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Review

A comprehensive review on the advances of bioproducts from biomass towards meeting net zero carbon emissions (NZCE)

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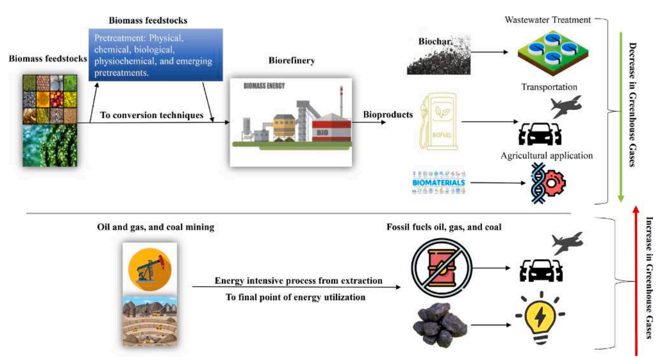
HIGHLIGHT

- Various materials and mechanisms for bioproduct as feedstock for NZCE.
- Intriguing use in water treatment and renewable energy.
- Futuristic insight on the NCZE on carbon dioxide.

GRAPHICAL ABSTRACT



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ABSTRACT

This review investigates the development of bioproducts from biomass and their contribution towards net zero carbon emissions. The promising future of biomasses conversion techniques to produce bioproducts was reviewed. The advances in anaerobic digestion as a biochemical conversion technique have been critically studied and contribute towards carbon emissions mitigation. Different applications of microalgae biomass towards carbon neutrality were comprehensively discussed, and several research findings have been tabulated in this review. The carbon footprints of wastewater treatment plants were studied, and bioenergy utilisation from sludge production was shown to mitigate carbon footprints. The carbon-sinking capability of microalgae has also been outlined. Furthermore, integrated conversion processes have shown to enhance bioproducts generation

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yield and quality. The anaerobic digestion/pyrolysis integrated process was promising, and potential substrates have been suggested for future research. Lastly, challenges and future perspectives of bioproducts were outlined for a contribution towards meeting carbon neutrality.

1. Introduction

Biomass energy is the energy harnessed from primary, secondary, or tertiary bioresources. One sizeable contributing sector to biomass is the agricultural sector. Tremendous amounts of agricultural wastes are used as a fuel source for generating electricity and heat (Henry, 2017). There is more to biomass than the burning of trees to produce energy. Different sustainable techniques for converting biomass into bioproducts are used to generate energy. Biomass burning to generate electricity is a straightforward way to produce bioenergy. This application uses a high energy content within the plant biomass lignin. It further allows the thermal conversion of the carbohydrate fraction of the biomass to biofuels or biomaterials (Nille et al., 2021). Using biomass as an energy source can significantly reduce carbon emissions.

Net-zero carbon emissions can be defined as a means of mitigating greenhouse gas (carbon dioxide (CO_2)) emissions to almost zero, with the assumption that natural processes will remove the remainder. The idea of net-zero carbon emissions emerged from physical climate science (Fankhauser et al., 2021). However, its implementation is only operational through social, economic, and political systems (Fankhauser et al., 2021; Satola et al., 2021).

The net-zero carbon emissions will be met if all the CO_2 emissions are counter-balanced by mitigating CO_2 from the atmosphere through the carbon removal processes (Satola et al., 2021). The role of renewable energy utilisation and its impact on achieving net-zero emissions cannot be overemphasised. Biomass could be a game changer in meeting carbon neutrality. This review highlights bioproducts, which have been shown to remarkably contribute to reducing the dependency on fossil fuels for energy, chemicals, and other non-renewable materials. It will reduce greenhouse gas emissions due to fossil fuel usage and further assist in meeting net-zero carbon emissions goals. This review investigates bioproduct development from biomasses and how they contribute toward achieving net-zero carbon emissions (NZCE).

2. Biomass as a source of energy

Biomass has continued to be a valuable source of fuel in several countries. In developing countries, biomass is primarily used for cooking and heating, while biomass for transportation and electricity supply is gaining momentum in many developed countries (Cintas et al., 2021; Li et al., 2020). Though this may be due to the rise in fossil fuel prices, the view toward reducing greenhouse gas emissions is considerable.

The energy in biomass comes from the sun (Shah and Venkatramanan, 2019). Through the process known as photosynthesis, plants convert solar radiation into chemical energy in the form of carbohydrates. The chemical reaction of water molecules ($6H_2O$) with carbon dioxide ($6CO_2$) in the presence of solar radiation leads to the production of glucose ($C_6H_{12}O_6$) and oxygen ($6O_2$). The energy stored in the biomass can be directly burned to release useful energy or indirectly processed to produce bioproducts (Malmgren and Riley, 2018).

Biomass energy sources include crops and waste like corn, soybeans, sugar cane, algae, and by-products from food processing. These are mainly used to produce biofuels. Other forms of biomass are wood and wood processing wastes, organic fraction of municipal wastes, animal manure, and night soils primarily used to produce biogas (biomethane) (Khanal et al., 2020; Martín, 2016).

