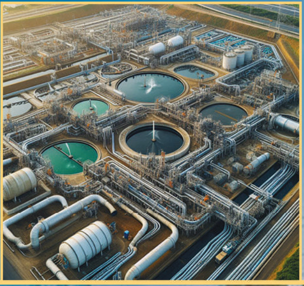

SEWAGE AND BIOMASS FROM WASTEWATER TO ENERGY

Edited By
Inamuddin, Tariq Altalhi,
Mohammad Luqman, and Joseph K. Bwapwa

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Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

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Thermal/Photocatalytic Conversion of Sewage Sludge and Biomass to Energy

Maria Siddique[1], Sumia Akram[2], Zainab Liaqat[1] and Muhammad Mushtaq[1]*

[1]Department of Chemistry, Government College University, Lahore, Pakistan
[2]Division of Science and Technology, University of Education, Lahore, Pakistan

Abstract
Recently, a great deal of research has been devoted to exploring renewable energy sources like sunlight, geothermal, hydropower, and bioenergy. Many developed countries like the United States of America are getting more than 20% of their energy needs from renewable sources and biomass can work as a fascinating renewable energy source. Biomass and sewage are considered viable alternatives to fossil fuels for sustainable energy production. Thermal and photocatalytic conversion technologies can generate energy from these materials, contributing to cost-effective and sustainable energy systems. Utilizing these technologies could reduce the environmental impact of energy production while creating new opportunities for economic growth and job creation. Additionally, utilizing biomass and sewage for energy production provides benefits such as addressing waste management concerns and mitigating the negative environmental impacts of waste disposal. Challenges and opportunities of biomass energy: The potential of thermal and photocatalytic conversion technologies to generate energy from biomass and sewage has been comprehensively highlighted in this chapter. A thorough examination of the various types of biomass and sewage and their energy content paved the way for scrutinizing the challenges and opportunities associated with using them as energy sources. Further investigation into thermal conversion technologies including pyrolysis, gasification, and combustion, in addition to the photocatalytic conversion process, was carried out. Scrutiny of each technology's respective advantages and disadvantages was done with great detail and analysis.

Keywords: Biomass, pyrolysis, photocatalysis, biofuel

**Corresponding author*: muhammad.mushtaq@gcu.edu.pk

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1.1 Introduction

In recent years, policymakers have been very excited to switch to clean and green energy sources as it not only can help them combat environmental pollution but also provide more renewable energy sources [1]. Meanwhile, rapid industrialization and urbanization have led to a significant increase in global energy demands and a shortfall in fossil fuels. The growing consumption of fossil fuel-based resources for energy has caused several substantial rises in greenhouse gas emissions. These consequences hold immense importance not just for the economy but also for human health [2]. An increase in awareness about future energy and environmental concerns has spurred the utilization of available renewable viable energy sources. Biomass is now regarded as a green renewable energy source owing to its eco-sensitive nature, transformability, and, cost-effectiveness [3–5].

As cities continue to grow and become more heavily populated, per capita energy consumption increases and this may lead to high levels of carbon emissions [6]. The scenario becomes more alarming in countries such as China, Pakistan, India, Indonesia, and other certain parts of the world which totally rely on fossil fuels for their energy demands. With dwindling global oil reserves, treating and recycling copious amounts of wastewater produced by these so-called 'megacities' offered new horizons of challenges. Many countries have successfully switched toward solar energy but this technology remained limited to regions of intense and longer sunlight which is not the case with many countries like Russia and other European nations [7, 8]. Consequently, a single energy source may not work fine for all nations and we need a hybrid energy system. For example, countries situated beside oceans like Brazil can exploit algal biomass as a viable source of energy. It has been estimated that algae can produce 30 to 100 times more biomass than that is produced by other photosynthetic sources on Earth. Meanwhile, researchers claim large-scale production of algal biomass is associated with more carbon conversion/capturing present in the air [9, 10].

