https://doi.org/10.1595/205651325X17128380208047

Johnson Matthey Technol. Rev., 2025, **69**, (1), 4–12

JOHNSON MATTHEY
TECHNOLOGY REVIEW

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A Comprehensive Exploration of Biomass Gasification Technologies Advancing United Nations Sustainable Development Goals: Part I

Mechanisms, sources, processes and products of gasification

M. N. Uddin*

School of Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia; SEM, FEM, Prince of Songkla University, Hat-yai, Songkhla 90110, Thailand; School of Energy and Science, Ontario Tech University, Oshawa, Ontario, L1G 0C5, Canada; NOVA IMS, University Nova de Lisboa, Lisbon, Portugal; School of Mathematical and Physical Sciences, University of Technology Sydney, PO Box 123, Australia; IPT, FIUNA, Universidad Nacional de Asuncion, San Lorenzo, Paraguay; ME, Dzemal Bijedic University Mostaru, 88104, Bosnia and Herzegovina; EEE, Northern University Bangladesh, Dhaka 1230, Bangladesh; Kulliya of Engineering, International Islamic University, 53100, Selangor, Malaysia; CPS, Tomas Bata University in Zlin, Zlin, Czech Republic

N. A. Nithe

School of Energy and Science, Ontario Tech University, Oshawa, Ontario, L1G 0C5, Canada

***Email:** engnasirbd@gmail.com

PEER REVIEWED

Received 28th January 2024; Revised 4th April 2024; Accepted 10th April 2024; Online 11th April 2024

The pursuit of sustainable energy sources on a worldwide scale is a crucial and pressing matter, with the United Nations Sustainable Development Goals (UNSDGs) offering a comprehensive framework for properly addressing this challenge. This two-part paper provides an overview of the various technologies now available for the process of biomass gasification. Compared to other renewable energy sources, which have undergone significant technological advancements in recent years, the field of biomass conversion is still relatively new. Keeping up with the newest breakthroughs becomes increasingly crucial as new conversion techniques are rapidly being created. In the thermochemical conversion process called 'biomass gasification', biomass solid source materials are degraded or incompletely burned in an oxygen-free or oxygen-deficient high-temperature atmosphere, resulting in the production of biomass gas. Part I delves into different biomass gasification techniques, including upstream, gasification and downstream processes, highlighting their importance in transforming biomass into clean and combustible gases.

Keywords

renewable energy, greenhouse gas, biomass, gasification, sustainability

1. Introduction

Presently, there is a growing fascination with renewable energy sources because of apprehensions regarding the expenses and ecological impacts of crude oil. Renewable energy sources are gaining importance, coupled with other environmental issues such as greenhouse gas (GHG) emissions (1–3). Biomass can be efficiently utilised for the manufacture of various biofuels, such as methanol, ethanol, dimethyl ether (DME), synthetic natural gas

(SNG) and hydrogen. Various countries have enacted efforts to encourage the utilisation of renewable energy sources, particularly emphasising biofuels. The European Union (EU) objective was to achieve a 14% market share of biofuels in the transportation sector by the year 2022. However, this target has been revised and the EU is now aiming for a higher share of renewable energy in the transport sector by 2030, as outlined in its Renewable Energy Directive II. In the USA, the production of biofuels has continued to increase steadily. Specific data for achieving a production of a billion gallons of biofuels by 2022 requires the most recent statistics from sources such as the US Department of Energy or other relevant agencies (4, 5).