Some of the processes used in converting biomass to energy are thermochemical conversions which include combustion, the most common technique of converting biomass to energy. The direct burning of biomass produces heat used in warming buildings and heating water. Direct burning is a source of heat for industries and generates electricity in steam engines (Lam et al., 2019). Pyrolysis and gasification are the other types of thermochemical processes. In both types, thermal energy decomposes biomass feedstocks in a gasifier. Temperature and oxygen may differ during the conversion processes (Boateng, 2020; Kirtania, 2018).

On the other hand, biochemical conversion is of three types: fermentation, which converts biomass to bioethanol; bioethanol can be used as vehicle fuel. The second type of biological conversion is anaerobic digestion. In this process, biomass is converted into biomethane. Properly processed biomethane can be used in place of fossil fuel natural gas (Pandey et al., 2021; Skvaril et al., 2017). Thirdly, the transesterification process utilises vegetable oils, animal fats, and greases into fatty acid methyl esters (FAME) and glycerol. These bioproducts produce biodiesel (Carmona-Cabello et al., 2021).

3. Bioproducts from biomass

Most bioproducts are natural, biodegradable, and biocompatible compounds (Cintas et al., 2021). These features attract the interest of researchers and industries in civil engineering, food, chemicals, textile, and energy sectors (Rana et al., 2019). Most bioproducts are derived from their sources directly or indirectly. Depending on the production process, these bioproducts are used as feedstocks for energy generation and other sustainable applications in water treatment (as natural coagulants and activated carbon) and in agriculture for soil amendment and biofertilisers.

Thermochemical and biochemical processes are the primary processes for producing bioproducts from biomasses. During the thermochemical processes, the amount of oxygen used is the significant difference. For biochemical processes, on the other hand, enzymes of bacteria or microorganisms decompose biomass through the process of fermentation, anaerobic digestion, composting, or transesterification to produce bioproducts.

Bioproducts produced from these conversion processes are used in different fields. One of the most renowned uses is in energy generation. The production of valuable bio-based chemicals and materials is also achievable. These chemicals and materials can serve as renewable alternatives to products produced from non-renewable sources, including plastics, fertilisers, lubricants, industrial chemicals, and adsorbents (Awasthi et al., 2020; Malmgren and Riley, 2018). A general overview of biomass conversion processes, techniques, and bioproducts is shown in Fig. 1.

4. The net zero carbon emission

Carbon dioxide is the global most crucial greenhouse gas. It absorbs heat to keep the Earth warm, and plants use it for photosynthesis. In the absence of CO_2, the Earth's natural greenhouse effect will be low, making the temperature below freezing. On the other hand, a high amount of CO_2 in the atmosphere causes a rise in the Earth's temperature, thus contributing to global warming, hence climate change (NRC, 2020; Wuebbles et al., 2017). The world's annual CO_2 emissions from fossil fuels and industries have been estimated to be around 35 billion tonnes (excluding land use changes) (Hannah, 2020). The need to mitigate global warming below 1.5 ^{0}C established the concept of carbon neutrality (IPCC, 2022a). Since this temperature rise is mainly associated with CO_2 emissions, the best approach is to lessen the emissions.

Furthermore, the increase in the world population increases the demand for energy, food, and water. These demands directly or indirectly contribute to carbon emissions. Therefore, meeting net zero carbon emissions will require the contribution of alternative ways of meeting the world's demand for energy, food, and water (IPCC, 2022b).

While other forms of renewable energies have been shown to contribute to providing power, biomass has been shown to contribute to the entire energy-food-water nexus (Chew et al., 2019; Chojnacka et al., 2020; Cruz-Paredes et al., 2017; Reza et al., 2020; You et al., 2019). The energy produced from biomass is regarded as renewable, where a limited amount of CO_2 is emitted (Li et al., 2020; Shah and Venkatramanan, 2019). Biofertilisers can replace synthetic fertilisers, eliminating the need for their manufacture (You et al., 2019). Regarding water treatment, activated carbon is used in advanced water treatment to remove heavy metals from the water via adsorption mechanisms (Reza et al., 2020). Emerging natural coagulants are also types of biomasses used in the coagulation and flocculation process of water treatment (Aziz et al., 2021; Chua et al., 2019; Chua et al., 2020; Manholer et al., 2019). Natural coagulants contribute as an alternative to chemical-based coagulants, which generally result in the generation of toxic sludges, and the chemical production process contributes to carbon emissions. Advancing the utilisation of biomass energy to meet the energy-food-water demands will contribute to achieving carbon neutrality.

5. Current development of bioproducts from biomass towards net zero carbon emissions

Several developments have been met in the last few years towards producing bioproducts from biomass. This development will assist in meeting the net zero carbon emissions goal if biomass energy sources are optimised and practically applied in all aspects. Modern technologies have led to the production of different bioproducts from biomass (De-Bhowmick et al., 2018). These technologies are improved types of thermochemical and biochemical conversion processes. In this section, some bioproduct conversion techniques and their advances have been studied with focus on contributions toward mitigating carbon emissions.

