

Review

# Socio-Economic and Environmental Impacts of Biomass Valorisation: A Strategic Drive for Sustainable Bioeconomy

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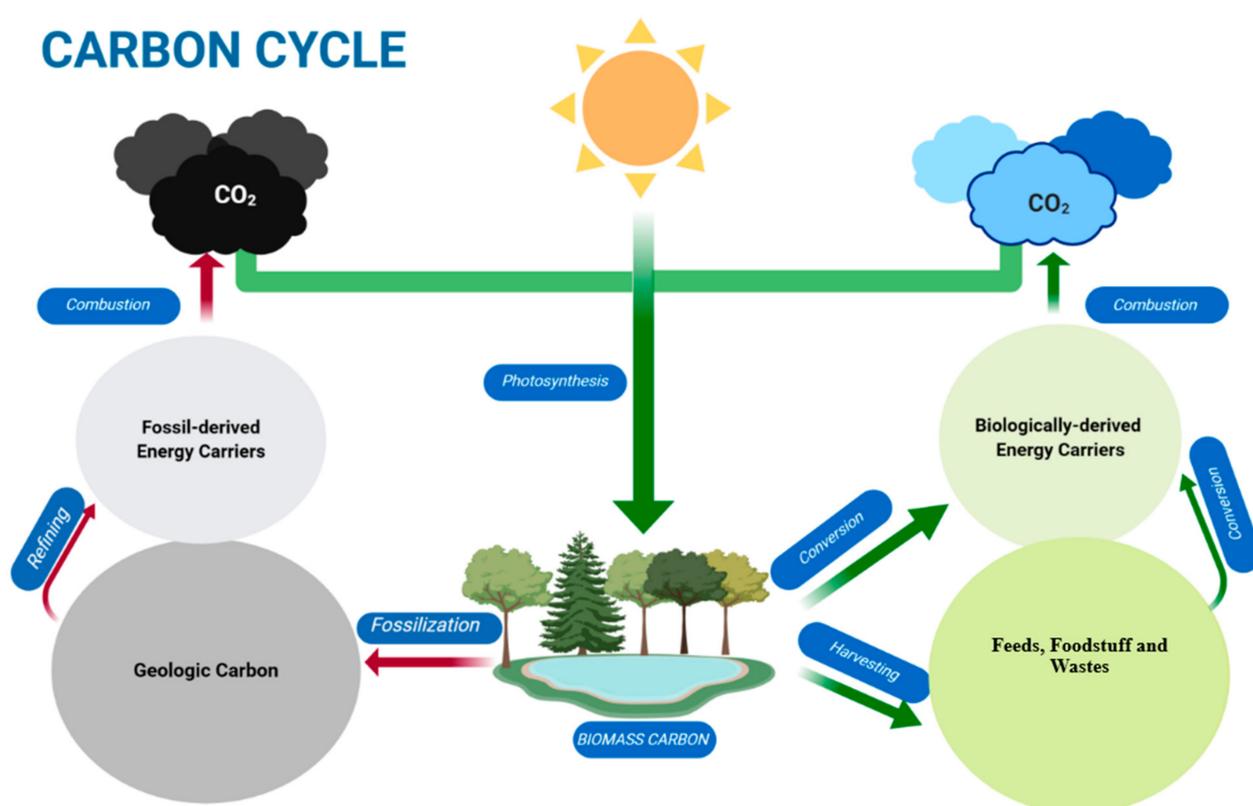
**Abstract:** In the late twentieth century, the only cost-effective opportunity for waste removal cost at least several thousand dollars, but nowadays, a lot of improvement has occurred. The biomass and waste generation problems attracted concerned authorities to identify and provide environmentally friendly sustainable solutions that possess environmental and economic benefits. The present study emphasises the valorisation of biomass and waste produced by domestic and industrial sectors. Therefore, substantial research is ongoing to replace the traditional treatment methods that potentially acquire less detrimental effects. Synthetic biology can be a unique platform that invites all the relevant characters for designing and assembling an efficient program that could be useful to handle the increasing threat for human beings. In the future, these engineered methods will not only revolutionise our lives but practically lead us to get cheaper biofuels, producing bioenergy, pharmaceuticals, and various biochemicals. The bioaugmentation approach concomitant with microbial fuel cells (MFC) is an example that is used to produce electricity from municipal waste, which is directly associated with the loading of waste. Beyond the traditional opportunities, herein, we have spotlighted the new advances in pertinent technology closely related to production and reduction approaches. Various integrated modern techniques and aspects related to the industrial sector are also discussed with suitable examples, including green energy and other industrially relevant products. However, many problems persist in present-day technology that requires essential efforts to handle thoroughly because significant valorisation of biomass and waste involves integrated methods for timely detection, classification, and separation. We reviewed and proposed the anticipated dispensation methods to overcome the growing stream of biomass and waste at a distinct and organisational scale.

**Keywords:** waste to value; bio-residues; bioconversion; renewable; bioenergy; biodiesel; bioactive compounds; polyhydroxyalkanoates (PHAs)

## 1. Introduction

In the 21st century, it has become challenging to provide clean, affordable, and reliable energy sources, which are very important from the socio-economic and environmental perspectives. To manage these crucial problems, biomass is the most favourable renewable source at the moment [1]. Biomass has drawn attention in the latest years as the only

continuous carbon source available on earth. Therefore, it is regarded as a perfect substitute for fossil fuels. The use of biomass is a modern approach for power generation and is considered an excellent neutral resource where CO<sub>2</sub> emissions are reduced. Biomass is an attractive feedstock due to several reasons. Firstly, it reduces greenhouse gas (GHG) emissions and is a new source, which will be established in the future. Lastly, it has the benefit of providing economic benefits to society. However, biomass possesses an adverse effect when utilised in conventional stoves. It emits polycyclic aromatic hydrocarbons (PAHs). PAHs are composed of more than 100 chemicals that include furans (which are toxic to health either inhaled or ingested), volatile organic compounds, and heavy metals [2,3]. Biomass consists of diverse organic materials which contain chemical energy. Green plants generate this chemical energy by photosynthesis, where sunlight serves as an energy source [4]. Figure 1 illustrates the derived carriers of the resultant energy. These carriers utilise biomass and fix CO<sub>2</sub> (i.e., photosynthesis) with a concurrent transformation of solar energy into chemical energy.



**Figure 1.** Model of carbon cycle illustrating how energy carriers are derived from biomass. Biomass carbon is generated via photosynthesis upon fixing atmospheric CO<sub>2</sub> with the simultaneous conversion of solar energy into chemical energy stored in biomass. Biomass carbon could be transformed into several energy carriers through either an environmentally amicable route (shown in green) or an environmentally unfriendly route (shown in red). If biomass carbon, harvested crops, or wastes are converted into fuel, the process is renewable with no atmospheric CO<sub>2</sub> build-up. Conversely, biomass decomposed over several epochs (geologic carbon) can also be partially recovered and utilised. However, the later process is slow, non-sustainable, and potentially harmful to the natural environment.

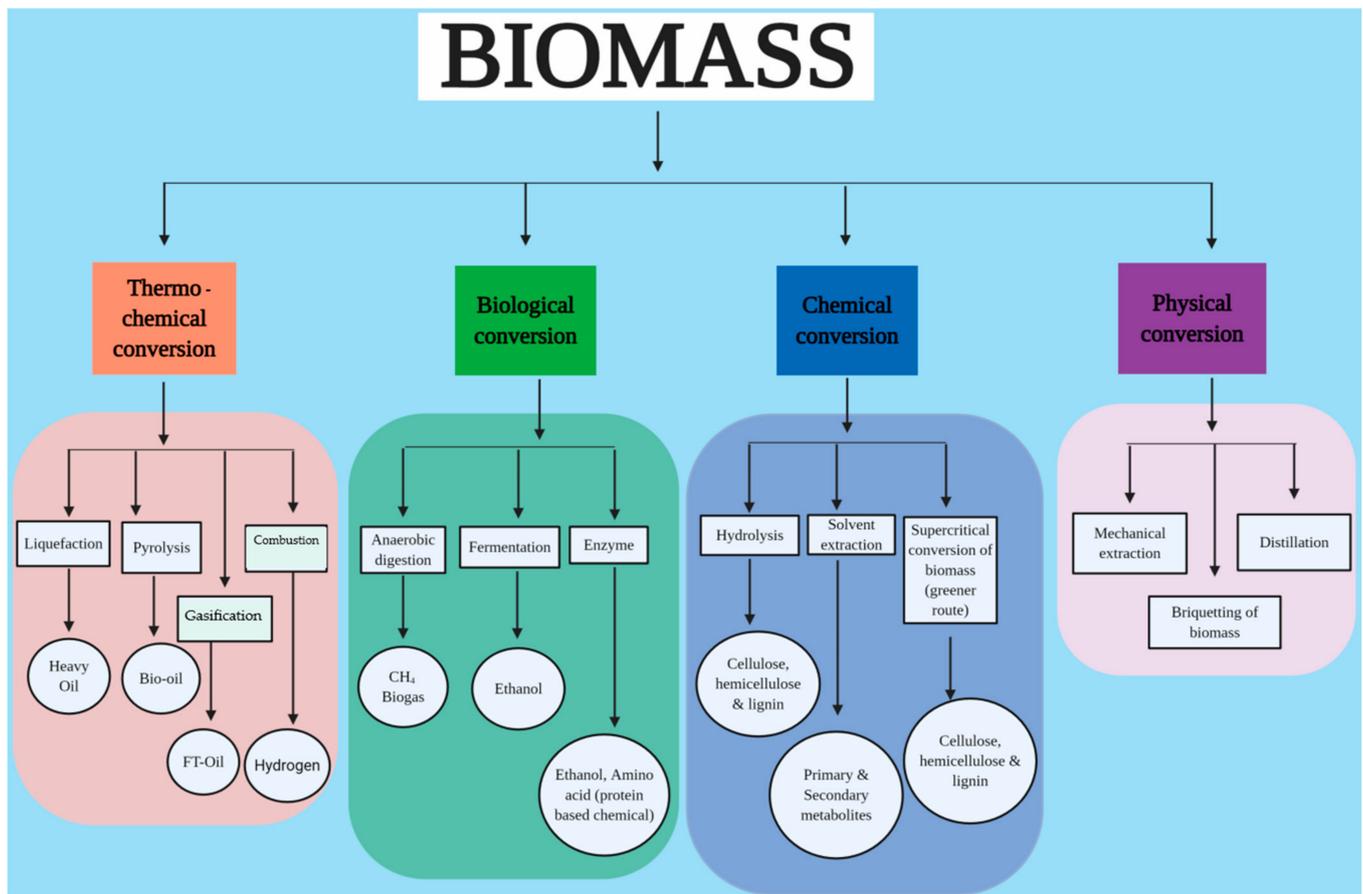
Biomass, if not used for alternate energy sources, may lead to severe hazards to the environment in the form of discarded materials like waste, which has become a striking and crucial problem of civilised human societies [5,6]. In the US, people throw away the waste/garbage equivalent to their body weight on a monthly basis where a significant part of discarded material is composted or recycled and/or incinerated or landfilled. Waste production has increased ten-fold because of the affluent and urban population of the