Although the exact definition and composition of biomass vary from country to country and source to source (Figure 1.1), we, in this monograph, are going to treat the underutilized agricultural residues, seaweeds, organic pollutants, and livestock residues as biomass. In a broader sense, biomass refers to a wide array of living entities that are obtained from the process of photosynthesis [11], including organisms of the plant, animal, microbe, and some byproduct classifications [12]. Various types of biomass

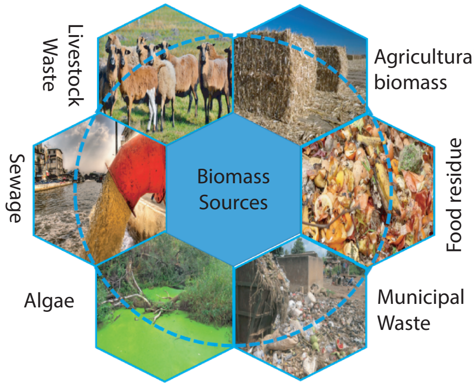

Figure 1.1 The key biomass/waste residues that can be exploited as alternative energy sources.

waste may comprise dissimilarities, for instance, agricultural waste forms encompass straw, crops, wood chips, and animal byproducts [13, 14]. Furthermore, industrial organic wastes include textile and food processing wastes, leftovers, and organic wastewater [15, 16], whereas municipal solid wastes cover food and kitchen waste, as well as domestic waste.

In countries undergoing rapid urbanization and an increase in population, the conversion of municipal waste into energy/electricity has been an essential area of research. The global annual municipal solid waste production is anticipated to be reached around 2200 million tons by 2025 as per the World Bank report [17]. The utilization of solid waste as an alternative energy source especially biomass and bio-solid wastes can help us to resolve not only waste management issues but also improve associated social and environmental standards [18, 19]. In another report, the yearly amount of worldwide solid waste production is estimated at 2400 million tons and is projected to reach above 2600 million tons in the next 6 years [20]. Furthermore, wastewater treatment plants produce around 1000 tons of solid waste each day [21]. With the proper technology, loads of energy required for the process can be minimized and also utilized for the production of sustainable energy sources.

1.2 Biomass as Energy Sources

Sewage and biomass are two promising renewable energy sources that have gained the interest of researchers, lately. Sewage or wastewater is an abundant source of organic matter along with other potentials; it can be useful in producing renewable energy such as biogas. Because sewage contains numerous complex components, it cannot be processed directly for energy production, rather it is required to be converted into a suitable form called sewage sludge [22, 23]. Therefore, the residue obtained from wastewater treatment is known as sewage sludge [24]. Sewage sludge can be distinguished both quantitatively and qualitatively, depending on the specific characteristics of the wastewater being processed and the approaches used for treatment. This process is relatively energy-intensive and definitively requires resources. This residue has long been classified as non-useful and often discarded in landfills [25]. A recent perspective regarding wastewater treatment approves of its conversion into energy and other useful products. It has been estimated that sewage sludge can potentially fulfill about 10% of our power demands as an alternative energy source [26, 27]. However, implementation of these perspective technologies is associated with high capital investment and needs considerable land area for sludge disposal. On the other side, sewage sludge production will keep growing with the population, and industrialization and its eco-friendly and sustainable management may cost much more particularly in developing countries [28].

Wastewater treatment plants are responsible for the sanitation of sewage water by separating its components, i.e., solids and minerals. It is also worth knowing that sewage sludge is an unavoidable material residue created at WWTPs, with significant amounts being created on a worldwide basis. According to the statistics, the annual dried sewage production of some countries was as follows: for the United States, it was 6.5 million tons in 2004 [29]; for China, it was almost 6.25 million tons in 2013 [30]; and for the European Union, it was 13 million tons in 2020 [31, 32].

Biomass is a popular phrase that relates to plant-derived and biological waste materials. However, the concept can include any sort of organic material. The total estimated production of carbon is 105 billion metric tons annually, evenly divided between terrestrial sources and oceans (algal biomass). Despite the fact that algal biomass constitutes a major part of world biomass volume, *wood* remains the primary biomass source used in various applications. Wood sources (cover forests) are often utilized for power generation and biopower, while agricultural remains like sugarcane bagasse, rice straw, cotton stalks, and wheat straw are classified as biomass [33–35].

Biomass can be employed as a powerful energy source to mitigate environmental risks associated with waste disposal and establish a sustainable and renewable energy alternative [36]. Bioenergy is another term used to refer to energy that is derived from biomass resources. It takes a series of stages, which include harvesting, drying, storage, moving, conversion, etc., to convert biomass into an energy source that can be utilized.