5.1. Anaerobic digestion as a conversion technique for bioproducts from biomass

In recent years, using different biomass as additives has enhanced the production of bioproducts. Qin et al. (2017) evaluated the enhancement of methane production from anaerobic digestion (AD) of organic fraction of municipal solid waste using magnetic biochar. An increase in 11.96 % methane production was achieved compared to the control AD. The retention of methanogens and regeneration of the magnetic biochar were possible. The retained methanogens are collected using a magnet and used as culture in AD systems, enabling the development of continuous flow anaerobic digestion systems. It will increase the

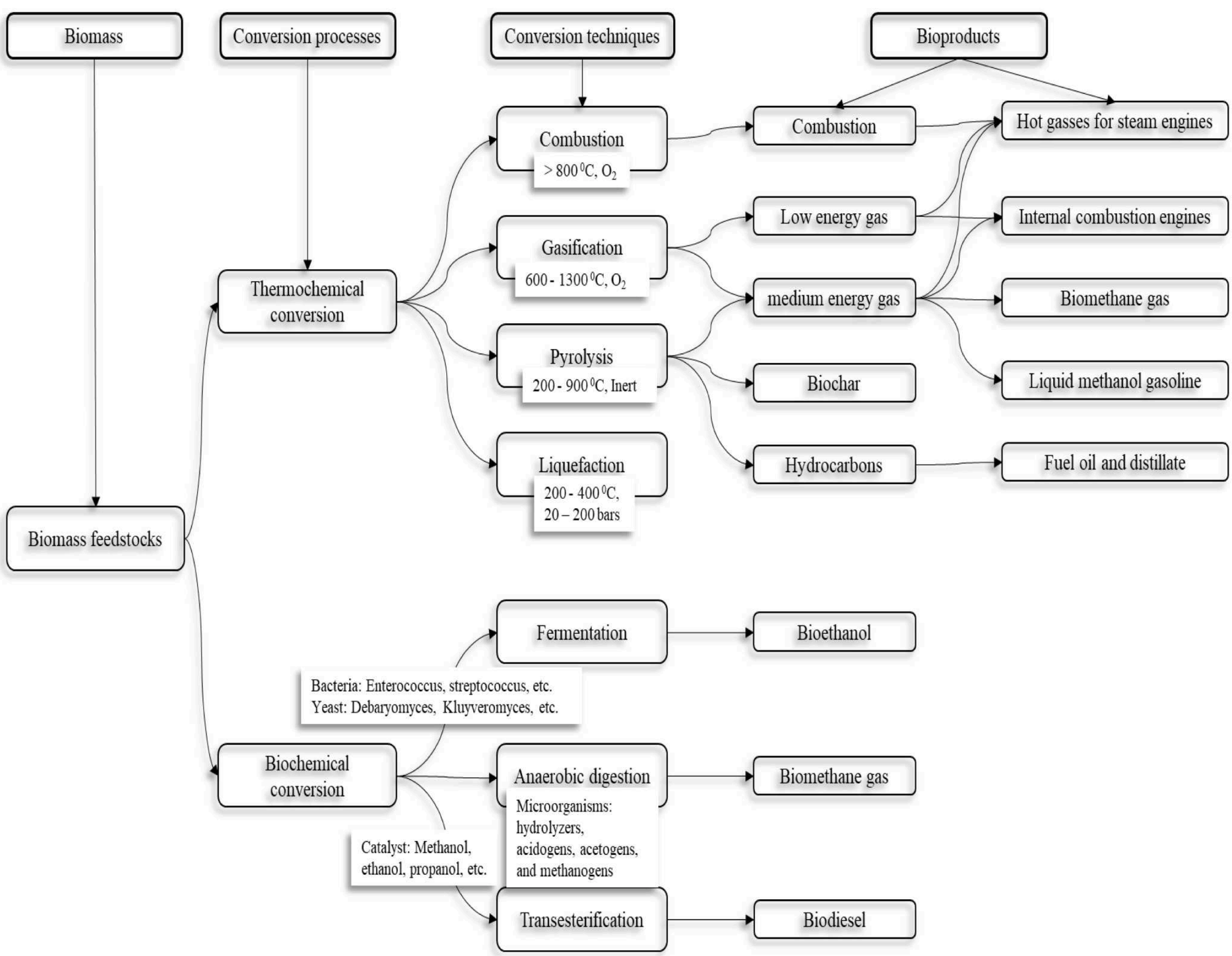

Fig. 1. A general overview of biomass conversion processes, techniques, and bioproducts (Nguyen et al., 2019; Ram and Mondal, 2022; Rana et al., 2019; Sharma et al., 2020).

methane gas production rate, making it possible for industrial use, thus reducing industrial carbon emissions.

The focus of researchers in AD is to advance the process for efficient production of bioproducts and significant contributions towards net zero carbon emissions (Ahmad & Reddy, 2019; Chan et al., 2019a; Dalantai et al., 2022; Leithaeuser et al., 2022; Liu et al., 2021a; Mostafa et al., 2022; Peyrelasse et al., 2021; Pomdaeng et al., 2022; Scherzinger et al., 2022; Zhang et al., 2022; Zhu et al., 2021). However, the efficiency of AD systems can be limited by several factors, including the presence of metals and antibiotics in feedstocks (Huang et al., 2022). Metals like zinc oxide nanoparticles (ZnO NPs) have been reported to significantly decrease methane production in an AD system (Chan et al., 2019b; Qi et al., 2021; Yang et al., 2020; Zhu et al., 2020).

