Sustainable Futures 10 (2025) 100835

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

A review on advancing sustainable energy: The role of biomass and bioenergy in a circular economy

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ARTICLE INFO

Keywords:
Biomass
Bioenergy
Conversion
Renewable energy
Bioeconomy

ABSTRACT

The progression towards sustainable energy production has been emerging in recent years with regard to economic and environmental perspective. Biomass based bioenergy plays a crucial role in the advancement of circular economy through conversion of biomass into value added products. The current review explores the different biomass conversion technologies such as thermochemical and biochemical methods for energy production. Detailed insights into different thermochemical and biochemical methods such as pyrolysis, gasification, fermentation, and anaerobic digestion has been provided. In unique, the review integrates the circular economy principles into bioenergy production that emphasizes the waste biomass valorization. This review discussed the applications of biomass and bio-waste derived materials for bioenergy production. Technical challenges and limitations of biomass utilization for the generation of bioenergy provides clear insights for the future research development. The content on future perspectives and biomass advantages in sustainable energy production highlights the importance of integrated approaches in achieving energy security.

1. Introduction

The escalating energy demand driven by industrial and anthropogenic activities has intensified the exploitation of resources. This demand has raised the energy demand and reliance on fossil fuels producing greenhouse gases that have a tendency to build up in the atmosphere and harm the environment. Eco-friendly and alternative energy sources are being prioritised in order to combat the simultaneous pressure of resource depletion and emission reduction [1,2]. Among renewable energy sources, bioenergy has the potential to replace conventional fossil fuel based reources. A large portion of the world's future energy supply will come from bioenergy. The contribution of this bioenergy to the world energy supply ranges from 10 to 13 % highlighting its crucial role in the future energy systems [3].

Biomass, an organic matter from numerous sources - plants, microorganisms, and animals offer a vast and diverse feedstock for bioenergy production. As a by-product of human activities, biomass residues from forestry, agriculture, and industrial processes are abundantly available and underutilized for many activities. These biomass residues represent a sustainable energy source, specifically in the view of rising global temperatures and depleting fossil fuel reserves [4,5]. After processing, many agricultural residues which has the untapped potential for bioenergy production. Recycling biomass leftovers can be used to create a variety of minor goods, but this has less potential because it might lead to secondary pollution of the environment [6]. Currently, biomass contribute to approximately 50 % of global energy supply emphasizing the importance in energy sector. Thus, understanding the usage of biomass residue has emerged as a crucial research area in recent years. Utilizing biomass as an energy source not only helps to preserve non-renewable resources but also advances economic growth and environmental conservation [7,8].

The use of biomass also complements the circular economy that emphasizes the resource recycling and reuse for achieving sustained growth. There are currently two first generation biofuels produced: biodiesel from vegetable oils and bioethanol made from sugar based crops. The production of first-generation biofuels is based on well-established technologies, and the final products are successfully utilised. However, due to the limited feedstock availability, high production cost, and competition, these biofuels are expensive [9,10]. Additionally, a rivalry between the food and fuel industries had been sparked, with the economy primarily emphasising the excessive utility of feedstock leading to the development of second generation biofuels

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https://doi.org/10.1016/j.sftr.2025.100835
Received 25 July 2024; Received in revised form 4 May 2025; Accepted 8 June 2025
Available online 12 June 2025

[11]. Second generation biofuels, which are produced from agricultural residues and by-products, organic wastes, and materials collected from purposefully grown energy plantations overcome sustainability challenges and expand feedstock options [12].

Biomass can be converted into useable forms of energy via a number of different processes. Selection of conversion process depends on the factors such as kind, quantity, and quality of the biomass feedstock, the desired form of energy or end-use needs, environmental legislation, policy, economic conditions, and project-specific considerations. Accessible feedstocks and the form in which energy is required are the most frequent elements that determine the appropriate process pathway, which includes biochemical, thermochemical, and physico-chemical methods [13,14].

The adaptability of these kinds of resources combats the rivalry between food producers and further supports the sustainable growth of biofuels. Even though conversion technologies and process operations for second generation biofuels are still being studied technologically, they are anticipated to meet requirements for minimal land usage and considerably improved CO_2 emissions reduction potential after commercialization [15,16]. The thermochemical and the biochemical conversion pathways are primarily employed to generate second generation biofuels. The Fischer-Tropsch (F-T) synthesis is followed by gas cleaning and conditioning operations after pyrolysis and/or gasification, which results in the generation of synthetic liquid fuels. The biochemical method entails the enzymatic conversion of cellulose and hemicellulose to sugars, accompanied by fermentation to produce bioethanol [17]. Fermentation, photosynthesis, and anaerobic digestion are the common biochemical processes employed for biomass conversion to biofuel. Biofuels generated from biomass also finds applications in diverse fields [18].

The biomass potential for sustainable energy systems has been extensively reviewed in the previous literatures. However the current review seeks to fill a crucial gap by focusing on the role of bioenergy within the framework of a circular economy. The circular economy highlights the resource efficiency through waste recycling minimizing the hazardous impact and reliance on fossil fuels. By aligning bioenergy with circular economy principles, the present review offers a unique perspective on sustainable biomass utilization. This review entails on the green and circular economy of biomass conversion to bioenergy. A brief overview on biomass and it composition has been included in the review. A description on bioenergy and potentiality of biomass for bioenergy production has been included. A detailed account on thermochemical, biochemical, and physico-chemical conversion processes was entailed in the review. Some of the applications of biofuels derived from biomass has been included in this review. Articles were identified through electronic databases such as scopus and google scholar with important keywords till year 2024. Research and review articles were preferred for understanding of biomass based bioenergy production. Studies were screened based on the relevance of the topic to give a comprehensive overview of the bioenergy production.