The direct combustion of wood and biomass has been used as an energy and heat source since prehistoric times. However, the conventional burning/incineration of agricultural residues causes a variety of environmental issues and their transformation into biofuels via a variety of processes (chemical, biological, and physical) renders them a renewable energy source. In many countries, the open burning/combustion of agricultural residues like sugarcane bagasse, rice straw, cotton stalks, and wheat straw is a punishable act [37]. Likewise, planned deforestation or accidental forest fires cause a variety of environmental issues. On the flip side, rural areas of many underdeveloped countries use agricultural and livestock biomass as energy/heat sources in houses, factories, and mills. The only thing that needs to be pointed out here is that direct conversion of agricultural, livestock, domestic waste, or industrial waste (paper and plastics) causes a variety of known and concealed environmental issues and health issues. For similar reasons, agriculture biomass, livestock waste, and municipal waste are subjected to controlled pyrolysis, anaerobic digestion (AD), gasification, and fermentation for the cogeneration of heat and electricity [38]. The algal biomass can work as a fascinating alternative energy source as its production involves the uptake of carbon dioxide and does not need valuable arable land and fresh water. The seaweeds have been successfully transformed into biofuel; however, another school of thought believes that algal species have the potential to be used as superfoods for human and animal consumption.

1.3 Biomass Types and Energy Content

The waste is a fusion of municipal and industrial materials, normally composed of sewage sludge, regular waste, food waste, shrubbery, paper items, latex, fabrics, firewood, debris, and soil. The biomass in contrast covers seaweed, food, and agricultural wastes, and a fraction of domestic or industrial refuse that contains carbon and hydrogen. The exact ratio of components in any waste collected from one location can differ from other sites [39]. Biomass often denotes a form of waste residue derived from sources such as firewood, timber, crops, aquatic plants, shrubs, municipal waste, and human waste. The exact composition of biomass depends upon its source, i.e., agricultural residues mainly consist of cellulose, hemicellulose, lignin, and trace amounts of minerals, vitamins, and extractives [40].

Besides, legal regulations, lifestyle and seasonal elements, preparation, and recycling procedures cause waste streams to vary with time. Underdeveloped nations often have waste that predominantly consists of decomposable material in comparison to plastics. Likewise, municipal waste may be rich in pigments, plastics, glass, and other nonbiodegradable materials. For the production of energy, chemical manufacturing, and biofuel production, it offers more benefits than traditional fuels [41]. According to the International Renewable Energy Agency (IRENA), biomass is expected to become one of the leading renewable energy sources by 2030. According to their roadmap, biomass is capable of meeting up to 60% of global energy consumption [42]. In many developed countries like the United States, biomass contributes more than 2% of renewable energy sources; however, for countries like Brazil which produces more than 20,000 tons (algae year^{-1}), the contribution of biomass as an energy source may exceed.

The use of biomass and other organic waste materials as renewable energy sources has become a fascinating choice for the global energy supply and it has already accounted for about 20% of the global energy production, securing its position as the fourth-largest energy source [27]. Biomass-based sources have been extensively explored to meet our energy demands for the past 30 years, and they can be speculated to be the top energy source fulfilling over half (~56%) of the demands as compared to renewable sources [43]. It has been also anticipated that clean energy sources like biofuel will cover 2 to 27% of our energy source in the immediate future [44]. Organic contents of sludge are typically made up of proteins (24 to 42%), carbohydrates (7 to 18%), and lipids (1 to 14%). The chief functional groups of such organic compounds comprise carbonyl moiety, carboxylic acids, different amines, amides, some aromatics, and methyl. In underdeveloped countries of Asia and Africa, biomass can account for around 33% of the total energy needs [45]. The widespread accessibility of biomass as an energy source makes it advantageous compared to other conventional energy sources [46].

1.4 Conversion of Biomass to Energy

Incineration has been applied for years to destroy hazardous materials or contaminants. For many years, the incineration of organic material has been applied to produce a stream of gasses or heat to run turbines and produce electricity. Nowadays, thermal and photocatalytic methods have been applied to initiate a chemical reaction for the conversion of biomass into energy. Thermal processes use heat to change organic matter into energy, whereas photocatalytic processes rely on light to initiate chemical reactions that generate energy afterward. The power generation system nowadays utilizes waste as fuel and produces energy from the abundant materials present in trash gathered from both residential and industrial sources. As the exact composition of waste or biomass varies with location, the exact incineration, thermal, or photolytic conversion process varies widely [39].