An excellent example from Qi et al. (2021) where ZnO NPs at a dosage of 5 mg/g – 100 mg/g TS in a batch reactor using cattle manure as substrate at a temperature of 55 °C, a decrease in methane production by 84.55 % up to 93.72 % was recorded. However, Ahmad (2020) reported an increase in methane production with the effect of the same ZnO NPs, at a dosage of 0.5 – 5.5 g VS/L using a batch reactor with petroleum wastewater as substrate. These indicate that metals' effect on AD systems varies depending on the metal type, its concentration, and the type of substrates used. Therefore, understanding the impact of different metals on different AD will ease the enhancement of AD systems, increasing the production of biogas, and making it readily accessible, hence its use as a substitute for fossil fuels, in turn contributing to the mitigation of carbon emissions.

Mushtaq et al. (2022) have reported the effect of oxytetracycline concentration on the production yield of biogas in an AD of cattle manure. At a lower concentration (0.12 – 1.2) mg/L, no inhibition of the AD process was recorded. At a higher concentration of greater than 3 mg/L, inhibition was observed with a decrease in biogas production. Liu et al. (2021b), on the other hand, observed an increase in the production of biogas at lower concentrations of tetracycline at 2 mg/L and 4 mg/L, and inhibition of AD was observed at higher concentrations (greater than8 mg/L) with swine wastewater as substrate in a semi-continuous AD reactor for 54 days. In summary, investigating the combined effect of metal and antibiotics could mitigate some AD dysfunction, enhancing biogas production (Huang et al., 2022).

Jiao et al. (2022) reported the enhancement of methane production by 133.29 % by enriching the culture with the microbial electrochemical system in low-temperature anaerobic digestion systems. Their research displays the potential for AD systems to flourish in low-temperate regions, converting organic waste into biogas and biofuels for use in place of fossil fuels, thus advancing carbon neutrality.

Several studies have been conducted on reducing carbon footprint (CF) of wastewater treatment plants (WWTP) energy balance improvement. However, according to Maktabifard et al. (2020), these studies have not elaborated on the relationship between the CF and energy mitigation of the WWTPs. The investigation from Maktabifard et al. (2020) observed that the total CF of WWTPs were between 23 and 100 kg carbon dioxide equivalent (CO_{2e}) per population equivalent (PE). The CF of WWTPs were not correlating with the plant's capacity; other parameters, such as sludge disposal methods, energy efficiency, and wastewater characteristics, have contributed to the CO_{2e} emissions. The study recommended technological upgrades and a change towards renewable energy utilisation in WWTPs. The study has shown the significance of co-anaerobic digestion (co-AD) as an option contributing tremendously towards carbon neutrality.

In similar research, Chai et al. (2015) reported on CF analyses of mainstream WWTPs under different sludge treatment scenarios in China. An annual estimate of 5817–9928 tons of CO_{2e} CF was recorded. In the research, sludge disposal/treatment methods have been shown to contribute significantly to the CF, where sludge AD and biogas utilisation reduced the CF by 37 %, 34 %, and 24 % from anaerobic-anoxic–oxic (A-A-O), sequencing batch reactor (SBR), and oxygen ditch (OD), respectively.

5.2. Fermentation as a conversion technique for bioproducts from biomass

The use of a novel Gram-positive bacteria *Clostridium* sp. strain WST was investigated for highly efficient production of biobutanol with uncontrolled strategy. Shanmugam et al. (2018) reported the potential for the sustainable production of biobutanol at an industrial scale. Using novel bacteria, glucose and galactose were converted into a high amount of biobutanol from low concentration substrate via anaerobic fermentation. Biobutanol production amounts of 16.62 and 12.11 g/L, and the yield of 0.54 and 0.55 g/g from glucose and galactose, respectively, were observed to be higher than previous reports on Clostridial batch fermentation.

Chen et al. (2018) investigated a mixture of corn stover with liquefied corn conversion to bioethanol via fermentation. Two different mixtures were prepared, firstly were alkali pre-treated corn stover and corn at solid loading rate10% and 20 %, respectively. This yield 92.30 g/L of ethanol production. The yield improved to 96.43 g/L with a fed-batch strategy. The Second was for the mixture of diluted acid pre-treated corn stover and corn; a better performance was achieved. Ethanol production of 104.9 g/L with 80.47 % ethanol yield was recorded, and the production rate was as high as 2.19 g/L/h. The intention was to increase biofuel production yield from biomass, aiming to provide enough to sustainably reduce the dependency on fossil fuels, hence reduction in carbon emissions.

5.3. Microalgae biomass for bioproduct generation

Ang et al. (2020) have reviewed microalgae harvesting using natural coagulants to produce biofuels. Coupled with the fact that microalgae serves as a carbon sink and can utilise nutrients from municipal wastewaters, a natural alternative to alum will have a significant role in reducing the use of chemicals, which obviously may affect the microalgae properties and will require a high amount of energy to produce, in turn reducing the carbon footprint (CF) of wastewater treatment plants (WWTP).

Vo Hoang Nhat et al. (2018) reviewed algae characteristics for its applications, technical approaches, strengths and drawbacks, and future perspectives. Based on algae's prominent features for biofuel production and wastewater treatment, their life cycle assessment was reported to have a high energy return for bioenergy compared to fossil fuels due to their ability to capture CO_2 and utilise it for energy. Fig. 2 presents microalgae biomass applications.