2. Energy valorization of biomass resources

2.1. Energy production pathways

Energy production pathways includes the processes where the primary energy sources are converted into energy such as fuel or electricity. Conventional methods for energy production include fuel based pathways such as coal combustion, combined cycles, and oil refining. With regard to sustainability and low environmental influence, solar, wind turbines, geothermal, and biomass energy, attention has been shifted towards these renewable energy sources. Bioenergy derived from biomass has emerged as a significant energy in the global aspects. Petroleum by-products are used for the biomass processing to generate biofuels. Biofuel is viewed as a significant energy substitute for fossil fuels to minimize energy vulnerability from the standpoint of energy supplies. The total energy potential of biomass plays a crucial role in bioenergy generation [19]. Each step of the biofuel manufacturing process, from growing crops to crop conversion into bioenergy, demands a considerable amount of energy. Various raw materials used to produce biofuel has diverse energy demands. For instance, starch granules, like maize, and polysaccharides, such as sweet millet, both consumed 1.47 MJ/MJ and 1.46 MJ/MJ. Corn-based biofuel generated through conventional method had a quality of 5.22 MJ/MJ whereas corn-based biofuel generated through wet milling had a quality of 5.25 MJ/MJ [20,21]. As a green energy source, biofuel is thought to be able to reduce the issues of air pollution and global warming brought on by the usage of conventional fuels. After examining the production, use, and (global) commerce of biofuels, it was discovered that utilising biofuels in the European Union (EU) in 2012 resulted in an annual profit of around 27 tonnes of CO_2-equivalent, or 54 % less than using fossil fuels solely [22]. The use of non-renewable sources of energy, such as gasoline and electricity, contributes to greenhouse gas emissions throughout the conversion process.

2.2. Biomass utilization in energy systems

Biomass serves as a valuable resource for the bioenergy production. Prior to the initiation of mining activities in the 18th century, lumber and coal, both of which constitute biomass, provided power required by humans. Following which coal became the primary fuel source of industrialization [23,24]. Biomass is the sole biological, sustainable source of carbon that is generally listed to be substantial enough to replace coal.

Unlike oil and coal, biofuel is a renewable energy source that can be used directly or converted into different forms. The carbon emissions from biomass are considered neutral as carbon dioxide released during the process refers to the amount of CO_2 absorbed by biomass during the growth. Currently, biomass serves a variety of industries well: it may be used as energy or nutrition to produce power, heat, and fuels, or it can be used as a resource and commodity in industries like the timber, pulp, and petrochemical industries [25,26]. Biomass derived from trees, agro-forest leftovers, grasses, aquatic plants, and crops play crucial role in bioenergy production and sustainable development. Plants convert water and carbon dioxide into primary and secondary metabolites through the process of photosynthesis. For instance, Biesdorf et al. [27] assessed the quality of *Acrocomia aculeate* leaf biomass for bioenergy application. The case highlights the region specific and least explored biomass resource – *Macauba* leaves for energy production. The research inferred high water availability enhanced biomass production with energy yield reaching upto 122 GJ ha^{-1} $year^{-1}$ [27]. Similarly in another study, potential of bioenergy derived from agricultural residues and energy crops have been assessed. The study inferred that around 7.9 Mt and 15.6 Mt of biomass can be yielded from animal waste and crop residues by 2050. Life cycle assessment analysis confirmed the potential of 8.01 TWh of bioenergy with lower greenhouse gas emissions [28]. The study underscores the importance of sustainable production of bioenergy from biomass with reduced environmental impacts. The biomass contains significant amount of lignin and carbohydrates, known as lignocellulose. Hemicelluloses (10 %–50 %), lignin (5–35 %), and cellulose (9 %–80 %) make up the majority of the biomass resources [17,29]. Lignin, a complex polymer provides rigidity and act as a barrier to enzymatic degradation. Lignin is resistant to breakdown reducing the efficiency of fermentation process. Cellulose and hemicellulose which are complex glucose polymer units is required for fermentative based bioenergy production. However, the crystalline nature of cellulose poses challenge for enzyme accessibility. In one of the study, degree of polymerization has been found to be negatively correlated to cellulose hydrolysis. Long cellulose chain consists of more hydrogen bonds making it tedious for hydrolysis process [30]. In case of hemicellulose, although being amorphous in nature, it leads to complex mixture of sugars necessitating the need of better microbial strains for the conversion process. To overcome the biomass recalcitrance and structural complexity, advanced pre-treatment methods is essential for enhancing the bioenergy production. Additionally, virgin biosolids, microalgae, and grains developed for biofuels are utilised as raw materials in the manufacturing of bioenergy [31,32]. Lipids are energy-rich compounds and can be subjected to breakdown into long chain hydrocarbons that are suitable for liquid biofuel production. Macroalgae can accumulate lipids up to 20–50 % of dry weight and even up to 80 % under stress conditions. This high lipid concentration makes macroalgae a potential source for pyrolysis aiding in the production of syngas. In relative to lignocellulose biomass which requires pre-treatment, macroalgae can be directly processed for bioenergy production as they lack complex lignin content. In addition, macro-algae are abundant and lack competitiveness with food crops making them a sustainable and non-competitive source [33]. These properties facilitate macroalgae as promising alternate for other biomass resources.

While biofuels are promoted as renewable alternate to fossil fuels, concerns regarding energy input has raised in recent years. Certain studies have inferred that bioenergy production relies on intensive agricultural practices requiring more energy input than the production [34]. However, the bioenergy energy requirement is highly dependent on type of biomass. For instance, bioenergy derived from agricultural residues require less cultivation and processing improving the energy performance of the system. Algae based biomass feedstock does not require pre-treatment process reducing the need for energy. Additionally certain challenges like land use competition and lifecycle emissions limit its applicability. Growing energy crops competes with land for food production leading to food insecurity. Also, biomass cultivation for energy production might lead to deforestation contributing to indirect emissions in the atmosphere [35]. Lifecycle emissions and air pollution resulting from biomass combustion are other critical issues arising from the use of biomass in bioenergy production. Thus, choosing appropriate feedstock is crucial for accurately accessing the energy efficiency and type of conversion process for bioenergy production systems. Different conversion processes of biomass for bioenergy production has been elucidated in Fig 1.