1.4.1 Thermal Conversion of Biomass to Energy

Figure 1.2 illustrates the general way out for the thermal conversion of biomass into a set of products. Despite having an effective system of recycling and reconversion of wastes, many biomass or waste ingredients are hard to break, it is important to have an exact composition of biomass for effective conversion [47]. A variety of approaches are used to convert solid waste into something more beneficial to the planet, including hydrothermal liquefaction [48], pyrolysis [49], and gasification [50]. The key objectives have to apply biological, chemical, or thermal approaches to generate heat and electricity. Using fuel produced from waste materials can have a smaller environmental impact than burning fossil fuels [37]. The energy production from the waste can solve the solid waste disposal issue and produce electricity. For example, during thermal conversion, the wastewater is heated to high temperatures that then generate gasses, especially methane,

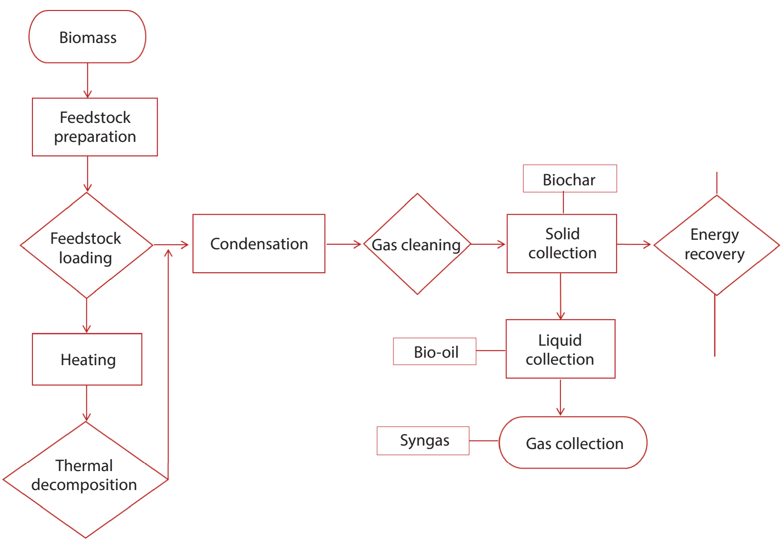

Figure 1.2 Process identification diagram for traditional thermal conversion of biomass.

and hydrogen as byproducts that further act as fuel to generate electricity and heat. However, the method uses a substantial amount of energy in getting high temperatures, making it generate harmful air pollutants.

In contrast, the photocatalytic conversion uses less energy to decompose the organic material in the wastewater. This method produces hydrogen gas and CO_2 which can serve as fuel. Photocatalysts (such as titanium oxide) offer several advantages over traditional thermal conversion such as minimal energy input, reduced pollutants, and higher conversion efficiency. The wastewater even has the potential to be transformed into energy using diverse methods mainly in the presence of catalysts, heat, and/or light. However, it is still in the experimental stage, and further research is necessary to improve its efficiency and scalability.

1.4.1.1 Combustion/Incineration

The incineration process involves burning and converting feed materials into beneficial products. This generates heat that can be used in vapor-based turbines and heat exchangers to generate power. The temperature range is in the vicinity of 800°C to 1000°C. Practically, the biomass rich in organic (carbon) that has been dried and holds a water level of less than 50% can be burned in the process [51]. The biomass with higher water levels is usually transformed into energy through biological means. Incineration can decrease the volume of solid waste by 80 to 85% [52]. However, this technique has been around for a long time and is associated with toxic airborne discharges, including dioxins and heavy metals. Also, the inorganic contents like arsenic, mercury, cadmium, and uranium in the ashes which cannot be burned can be dangerous to one's health [53].

1.4.1.2 Hydrothermal Carbonization

This technique involves temperature-based conversion and has captured the interest of many researchers, particularly attractive to scientists working with waste materials that have a moisture content higher than 80 to 90%. This process is considered a "wet" process as it transforms different kinds of waste into a usable energy source subjected to consistent pressures and relatively low-temperature conditions between 180°C and 350°C [54, 55]. This process has multiple advantages such as larger waste handling capacity, removal of odors along with contaminants, and shorter incineration period. Furthermore, an increase in the temperature of the procedure can decontaminate various hazardous materials. The byproducts and certain nutrients can be used for the production of gasses and fertilizers.

The hydrothermal carbonization process simultaneously causes hydrolysis, condensation, dehydration, and decarboxylation in the damped raw material [56, 57].

1.4.1.3 Biomass Pyrolysis

Pyrolysis is the thermal decomposition of material in an oxygen-free environment by using an external heat source to keep the temperature between 300°C and 850°C. The expression pyrolysis is derived from the Greek words 'pyro' signifying fire and 'lysis' implying disassembly or breaking into separate parts. The result of this process is typically char, solid residue, and a blend of carbon and ash. It is also possible to condense the product to yield tar, crude wax, lubricants, and oil. On average, the syngas created from pyrolysis contains a net calorific value of 10 to 20 MJ/Nm^3 [58].