Bhola et al. (2014) reported that microalgae could sink CO_2 50 times more than plants. In 1 ha of microalgae farm, 513 tons of CO_2 can be absorbed during their growth period. Iglina et al. (2022) noted that naturally cultivated microalgae can sink an estimated 2200 tons of CO_2 per annum in a 4000 m^3 pond, which is approximately 0.5 tons per 1 m^3. Despite the high price of biofuel from algae, the pursuit of meeting net zero carbon emissions will normalise the price, making it acceptable. A 75 % market dominance was anticipated, as reported by Ruiz et al. (2016).

Shen et al. (2018), in a study towards promoting the use of biomass for environmental bioremediation, Shen et al. used a biochar pellet of water hyacinth immobilised with *Chlorella* sp. (unicellular freshwater microalgae) for bioremediation of Cadmium (Cd). With several investigations of parameters including pellet materials, algal culture age, and illumination intensity, optimisation of Cd removal efficiency was found possible. A maximum removal efficiency of 92.45 % was obtained, and recovery tests of pellets and microalgal cells were found to be sustainably possible. This will eliminate the need for chemical precipitation, thus reducing CF.

Hussain et al. (2021) and Ali et al. (2021) demonstrated simultaneous wastewater treatment and bioproduct transformation possibilities. The fact that microalgae cultivation is expensive limits its application at the industrial scale. However, the simultaneous use of microalgae for wastewater treatment and biofuel production has

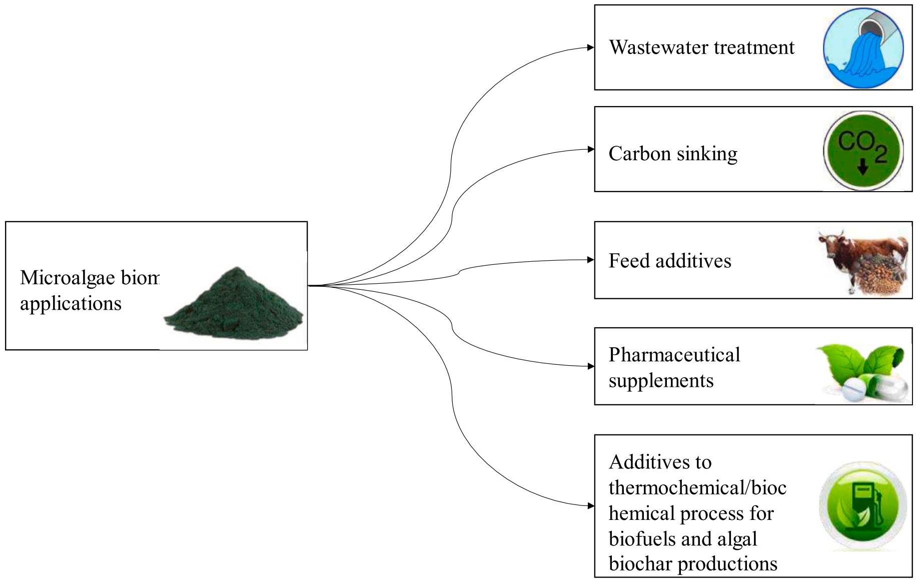

Fig. 2. Microalgae biomass applications.

softened the challenge of practicality and cost-effectiveness. Treatment of industrial effluents through microalgae cultivation can reduce the energy used for water management strategies and lead to the regeneration of valuable nutrients. This makes the possibility of transforming bioactive compounds into bioethanol, biopolymer, biofertiliser, and supplements for animal feeds. Table 1 outlines more research on using microalgae to produce bioproducts with some biofuels' production yields and heating values. Table 2 presents more examples of bioproducts from biomass used as alternatives to fossil fuels, chemicals, and non-renewable materials to mitigate carbon emissions.

5.4. *Wastewater remediation using biochar as a bioproduct*

While most of the research aimed at environmental, social, and economic development, notwithstanding, directly or indirectly, these processes will contribute towards reducing carbon footprint in their respective fields of application. Biochar for water and wastewater treatment is a typical example of lowering carbon footprints using bioproducts. Biochar is used in an advanced treatment process in water and wastewater treatment, where traces of heavy metals are adsorbed out of the water. Biochar eliminates the use of chemicals, reducing the carbon footprint of wastewater treatment from chemical production through the transportation of chemicals, where fossil fuels are commonly used as a source of energy. Though, a study on life cycle assessment analysis of different wastewater treatment plant processes by Rahmberg et al. (2020) has concluded that pre-precipitation with chemical coagulants has less carbon footprint than a biological process. However, their conclusion was only on phosphorus removal and excluded CF concerning other operations, including sludge treatment, etc.

Foong et al. (2022) noted an overview of biochar production from rice straw and its application for wastewater remediation. Their findings have shown the feasibility of biochar in the effective removal of metal ions and organic compounds, which are achievable via various synthesis and modification techniques. However, further research on removal mechanisms for other contaminants with an insight into the regeneration of the rice straw biochar was recommended. Similarly, using natural coagulants in water treatment will eliminate the need for chemical coagulants, thus removing the fraction of carbon emissions from chemical production and their transportation. Using these natural coagulants will eliminate the need for further sludge treatment, which is energy intensive hence, further preventing carbon emissions.