world, which will double by 2025. Dealing with waste is one of the most critical issues in developing countries, resulting in increased municipal budgets [7]. Landfills like Laogang (China), Bordo Poniente (Mexico), and Jardim Gramacho (Brazil) are competing for the name of the biggest dump in the world. The urbanisation of the world's population increases solid-waste generation around the globe. It is hard to predict the expanding socio-economic trends leading towards the 22nd century. We are putting our efforts to avoid the maximum rate of waste production in this century. Our efforts will be in vain until we decrease people's growth and the rate of consumption material, otherwise, the world will have to bear a growing problem of waste [8].

## 2. Transformation of Biomass and Waste into Bioproducts

The transformation of biomass into biofuels and chemicals increases worldwide moderate energy sources and reduces global warming [9]. Biomass is a neutral resource of renewable energy and generally burns cleaner than fossil fuels [10–13]. Different biomass forms are converted into fuels and chemicals, like wood and timber waste, plants in agriculture, industrial waste, sludge, and waste from food processing. In contrast, wood logs can be used directly. Wood waste is easily recycled and used as fertilizer as sawmill residues, slashed from logging and municipal wood waste by most plants and crops [12].

It is possible to use various procedures to transform biomass into energy and other industrially relevant high-interest products (Figure 2) [13–15]. Biomass can be converted into fuel, biogas, bioethanol, biodiesel, or changed into syngas [16,17]. Bio-refinery, where several significant processes are integrated and joined with downstream upgrades and cultured separations, will be very attractive to get the most out of feed use and product value [18]. The production of biofuels and chemicals by transforming biomass is becoming popular worldwide to expand energy resources and mitigate global warming. The following characteristics, such as renewable natural sources and carbon-neutral sources, underpin the significance of the biomass. Moreover, resultant fuels acquired from biomass are an important source of sustainable energy because they burn cleanly compared to fossil fuels. Evaluations of the estimated contribution to global energy (i.e., biomass) range from a minimum of 100 EJ/year to a maximum of 400 EJ/year [9]. For example, the total consumption of energy in the USA is around 100 EJ/year and, in 2005, the global commercial consumption of energy was 440 EJ/year. Primary sources of this energy were hydroelectricity, natural gas, oil, coal, and nuclear energy [19]. This means that biomass could contribute between 20% and 90% of world energy demand.

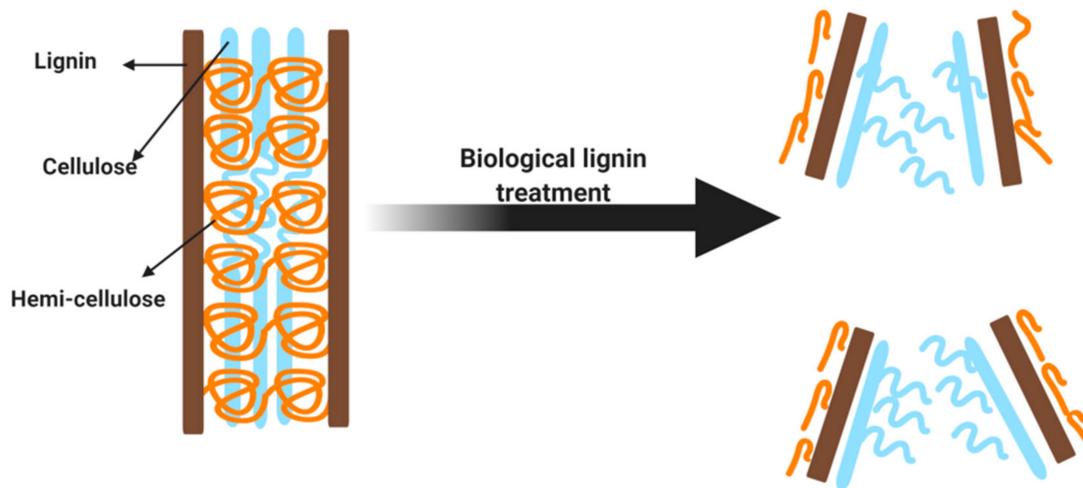


**Figure 2.** The biomass conversion process and their resulted products of industrial interest.

### 3. Sources of Waste/Production of Biomass

#### 3.1. Agricultural Aspects

In agricultural production systems, large quantities of harvested crop residues are generated. The cultivation of wheat, rice, vegetables, fruits, and other crops creates substantial amounts of residues essential for the yearly production of biomass. Therefore, biomass produced from agriculture significantly enhances the generation of sustainable energy used in the industry and the domestic processes [15,20–22]. Unused biomass from agricultural sources can be split into two categories: (1) parts of the plant kept in the field, (2) loss of plant components owing to harvesting techniques. However, all types of residues could not be used for biomass in the past. Nowadays, such biomass residues can be used for many purposes like biofuels (biogas/bioethanol) or energy production and forage, which contribute significantly to a country's economic growth [23–25]. In horticulture, fruit plants, particularly drupes, have endocarp tissues. A drupe fruit's endocarp is the hard and uneatable portion of the fruit, whereas the eatable part is mesocarp. The woody biomass of drupe endocarp is the leading lignin source that usually generates 50 percent of the total [26–28]. Lignin has a greater energy density than cellulose as a biofuel. Lignin plays an essential role in energy production by using endocarp of fruits in horticulture [29–31]. Lignin degradation and the function of the pre-treatment are graphically represented in Figure 3.



**Figure 3.** Schematic of the role of biological pre-treatment in biomass lignin degradation. The initial step of lignin biodegradation is when the oxidative enzymes induce new functional groups into lignin’s macromolecular structure, making lignin vulnerable to other enzymes’ consequent degradation. The natural form of lignin has numerous different functional groups that could be specifically functionalized.

### 3.2. Industrial Aspects

Microorganisms can be used for biomass production in industry. Particularly yeast which serves as biocatalysts and used in bakeries, lactic acid (used as starter culture in manufacturing of dairy products), breweries, probiotics, aqua and animal feed production [32,33]. On a large scale, fermentation can be used with economical substrates and products for biomass production. These economical substrates include soya bean meal, sugar cane molasses, and various industries’ wastes [34–36]. Solid biomass is preferred to use in the industry. Liquid waste and biogas are also used in industrial applications, but particularly solid biomass is important for the past 7 years. In other countries, 80 percent of the global biomass has significant application in industry. Most of the industry’s biomass is obtained from forests in the United States and mostly black liquor [1]. In Sweden, 41 percent of the industries consumed biomass in 2010. The Finnish timber processing sector accounted for 54 percent of total industrial power consumption in 2010. In particular, wood-based biomass is used by the wood processing sector, which accounted for 45 percent of total industrial power use in 2010.