Pyrolysis has grown significantly popular due to its adjustable nature, aptitude for using many different feedstocks, and possibility for varied outputs. During this process, which does not require oxygen, heat is applied from outside sources, and biomass components are broken down into gasses and vapors which usually have subsequent reactions, thus providing a broad scope of results. The circumstances that can have an immense influence on both the products and the process performance consist of feedstock, technology, reaction temperature, accompaniments, accelerants, vaporization stay time, solid stay time, and pressure. For thousands of years, pyrolysis has been utilized to create charcoal, yet only within the past 35 years have efforts been made to invent rapid pyrolysis for the production of liquids. Such pyrolysis needs to occur at approximately 500°C for a very brief period of time with the vapor's stay in this hot area lasting less than 2 s. This kind of quick pyrolysis is of particular fascination because it can produce liquids in high yields of up to 75 wt% [59]. The slow and intermediate pyrolysis process centers on the production of dry char and biomass, which can be directly utilized in a wide range of applications, offering energy density and/or serving as a biofuel source. More attention is now being paid to maximizing the resulting products. This method of burning has been practiced for more than seven decades in order to reduce the amount of disposed waste while making the remainder less ecologically damaging.

Thermochemical conversion of biomass takes place through pyrolysis, gasification, liquefaction, and combustion. Pyrolysis is the origin of all of these conversions, which breaks a compound down into solid, liquid, and gas components with no oxygen. Particular importance is placed on the technologies that can create either gaseous or liquid products which can be improved to become useful energy sources such as electricity and transportation fuel.

When placed inside a reactor and heated, the organic elements in the wastewater sludge commence transforming at around 200°C, leading to volatile products and a nonvolatile solid byproduct known as char created by several breaking and forming processes [60]. Primary pyrolysis and the vaporization of moisture contained in a material are both essential initial steps for all of the processes involved in transforming something through chemical reactions with heat, including burning, generating gas, forming a liquid, and changing the composition of carbon.

1.4.1.4 Noncatalytic Pyrolysis

Pyrolysis is an advantageous way to treat sewage sludge because it changes the solids in the sludge into biochar, bio-oil, and gasses (such as hydrogen, carbon monoxide, and some other frothy gasses) while emitting only a small amount of pollutants in a temperate to moderate temperature range, in the absence of oxygen. Specifically, pyrolysis involves thermally breaking down the sludge solids at high temperatures (400°C to 600°C) in an oxygen-free environment, to obtain the required output. Pyrolysis can be of various types including slow, fast, hydro, vacuum, and flash pyrolysis [61, 62]. Crucial elements that can affect the pyrolysis operation include heating rate, feedstock size, duration of residence of reactant, and temperature. Pyrolysis has been utilized to treat various feedstocks such as plastic waste, municipal solid waste, oily sludges, sewage sludges, and woody biomass.

1.4.1.5 Slow Pyrolysis (Carbonization/Torrefaction)

Slow pyrolysis (carbonization/torrefaction) typically comprises temperatures below than 400°C. The goal of this process is to condense moisture and densification, and also make the material more grindable. Generally, slow pyrolysis results in a greater volume of char and lower amounts of bio-oil and gas. The solid that is left behind is referred to as charcoal. The carbonization process eliminates the presence of NO_x, SO_x, and additional contaminants along with the densification of sludge and also raises the C/H ratio and calorific value [63, 64]. When sewage sludge is burnt at 900°C, it produces a noteworthy decrease in NH_3 (46%) [65]. Furthermore, sewage sludge or biomass can be mixed and burned to form a large biochar product. Factors of importance to assess include balances of energy and mass to identify the productivity of torrefying sewage sludge.

1.4.1.6 Rapid/Fast Pyrolysis

This type is employed for the conversion of sewage sludge into different bio-oil products. It differs from slow pyrolysis in its heating rate, stay time, and temperature range (400°C to 600°C). The fast pyrolysis of biomass produces more bio-oil [66]. Bio-oil produced via fast pyrolysis of sewage sludge mainly comprises hydrocarbons, organic acids, high molecular weight carbonyl compounds, phenols, ketones, a broad range of both aliphatic and aromatic compounds, acetic acid, different alcohols, nitrogen, and sulfur-containing compounds along with water [22, 67–69]. The bio-oil is found to be more eco-friendly than traditional heavy fuel oil, as it contains additional constituents and has higher moisture levels thanks to the presence of oxygenated compounds that divide it into two fractions, one lighter, and the other with a higher concentration of organic oil. The organic phase which is lightweight largely consists of water, with the heavier one being abundant in benzene, toluene, styrene, naphthalene, phenol, and so forth. The mean heat energy value of bio-oil (30.1 MJ/kg) is less than fuel oil (40.2 MJ/kg). Due to pyrolysis, the heat energy of the bio-oil becomes low and the resultant product is typically used for combustion and heating purposes, although the small heat energy acts as a hindrance to this method. Research on how to improve the quality of bio-oil has been conducted to raise the C/H ratio and diminish oxygen concentration.