5.5. *Artificial intelligence as a tool for enhancing bioproduct generation*

Among the advancements in bioproducts from biomass production is the use of artificial intelligence (AI) and machine learning (ML) to reduce experimental work (Seo et al., 2022). The accuracy of prediction by experience or theory has been a limiting factor in bioenergy systems. With machine learning, new opportunities in predicting bioenergy systems are possible (Wang et al., 2022). It involves classifications, regressions, and optimisations in the bioenergy system. Machine learning can further enhance the conversion possibilities in lignocellulose biofuels and microalgae cultivation.

The application of machine learning and artificial intelligence has been demonstrated using Artificial Neural Network (ANN) modelling (Uzun et al., 2017). Other techniques such as support vector machine (SVM), random forest (RF), multilinear regression (MLR), and decision tree (DT) all have been successfully used in the pyrolysis and gasification of biomass (Ullah et al., 2021).

The simultaneous recovery of bioenergy and materials has also been studied from other perspectives. In the research of Geng et al. (2018), a novel electrodialysis membrane (EBPR) sludge treatment for the recovery of bioenergy and phosphorus was investigated. A 30-day stable voltage output of 0.32 W/m^3 as maximum power density was reached. The study demonstrated the possibility of optimising processes for energy and material production from biomass, thus reducing the share of fossil fuels needed to produce phosphorus. This further reduces carbon emissions from fossil fuels, contributing to carbon neutrality.

The direct and indirect contribution of biomass bioproducts towards net zero carbon emissions can be elucidated from several relevant research. The type of biomass regarded as challenging to convert has been identified as lignocellulose biomass (Zhao et al., 2022). The challenge is due to its recalcitrant and heterogeneous structure. However, recent research has shown the feasibility of converting the lignocellulose biomass into valuable bioproducts other than open burning to release useful heat. Achieving this has been related to pretreatment techniques by Zhao et al. (2022). Pretreatment techniques have been shown to offer solutions by separating the main component of the lignocellulose, exposing the available cellulose, which can be converted into bioenergy. These pretreatments include Physical: mechanical, ultrasonic, and thermal; chemical: acid, alkali, oxidative, organo-solvent; biological: bacteria, termite, fungal, yeast; physiochemical: steam explosion, alkali-heat, ammonia fibre, extrusion; and emerging pretreatments to include biochemical, ionic liquid, deep eutectic solvents, supercritical fluid, etc.

Table 1
Microalgae as feedstocks for production of biofuels of high heating values (HHV).

Feedstock (Microalgae Species)	Process	Findings	References
Microchloropsis salina (SAG 40.85)	Batch process of thin-layer cascade photobioreactor	High lipid concentration of 6.6 g/L with high CO2 conversion efficiency at an alkalinity of 10 mM	Schadler et al. (2019)
Spirulina platensis	Biphasic processing techniques with sonication treatment	94.89 % recovery yield of phycobiliproteins (C-phycocyanin) and a purification fold of 6.17	Chia et al. (2019)
Monoraphidium sp. KMC4	Transesterification	78 % biodiesel production efficiency with high heating value of 20.33–22.14 MJ/kg	Mishra and Mohanty (2019)
Chlorella sp. FC2 IITG	Transesterification	96.9 % biodiesel production efficiency with high heating value of ~ 39.4 MJ/kg	Chauhan et al. (2020)
Chlamydomonas reinhardtii and *Thiomonas Intermedia*	Biochemical via photobiological hydrogen production	Hydrogen production at 255.52 μmol/mg Chl	Ge et al. (2019)
Chlorella sp. and septic tank sludge	Biochemical via Anaerobic Digestion	Methane production at 300 mL/g VS	Lu et al. (2019)
50 % olive mill solid waste-50 % *Chlamydomonas reinhardtii* 6145	Biochemical via Anaerobic Digestion	Methane production at 542 ± 4 mL CH_4/g VS	Fernández-Rodríguez et al. (2019)
Microalgal biomass	Thermochemical process via Hydrothermal carbonisation	37 % Hydrochar production with a high heating value of ~ 12.1 MJ/kg	Marin-Batista et al. (2019)
Sewage sludge and *Chlorella sp.*	Thermochemical process via Hydrothermal carbonisation	87.68 % Hydrochar production with a high heating value of 5810 kcal/kg	Lee et al. (2019a)
sewage sludge (SS): *Chlorella* sp. (1:1)	Thermochemical process via Hydrothermal liquefaction	57.87 % bio-oil energy recovery: Chlorella sp. 17.31, and SS 16.14	Xu et al. (2019)
Nannochloropsis sp.	Thermochemical process via Hydrothermal liquefaction	30.0 wt% of bio-oil with high heating value of 23.11 MJ/kg	Saber et al. (2016)
Nannochloropsis Oceanica	Thermochemical process via Torrefaction	99.82 % biochar production with high heating value of 21.016 MJ/kg	Zhang et al. (2019)
Chlorella Vulgaris, and hog manure wastewater	Biofilm photobioreactor	~7.37 g/m2 biomass of C. Vulgaris with a lipid content of 14.29 % and 10.17 % in suspension, and on membrane structure, respectively.	Wu et al. (2019)
Microalgal biomass	Novel phase separated biological pretreatment (PSBP) via cell disintegration	Methane production of 411 mL/g COD with a net energy production of 6.467 GJ/d	Kavitha et al. (2019)

Table 2
Biomass substrates, conversion techniques, and bioproducts used for energy and water treatment.