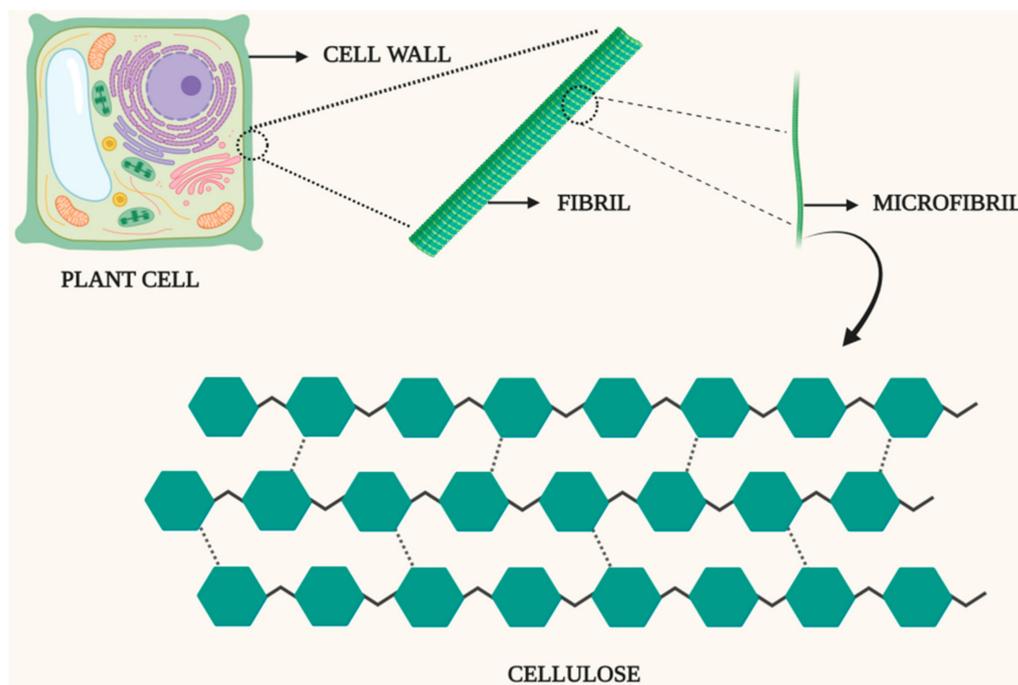
### 3.3. Domestic Food Waste and Considerations

Economic growth is facing pivotal problems worldwide due to increased waste products that cause energy loss, damage to the environment and human health, and adversely affect quality of life [37,38]. The European Union’s goal to discover an effective source for the “Recycling Society” can be a better resource to prevent waste generation. Biological waste is the most significant portion of municipal solid waste (MSW), primarily food waste [39,40]. As a result, the rise in the population increased the utilisation of food, and the production of waste (i.e., food waste) is also expected to increase substantially. Food waste is primarily controlled at the EU level by the Waste Framework Directive [41]. Therefore, it is evident that efficient and alternative methods of handling biodegradable waste generated in homes need to be found [36,42,43]. Domestic composting and anaerobic digestion are both familiar, distributed, and compact processes. Still, they fail many times and cause more problems than fixing them, such as odours and greenhouse gas (GHG) emissions [44,45]. Approximately 23% of the 4.8 million tons of municipal solid waste produced yearly are reused (mostly waste from packaging), however, the remaining 77% are disposed of without proper treatment. In the shortage of new innovative projects, the proportion of produced waste is expected to increase continuously with severe environmental issues in the foreseeable future.

#### 4. Characteristics and Composition of Biomass

There is a broad range of produced biomass, thereby there are significant variations in the composition of industrial or domestically generated biomass. Cellulose, hemicelluloses, lignin, starch, and proteins are some of the main elements [46–49]. **Cellulose:** A polysaccharide where  $\beta$ -glucoside bonds evenly connect D-glucose. Organic compound cellulose is an important component in the primary cell wall of the plants. It supports the structural assembly of the cell wall [50,51]. Cellulose assembles into unbranched and long micro fibrils that provide supports. Several bacterial species secrete cellulose to facilitate biofilm formation [52]. Its molecular formula is  $(C_6H_{10}O_5)_n$ . The polymerisation degree stated by  $n$  is broad, ranging from thousands to many tens of thousands. A schematic illustration of plant cellulose is given in Figure 4. **Hemicellulose:** Hemicellulose comprises several heteropolymers. It is a polysaccharide with 5-carbon monosaccharide units including D-xylose, D-arabinose, and 6-carbon monosaccharide units which have D-Galactose, D-glucose, and D-mannose. Hemicellulose possesses a lower molecular weight than cellulose and has a less specialised structure than cellulose [53–55]. Hemicellulose is known as a second main component of the biomass from the plant. The industrial use of hemicellulose has expanded with time and the integration of modern techniques into the existing methods. **Lignin:** A compound whose constituent units, phenyl-propane, and its derivatives are 3-dimensionally linked. Cellulose, hemicelluloses, and lignin are widely discovered in many types of biomass [55]. A network of irregular polymers that consists of cellulose and hemicellulose fibres is recognised as lignin. The said network provides structural support to the plants. The irregular formation and complex structural identity make its exploitation challenging in the industry sector. The complex structure is impervious to most of the chemical and hydrolysis treatment methods. Plant biomass chemical composition differs between species. Generally, crops are comprised of about 25 percent lignin and 75 percent carbohydrates. The percentage of carbohydrates is composed of many sugar molecules in the form of polymers. There are two distinctive categories: cellulose and hemicellulose. The moisture content is considered the most significant property of biomass feedstock. The moisture content negatively affects the fuel's energy when used for incineration and other processes (e.g., thermo-chemical) [13,14]. Dry biomass has a higher heating value because it utilises little energy to evaporate any moisture. There is a direct association between the energy ratio and humidity, an increase in humidity entails less energy [14,56,57]. Biomass materials contain a certain amount of humidity, from 10% for a dried straw to over 50% for new cut timber [58].

**Carbon:** Biomass carbon content is around 45%, while coal has 60% or higher. A greater carbon content results in a higher heating value [58]. **Hydrogen:** Biomass hydrogen content is about 6% [59]. A greater content of hydrogen results in a greater value of heating. **Nitrogen:** Biomass nitrogen content ranges from 0.2 percent to over 1 percent [59]. Fuel-bound nitrogen is responsible for most emissions from the biomass combustion of nitrogen oxide (NO<sub>x</sub>). Lower nitrogen content should result in reduced emissions of NO<sub>x</sub> in the fuel (e.g., diesel). **Sulphur:** Biomass fuels have a sulphur content of less than 0.2 percent, with a few exceptions as elevated as 0.5–0.7 percent. Coals range from 0.5 percent to 0.75 percent [58]. **Chloride:** Biomass combustion with elevated levels of chloride may result in enhanced fouling of ash. The boiler tubes' high chloride content results in hydrochloric acid formation, leading to corrosion resulting in pipe failure and water leakage in the boiler.

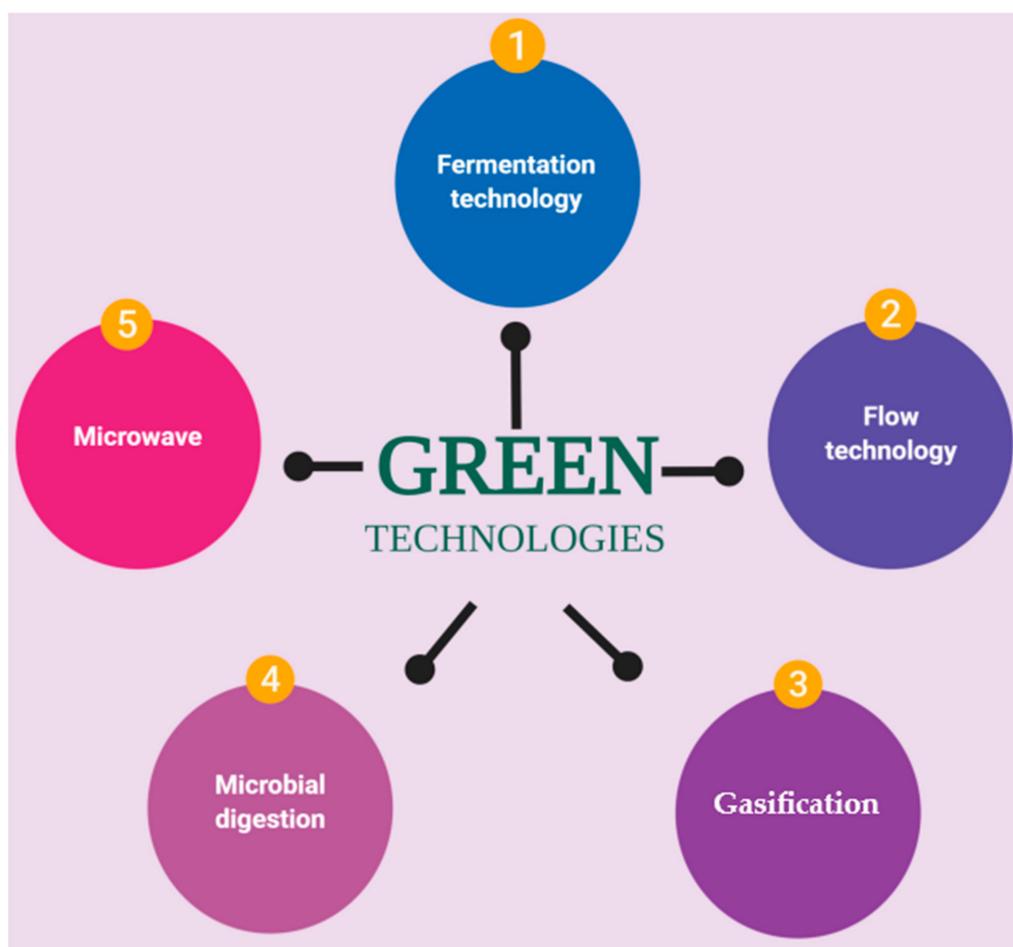


**Figure 4.** Schematic illustration of plant cellulose.

## 5. Green Technologies for Biomass and Waste Valorisation

Waste valorisation is a process that converts waste materials into valuable products like chemicals, fuels, and materials. The waste valorisation concept relies on the thought; the waste products contain unused polymeric products that can convert into energy and different forms of chemicals [60,61]. These types of products make the waste residues a valuable source that could not be left unharnessed. This idea can be applied to artificial waste or bio-waste, and it will become the basis of the waste-to-energy approach. Waste valorisation is not magnificent because of the deletion of natural resources, but it is much-needed technology for waste management and renewable energy production and also produces high values of nano-bioplasic products and ethanol, which are cost-effective and sustainable [62]. Figure 5 illustrates a graphical representation of green technologies applied for biomass and waste valorisation.