3. Necessity and global scenario for bioenergy production

Increasing need for climate change and transition towards sustainable energy systems has made bioenergy a vital component in global strategies to mitigate climate change and future energy demands. Beyond offering a renewable energy source, bioenergy also plays a crucial role in the carbon dioxide removal through BECCS. BECCS results in negative CO_2 emissions through integration of carbon capture with biomass energy. Inter-governmental Panel on Climate Change (IPCC)s fifth assessment report outline extreme remediation conditions which are aimed at reduction of atmospheric CO_2 to 450 to 550 ppm by the year 2100. The report primarily relies on large scale deployment of BECCS and biofuel production [36]. The main carbon dioxide removal techniques which were most frequently incorporated in combined routes simulated for the IPCC SR1.5 assessment were BECCS and vegetation, respectively. BECCS works by biomass cultivation absorbing CO_2 during propagation. Biomass when processed into bioenergy releases CO_2 which are captured by and stored rather than being released into the atmospheric environment. Besides negative emissions, certain challenges like high land, water use, biodiversity loss, and scalability issues occur. Despite the limitations, BECCS has been crucial in bridging the gap between emissions and climate change requiring careful consideration of environmental trade-off. A few approaches depended more heavily on BECCS than others [37]. Such routes were created utilizing holistic evaluation methods such as integrated assessment models (IAMs), that are used to examine possibilities of the future direction of global oil, agriculture, commerce, and environment. These models play crucial role in exploring long term scenario of global trends in bioenergy production and environmental sustainability. By integrating biophysical process with socio-economic factors, IAMs offer better solution. For instance Riahi et al. [38] focused on shared socio-economic pathways (SSPs) for exploration of impact of variations in socio-economic development on climate change mitigation. SSPs outline five socio-economic objectives projecting wide variations in energy use and emission by the year 2100. Through multi-model approach showing the energy demand and emissions that could vary between 25 and 120 $GtCO_2$. The study highlights the inference of dependence of mitigation cost on socio-economic factors [38]. Similarly Calvin et al. [39] expanded the IAM application for demonstrating variation in socio-economic factors for bioenergy production. Integrated policy responses have been evaluated emphasizing the importance of IAM model [39]. These models provide better foundation for assessing the bioenergy production potential under varying policy and environmental conditions. The usage of modelled biofuels can be affected by a number of modelling presumptions [40,41]. Many IAMs include restrictions on bioenergy generation's financial and technological possibilities in order to represent geophysical limitations and worries about ecological consequences [42]. This may be accomplished in a variety of ways. For instance, certain scenarios of restricted farmlands [43,44] incorporate subsidies for agricultural sequestering carbon. Numerous different crucial approaches utilize those related to the price and access of fossil energy, the

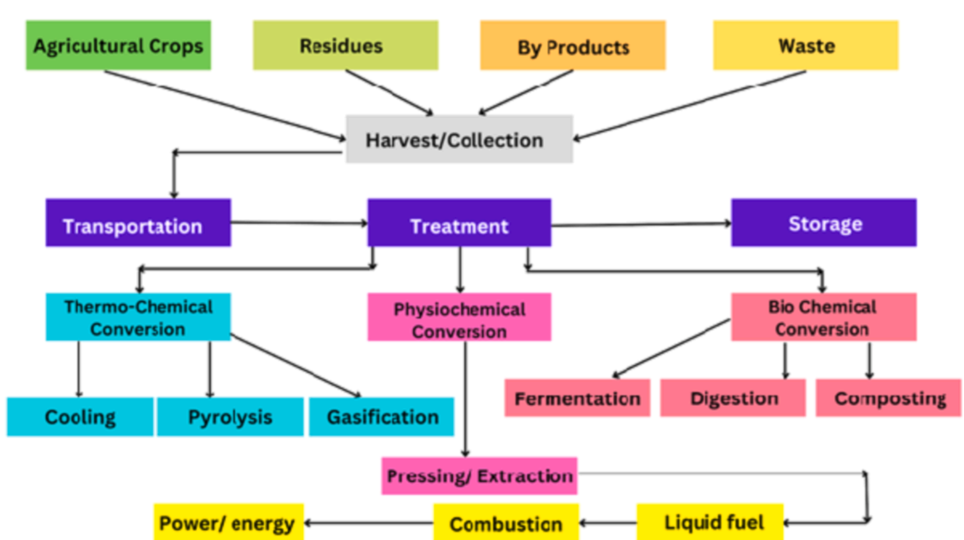

Fig. 1. Different conversion processes of biomass for bioenergy production.

price and accessibility of alternative mitigation strategies [41,45,46], the proportion of technology advance, along with crop yield. For instance, the latter statement assumes that all Carbon intensity processed inside the power system will have an equal pricing for carbon that is imposed worldwide [47].

While IAMs monitor all carbon shifts associated with the generation and utilization of biomass for energy (including land-use change), they operate under the assumption of carbon neutral nature of bioenergy. This results in exclusion of bioactive carbon fluxes like carbon sequestration by biomass and biofuel burning emissions. In one of the research by Hanssen et al. [48], implications of representing carbon fluxes in IAM has been demonstrated. Substantial reduction in role of bioenergy in future environment has been accounted by biogenic carbon emissions. With the absence of the corrections, models overestimate bioenergy benefits. The study emphasized that ignoring carbon fluxes results in unsustainable practices [48]. Simplification affects the model outputs in scenarios with more reliance on bioenergy. As the assumption overlook on spatial and temporal variability in carbon uptake, it may lead to overestimation of mitigation potential of bioenergy. Current research has been focussed on refined IAM frameworks incorporating realistic representation of carbon cycle. For instance, Singh et al. [49] investigated a number of policy options to price biogenic carbon fluxes (both absorption and releases). Analysis inferred that the application of carbon price to emission and sequestration reduced biofuel usage up to 30 % relative to carbon neutrality assuming models. The sensitivity of bioenergy deployment with policy assumptions emphasizing the need for carbon accounting has been inferred to avoid overestimation of mitigation potential [49]. The findings have significant policy implications in accordance with the international agreement like Paris accord. By ensuring the policy frameworks with accurate IAM models, inaccurate assumptions can be minimized and reliance on IAM for policy recommendations. If the bio-energy is based on carbon-neutral solution, countries overestimate the potential to meet carbon reduction.