Industrial facilities typically concentrate their efforts on producing biogas for the purpose of electricity generation or upgrading it for grid injections. The generation of biogas is a highly efficient and streamlined procedure that entails the transformation of organic substances into biogas, often with a proportion ranging from 5–10 wt%. The proportion depends on the individual attributes of the biomass and the operational conditions (6, 7). Other biofuels that can be produced using established technologies include biodiesel and bioethanol. Nevertheless, the manufacture of these fuels gives rise to certain ethical and societal concerns about the food supply, including the utilisation of vegetable oils, cereals, beets and sugar cane (8). Using lignocellulosic biomass, a byproduct or derivative of agro-industrial waste, presents a practical solution to prevent competition between food and non-food resources. Second-generation biofuels do not present a risk to food production (9–12). The objective of this work is to provide a thorough evaluation of biofuels produced from syngas using the biomass gasification technique (13). The discussion will centre on the thermodynamics and kinetics associated with the generation of useful biofuels, such as methanol, bio-hydrogen, ethanol, DME, SNG and biofuels produced using the Fischer-Tropsch process (14–17). Research conducted by the EU, the USA and the International Energy Agency, as well as the US Department of Energy, indicates that it is possible to achieve a 50% reduction in CO_2 emissions by 2050. Additionally, the research suggests that biofuels can contribute up to 26% of the energy mix (18). Biofuels have the potential to serve as a feasible method for achieving sustainable development and promoting

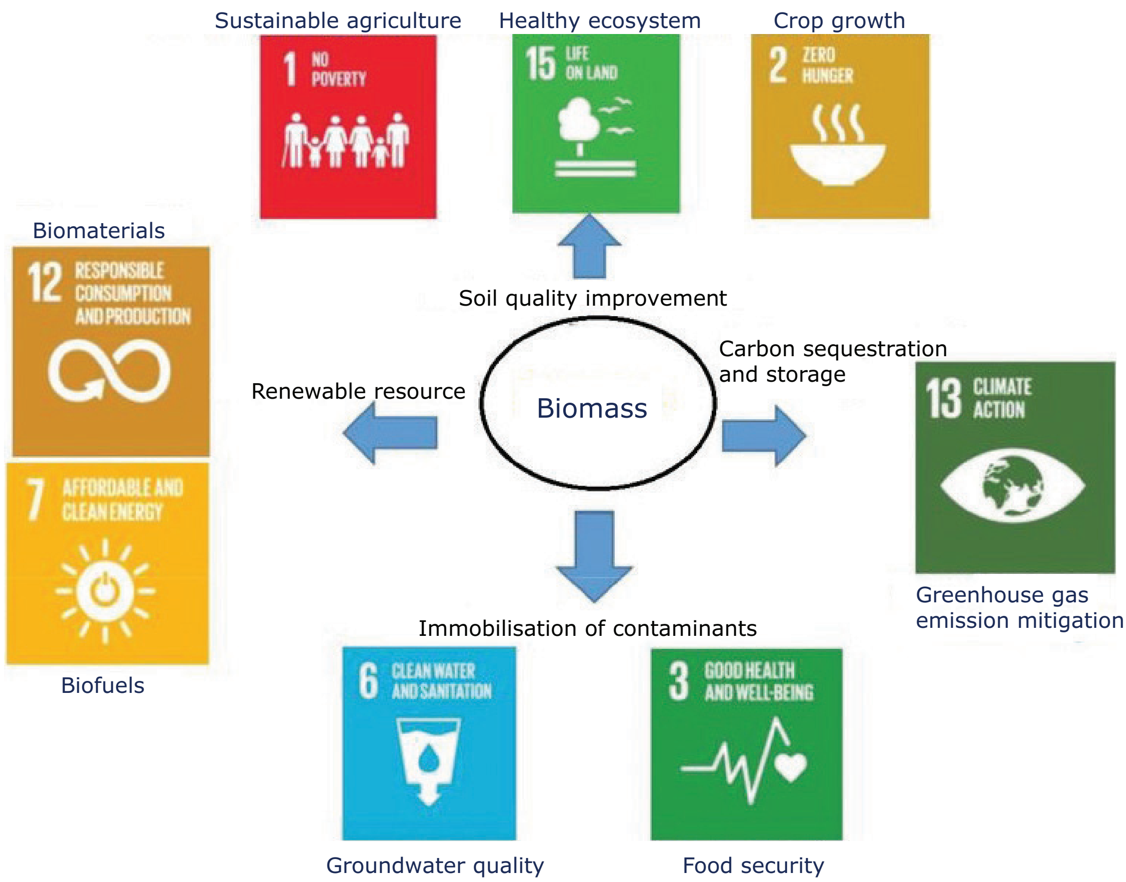

Fig. 1. Biomass application associated with sustainable development goals (19)

economic growth (**Figure 1**). By 2011, this sector had already hired almost 3.4 million workers (20).