Substrates	Conversion Technique	Bioproducts/ findings	References
Microalgal	Mixotrophic cultivation strategy (MCS)	MCS increases microalgal production for valued products to include biochemicals, biofuels, bioplastics, algal carotenoids	Patel et al. (2021)
Syngas (H_2/CO_2) with methanol and *Eubacterium Limosum* (KIST612),	Anaerobic cultivation of bacteria and fermentation	Methanol speeds up fermentation process for enhanced production of biofuels and biochemicals	Kim et al. (2021)
Bioplastics	Anaerobic co-digestion	Anaerobic co-digestion enhances sustainable waste management with improved bioenergy production	Abraham et al. (2021)
Food wastes	Integrated biological processes to include transesterification, bio-pyrolysis, fermentation, Anaerobic digestion, etc.	Integrated biological processes can enhance the quality and yield of bioproducts to include biodiesel, biohydrogen, biomethane, bioethanol, biobutanol, etc.	(Anwar et al., 2018; Dahiya et al., 2018; Fadhil et al., 2017; Talan et al., 2021; Xiong et al., 2019)
Agricultural residues to include Agro-industrial wastes, wood and wood industry waste, etc.	Microbial-Enzymatic conversion valorisation	Microbial-Enzymatic conversion will enhance production of biofuels, bioplastics, organic acids & chemicals.	Usmani et al. (2021)
Dairy wastes to include cheese whey, food waste, vinasse, etc.)	Enhanced dark-fermentation process	Enhanced dark-fermentation process stabilises and increase biohydrogen yield	Garcia-Depraect et al. (2021)
Catering services waste (Microbial lipid derived from food waste)	*Rhodosporidium toruloides* fermentation with hydrolysis as pretreatment. Solid state fermentation of *A. awamori*	valorisation of food waste for microbial oil biodiesel production was shown to be feasible	Carmona-Cabello et al. (2021)
Citrus peels waste (CPW) with Engineered yeast (*Saccharomyces cerevisiae*)	Biological valorisation via fermentation	Engineered yeast (*S. cerevisiae)* shows to be able to ferment pectin fraction of CPW enhancing the production of bioethanol, and bio-based nylon (mucic acid)	Jeong et al. (2021)
Digestate from Anaerobic digestion	Integrated biological and thermochemical valorisation processes	Integrated biological and thermochemical conversion processes will enhance and increase the	Wang and Lee. (2021)

(*continued on next page*)

Table 2 (*continued*)

Substrates	Conversion Technique	Bioproducts/ findings	References
		production of methane, bioadsorbents (pyrochar, and hydrochar), adsorbent for CO_2 capture.	
Food waste	Advanced conversion techniques to include Ultrasound-assisted extraction, microwave-assisted extraction, bioreactors, enzyme immobilisation-assisted extraction, and their integrated processes	Sustainable processing of food wastes via advanced techniques will improve production yield and quality of biohydrogen, biodiesel, bioethanol, biobutanol, biogas, bioenergy (electricity), biomaterials and chemicals.	Sharma et al. (2021)

In view of the current development of biomass contribution towards meeting carbon neutrality, biomass is regarded as an essential resource for developing sustainable value-added bioproducts (Usmani et al., 2021). Different biomass categories have been experimented with using different conversion techniques to produce valuable bioproducts. Among several advancements in biomass conversion, integrating biochemical and thermochemical methods, valorisation of biological methods using engineered yeast and bacteria, and developing a continuous flow process towards biorefineries, all have contributed to enhancing product quality and yield of bioproducts from biomass.

6. Challenges and future perspectives

The use of biomass as a source of energy can be dated back to the stone age when humans used wood to make fire. However, the advancement in biomass energy sources is just over a century old, and more investigations are being conducted to exploit more possibilities in the sustainable use of bioproducts from biomass. Most existing studies focused on three aspects of biomass conversion to bioproducts: pretreatment of biomass, improvement of bioproduct quality, and integration of system designs.

The pretreatment processes alter the physiochemical properties of biomass, significantly impacting its conversion process, product distribution, and properties (Zhao et al., 2022). When looking at lignocellulose biomass, the recalcitrant structure of lignocellulose makes the efficient utilisation of lignocellulose still difficult for its practicality. Recent research in lignocellulose pretreatment reviewed and discussed the barriers hindering the development of conversion processes and the future opportunities available.

Meanwhile, several research gaps need to be filled. Among these gaps are lack of ideal pretreatment, high cost of current pretreatments, low lignin content from lignocellulosic metabolism, less research on integrated biorefineries to mitigate the difficulties of lignocellulose metabolism, and low interest in research on the potential development towards enhancing bioproducts production processes into practical biotechnologies for biomass treatment and value-added materials recovery. Improvement of bioproducts quality, on the other hand, focuses on extending the practicality of production and increasing the economic benefits of bioproducts (Garcia-Depraect et al., 2021; Jeong et al., 2021; Usmani et al., 2021).