4. Biomass conversion process

4.1. Thermo-conversion

4.1.1. Gasification

Carbonaceous biomass is transformed to combustible gasses (H_2, CO, CO_2, and CH_4) with distinctive heating values by utilizing partial oxygen supply, usually 35 % of the oxygen supply that is required for the complete combustion. Gasification is a process that is similar to combustion that proceeds in a gasifier but regarded as partial combustion, the elevated temperature range of the entire process is of the range 800–1300 °C. Minimal equipment footprint requirements, excellent thermal efficiency, precise combustion control, and low CO_2 emissions are a few benefits of biomass gasification [50,51]. Syngas is a gaseous form of bioenergy that is produced as a result of gasification which can be distinguished into 4 unique kinds based on their heating values. Fixed bed and fluidized bed gasifiers are the two common gasifier types used in the biomass conversion process. Fixed bed gasifiers are cylindrical system, primarily deployed for the generation of low heating value syngas, wherein the fed biomass and the produced syngas moves either in the upward or downward direction. This system has a simple construction design, operates with minimal ash carry over and gas velocity, however it is challenging to maintain uniform temperature because the system is devoid of agitation.

The gasifiers are grouped into various types, which includes updraft (counter-current), downdraft (co-current), cross-flow, and open-core gasifiers depending on the direction of the air that enters the reactor for biomass gasification. In the updraft type, the biomass and air are injected into the top and bottom of the reactor respectively. At the base of the bed, char completely burns, releasing CO_2 and water. These hot gasses, with temperature about 1000 °C, pass above the bed and are converted to CO and H_2, which is further cooled to 750 °C. The reducing gas at the top continues to pyrolyse the incoming wet biomass to dry, ultimately reducing the reactor's temperature to 500 °C. The obtained producer gas is rich in tar which makes it unsuitable for engine applications, however it is recommended for thermal utility. Song et al. [52] carried out the gasification of pine saw dust in an updraft gasifier system for the production of hydrogen gas. The analysis revealed that generated syngas contains high H_2 content with low CH_4 content. Highest gas yield of 2.27 Nm^3/kg feed has been obtained with the gasification process [52]. Downdraft technique is deployed where conversion of high volatile fuel to low tar gas is required, a suitable mechanism for power generation. In a packed bed of solid fuels that is flowing downward, air is supplied, and gas is drained out at the bottom [53]. A research explored both updraft and downdraft fixed-bed gasifier systems for hydrogen production from olive pomace. Hydrogen content of 49 % and 53 % were observed from downdraft and updraft gasifiers. The study inferred that updraft gasifier proved to be more effective in hydrogen production from oil pomace in both oxidizing environments [54]. Although gasification in updraft gasifiers are capable of handling high moisture biomass, high tar content is observed with the product. As tar condense and clogs the pipelines and reduces the conversion efficiency. Cross-drafter is an appropriate method for wood, charcoal and coke category biomass. Open-core gasifier system stands out from the rest due to the possession of a wide mouth for the biomass inflow rather than a narrow opening. This unique property also prevents the flow inhibition that occurs due to bridging. Furthermore, the setup is employed with a water basin and rotating grates that enables ash removal [55].

On the contrary, a fluidized bed gasifier facilitates uniform temperature over the gasification zone. In this model of gasifier, the air is circulated across a bed of solid particles swiftly to keep them suspended. Upon heating the system externally to an adequate temperature, the feedstock is injected. The fuel particles delivered to the reactor's bottom are rapidly combined with the bed material and heated to the bed temperature promptly. The fuel undergoes this treatment, which leads it to pyrolyze rapidly and generate a component mix that contains a sizable number of gaseous elements. In the gas phase, subsequent gasification and tar-conversion processes take place. To reduce char blowout to the greatest extent, internal cyclones are furnished in the majority of the systems. In order for the gas to be employed for engine applications, ash particles must be eliminated from the gas stream that is passed over the roof of the reactor [56,57]. Meng et al. [58] explored the gasification of sawdust biomass in a pilot fluidized bed system. Different gasifying agents such as air, oxygen enriched air, oxygen-steam, and oxygen-air has been used for the gasification process. Oxygen enriched air exhibited or increased the heating value of H_2. However, owing to better gas shift reaction, air stream favoured high H_2 production [58]. Another study by Sapariya et al. [59] evaluated the performance of bubbling fluidized bed gasifier system for syngas production from three different biomass. Study showed that higher temperature resulted in better calorific value of syngas. Fluidized bed gasifier when operated at optimum temperature and equivalence ratio of 0.3, enhances the quality of syngas. Bubbling fluidized bed system using air as gasifying system demonstrated better scalability and stability [59]. Thus, fluidized bed gasifiers enables uniform distribution of temperature enabling rapid pyrolysis for bioenergy production.

As syngas is the primary product in biomass gasification, raw syngas contains contaminants unwavering the intended applications. Also, high tar content can be observed in updraft gasifiers leading to clogging and catalytic poisoning which necessitates the requirement of gas clean-up methods. Advanced gas cleaning technologies include scrubbing, filtration, catalytic reforming, and absorption. Filtration systems employ ceramic and bag filters which helps in removal of solid particulates. In the catalytic reforming, nickel based catalysts or dolomite is being used which converts the complex hydrocarbons into lighter gases leading to hydrogen production [60]. These advanced syngas cleaning technologies enables the commercialization and scalability of biomass gasification process.

4.1.2. Pyrolysis

Pyrolysis is a vital, industrially recognized thermochemical conversion process that predominantly occurs at amplified temperature and pressure. Based on TGA analysis, pyrolysis is categorised into pre pyrolysis, main pyrolysis and continuous char devolatilization. According to the research conditions like; temperature, residence time, heating rate, and particle size, pyrolysis processes can be grouped into three categories: slow, fast, and flash pyrolysis [61,62]. A better yield of liquid product is typically achieved when rapid reaction times and high temperatures are combined. The reaction temperature is often around 100 C greater than that of slow pyrolysis, and fast pyrolysis typically has a very little residence period (1 s) (500 °C vs. 400 °C). Integrating all the aforementioned elements, it can be said overall that low temperatures and lower heating value rates are required to enhance the charcoal generation. A combination of a moderate temperature, a brief gas residence period, and a high heating rate is necessary if liquid is the desired result [63,64]. However, slow pyrolysis has some disadvantages such as requirement of high energy and increased bio-char production which is undesirable during bioenergy production. Thus, low bioenergy yield is obtained with high carbon monoxide emissions. In alternate, fast pyrolysis is employed for the bioenergy production.