2. Biomass Gasification

Biomass gasification involves the transformation of solid biomass material into a fuel source by reducing the oxygen level to below what is required for complete combustion. This process occurs within a gasifier reactor, where various reactions take place to convert the biomass into gaseous and liquid fuels. The resulting products find applications in a wide range of uses, including powering gas engines, gas turbines, direct heating systems and fuel cells. Despite its potential for thermal and electrical energy generation, biomass gasification faces several technological challenges that limit its widespread adoption. However, as an established alternative fuel, it offers a viable option for engine operations in transportation and electricity production. Furthermore, its cost-effectiveness in energy generation, along with its ability to reduce emissions and maintain environmental cleanliness, underscores its significance in sustainable energy solutions (21). Nevertheless, some modifications to the engine and adherence to specific criteria are necessary to attain the advantages offered by the engine fuel producer's gas. The producer gas must possess all the essential attributes of an ideal fuel to efficiently power the engine. The features encompassed in this context are elevated gas purities and high-temperature concentrations, extremely low tar content (less than 100 mg Nm^{-3}) and the complete absence of hazardous gases like ammonia and sulfur dioxide (22). Furthermore, the fuel properties of producer gas vary depending on its specific applications, such as gas reforming, power generation and engine usage for transmission. Over the past few decades, researchers worldwide have conducted extensive studies on gas production using gasification (23–31). The quality of producer gas is influenced by various parameters, including the shape of the feed material, reactor design, operating circumstances and gas cooling and purification technologies. This is due to the involvement of numerous intricate chemical processes and subsystems in the gasification process (32).

3. Mechanism of Gasification Process

Gasification is the process by which biomass is transformed into syngas within a gasifier through controlled air flow. This process typically consists of four main steps: drying, pyrolysis, oxidation and reduction. Drying and pyrolysis are endothermic processes, while oxidation is exothermic and reduction is another endothermic stage. Tar-reforming is a technique used to convert complex tar molecules into lighter hydrocarbons (33–38). Equation (i) (22) represents a simplified gasification reaction and the primary reactions are summarised in **Table I** (33–38). The gasification process can be facilitated by externally provided heat through exothermic combustion reactions (39, 40).

$$\text{Biomass} \rightarrow CO + H_2 + CO_2 + CH_4 + H_2O + H_2S + NH_3 + C_xH_y + \text{tar} + \text{char} \quad \text{(i)}$$

Gasification is a process of partially oxidising biomass at temperatures typically ranging from 800°C to 900°C (41). Steam is utilised as a gasification agent in certain circumstances. The gaseous byproducts generated by the gasifier can be harnessed to generate power using gas engines or gas turbines. The gasification process can be divided into three main stages: upstream processing, gasification and downstream processing as shown in **Figure 2**.

Table I Major Reactions of the Gasification Process (19)

Gasification steps	Reaction
Pyrolysis	Biomass → $CO + H_2 + CO_2 + CH_4 + H_2O$ + tar + char
Oxidation	Char + $O_2 \rightarrow CO_2$ char + $O_2 \rightarrow CO_2$ (char oxidation) C + $12O_2 \rightarrow CO$ (partial oxidation) $H_2 + 1/2O_2 \rightarrow H_2O$ (hydrogen oxidation)
Reduction	$C + CO_2 \leftrightarrow 2CO$ (Boudouard reaction) $C + H_2O \leftrightarrow CO + H_2$ (reforming of char) $CO + H_2O \leftrightarrow CO_2 + H_2$ (water gas shift (WGS) reaction) $C + 2H_2 \leftrightarrow CH_4$ (methanation reaction) $CH_4 + H_2O \leftrightarrow CO + 3H_2$ (steam reforming of methane) $CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ (dry reforming of methane)
Tar Removing	Tar + $H_2O \rightarrow H_2 + CO_2 + CO + C_xH_y$ (steam reforming of tar)
	Tar cracking: tar → lighter hydrocarbons + gaseous byproducts tar → lighter hydrocarbons + gaseous byproducts
	Tar reforming: tar + steam → hydrogen + carbon monoxide tar + steam → H_2 + CO

