using the two-stage pyrolysis-gasification degradation process of plastic waste has increased the development of hydrogen-enriched gas and, to some extent, exhibited better performance than the catalytic gasification [94].

It has to be kept in mind that each polymer present in plastic waste undergoes different ways of degradation and is determined by the volatile substances formation. Random
| Types of plastic waste | Different types of Bed material | Properties of the bed materials | Types of reactors used | Temperature (°C) | Tar yield (g m⁻³) | Gas composition (% vol) | Gases yield (m³ kg⁻¹) | References |
|------------------------|-------------------------------|--------------------------------|-----------------------|-----------------|-----------------|------------------------|----------------------|------------|
| Polyethylene           | Polypropylene                 | Olivine                        | Fluidized bed         | 850             | 190             | Hydrogen: 38, Carbon-monoxide: 7 | 30 | 1.2 [128,129] |
|                        |                               |                                | Fluidizedbed          | 850             | 180             | Carbon-monoxide: 34, Carbon-dioxide: 4 | 8 | 1.0 [14,104,138] |
| Polyethylene           | Olivine                       | Olivine is natural mineral containing magnesium, iron, and silicon. Usage of olivine reduces the amount of tar produced and enhances the quality of the gas produced greatly. The catalytic activity of olivine for tar elimination is due the magnesite and iron oxide contents. | Spouted bed           | 900             | 15              | Hydrogen: 58, Carbon-monoxide: 27, Carbon-dioxide: 3 | 7 | 3.2 [123,139,141] |
| Polyethylene           | γ-Alumina                     | γ-Alumina textural properties like surface area, pore volume, pore size distribution and acid/base characteristics are mainly related to their surface chemical composition, local microstructure, and phase composition. Nevertheless, the chemical and hydrothermal stability of γ-Al₂O₃ is still a critical point for catalytic applications. In terms of tar and char yields, it is slightly superior to olivine, although gas yields are comparable. | Spouted bed           | 900             | 16.1             | Hydrogen: 59, Carbon-monoxide: 26, Carbon-dioxide: 2 | 8 | 3.3 [124,130,131] |
| Polyethylene           | Ni/γ-Al₂O₃                    | Breaking carbon bonds with high reactivity, improving the water-gas shift reaction, lowering solid yield, and increasing gasification rate. | Fixed bed             | 700–900         | 106–113          | Hydrogen: 17–37, Carbon-monoxide: 20–27, Carbon-dioxide: 21–35 | 10–21 | 1.22–2.04 [92,133,140] |
| Polystyrene            | Ni/Dolomite                   | NiO/dolomite catalyst has capability to exhibit high degree of carbon conversion. | Batch fixed bed      | 850             | 290             | Hydrogen: 29, Carbon-monoxide: 43, Carbon-dioxide: 26 | 43 | 1.7 [18,134] |
| Polyethylene terephthalate | Activated carbon             | It is more effective in adsorption and tar removal than dolomite. | Semi-batch fixed bed | 1000            | –               | Hydrogen: 61, Carbon-monoxide: 6 | 12 | 2 [135,137] |
| Mix of all the Plastic waste | –          |                                | Plasma                | 1200            | –               | Hydrogen: 62, Carbon-monoxide: 34 | – | 3.5 [131,132,136] |
degradation is the primary thermal degradation process for plastic wastes. Random degradation occurs in the polymer chains at every arbitrary point, contributing to a large distribution of products. Plastic waste exhibits random degradation by transforming hydrogen atoms from one carbon atom to another, which can lead to two-fragment generation. Some degradation processes like chain-end splitting can evolve at higher temperatures of about 800 °C [129]. Therefore, the product portion occurred may be of varied sizes than the normal monomeric types. Still, some plastic wastes can form monoaromatic as well as polyaromatic volatiles in the gaseous form based on the effects of temperature and residence time. Apart from that, these plastic wastes can also be degraded randomly, forming some vinyl and carboxyl compounds as well as certain oxygenated compounds of gaseous forms like acetylene, benzoic acid, aldehyde and terephthalic acid. It has been identified that feedstock compositions can greatly influence the yield of the products and their major constituents (liquid oil, gas, char) during the pyrolysis process and these factors clearly provide the distinction of pyrolysis and gasification process. On consideration of the gasification process, the feedstock of plastic waste only influences the syngas production as well as their compositions and they can efficiently reduce or eliminate the other products like tar and char, which clearly indicates gasification would be a better technique in the plastic waste degradation and treatments [36].

Future perspectives and challenges

The review describes the usage of the gasification and pyrolysis technique, which has been widely used to treat the general plastic waste feedstock into useful energy-yielding products. The same technologies can be applied for the COVID-19 plastic waste treatments since numerous amounts are generated nowadays. In this aspect, limited research works or industrial application related to COVID-19 plastic waste treatments has been reported; in this, most of the works are based on stimulation predication. Still, now most developed/developing countries have been using incineration techniques for COVID-19 plastic waste treatments, that emits certain hazardous and harmful gases such as dioxins, furans, and polychlorinated biphenyls resulting in some adverse environmental consequences. To reduce the emission of such harmful gases, the best option would be to adopt thermochemical processes such as gasification or pyrolysis. The major advantages include the limited space requirement to install this equipment, and produced high efficient energy products with less pollution. The major constraint is the expensive of these technologies when compared to the incineration process. In the future, more compactable and cost-effective reactors with all the in-built sensors can be developed or designed for gasification or pyrolysis process, which can be used to degrade any plastic waste and effectively convert them into energy-yielding products. One of the major challenges in developing countries lies in collecting this COVID-19 plastic waste mixed with municipal waste since there is no separate collection system for this waste. It will require a different waste management system to collect COVID-19 plastic garbage and transport it without causing harm to the person who handles. Sanitary worker’s exposure to the COVID-19 virus can be prevented by implementing an in-built sterilized mobile vehicle from the collection site to a treatment center, or the whole process should be adopted with AI-enabled technology without using any manpower.

Conclusion

The COVID-19 pandemic has led to an increase in the single-use of plastics to protect from viruses and minimize the spreading. The healthcare centers, hospitals, and household wastes (i.e., groceries and food packaging plastics, etc.) are the major source of CPW, which cause severe threat to the human life and environment if not properly managed. Plastic wastes are difficult to process compared to other biomass materials. The incineration technique is widely used for the treatment of CPW, which emits harmful gases. Recently, thermochemical techniques such as like pyrolysis and gasification are adopted to treat the CPW. Recent studies showed that pyrolysis is an effective method for producing high-energy products like liquid oil, waxes, and some hydrocarbon compounds with pure fuels or chemicals for further refinement. On the other hand, gasification is a technique wherein the feedstock are treated at high temperatures using oxidizing agents to produce syngas, constituting of hydrogen and carbon monoxide. Besides, this review addresses the importance of integrated technology like co-gasification and two-stage gasification processes to obtain higher gas yield. Their synergistic impacts often increase the energy composition of the syngas to produce hydrogen. However, these techniques are compelling; the cost is the major barrier that hinders for treatment of CPW. Compactable and cost-effective reactors for gasification or pyrolysis processes could be brought up in the future to encourage the conversion of CPW to energy-yielding products.

Declaration of competing interest

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

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