In fast pyrolysis process, biomass is thermolyzed at extreme heat (577–977 °C) in an inert atmosphere during the fast pyrolysis process. Based on the feedstock employed, fast pyrolysis operations have a yield of 15–25 wt % of solid char, 10–20 wt % of non - condensable gases and 60–75 wt % of liquid bio-oil, [65]. The liquid products (bio-oils), which are the major component of fast pyrolysis are made up of an aqueous phase that contains a number of light, low-molecular-weight organo-oxygen compounds and a non-aqueous phase (tar) that contains a number of insoluble, aromatic, high-molecular-weight organic compounds. Fast pyrolysis has been discovered to produce hydrogen gas in conjunction with bio-oil at higher temperatures (700–1000 °C). Steam reforming (Reaction 1) and water-gas shift (Reaction 2) processes were discovered to be the two principal types of reactions that transform methane (CH_4), various hydrocarbon vapours (C2-C5), simple aromatics, etc. into H_2 [66,67]. Fu et al. [68] comparatively studied the rapid pyrolysis of rice husk for the hydrogen production. Initially bio-oils were derived from biomass through pyrolysis process after which hydrogen has been produced. Ethylene glycol based bio-oil derivative provided better H_2 yield [68].

With a high yield efficiency of up to 70 %, flash pyrolysis technique can create biomass crude oil that is equal to petroleum. The production of heat or electricity can be fueled by refined crude oil. The flash pyrolysis process runs at a temperature between 777 and 1027 °C. One of the main downsides of the bio-oil produced by this technique is that the actual outcome contains pyrolytic water [69]. The presence of pyrolytic water leads to phase separation destabilizing the product during storage limiting its direct fuel application. This reduces the calorific value of the oil reducing the overall production and application efficiency. Also, downstream processes would become difficult as it might deactivate the catalyst in catalytic cracking based separation. To address these challenges, post condensation phase separation and membrane based separation can be applied for the pyrolytic water removal which facilitates the practical implementation in commercial scale [70].

Slow pyrolysis is common for traditional charcoal kilns to exhibit slow pyrolysis, which is widely recognized. High continents of charcoal are attributed to slow pyrolysis of biomass. In the slow pyrolysis process, the temperature range typically falls between 550 and 950 K. Charcoal has been made for countless years using a traditional moderate or slow pyrolysis process, which has a reasonably long vapour residence time and low heating rate. Biomass feedstocks with increased lignin and decreased hemicellulose concentrations can provide a greater return of charcoal. Slow pyrolysis does not actually require a fine feedstock particle size, in contrast to rapid pyrolysis (smaller than 1 mm) [71,72]. The reactors with bubbling fluidized beds, circulating fluidized beds, ablative, entrained flow, spinning cones, and vacuum reactors are the ones that are most frequently employed for fast pyrolysis. For raw materials that cannot be processed into powders or tiny particles, a conventional pyrolysis procedure in a moving bed reactor or rotary kiln reactor can be utilised [73].

One of the major challenges in bio-oil utilization during pyrolysis is the poor stability which might occur due to high oxygen content. To overcome the limitations, certain bio-oil upgrading techniques has been carried out. Chemical upgrading processes include hydro-treating, catalytic cracking, steam reforming, and esterification. Physical upgrading process includes distillation, supercritical fluid extraction, liquid-liquid extraction and emulsification. Advanced supercritical and liquid-liquid extraction provides better bio-oil upgrading offering better performance and efficiency [74]. Recent advancements in pyrolysis such as catalytic pyrolysis infers to be promising in addressing the challenges. Catalytic pyrolysis involves the use of different commercial catalysts such as zeolites to produce bio-energy. In one of the research study, a novel Ni-Mo/Al_2O_3 and Co-Mo/Al_2O_3 catalyst has been used for the biofuel upgrading. The use of catalyst had more selectivity towards the cyclic compounds production with 21.74 % in pyrolysis based bio-oil production [75]. The study suggests the potential of catalytic pyrolysis process for advanced bioenergy production. In addition, co-pyrolysis involving the simultaneous pyrolysis with two or more biomass for biofuel production has been a proven strategy to improving the final product yield. Nawaz et al. [76] implemented co-pyrolysis of microalgae biomass with plastic waste for inhibiting the oxygen transformation to bio-oil increasing the conversion of water to gaseous products [76]. These advanced pyrolysis techniques enhances the viability of bioenergy as an alternate to conventional fuels and overcomes the barriers in scale-up process.

4.1.3. Combustion

Combustion is one of the thermochemical conversion process involving a series of chemical reactions where carbon is converted into carbon dioxide and hydrogen. Calorific value (CV) of biomass is crucial in the combustion based conversion process. More stability and less emissions will be produced by a feedstock for combustion in a power plant that has a lower CV variability. A substance's CV decreases with the amount of O—H bonds present in the substance. This decreased CV results from a portion of the heat generated during combustion being utilised to evaporate moisture from the feedstock [77]. Products primarily for the chemical energy is stored in the biomass and will be liberated after combustion, hence end consumers of biomass feedstock search for products with the highest potential CVs. It is therefore crucial to understand the CV of biomass chips and pellets. Another aspect of biofuel that is significant for combustion is its carbon content. Incomplete burning of the material will result in unburned hydrocarbons and excessive carbon monoxide emissions if the combustion chamber is given insufficient air supply. An upsurge in NOx emissions occurs when the air supply is excessive [78,79]. Table 1 describes the process condition with biomass substrate and bioproduct yield of different thermochemical conversion techniques. To enhance the relevance, successful implementation provides valuable context in bioenergy production. In a study by Abioye et al. [80], combustion process have been employed for the bioenergy production from alum sludge and palm oil decanter cake. Higher bioenergy production with optimal reaction rate achieved at 50 % alum sludge has been inferred from the study. This indicates the superior suitability of bioenergy production [80].