In this context, waste-to-value (WtV) and, more specifically, waste-to-energy (WtE) have noteworthy potential that should be considered in future considerations prior to the development and implementation of tools like Life Cycle Assessment (LCA), Ecological Indicators (EI), and/or Ecological Footprint Analysis (EFA) [63,64]. Using WtV and/or WtE thematic concepts with a zero-waste approach, fine chemicals and/or valuable energy are produced from waste residues using processes, such as green processing technologies, using organic and inorganic chemicals, genetically engineered organisms, and others. Other technological WtE solutions, such as anaerobic digestion, incineration, gasification, pyrolysis, landfill waste, and agro-industrial waste biomass residues to bioenergy, are considered valuable drivers to optimise the waste supply chain management to strengthens the modern WtE facilities [64]. Some of the technological and in practice strategies are taken as model examples and thus are discussed in the following subsections.



**Figure 5.** Green technologies applied for biomass and waste valorisation.

### 5.1. Fermentation Technology

On a commercial scale, fermentation is used in different countries to make ethanol. The synthesis of ethanol is performed using sugar crops (i.e., sugar beet) and starch crops (i.e., wheat). Starch combines with enzymes to convert sugars, sugars are transformed with yeast into ethanol [65,66]. Distillation of the ethanol is an energy-intensive phase and produces approximately 450 mL of ethanol per ton of dry maize. The strong residues used as a bovine feed form the fermentation method. For boilers or gasification, it can be used as a bagasse fuel. The more complex biomass is converting lingo-cellulosic biomass because long-chain polysaccharide molecules are present and require acid before the sugars are fermented to ethanol [14,67].

### 5.2. Flow Technology

When considering fresh procedures, the elevated amount of biomass's physical and chemical complexity is a major problem. One prospective key to overcoming the difficulty of biomass includes converting it into simpler fractions that are easier to handle in downstream procedures. In a single petroleum industry facility, bio-refinery is the source of chemicals, energy, and fuel production [20,68,69]. These significant biomass derivatives (so-called platform molecules or construction blocks) are comparatively easy compounds with various functionalities in their structures that are appropriate for a range of useful chemical compound transformations [70]. Continuous flow processing enables the response conditions to be better controlled. This is beneficial when dealing with extremely reactive feedstock such as biomass-derived feedstock. Flow processing also promotes scaling up, considering that many biomass procedures are still on the laboratory scale,

which is a significant point. Therefore, the development of flow technologies in the near future will contribute to the marketing of biomass technologies [71,72]. Since the chemical structure of biomass feedstock is usually very distinct from that of the final products, various processing steps are typically needed in such transformations, negatively influencing the process economy. Using stream processing techniques enables chemical processes to be intensified, thereby contributing considerably to technology simplification [73].

### 5.3. Gasification

The gasification process is the partial oxidation of organic/natural products producing syngas at a constant temperature (i.e., 500–1800 °C). The gasification method appears as a char that responds to hydrogen and carbon monoxide with water vapour and CO<sub>2</sub>. In equilibrium reaction, the concentration of steam, CO<sub>2</sub>, hydrogen, and carbon monoxide become stable very fast at the given temperature in a gasifier [74,75], to produce heat or electricity, which is used as fuel through syngas. The gasification agents, which are the combination of carbon dioxide, oxygen, and steam, are used in a gasifier. The gasification process can be used as a cleaner and is a more logical technology than combustion [76]. Before its commercial organisation, biomass gasification must control some barriers. The main application of gasification is to remove tars, problems related to the production and pre-treatment of biomass feedstock, and the effect of biomass properties must be clearly understood [77]. Supercritical gasification of water in wet biomass is an advanced technology nowadays and seeks the attention of all big countries like the USA, Germany, Netherlands, and Japan [78]. Super Critical Water Gasification (SCWG) has the advantage that this technique does not require any dry method for the wet biomass before subjecting to gasification [79].

### 5.4. Microbial Digestion

Microbial digestion of organic matter through metabolic pathways leads to CO<sub>2</sub> and methane formation [80,81]. Biogas is called a combination of carbon dioxide and methane [82–84]. Anaerobic digestion gives renewable energy production possibilities and a higher quality of agro-residue-waste treatment. Recently, this technology became an appealing technique for biodegrading strong municipal waste organic fractions in Europe [85]. The method takes place in well-designed ships called the anaerobic bioreactor/anaerobic digester. A biogas plant includes the entire feedstock, digester, biogas holder, and digestive tank system.

### 5.5. Microwave Technology

Biomass feedstock is traditionally heated with pressure (i.e., ~60–100 bar). The heating activity is carried out between 180 and 200 °C in the closed vessel where oxygen (O<sub>2</sub>) is not present for at least 12 h [86–88]. Through conduction and convection, heat transfer is accomplished through temperature gradients. Potential disadvantages of standard heating techniques include extended periods of residence and surface heating [89]. The microwave hydrothermal carbonization method was suggested to solve these disadvantages. Over the years, microwave technology has been used to substitute standard heating with carbohydrate [90,91] digestion, sterilisation [92], synthesis [93], and recently the dry pyrolysis method of the biomass feedstock to produce char and gas [56,94,95]. Besides the benefit of shorter periods of residence, microwave heating provides fast, selective, and volumetric heating, promoting fresh response paths and appropriate conditions for new products [96,97]. In conclusion, the operational considerations are met by the accurate and well-regulated nature of microwave technology and its prospective portable processing capability (owing to the comparatively small size of a reactor) [98]. The suitability of microwave heating to process human bio-wastes arises from their comparatively elevated water molecule, which is easily coupled with electromagnetic fields that cause “microwave dielectric heating” [99–101].

## 6. Applied Potentialities—A Drive towards Sustainability

Waste and biomass can be beneficial if proper techniques and conditions are applied to them, they can produce a huge variety of products. The world is moving towards the era where green energy is much preferred to fossil fuels. Two major factors that favour the use of green energy are using renewable resources, especially waste, and less pollution. Biomass and waste both possess other applications in different synthetic industries where they are processed as raw materials and supplements to improve the quality of various chemicals. Additional products and how they are synthesised from waste and/or biomass will be discussed in the following section.

### 6.1. Biofuels and Energy Production

Global energy demands have continued to increase since the beginning of the nineteenth century. To overcome these demands, fossil fuels were consumed at a higher rate. This higher rate of consumption imposed a threat of depletion of non-renewable resources of fossil fuels. Moreover, higher fossil fuel consumption increases carbon dioxide concentration hence the air pollution increases [102]. That is why alternative sources of energy are required. This has driven us into a new search to find renewable energy sources with a less negative impact on the environment. Biomass and waste, specifically organic waste, can be used as renewable energy production sources. The term “biofuel” involves bio-butanol, biodiesel, bioethanol, bioether, biogas, biohydrogen, and syngas [103].

**Bioethanol:** In the beginning of this field, sugar and starch crops were used to synthesise bioethanol. Using yeast species, e.g., *Saccharomyces cerevisiae* or *Zymomonas mobilis* six-carbon sugar-based biomass is fermented to produce bioethanol [67,104–106]. Sources used to provide this six-carbon sugar-based biomass are traditional feed stocks that are high in sugar like sugarcane, sugar beet, etc. [107–109]. To replace these traditional feedstocks, lignocellulosic biomass plays an important role. Lignocellulosic biomasses can be attained from these sources: wood chips, agricultural, forest residue, municipal and industrial solid wastes [110,111]. However, using lignocellulosic biomass requires pre-treatment action before its use to enhance the efficiency and yield [112]. The pre-treatment process increases the chances of availability of cellulose and hemicellulose for saccharification. To convert lignocellulosic biomass to ethanol, a biochemical route is taken in which biomass contents such as cellulose and hemicellulose are hydrolysed to release monomeric sugar, and thereby, these monomeric sugars are fermented to produce ethanol [113]. The process in which cellulose contents and hemicellulose contents are hydrolysed is termed saccharification. This saccharification activity is achieved in two ways; either using sulphuric acid in acid hydrolysis or using cellulose or xylanase enzymes in enzymatic hydrolysis [110,114]. Compared to acid hydrolysis, enzymatic hydrolysis gives a high yield and high selectivity with no by-products. However, fermentation can also be used in which *S. cerevisiae* acts as a fermentative microorganism. Bioethanol can be burnt directly or blended with petroleum, which reduces carbon dioxide emissions during petroleum consumption in automobiles. A study showed that using a commercial petroleum product known as E10 that contains petroleum blended with 10% ethanol can reduce the use of petroleum from 6% to 2% in CO<sub>2</sub> emission and 3% in fossil fuels energy [115,116].