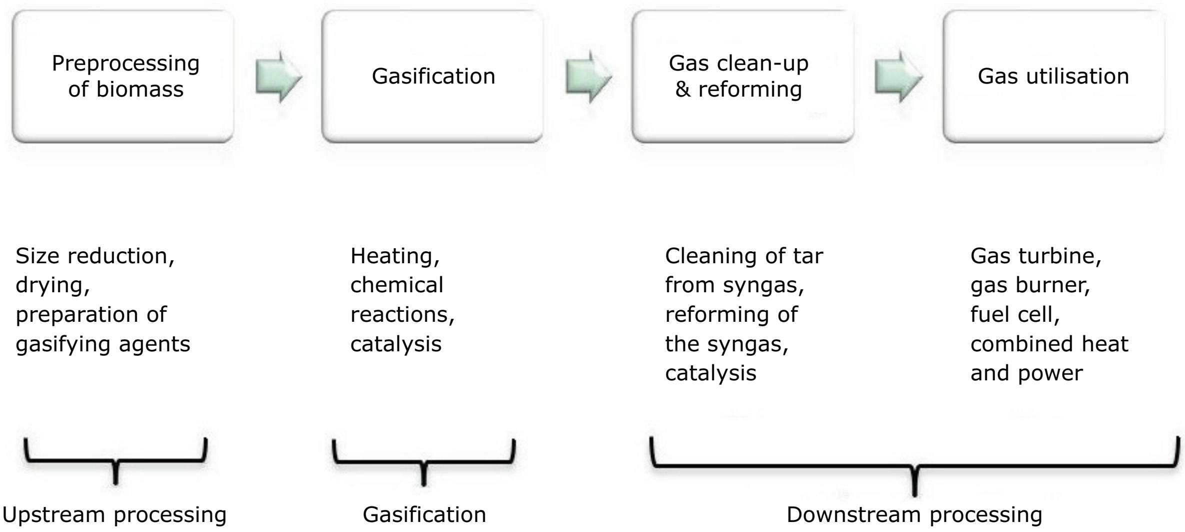

Fig. 2. Procedures involved in biomass gasification (42)

4. Sources of Biomass and Their Properties

Biomass energy ranks as the third most significant energy source globally. A significant proportion, ranging from 40% to 50%, of the energy consumption in numerous emerging countries heavily relies on biomass derived from their extensive forest and agricultural areas. Through the process of photosynthesis (43, 44), green plants transform sunlight into plant material, so generating biomass either directly or indirectly. Biomass resources encompass a wide range of natural and generated materials, including crops and residues, wood and leaf debris, municipal solid waste (MSW), forests and mill waste, animal residues and sewage. Farm crops and wastage such as sugarcane, cassava and corn provide sources of carbohydrates and starch. Biomass species commonly consist of wood biomass, straw, beech wood, seedcakes, bagasse and urban solid waste (45–51). **Figure 3** illustrates the biomass sources that are now accessible. Biomass is an extremely versatile feedstock in terms of its shape and physical characteristics. The substances can exhibit varying levels of moisture, ranging from wet to dry and possess different textures, such as being fluffy. Biomass can also have varying amounts of ash, either high or low. In terms of shape, particles can be small or large and composition may be homogeneous or uniform. Utilising biomass fuels in dedicated gasifier reactors becomes more challenging due to this variability, often necessitating biomass pretreatment. The significance lies in the feedstocks utilised for gasification and their respective physical and chemical characteristics.