While combustion is one of the most established technique in bioenergy production, conventional combustion processes release significant amount of pollutants such as sulphur oxides, nitrogen oxides, carbon monoxide, and volatile organic compounds. These flue gases released during the combustion process has adverse effects on human and environment. Conventional emission control strategies include staged combustion, selective catalytic reduction, and fuel gas recirculation. However, these conventional post combustion emission control methods face limitations in addressing the fine particulate emissions.

Table 1
Process condition with biomass substrate and bioproduct yield of different thermochemical conversion techniques.

Type of thermochemical conversion	Biomass substrate	Process conditions	Bioenergy Products	Yield	References
Co-Gasification	Palm oil fiber waste	Temp – 600 to 1200 °C Gasifying agent - Steam	Hydrogen	60 %	[81]
Gasification	Wood biomass with organic and residual matrices	Temp – 800 to 900 °C	Syngas	1.84 to 2.32 Nm^3/kg	[82]
Gasification	Palm kernel shells	Temp – 850 °C Biomass feed – 57.1 kg/h Steam to biomass ratio – 0.85	Hydrogen	80.4 %	[83]
Gasification	*Tamarindus indica* shells	Time – 4 h Mass flow rate – 18 to 25 kg/h	Hydrogen	1.95 Nm3/kg	[84]
Gasification	Algal Biomass	Temp – 500 °C	Hydrogen	11.63 mmol/g	[85]
Pyrolysis	Wood sawdust	Temp – 550 – 700 °C Flow rate – 30 mL/min	Hydrogen	62.2 %	[86]
Pyrolysis	Oat straw	Temp – 600 °C Flow rate – 50 L/min	Char Hydrogen	56 % 19 %	[87]
Pyrolysis	Linseed residue	Temp – 500 °C N_2 flow rate – 200 cm^3/min	Bio-oil Biogas	32.68 % 46.96 %	[88]
Co-pyrolysis	Corn straw and human hair waste	Temp – 450 °C Flow rate – 15 °C/min	Bio-oil	46.3 %	[89]
Hydrothermal liquefaction	*Prosopsis juliflora*	Temp – 320 to 440 °C Heating rate – 10 °C/min	Bio-oil	46.5 %	[90]
Liquefaction	Household waste	Temp-250 °C Time – 3 h	Hydrogen	32 %	[91]
Hydrothermal liquefaction	Spirulina	Temp – 500 °C Heating rate - 10 °C/min	Bio-oil	43.6 %	Liu et al., 2021

Promising emerging techniques has been carried out in recent years. For instance novel particulate matter collectors helps in achieving around 99 % efficiency in the reduction of nitrogen oxides. 90 - 95 % NO_X and SO_X reduction efficiency was achieved from electrochemical and therma-plasma system based bioenergy production [92]. Integration of these advanced techniques offers a sustainable pathway for emission control in combustion based hydrogen production. Large scale deployment of biomass combustion has shown a significant potential advancing the commercial scale of bioenergy production. One of the example is the Drax power plant in UK which involved in the conversion of coal to biomass that can further lead to bioenergy production with 80 % reduction in CO_2 emissions [93]. These studies infer the possibility of bioenergy production in commercial scale. The overall thermochemical processes for biomass based bioenergy production is depicted in Fig 2.

4.2. Biochemical conversion

4.2.1. Fermentation

A distinct group of microorganisms, typically yeasts, convert the simple sugars from the biomass feedstock to alcohol and carbon dioxide during fermentation, which is an anaerobic biological process. Several nations employ commercial fermentation on a big scale to transform starch and sugar crops (such as sugar cane and sugar beet) into ethanol (e.g. maize, wheat). The starch in the biomass is broken down into sugars by enzymes, and yeast uses the sugars to produce ethanol by turning them into cellular energy. The mixture is then heated to distill the ethanol (C_2H_5OH), causing the ethanol to boil off and then be cooled and condensed into a liquid again [49]. In the instance of sugar cane, the bagasse can indeed be utilized as a fuel for boilers or for further gasification, and the solid byproducts of the fermentation process can be employed as cattle fodder. Wheat and sugar beet are the main producers of substrate for fermentation in Europe. In many regions of the world, fermentation is not projected to be employed on a large scale for the generation of bioenergy because both of these crops are cultivated for food and do not have considerable surpluses. There are significant research efforts to promote advanced technologies to enable the fermentation of lignocellulosic feedstocks by pre-treatment and/or recognition of suitable enzymes, but fermentation can also be used as a path leading to a wide range of goods in a biorefinery, which can substitute fossil fuel hydrocarbons in conventional refineries. Intasit et al. [94] studied the valorization of palm biomass wastes for its conversion into biodiesel feedstock using solid state fermentation process. The study inferred that increase of around 50 % of cellulose content was achieved with reduction in potassium content of the biomass. Maximal fungal oil of 169 mg/g of oil was produced in the process which acts as a feedstock for biodiesel production [94]. Fermentative conditions with biomass and productivity of different biofuels is listed in Table 2.

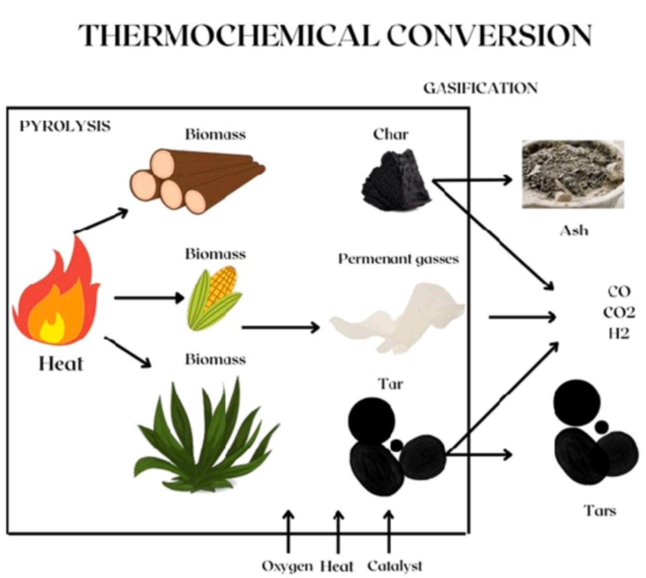

Fig. 2. Thermochemical process for biomass conversion to biogases.