**Biodiesel:** Transesterification is the process in which oil (extracted from oil nuts and seeds) is combined with alcohol (mostly methanol) to produce biodiesel. Transesterification can be of two types, catalytic or non-catalytic [117]. In catalytic transesterification, alkali catalysed transesterification is commonly used to produce biodiesel because it requires low temperature and pressure conditions with a 98% yield of biodiesel [118–120]. However, enzyme catalysed transesterification is also used, but having costly enzymes and a slow reaction rate are the two main hurdles that prevent this process from being commercialised [121]. In non-catalytic transesterification, supercritical methanol (SCM) provides higher biodiesel concentration yield in a short time duration [122–124].

**Biogas (biomethane, biohydrogen, and biohytane):** Taking lignocellulosic biomass as a source to produce biofuels, anaerobic digestion is the cheapest, most stable, and well-

established technique that recovers a higher amount of energy from the source [125–127]. Digestion of cellulose and hemicellulose (i.e., lignocellulosic biomass) underpins that anaerobic microbes can synthesise methane-rich biogas [128,129]. Lignin also reduces the substrate availability to the enzymes of anaerobic microbes, decreasing the productivity of methane [130]. The physicochemical properties, structure, and composition of lignocellulosic biomass can be altered using different pre-treatments, enhancing methane production [131–133]. The most preferred and commonly known technique is alkaline pre-treatment which solubilises lignin, cellulose, and hemicellulose. This technique is adapted to degrade the ester bonds present in-between carbohydrates and lignin and most prominently degrades the crystalline structure of the cellulose, which drastically affects the efficiency of anaerobic digestion [125,126,134]. The most commonly used alkali is sodium hydroxide (NaOH) [130,135]. This pre-treatment technique increases methane production from the lignocellulosic biomass (from 0% to 174.2%) compared to untreated biomass [136,137]. Various process parameters affect the production of biomethane, such as type of inoculum [138], design of reactor [139], organic loading rate (OLR), pH, temperature (°C), carbon (C) and nitrogen (N) ratios, etc., [140]. Biohydrogen can act as a sustainable green fuel and replace fossil fuels as the main transportation fuel [141]. Three processes can be utilised to synthesise biohydrogen from biomass and waste; (i) biophotolysis, (ii) photofermentation, and (iii) anaerobic fermentation (AF) [142]. Production of biohydrogen can be enhanced by combining anaerobic fermentation with photofermentation, whereas the metabolites from the anaerobic fermentation can be utilised in photofermentation. Conjugation of these two techniques can be performed in a two-phase operation [143]. Biomethane and biohydrogen are mixed in the ratio of 1:4 to obtain biohythane [144]. Specific yields of biohydrogen and biomethane from a total volatile solid (TVS) feed are combined to make high-quality biohythane [145].

**Biobutanol:** Biobutanol can replace gasoline and is known as a drop-in-fuel. Crops having a high concentration of starch-like maize and wheat are good substrates for biobutanol production [146,147]. A study was performed in which acetone-butanol-ethanol (ABE) fermentation was conducted on the glucose-based culture of *Clostridium beijerinckii*. ABE production took place until the fermentation terminated after 66 h. About 0.46 g/L/h productivity was obtained based on the 41 h fermentation time [148,149].

## 6.2. Organic Acids and Chemicals

Besides biofuel and energy production, biomass and waste have a special position in synthesising different important synthetic chemicals and organic acids. In a study, scientists used kitchen waste as feedstock and converted the waste into organic acid using anaerobic digestion [150]. They found that with the increase in the fermentation media's pH and temperature, organic acid production increases. They examined four pH values (uncontrolled pH, pH 5, pH 6 and pH 7) and five temperature values (uncontrolled at ambient, 30, 40, 50, and 60 °C) [151]. The fermentation period usually lasted for 10 days, and the yield of organic acid was detected using HPLC (high-pressure liquid chromatography) [152,153]. The composition of organic acids produced during fermentation contained a higher amount of lactic acid, about 65–85%. However, 10–30% of acetic acid, 5–10% of propionic acid, and 5–20% of butyric acid yield were detected [154].

Acid-catalysed hydrolysis requires comparatively mild temperatures (i.e., 100–250 °C) and performs a significant role in the bioenergy production that is commonly used to produce glucose, 5-hydroxymethylfurfural (5-HMF), and levulinic acid (LA) [155–157]. Removing a water molecule from all types of monomeric and polymeric carbohydrates makes them raw biomass used for 5-hydroxymethylfurfural (5-HMF) production [158]. Degradation of 5-hydroxymethylfurfural (5-HMF) in acidic conditions produces LA and formic acid (FA) with some chemicals as by-products. An intermediate 2, 5-dioxo-3-hexenal is produced from 5-hydroxymethylfurfural (5-HMF) via a chain of hydration and rearrangement reactions. Formic acid is released from 2, 5-dioxo-3-hexenal, and after some rearrangement reactions, LA is produced [159,160].

Formic acid (FA) can be synthesised as a by-product in a process called biomass hydrolysis [161,162]. FA uses a hydrogen donor for hydrogenation of LA to yield fuel adjunct, like  $\gamma$ -valerolactone [163]. There are different methods to produce lactic acid. The first method is chemical synthesis, in which acidic hydrolysis of lactonitrile with strong acids results in D-lactic acid and L-lactic acid solutions [19,164]. The second method is based on fermentation using microbes which is more beneficial than chemical synthesis because microbial fermentation is more product specific and economical [165,166]. Microbes like lactic acid bacteria use pyruvate as substrate and convert pyruvate to lactic acid in combination with lactate dehydrogenase. These bacteria include *Lactobacillus*, *Streptococcus*, *Tetragenococcus*, and *Weissella*. *Lactobacillus* genus is the biggest and most prominent fungi, including *Mucor*, *Monilia*, and particularly *Rhizopus* to produce lactic acid [167].

Propionic acid (PA) ( $C_3H_6O_2$ ) is a monocarboxylic acid. A bacteria known as propionibacteria is commonly utilised to produce PA, providing anaerobic conditions to grow propionibacteria [168]. This bacteria is less tolerant to the acidic environment created due to the availability of produced propionic acid [169]. However, immobilisation of bacteria can increase their acid tolerating capacity. Additionally, they knocked out the gene for acetate kinase to reduce acetate production, which was beneficial in two ways. It increases propionic acid production in high concentrations and enhances the tolerance of bacteria to the acidic medium [169,170].

Succinic acid (SA) ( $C_4H_6O_4$ ) is a saturated dicarboxylic acid with a linear carbon chain and a white crystalline appearance under standard conditions. Succinic acid can be produced using different bacterial strains [171,172]. Phosphoenolpyruvate (PEP) directs carbon to the C3 pathway instead of the C4 pathway. PEP-carboxykinase produces oxaloacetate (OAA) by catalysing the reaction between PEP and carbon dioxide. There is a series of three reactions that convert oxaloacetate to succinic acid. Oxaloacetate is converted into malate, and malate is converted into fumarate, and finally, fumarate is converted into succinic acid. These three steps require electron donors like nicotinamide adenine dinucleotide (NAD) + hydrogen (H) (NADH), which supports the synthesis of succinic acid instead of formic acid and acetic acid [167,173]. Meynial-Salles et al. produced succinic acid (83 g/L) by cultivating an *Anaerobiospirillum succiniciproducens* strain in their developed integrated membrane-bioreactor-electrodialysis [174]. Glycerol and sorbitol are two carbon sources that are more reduced than glucose and xylose. Hence, both provide a concentrated yield of succinic acid [175,176].

Malic acid (MA) ( $C_4H_6O_5$ ) is known as a dicarboxylic acid that can be synthesised using various yeast strains, such as the fungus *Aspergillus* and *Escherichia coli* strains which are modified by genetic engineering for the fermentation process. *Aspergillus flavus* produced a high concentration of malic acid (113 g/L) in batch cultures from glucose [177]. *A. flavus* produces aflatoxin which negatively affects their use in the production of food-grade chemicals [167]. West reported a yield of 19.0 g/L of MA using *Aspergillus niger* strain [178]. Moreover, Zhang et al. used a genetically engineered *E. coli* strain and produced 34 g/L of malic acid by two-stage fermentation within 72 h [179]. The most promising results reported used a *Zygosaccharomyces rouxii* strain which used glucose in addition to 0.5% of glutamic acid and generated 74.90 g/L of MA [180].