Conversion process integration is among the new perspectives for improving biomass conversion. Most notably is the design of integrated systems for converting different types of feedstocks (Anwar et al., 2018; Dahiya et al., 2018; Fadhil et al., 2017; Talan et al., 2021; Xiong et al., 2019). Examples of some commonly discussed integrated process which, however, focuses on only one feedstock (digestate) are Anaerobic digestion (AD) which is a type of biological process and some thermochemical processes (pyrolysis, hydrothermal and gasification) (Wang and Lee, 2021). Concisely, results from Wang and Lee (2021) reveal that regardless of the feedstock combination, the AD/pyrolysis integrated system has demonstrated positive benefits among the different integrations. Although the research confirmed the promises of digestate as a renewable resource only, suggested investigations apply to other feedstocks. Therefore, more studies are required on the irreversibility that may deteriorate the benefits of feedstock valorisation. More comprehensive databases are also essential for different feedstocks' characteristics and valorisation options. Table 3 outlines some potential feedstocks for the AD/pyrolysis integrated system.

According to Lee et al. (2019b), transesterification is a sustainable technique for producing biodiesel in large quantities from biomass residues. Transesterification is considered the most viable pretreatment method, where fats and oils are converted into esters and glycerol. These techniques improve the conversion of biomasses, and fatty acid methyl ester (FAME) produced can be used as biofuels. Decentralised and mobile systems for renewable energy from biomass conversion are promising. Research by Kang et al. (2021) on decentralised and mobile systems for renewable energy production has highlighted the carbon footprint issue due to hauling biomass feedstocks from collection to the conversion facility site. The effort to reduce biomass feedstocks cost was further suggested by Seo et al. (2022). While outlining two general conceptual modes of operations, the centralised and decentralised conversion facilities, both are aimed at minimising logistics cost, thus reducing carbon emission as well.

Life cycle assessment analysis (LCA) is also necessary to ascertain the most sustainable type of integrated biorefinery systems. For example, the LCA of an anaerobic digestion system will indeed depend on the type of substrates used and the type of system used. Since LCA of bioenergy identifies the efficiency of a system based on its energy consumption, energy generation, and its level of impact on the environment with much focus on greenhouse gases emissions (Duan et al., 2020; Gopal et al., 2019; Lanko et al., 2020; Sakhaee and Sakhaee, 2022). Lanko et al. (2020) conducted a comparative LCA of three different types of AD systems (mesophilic, thermophilic, and temperature-phased anaerobic digestion(TPAD)). 1 m^3 functional unit was used for the whole WWTP and sludge line, with nine environmental impact factors analysed. TPAD performed better than mesophilic and thermophilic AD for the entire WWTP LCA. For the sludge line, thermophilic performed best, with mesophilic and TPAD following. Even though the differences between the LCA were suggested to be attributed to the functional units chosen, it demonstrated the differences of AD systems, which necessities system assessments of all types except when dealing with a similar design, then data adoption can be practiced.

Similarly, with microalgae biomass production, LCA is affected by cultivation techniques and weather conditions (Chia et al., 2018; Guiton et al., 2022; Koyande et al., 2019). The contribution of biomass energy to the world's energy supply is visible and measurable. In world data for modern renewable energy generation by sources, Hannah et al. (2020)

Table 3
Potential feedstocks for AD/pyrolysis integrated conversion process.

Potential feedstocks	Integrated processes	References
Wheat straw	AD/pyrolysis	Rani et al. (2022)
Rice straw	AD/pyrolysis	Ngan et al. (2020)
Corn stalk	co-AD/pyrolysis	Lv et al. (2018)
Palm oil mill waste	AD/pyrolysis	Fikri Hamzah et al. (2020)
Food waste	AD/pyrolysis	Pramanik et al. (2019)
Sewage sludge	co-AD/pyrolysis	Hanum et al. (2019)
Lignocellulosic residues	co-AD/pyrolysis	Neshat et al. (2017)

have presented bioenergy as the fourth contributing renewable energy source, with an annual generation rate of 800 terawatt hour (TWh). Hannah et al. (2020) further present the yearly biofuel production by country measured in terawatt-hour per year, with the United States of America being the highest producer at approximately 400 TWh.

Countries like the United States of America, Canada, China, India, Netherlands, etc. have researched pilot and industrial-scale biomass conversion systems using thermochemical systems with agroforestry feedstocks to produce bioproducts for energy generation (Kang et al., 2021). With the proper education and training, and the use of the appropriate system combination, the contribution of bioproducts from biomass will tremendously add up towards meeting net zero carbon emissions.

7. Conclusion

The various advances in the conversion of biomasses into bioproducts have been critically discussed in this review. Bioproducts like biochar, natural coagulants, biofertilisers, and biofuels have been shown to be good alternatives to chemical-based materials and fossil fuels. New designs and technologies for biomass conversion including integrated conversion processes like AD/pyrolysis; and pretreatment methods like transesterification are improving bioproducts yield. These make biomasses good contributors to meeting net zero carbon emissions. With the proper education and training and development of special skills to design, construct, operate, and maintain biomass conversion systems, bioproducts will contribute excellently to meeting carbon neutrality.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yeek-Chia Ho reports financial support was provided by Murata Science Foundation.

Data availability

No data was used for the research described in the article.

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