Although fermentative based bioenergy production is employed in recent research studies, its large scale applicability is limited by substrate dependency and low hydrogen yield. Also, biomass predominantly contains lignocellulose substances which necessitates the intensive pre-treatment for bioenergy production. Also, the accumulation of inhibitory products during fermentation process suppresses and cause impairment in hydrogenase function and microbial activity. To overcome the limitations, tolerance to toxic by-products and enhanced hydrogenase expression has been carried out. Comprehensive metabolic engineering can also be used to enhance the bioenergy production from biomass. A study highlighted the use of combined multi-targeted genetic engineering strategy in *Rhodobacter sphaeroides* for the biomass based hydrogen production. By modifying the electron transport chain and light harvest complexes, fermentative efficiency has been improved. Also, co-metabolic engineering aids in the simultanaeous optimization to overcome certain limitations and enhance the yield. Around 93 % increase in hydrogen production has been observed from the co-metabolism approach [109]. Thus, multi-dimensional metabolic rewiring can synergistically optimize the metabolic flux and energy balance in the fermentation process leading to enhanced hydrogen production.

Table 2
Fermentative conditions with biomass and productivity of different biofuels.

Biomass	Fermentation type	Type of biofuel produced	Reaction conditions				Biofuel Yield / Productivity	References
			Microorganism	Time	pH	Temperature (°C)		
Corn Starch	Simultaneous saccharification and fermentation	Bioethanol	*Bacillus paralicheniformis*	8 h	4.5	60	87.8 %	[95]
Napier grass	Separate hydrolysis and fermentation	Bioethanol	*Saccharomyces cerevisiae*	12 h	5	50	30.6 g/L	[96]
Food waste	Dark fermentation	Biohydrogen	*Aspergillus tubingensis*	24 h	5	30	77 mL H_2/g VS	[97]
Corncob	Two stage fed-batch fermentation	Biohydrogen	*Kluyveromyces marxianus*	72 h	5	60	0.41 g/g	[98]
Corn stalk	Co-fermentation	Bioethanol	*Saccharomyces cerevisiae* and *Pachysolen tannophilus*	12 h	5	30	0.46 g/g	[99]
Vegetable residues	Dark fermentation	Biohydrogen	Effluent based mixed microbial flora	7 days	-	35	151.67 mL H_2/g VS	[100]
Food and vegetable wastes	Dry fermentation	Biohydrogen	Biogas microbial inoculum	-	5.5–6.5	55	27.19 NmL H_2/g VS	[101]
Beet molasses	Batch and repeated batch fermentation	Bioethanol	*Saccharomyces cerevisiae*	36 h	5	30	1.45 g/L/h	[102]
Banana frond juice	Batch fermentation	Bioethanol	*Saccharomyces cerevisiae*	57 h	6.8	30	65 %	[103]
Melon seed shell	Batch fermentation	Bioethanol	*Saccharomyces cerevisiae*	24 h	3	30	25.6 %	[104]
Date fruit wastes	Batch fermentation	Biohydrogen	*Enterobacter aerogenes*	12 h	6.5	37	238. mL/g	[105]
Garden and food waste	Co-fermentation	Biohydrogen Biomethane	*Caldicellulosiruptor saccharolyticus*	-	7–7.2	37	46 L/kg 682 L/kg	[106]
Wheat powder	Dark fermentation	Biohydrogen	Mixed microbial culture	6 h	5.0–6.0	37	645.7 mL/g TS	[107]
Sugar beet pulp, corn silage, food and vegetable wastes	Dark fermentation	Biohydrogen	Anaerobic sludge	3 d	4.0	35	52 cm^3/g VS	[108]

4.2.2. Photosynthesis

Hydrogenase and nitrogenase enzymes of algae, purple sulphur, and non-sulfur bacteria use carbon dioxide and water in the photosynthesis reaction to make carbohydrates, hydrogen, and oxygen. While being exposed to radiation, some strains, like *Rhodopseudomonas capsulata*, create hydrogen when organic substances like maleate, succinate, etc. are present. The most prevalent classes of phototrophic prokaryotes that could create hydrogen are cyanobacteria (B-G algae). Direct biophotolysis is, however, oxygen-sensitive, making it challenging to maintain hydrogen generation. By creating hydrogen and oxygen at various phases, indirect biophotolysis can alleviate the problem of oxygen sensitivity [110–112].

The disorganised R&D effort to connect the quantity of hydrogen and the rate of hydrogen demanded by the typical Proton Exchange Membrane Fuel Cell (PEMFC), an extremely effective hydrogen-linked transportation fuel system, is a major barrier to the practical deployment of bio-hydrogen systems. According to a study of the prospective bio-hydrogen processes' rates of hydrogen synthesis, photosynthesis-based hydrogen production is far too inefficient to continuously power a 1 kW PEMFC [113,114]. Lu et al. [115] studied the photosynthetic hydrogen production from apple waste by HAU-M1 bacteria. Here, apple waste has been utilized as a carbon substrate for hydrogen production. A maximum H_2 yield 111.85 mL H_2/g TS has been obtained with optimized process conditions [115].