In general, biomass with high volatile content produces a substantial quantity of syngas and bio-oil, but an increase in fixed carbon leads to greater bio-char production. The moisture content in biomass has a direct impact on the heat transmission mechanism and has a substantial influence on the distribution of products. **Tables II** and **III** display the tangible and chemical characteristics of biomass. The biomass is composed of carbon, oxygen, hydrogen and nitrogen. Sulfur is present in lower quantities and certain biomass forms also include significant amounts of inorganic species. The involvement of the chemical industry in supplying inputs and final products to various economic sectors, such as agribusiness, petrochemical, automotive, pharmaceutical, cosmetics and building, will enhance biomass production chains by utilising chemicals derived from co-products and residues (53).

5. Gasification Process

Extensive research has been conducted on gasification technology, which has proven to be highly adaptable and versatile for converting various forms of biomass in varied operational conditions. Biomass gasification is seen as a viable and sustainable technique for clean development, offering enhanced economic, social and environmental sustainability. Gasification is a technical process that converts carbon-based raw

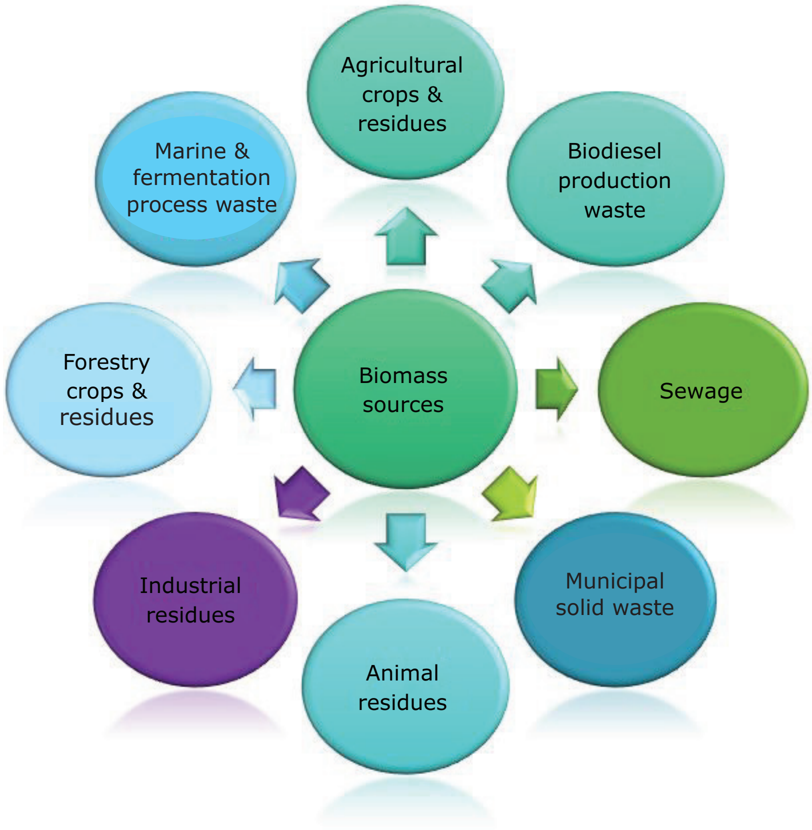

Fig. 3. Available sources of biomass. Reprinted from (52) under Creative Commons license 4.0 (CC BY 4.0)

Table II Physical Properties of Biomass[a]

Feedstock	Density, kg m^{-3}	Moisture content, %	Ash content, %	Volatile matter, %	Fixed carbon, %
Wood	380	20	0.4–1	82	17
Bituminous coal	700	11	8–11	35	45
Wheat straw	18	16	4	59	21
Barley straw	210	30	6	46	18
Pine	124	17	0.03	–	16
Polar	120	16.8	0.007	–	–
Switchgrass	108	13–15	4.5–5.8	–	–

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Table III Chemical Properties of Biomass[a]