Fumaric acid ( $C_4H_4O_4$ ) is also known as a dicarboxylic acid. Most studied fungi like *Rhizopus arrhizus* or *Rhizopus oryzae* can produce lactic acid or fumaric acid in an aerobic environment [167]. Ling and Ng reported the highest fumaric acid yield. They used  $CaCO_3$  as a neutralising agent and controlled the concentration of dissolved oxygen to 80–100% during fungal growth and 30–80% during the production of fumaric acid [181]. Cao et al. used immobilised fungal cells and reported the highest yield of fumaric acid, and via adsorption, they separated fumaric acid with high efficiency [181,182].

Butyric acid ( $CH_3CH_2CH_2COOH$ ) is recognised as a four-carbon-aliphatic organic acid. Microorganisms of different genera like *Clostridium*, *Fusobacterium*, *Megasphaera*, and *Eubacterium* can be used to produce butyric acid from biomass and waste [183,184]. The strain of *Clostridium tyrobutyricum* produces butyric acid in anaerobic conditions and is a

widely used strain all over the world. An elevated volumetric production was attained in the fermentation process of cane molasses by *C. tyrobutyricum* [185]. Immobilisation of cells can enhance the efficiency of butyric acid production [184,186]. In contrast, metabolic products find it challenging to produce butyric acid using the fermentation method because they inhibit fermentation [187]. The utilisation of mutants strain of *C. tyrobutyricum* ATCC 25755 instead of wild-type did not support the reduced acetic acid production [188]. Engineered strains could be potentially used to solve these problems when glucose is adapted as a carbon source. For example, genetically engineered immobilised *C. tyrobutyricum* produces a good yield of butyric acid [184].

### 6.3. Enzymes and Lipids

Biomass and waste, especially from food industries, are commonly used to produce industrial enzymes because of the low production cost of enzymes from food waste. A step known as enzymatic hydrolysis is involved in the lignocellulose pre-treatment [189] combined with the fermentation process in the presence of fungi that can grow and digest food waste is used to produce industrial enzymes, for example, *Aspergillus sp*, *Melanocarpus sp*, and *Pleurotus sp*. [190–192]. Different oxidative enzymes like amylase can be synthesised using food waste [193,194]. This waste's heterogenic nature can cause difficulties in downstream food waste processing, and in the end, isolation and purification of enzymes become highly expensive. To overcome these difficulties, purification in one step and enzyme immobilisation was performed [195,196]. To do one-step purification and immobilisation, three strategies are used: (i) immobilisation at one point, (ii) use of specially synthesised supports for specific binding, and (iii) use of directed mutagenesis to increase the affinity of target protein towards the supports [197]. Solid-state fermentation is a promising way to produce industrially important bacteria in a high amount with low manufacturing costs [198,199]. Because of their friendly nature with the solid-state fermentation process conditions, Basidiomycetes fungi are commonly used to synthesise most of the industrial enzymes [200,201].

Talking about non-enzymatic proteins, collagen is commonly found in organisms. It is also produced from food waste, and biomass like fish waste is broadly used as a biomass source to produce collagen [202,203]. In a study, NaOH was used to isolate acid-soluble collagen from all non-collagenous proteins present in cod bone [204]. Cheese whey waste water (CWW) contains different proteins precipitated based upon their denaturation properties at high temperature and isoelectric pH [205]. Denaturation causes the unfolding and aggregation of proteins. The application of centrifugation and filtration methods after precipitation enhances the efficiency of separation and purification of protein fractions [61]. However, it is a challenge to make these isolated proteins thermally stable and functional [206,207].

Under other conditions, biomass and food waste are used to produce lipids. Lignocellulosic biomass and food wastes are commonly used organic carbon sources in the production of lipids. A drastic decrease in the cost of lipid production was observed [208,209]. To convert lignocellulosic biomass, microorganisms, specifically oleaginous microorganisms such as yeast algae and fungi are used [210]. Microorganisms produce lipid via fermentation, but the crystalline structure of cellulose and lignin contents requires pre-treatments such as acid, base, and enzymatic treatments, which will break down the crystalline structure of cellulose, making it available to microorganisms for fermentation [211,212]. After pre-treatments, biomass is fermented either in solid-state fermentation or submerged fermentation. The choice of fermentation state depends on the characteristics of available biomass, whether from rice or wheat, etc. [213]. Microorganisms use three different enzymes for the conversion of cellulose to lipids, which are Acetyl-CoA Carboxylase (ACC), Citrate Lyase (CL), and Malic Enzyme (ME) [214–216]. Different sources of biomass feedstock require various oleaginous microorganisms to carry out the fermentation process. For example, *Trichosporon fermentas* hydrolyses rice straw [217], *Cryptococcus curvatus* hydrolyses wheat straw [218], and *Trichosporon cutaneum* hydrolyses corn stover [219].

#### 6.4. Biological Macromolecules

Biological macromolecules are cost-effectively produced by using biomass and waste. For example, bioplastics, polyhydroxyalkanoates (PHAs), lignin, cellulose, etc. To avoid the overconsumption of petroleum products in the plastic-making industry, scientists created a replacement known as bioplastic. Bioplastics are mainly composed of linear polyesters of hydroxy acids called polyhydroxyalkanoates (PHAs), a plastic-like material. The assembly of PHAs carried out by using biomass, and food waste reduces the cost of production and releases the stress of overconsumption of petroleum products [189]. A strain of *Burkholderia sacchari* (DSM-17165) can metabolise reducing sugars like glucose to produce poly-3-hydroxybutyrate (PHBs) (a simple type of PHAs). Moreover, coffee waste is an outstanding source of organic carbon for PHBs production. The solid portion left as residue contains cellulose and hemicellulose content. Starting with pre-treatment, these contents are converted into PHAs via enzymatic hydrolysis [220,221]. Reis and colleagues proposed another method to produce PHAs [222]. The first stage of the process is acidogenic fermentation (crucial for high yield of PHAs). The second stage is selecting and producing bacterial strain under dynamic feeding, and in the last stage, PHAs were accumulated in batch conditions. The first stage is very important because bacterial cultures tend to store glucose as glycogen, not as PHAs, acidogenic fermentation converts glucose into volatile fatty acids (VFA) that are easily convertible into PHAs [222].

The most abundant biopolymer present in nature is plant cellulose ( $C_6H_{10}O_5$ )<sub>n</sub>. However, using this biopolymer for productive applications is very difficult because it cannot be attained in fully purified form because of the following components: lignin and hemicellulose. Different microorganisms like some algae (e.g., Rhodophyta, Phaeophyta) and bacteria were used to synthesise cellulose to avoid this difficulty. The synthesised cellulose possesses structural similarity but exhibits different properties than plant cellulose, like a higher degree of polymerisation, high purity, and more water holding capacity, making it suitable for industrial use [223–225]. *Acetobacter xylinum* carries cellulose synthase that adds uridine diphosphate glucose (UDP glucose) to the cellulose chain terminal. The rate of polymerisation is reduced by the rate of crystallisation of the cellulose complex. In the following step, bacterial cellulose egress bacterial cells in an elementary fibril forming a 3D network. The stated mechanism of bacterial cellulose is known as the “model microorganism” [226]. Some carbon sources such as glucose, glycerol, sucrose, and maltose are used to produce bacterial cellulose. Many studies revealed that the addition of various nutrient supplements resulted in a high yield of bacterial cellulose [227,228]. *Gluconacetobacter xylinus* was used in the fermentation process, and glucose was a source of carbon. The increase in bacterial cellulose production was observed when supplemented the lignosulfonate [229–231]. Researchers tried to achieve enhanced bacterial cellulose concentration. For this purpose, they used an agitated culture of *Acetobacter xylinum* and after trying different additives, they achieved the highest bacterial cellulose yield by the addition of carboxymethylcellulose [232].

#### 6.5. Food/Feed Products

Different monomeric sugars like glucose, galactose, ribose, and fructose can be produced when food waste is treated with acids [233]. Low concentrations of HCl and H<sub>2</sub>SO<sub>4</sub> are generally applied directly but can also be involved in conjugation with enzymes to avoid by-products that degrade sugars like furfurals. Additionally, different enzymes like α-amylase and β-amylase can be used to degrade starch-like polymers to monomeric sugars [234–236]. The synergy of both treatments, such as enzyme hydrolysis can produce a higher yield of sugars. The enzyme (i.e., α-amylase and glucoamylase) mediated hydrolytic treatment of kitchen waste and increase the yield of fermentable sugars. These sugars can later be used in the fermentation method to synthesise bioethanol [237–239]. Moreover, physical and chemical procedures may enhance the yield of monomeric sugars from polysaccharides [240,241]. Cellulase activity becomes less efficient because non-productive binding occurs in-between enzyme and lignin. To reduce this problem, surfactants are

added that tend to inhibit the formation of enzyme-lignin complex [242]. It is believed that surfactants bind with the binding site of cellulase on the lignin molecule hence cellulase is available to bind with cellulose to produce sugars. Surfactant-mediated cellulose hydrolysis via cellulase enzyme enhances the sugar production from recycled newspaper or waste [243–245]. Various pre-treatment methods can be adopted to produce sugars depending upon the type of feed stock. If we talk about paper products like newspapers and office paper, different pre-treatment approaches such as steam explosion [246], bacterial pre-treatment [247], and ozonolysis [248] have been observed. However, weak acid pre-treatment of lignocellulosic biomass such as phosphoric acid showed many promising results [249,250].