The gas stream released as the result of sewage sludge pyrolysis consists of lighter gasses such as hydrogen (H_2), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), ethylene (C_2H_4), propane (C_3H_8), and butane (C_4H_{10}) with energy values of 32.2 MJ/kg for bio-oil, 12.3 MJ/kg for char, while 25 MJ/kg for gas, with the process taking place at 500°C [70]. If a higher temperature is used during the pyrolysis, the quantity of gas rises; though at the same time, increasing the possibility of emissions such as nitrous oxide (NO_x), sulfur oxide (SO_x), tar, polycyclic aromatic hydrocarbons (PAHs), and particulate matter (PM). The percentage of PAHs in sludge products of pyrolysis at different gas residence times and temperatures of 1000°C can rise from 1.14 wt% up to 6.33 wt%, thanks to high flow rates of the gasses produced. These pyrolysis gasses may have reduced energy content when heated in a medium to low range, yet they still have the possibility of being used to generate heat [71, 72].

The char obtained from the rapid thermal decomposition procedure includes a combination of carbon and has been utilized as an adsorbent due to possessing a very large exterior area or for more utilization in the generation of syngas and chemicals in the process of gasification. The heating values of the chars mainly vary according to their basic material, and the readings generally range from 11 to 15 MJ/kg [72].

1.4.1.7 Co-Pyrolysis

Incorporating alternative feedstocks alongside sewage sludge through co-pyrolysis proves to be a beneficial approach for improving both the quantity and quality of obtained pyrolysis outcomes. Among the feed fuels, reported to be used with sludge in such pyrolysis are pinewood saw [73], microalgae [74], wood dust [75], paddy straw [76], wheat chaff [77], bamboo wood dust [78], compost [79], filbert shell [80], wool + stalk [81], cannel shale/fossil oil [82], lignite coal/brown coal [83], megass [84], and waste wood [85]. Such feed fuels raise the output of H_2, CO, and other gasses, boost the texture of biochars, and help take out oxygenated rainwater and different pollutions in the bio-oil. Organic sources like bagasse, wheat chaff, paddy straw, and filbert supplement additional mass reduction at 200°C to 600°C heat range rather than the sludge, so this can set off the dismantling of volatile matter and a rise in the supply of oil and gas.

1.4.1.8 Gasification

Gasification (Figure 1.3) lies between pyrolysis and combustion in terms of its processing temperature; it requires oxygen, air, steam, or a mixture of them and a heat of >650°C [86]. The net heat output of gasification is usually less than that of combustion or incineration, usually in the range of 4 to 14 MJ/Nm^3. The process is exothermal, meaning an external source

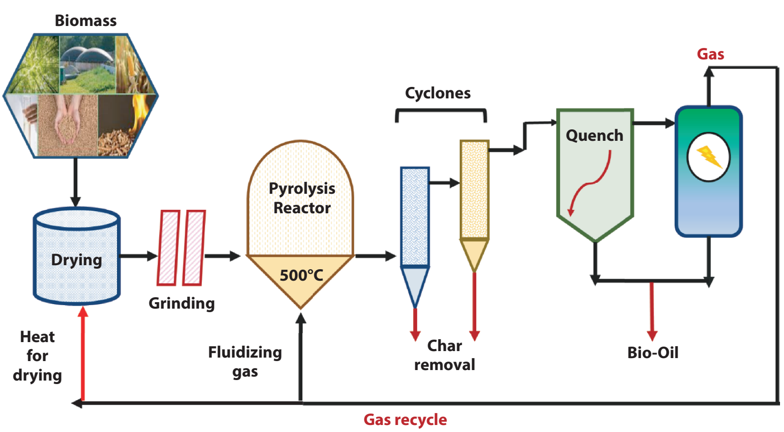

Figure 1.3 Layout for traditional thermal pyrolysis/gasification of biomass.