Feedstock	Carbon, %	Hydrogen, %	Oxygen, %	Nitrogen, %	Ash, %
Wood	51.6	6.3	41.5	0.1	1
Bituminous coal	73.1	5.5	8.7	1.4	9
Wheat straw	48.5	5.5	43.9	0.3	4
Barley straw	45.7	6.1	38.3	0.4	6
Pine	45.7	7	47	0.1	0.03
Polar	48.1	5.30	46.10	0.14	0.007
Switchgrass	44.77	5.79	49.13	0.31	4.30

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materials, such as coal, into fuel gas, commonly known as synthesis gas or syngas. Gasification occurs within a gasifier, often a tank operating at high temperature and pressure, where oxygen (or air) and steam come into direct contact with coal or another substance being fed. This leads to chemical reactions that convert the feed into syngas and ash or slag (mineral wastes). Syngas has a historical reputation as an intermediate product in the manufacturing of synthetic natural gas. Syngas is a mixture of colourless, odourless and highly flame-resistant gases, primarily carbon monoxide and hydrogen. It has various applications. The syngas can be converted exclusively into hydrogen and CO_2 by introducing steam and a catalyst into a hydro-gas shift reactor. When hydrogen is combusted in the exhaust gases, it generates only heat and water, leading to the absence of carbon dioxide emissions. Moreover, hydrogen derived from coal or alternative solid fuels can be utilised in the process of oil refining or in the production of commodities like ammonia and fertiliser. Significantly, syngas can be utilised to produce gasoline and diesel fuel by including hydrogen. Gasification technologies are exclusively employed in poly-generation plants, which produce multiple products. Carbon dioxide can be efficiently absorbed from syngas, preventing its emission as a greenhouse gas into the atmosphere and enabling its utilisation (for better oil recovery) or environmentally friendly processing.

Gasification offers an alternative to established techniques for converting feedstock, such as coal, biomass and certain waste streams, into power and other valuable products. Gasification can offer benefits to global energy and industry markets, namely in terms of environmentally friendly electricity generation from coal, under specified uses and conditions. The global abundance and stable pricing of coal serve as the primary drivers for the development and implementation of gasification technology. The adoption of gasification technology in the market will be determined by technology placement markets, considering a range of technoeconomic and political factors. These factors include prices, reliability, availability and maintainability (RAM), environmental considerations, performance, feedstocks and product versatility, national energy security,