Edible mushrooms like *Agaricus sp.* and/or *Grifola sp.*, etc., can ferment various agricultural wastes to harvest better-quality animal feed [251,252]. These fungi increase the degradation of lignocellulosic material using enzymatic activities and utilise the provided substrates to supplement animal feed's protein content [253,254]. In another study, *S. cerevisiae* produced single-cell protein from cucumber and orange peels in submerged fermentation. Protein content produced by cucumber peel is higher than from orange peel or other used substrates [255]. The advantage of food waste fermentation using fungi results in risk-free animal feed [256,257]. *Lentinus edodes*, *Leurotus sp.*, *Phanerochaete chrysosporium* and *Coriolus versicolor* *Phelbia sp.* are highly studied white-rot fungi which are used to produce the improved animal feed [258–264]. *Pleurotus sajor-caju* was used to ferment rice straw, wheat straw, and soy meal, resulting in increased protein content [265,266]. Solid-state fermentation of wheat straw using fungal pellet inoculum of *Trametes versicolor* and *Pleurotus ostreatus* improves the nutrient availability and digestion of wheat straw [267]. Ref. [262] showed that inoculum-type is significant in lignin degradation under solid-state fermentation to achieve a high level of improved animal feed. Albeit, biomass, and waste are important to use in food production, but the type of inoculum and other optimised parameters are required for enhanced and improved quality production.

#### 6.6. Bioelectricity via Microbial Fuel Cell (MFC) Technology

Bioelectricity is another useful product that can be synthesised from biomass and waste material. Lignocellulosic biomasses [268] and waste waters are a few biomass and waste residues that have been used in the past decade to produce bioelectricity via microbial fuel cell (MFC) technology [251]. Microbial fuel cell technology can convert the chemical energy of biomass and waste to bioelectricity [269,270]. Electrochemically active bacteria such as *Shewanella putrefaciens*, *Geobacter sulfurreducens*, etc., [271] can metabolically convert biomass and waste to bioelectricity [272]. The potential gradient of electrons ( $e^-$ ) and protons ( $H^+$ ) across the membrane developed by redox reactions in metabolic pathways of these bacteria generates electricity [273].

Just like an electrochemical cell, MFC systems also have anodes and cathodes separated by a membrane. The anodes catalyse the production of electrons and protons that electrochemically oxidise organic substrate. The terminal electron acceptor (TEA) present in the cathode, tends to force the electrons present in the anode to flow and harness energy externally. Protons ( $H^+$ ) from the anode move towards the cathode by passing the membrane [274]. It is a cathode chamber where the reduction of electrons ( $e^-$ ) and protons ( $H^+$ ) generate valuable products [275,276]. Microorganisms in MFCs catalyse the oxidation of biomass and food waste (anode) (Logan et al., 2006; Rabaey et al., 2007). Ref. [273] used integrated solid-state fermentation with MFCs to produce bioelectricity from merged canteen-based solid food waste. Microorganisms present in MFCs can utilise volatile fatty acids to generate bioelectricity [277–283]. Hydrolysis and acidogenic digestion of food waste leachate generate volatile product such as fatty acids [284], which are used in MFCs for bioelectricity [285,286].

MFCs proved to be the most promising way to deal with biomass and waste material by converting them into bioelectricity. However, MFC technology also faced some hurdles like relatively low bioelectricity output because of high internal resistance ( $R_{int}$ ) [283]. To

surpass this hurdle, scientists discovered that MFC power output could be improved if the anolyte and catholyte used in MFCs possess increased conductivity or ionic strength [188,287]. However, the proposed solution did not last permanently because varied salt tolerance of *Anodophilic* bacteria hinders increased ionic strength [288,289]. Ref. [290] added varying concentrations of NaCl to increase the ionic strength of the MFC chamber, which improves the output performance. In disagreement with the previously reported study, the highest coulombic efficiency (CE) can be obtained at a lower NaCl concentration [289]. Anolyte pH also affects the power output of MFCs, affecting the MFC ( $R_{int}$ ) [291–294]. Ref. [283] described that the highest output of power ( $P_{max}$ ) and lowest resistance ( $R_{int}$ ) is achieved when 100 mM NaCl is added in MFCs. This addition also increases the removing efficiency of chemical oxygen demand (COD). Neutral and alkaline MFCs can be more efficient in COD removal and CE. Moreover, neutral and alkaline conditions significantly increase  $P_{max}$  and decrease  $R_{int}$ . Along with the salt concentration, biomass, and food wastes, the pH range of anolyte can also affect the high-power density generation and COD removal using food waste leachate as a source to generate bioelectricity in MFCs.

#### 6.7. Paper and Pulp

Another industrial field where biomass and waste materials play significant roles is in producing paper and pulp, where it is recognised as a very low-cost production method. In the paper and pulp industry, biomass and waste from different sources are used in two ways. Firstly, biomass and waste material were burnt to produce the green energy required to produce paper and pulp. Secondly, these are used as supplements that improved the product quality and manufacturing of paper and pulp [295]. Paper and pulp industries are adopting biomass and waste as fuel to produce green energy that is more efficient and safer. They have lower production costs than energy generated from fossil fuels. Other than combusting purposes, paper and pulp industries use these organic masses and residues as supplements and raw materials for their production. For example, filamentous algae utilised as raw materials to make papers [296,297]. Some biomass is based on algae mixed in conventional paper pulp to improve the quality of the paper. A case study published in 2006 showed that the supplementation of algal biomass for tissue paper production decreases the production cost. Production costs were almost fifty percent lower compared to conventional pulp [298].

#### 6.8. Pharmaceutical

In the pharmaceutical industry, biomass and waste provide bioactive compounds with different pharmaceutical applications due to their properties such as antitumor, antioxidant, antibacterial, etc. [299,300]. Different biomass and waste feedstock can produce different bioactive compounds, a few of them will be discussed in this section for example lignocellulosic wastes, fungal biomass, and waste of seafood processing industries. Cultivation of *Lentinula edodes* on lignocellulosic waste produces high-value products. These products exhibit antiviral, anti-inflammatory, antibacterial polysaccharides, antitumor, and immunomodulating properties [301–303]. A compound named lentinan is a polysaccharide produced by *Lentinula edodes* cultured on lignocellulosic waste possessing anticlotting properties [252,304] and is used as adjuvant therapy in cancer patients [251,305].

Different compounds produced from fungi exhibit bioactive properties that make them useful in the pharmaceutical industry. For example, an exocellular homopolysaccharide named pullulan is produced by the fungus *Aureobasidium pullulans*, and in the pharmaceutical industry, it is used as bulking and binding agent in tablet manufacturing [303]. Lentinan can be used as an antitumor, and it affects different cells of immune systems, for example, macrophages, to modulate the activity of the immune system [305,306]. Chihara et al. [307] isolated and purified lentinan polysaccharides from edible mushrooms known as *Lentinus edodes* using three different techniques [307]. Recently [308] extracted lentinan from *Lentinus edodes* mycelia using a series of centrifugation techniques and purified it by anion-exchange column chromatography [309]. Oral lentinan was observed to be more ef-

fective than crude shiitake (*Lentinus edodes*) extract in inhibiting the colon carcinoma growth in mice [310,311]. Lentinan also exhibits antitumor activity against different synergic and autochthonous tumours and reduced tumour size by 90% in most specimens [312,313]. In conclusion, the production of tumour necrosis factor (TNF- $\alpha$ ) can be induced by lentinan in macrophages in vitro and the phagocytotic activity of mouse macrophages can be increased by the lentinan addition [314].

#### 6.9. Miscellaneous

Fish muscle can be digested very easily with specific amino acid concentration and composition [315,316]. Researchers observed the possibility of producing biologically active peptides from fish muscles [317,318]. Peptides and fish protein hydrolysates produced by enzymatic catalysis exhibit anticoagulant and antiplatelet properties [319,320]. Collagen and gelatine polypeptides are promising agents that can be used as potent antioxidants and antihypertensive treatments [321–324]. Microfibrillar collagen sheets are very efficient drug carriers to treat cancer [325]. Chitin, chitosan, and their derivatives exhibit antioxidant, antibacterial, antifungal, and antiviral activities [326–328]. They additionally show antibacterial activity by disrupting the membrane integrity of the bacterial cell [329]. Wound dressing material [330] is an excellent practical example of chitin and its derivative in the pharmaceutical and medicinal field. Some organic wastes and residues, such as rice husk, wheat barn, wheat straw, eggshell, and banana peel, were proven to help produce nanoparticles. This portion will mention how these organic wastes and residues are helpful in the production of nanoparticles.

Span 40 rice husk silica (RHS) immobilised Ni particles produced from rice husk silica (RHS). The silica of rice husk is used as a surface to anchor Pt and Ni nanoparticles and then modified by CTAB (cetyl trimethylammonium bromide). Non-ionic surfactant (Span 40) is added to RHS immobilised Ni particles which change these nanoparticles to synthesise acetaldehyde [331] efficiently. An example of nanoparticles produced from biomass is silver nanoparticles. These nanoparticles were produced when xylan extracted from the wheat barn is dissolved in sodium hydroxide and heated to 100 °C for half an hour with 1 mL of silver nitrate. The appearance of brown colour confirms the presence of silver nanoparticles in the solution [332]. Calcination of wheat straw then treated with NaOH and neutralised by HCL produces 100–200 nm silica nanoparticles [333]. In a separate study, wheat straw and  $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$  were used to prepare porous carbon-supported  $\text{Fe}_2\text{O}_3$  ultrathin film. Wheat straw was firstly calcinated under an inert environment, then Fe(II) was added to it followed by annealing at 200 °C producing porous carbon-supported  $\text{Fe}_2\text{O}_3$  ultrathin film [334]. Jayasankar and co-workers prepared  $\text{Dy}^{3+}$ -doped calcium silicate ( $\text{Ca}_2\text{SiO}_4$ ). They calcinated waste egg shell and rice husk at 1250 °C via solid-state reaction technique [335]. Calcium oxide nanoparticles were produced by using hen eggshells. Decomposition of crushed eggshells at a temperature above 800 °C makes CaO. This CaO was remixed in water, and then the calcination of CaO resulted in the formation of calcium oxide nanoparticles [336]. The banana peel was used to make  $\text{Mn}_3\text{O}_4$  nanoparticles of a size ranging from 20 to 50 nm by Yan and co-workers. They reported that banana peel reduces  $\text{KMnO}_4$  to form  $\text{Mn}_3\text{O}_4$  and prevents nanoparticles' agglomeration during their synthesis [337]. Another type of nanoparticle produced from banana peel was 20 nm  $\text{SiO}_2$  NPs. An alkaline solution of tetraethyl orthosilicate in ethanol was mixed with banana peel extract. After calcination of this mixture, nanoparticles were participated out [338].

Fruit waste contains a high concentration of carbohydrates and essential nutrients, which substantiates fungal growth to synthesise the single-cell proteins [339,340]. Using fruit waste for this purpose can help in dealing with waste disposal and, to some extent, in controlling pollution. Different microorganisms such as algae, bacteria, fungi, mould, and yeast can be inoculated to produce single-cell proteins. *S. cerevisiae*, a single-cell eukaryote (baker's yeast) is the best example. Ref. [341] used pre-treated grounded peel to produce the single-cell protein. In the study, 40 gm of ground peels was treated with

10% (*w/v*) HCl, and then the mixture was heated on a water bath for one hour at 1000 °C. Filtering this mixture via Whatman filter paper after cooling it gave filtrate autoclaved for 15 min at 121 °C after diluting the filtrate with distilled water. *S. cerevisiae* was used as a fermentation microorganism. Submerged fermentations in Erlenmeyer flasks gave a total carbohydrate yield of 39.66% produced from orange peel, which was lower than the yield made from cucumber peels. Furthermore, the quantity of crude protein (53.4%) generated from cucumber peels was higher when compared to orange peels (30.5%). In this study, they also used different growth media for *S. cerevisiae*. Growth media with extra glucose as a carbon source produces more protein and carbohydrates than the media with no excess glucose [255].

Non-renewable and unstable fossil fuels cannot be used to fulfil the energy demand around the globe for a long time because they are non-renewable and cause global warming, hence mankind should search for alternatives to fossil fuels [342]. Waste material, especially lignocellulosic biomass, produced as waste in huge amounts (200 billion tons), can be used to produce biofuel [130,131]. Because cellulose and hemicellulose are present, pre-treatment is required to enhance the production of biofuel. This study reported NaOH pre-treatment in conjugation with extrusion tends to enhance biomethane production. A Twin-Screw Extruder (manufactured by JXM80, Jinwor Machinery Co., Ltd., Nanjing, China) was used to reduce lignocellulosic biomass size NaOH was used as an alkaline reagent. After this pre-treatment, biomethane yield via anaerobic digestion of rice straw was 54.0% higher. Using this combination of pre-treatment with extrusion also increases the energy recovery efficiency (ER) (i.e., 38.9% to 59.9%). This increase in biomethane production and enhanced efficiency of the energy recovery (ER) were credited to the change in the lignocellulosic biomass's physiochemical structure. These changes increase the digestion in anaerobic digestion by degrading the cellulose and hemicellulose crystalline structure, hence increasing the biomethane production from rice straw [343].

New technology was developed to transform ferulic acid into vanillin by combining strains of fungi *A. niger* and *Pycnoporus cinnabarinus*. *A. niger* produces vanillic acid from free ferulic rice bran oil via preliminary treatment. Then vanillin is synthesised from vanillic acid by *P. cinnabarinus* cells. The highest yield of vanillic acid produced by *A. niger* was 2.2 g/L. *P. cinnabarinus* convert vanillic acid to vanillin and have 2.8 g of vanillin. <sup>13</sup>C isotopic analysis was used to identify and confirm the vanillin extracted in crystal form [344]. To simultaneously deal with waste treatment and globally increasing demand for energy generation, MFCs [345] are highly prominent in this context. MFCs can utilise chemical energy in waste materials to produce electrical energy by using catalytic bioprocesses of exo-electrogenic microorganisms [285,286]. This study reported the use of dual-chamber MFCs to produce bioelectricity from the LPW (liquid fraction of pressed municipal solid waste). Researchers studied the outcomes of adding substrate and mesophilic anaerobic sludge (MAS). Results of the experimental study tell that even with low input of chemical oxygen demand (COD), the highest energy (8-9 J/g ΔCOD/d) can be produced by using this substrate in an MFC system. A 1.2–1.9 kg COD /m<sup>3</sup>d COD removal rate with 94% maximum efficiency could be reached. These results lead to the conclusion that substrate (LPW) concentration in an anode chamber is the major factor that affects the efficiency of energy recovery, and low organic material loadings improve the performance of MFC [346].

## 7. Conclusions, Bioeconomy Challenges, and Socio-Economic Impacts

Bioeconomy is a diverse field that deals with different types of productive activities like agricultural residues to produce biomass. These contribute to the bioeconomy by producing sustainable biomass quantities either in terms of waste or by-product. Biomass is considered a renewable source, but it is limited because of its production requirements like land and additional resources (water, nutrients) [347]. These requirements of the bioeconomy affect the environment because the bioeconomy requires feedstocks from land and sea to produce valuable bioproducts instead of using fossil fuel-derived feed stocks [348]. To establish a stable bioeconomy, a significant challenge is the conversion of fossil-based

industry into the biomass-based industry. The development of industrial biotechnology (biorefineries), bio-based processes, and starting new markets to distribute the bio-based products made from these new industrial technologies are some of the significant changes that conventional industrial should adopt to establish a bioeconomy [347]. The most important question that arises to begin a bioeconomy is the supply of biomass to support and sustain the bioeconomy. This continues, and biomass's huge demand leads to increasing natural resources (water, land, etc.). More land is required to fulfil the massive demand for biomass and convert forests and grasslands to arable lands. This transformation of forests and grassland to an arable field releases CO<sub>2</sub> into the atmosphere [349,350]. Thus, bio-capturing CO<sub>2</sub> from the environment is another valuable strategy to recover value-added products [349].

The excessive use of land decreases soil fertility and soil productivity [351]. Efficient and increased production of crops by using fertilizers and pesticides can improve water and soil pollution. Irrigation of these crops puts additional pressure on water sources and could lead to water scarcity. Biological sources of the economy can negatively affect the environment and increase pressure on natural sources required for biomass production. Strategically, these requirements destabilise food security, and due to this, price levels and volatility of food will be increased that will negatively affect the poor people of society. These challenges can be surpassed by using degraded land, increasing productivity, and waste utilisation of biomass production. Furthermore, micro-algae can promisingly reduce the competition with food due to their higher productivity, and they have no competition with food crops for agricultural lands. For example, food waste can be a good and sustainable source of biomass. However, using food waste has its own advantages with some critical issues like collection and separation of food waste, low coordination between suppliers of food waste, storing food waste for later use, limitations in technology, and economically stable plants [348,352,353]. The consumption of food waste to produce biomass needs huge public awareness because converting to a more sustainable circular model need strong public agreement [354].

Firstly, biofuels made from biomass can improve the local economy by replacing two fossil fuels (gasoline and diesel) enormously used in transportation. Biodiesel is the replacement for fossil diesel and bioethanol for gasoline. Using biomass-based fuels to meet energy requirements can potentially decrease CO<sub>2</sub> released in the environment and sustain more employees due to its widespread opportunities. Biomass-based fuels are economically friendly because their diversity allows us to choose the transportation fuel depending upon the cost and availability of biomass for its production. For example, hydrogen and methanol can be synthesised from biomass, but hydrogen's synthesis cost is less than methanol [355]. With these biofuels, our dependency on fossil fuel will be reduced and there will be less greenhouse gas and pollutants in the environment. The bioeconomy can assist waste management by utilising municipal solid waste, vegetable and market waste, agricultural residue, slaughterhouse wastes, and industrial wastes to produce biofuels, energy, and other high-value products. Additionally, the bioeconomy produces new employment opportunities in different fields like biofuels' production and processing. The bioeconomy has many negative side effects, but those side effects are not permanent and can be easily surpassed. However, the benefits of the bioeconomy towards the environment and welfare of humankind can be sustainable for a long time if we discover and acquire those benefits very wisely.

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