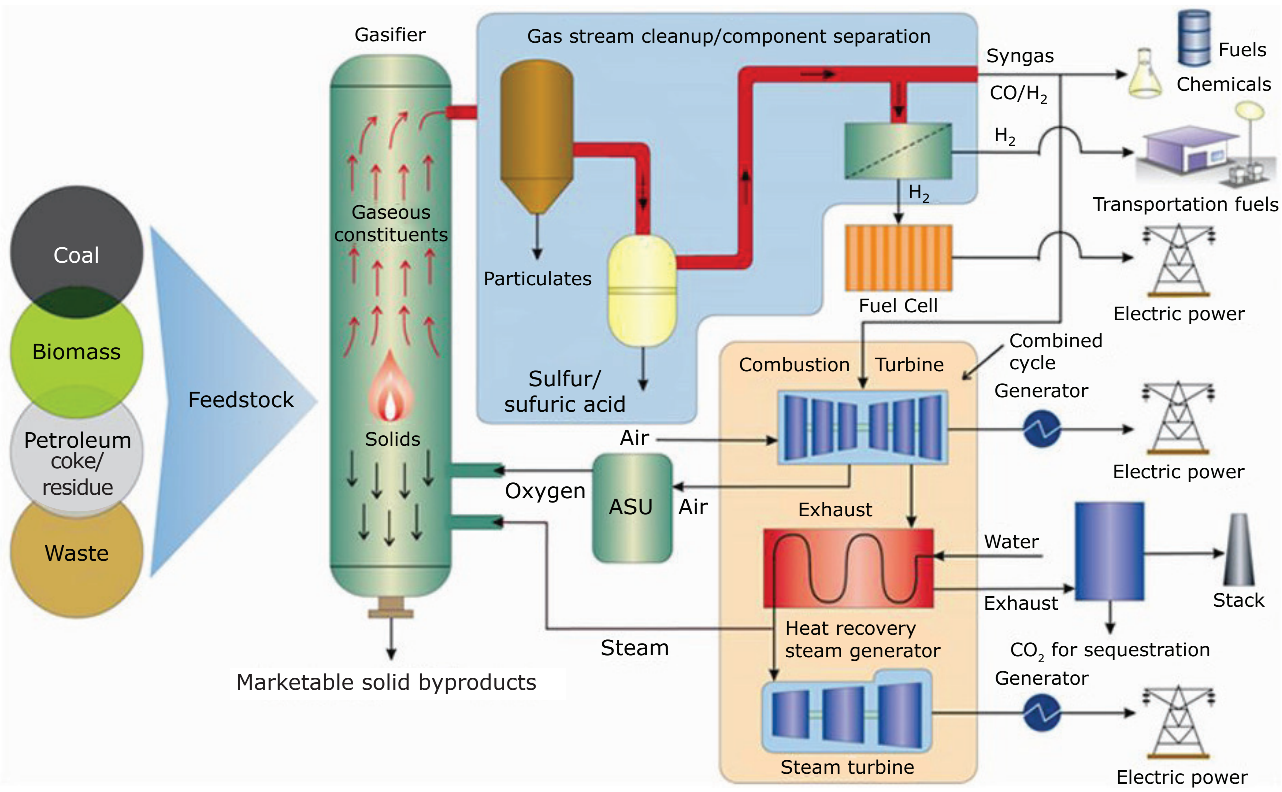

Fig. 4. A method of coal gasification that represents both the versatility of gasification feedstock and the vast range of products and application of gasification technology. Reprinted from (54) under Creative Commons license 4.0 (CC BY 4.0)

governmental policy and public perception. A method of coal gasification that represents both the versatility of gasification feedstock and the vast range of products and application of gasification technology is shown in **Figure 4**.

6. The Products of Gasification Process

Biomass gasification is a thermochemical process that converts biomass into high-temperature feedstocks. This conversion produces energy syngas as well as various chemical substances including methane, ethylene, adhesives, fatty acids, surfactants, detergents and plasticisers (55).

Syngas is obtained from biomass, is utilised in the production of both liquid and gaseous fuels such as methanol, ethanol, DME and Fischer-Tropsch diesel. It serves as a fundamental component in several thermochemical processes for the creation of second-generation biofuels (56–58). Specifically, the composition and calorific content of the biomass, as well as its manufacturing technique, are significantly altered (59–62). The production of liquid biofuels as an energy carrier has the potential to be highly cost-effective, as it can utilise the existing infrastructure, storage and transportation systems for liquefied petroleum gas (34, 63–66).

This review will be continued in Part II (67).

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.

Acknowledgement

MNU acknowledges OnTechUni, NOVA IMS and UTB ve zlin to carry out the research project.

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The Authors

Md. Nasir Uddin is currently undertaking his PhD in Chemistry and Biotechnology at the Swinburne University of Technology, Australia. He has completed an MSc in Engineering with Research from the International Islamic University Malaysia. He is a self-motivated academic researcher with a background in diverse aspects of sustainable energy. Over a span of six years, he served as Assistant Professor at Northern University, where he delivered lectures on sustainable energy, fuels, power and energy management in engineering to a student body of over 10,000. He has been honoured with the Best Paper Award for 2018 from the MDPI journal *Energies*. As a researcher, he has actively participated in several government and industry-funded initiatives. Additionally, he has had the opportunity to conduct research and travel in 60 different countries and to engage with scholars from other disciplines abroad.

Nasrin Akter Nithe is currently undertaking her PhD in Engineering at the OnTech University, Canada. She completed her engineering graduation from Bangladesh. She is a self-motivated academic researcher with a background in diverse aspects of sustainable energy. She now works for Inspectorate of Electronics & Instruments (IE&I), Bangladesh.