Although photosynthesis based hydrogen production can be employed for the bioenergy production, two major limitations such as low hydrogen production rate and sensitivity of hydrogenase enzymes limit its practical applications. To address these limitations, recent advancements have focussed on the genetic engineering or adaptation of photosynthetic micro-organisms to enhance hydrogenase activity through two major strategies. One of the recent study has focussed on the implementation of dark adaptation strategy for improvement in photosynthetic hydrogen production. Dark adaptation aids in activation of hydrogenases through lowering of intracellular oxygen levels. This led to average hydrogen production rate of 19.42 μmol H_2/mg.h for over 150 days. This non-genetic intervention underscores the potential for long term feasibility of hydrogen production [116]. By rewiring metabolic pathways, introducing and overexpressing hydrogenases, electron supply can be enhanced which leads to enhanced bioenergy production. A study highlighted the potential of genetic engineering advancement in enhancing hydrogen production. By deletion of regulatory N-terminal region of nifA1 gene in *Rhodobacter capsulatus* enhanced ammonium tolerance has been observed which enhances the hydrogen production. Also, the mutant strain outperformed the wild type photosynthetic bacteria increasing the hydrogen production by 2.6 fold [117]. These findings highlight the potential of genetic engineering in enhancing the photosynthetic hydrogen production. Thus, by enhancing the hydrogenase activity and photosynthetic pathway through modification, photosynthetic bioenergy production can be implemented.

4.2.3. Anaerobic digestion

The direct conversion of organic material to biogas, or a mixture primarily composed of methane and carbon dioxide with trace amounts of other gases such hydrogen sulphide, is known as anaerobic digestion (AD). In the absence of oxygen, microorganisms convert organic, non-lignocellulosic (non-woody) substrate, also known as feedstock. In an anaerobic environment, bacteria convert the biomass to a gas with an energy content that ranges from 20 % to 40 % of the feedstock's lower heating value (LHV). AD is a method that has been successfully used in the marketplace to treat organic wastes with high moisture contents (m.c.), or 80 %–90 % m.c [118,119]. Anaerobic digesters create circumstances that promote organic matter's natural decomposition by bacteria in the absence of air. The products of the AD are Biogas - This mixture contains traces of additional "contaminant" gases along with between 50 % and 60 % methane and 40 % to 50 % carbon dioxide and Organic fertiliser (digestate) - This is a moist, sterile substance that contains organic humus and is beneficial plant nutrients. For use on land or further processing, it can be divided into liquid and solid components [120]. Ameen et al. [121] co-digested the biomass of animal manure with microbial biomass for methane production through a three stage anaerobic digestion. With the mixed biodegradable substrates with microbial biomass, stable digestion and higher methane yield has been observed. Average methane yield of 0.442 L/g VS has been observed with the three stage anaerobic digestion process [121]. Fig 3 depicts the biogas and liquid biofuel production from biomass through biochemical conversion techniques. Type of digestion, microbial inoculum, type of

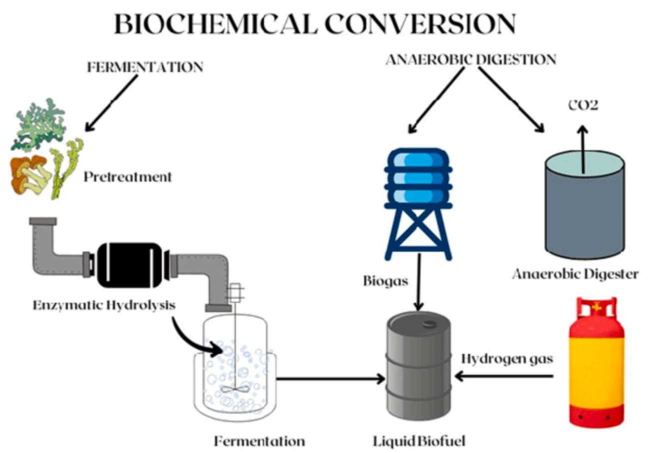

Fig. 3. Biogas and liquid biofuel production from biomass through biochemical conversion techniques.

reactor and bioenergy yield of different biosubstrates has been tabulated in Table 3.

4.3. Physio-chemical

Oil is extracted from the seeds of different biomass crops, including oilseed rape (OSR) and linseed, using the mechanical (physical) transformation process known as physio-chemical conversion, also known as mechanical extraction. This process creates a liquid fuel that can go through the esterification process, which transforms the oil into fatty acid methyl ester, more commonly referred to as biodiesel. The procedure yields not just oil but also a leftover solid or "cake" that can be used as animal feed. In Europe, waste fats and oils as well as vegetable oils from crops, especially OSR, are used on a large scale in this technology. The principal application for biodiesel is as a liquefied transportation fuel, typically combined with petroleum-derived diesel [132].

Fig 4 visually represents the physio-chemical conversion of bio-derived substrates to bioenergy products.

4.3.1. Pelleting/briquetting

Production of biofuel pellets for both residential and commercial usage has recently attracted more attention. The manufacturing of biofuel pellets has increased significantly in recent years in China, Europe, and North America. The market for biofuel briquettes and pellets is expanding as a result of the benefits that biomass pellets provide, including simple storage and transportation, as well as reduced pollution, decreased dust levels, and larger heating values than possible in the past. Pellets provide similar automation and optimization benefits to

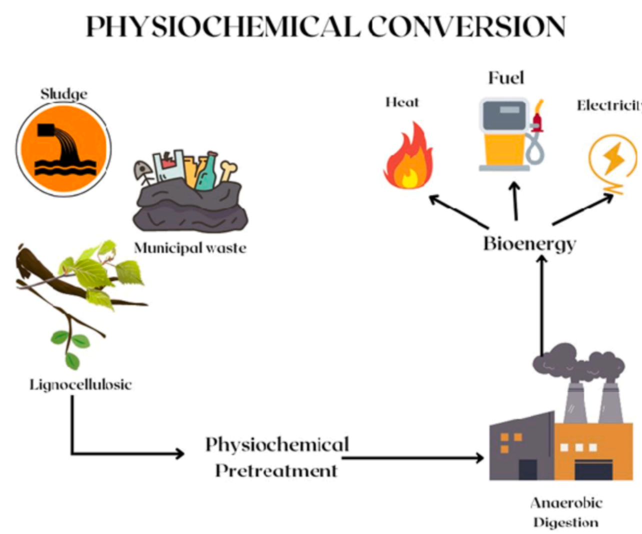

Fig. 4. Physio-chemical conversion of bio-derived substrates to bio-energy products.

Table 3
Type of digestion, microbial inoculum, type of reactor and bioenergy yield of different biosubstrates.

Bio-Substrate	Type of digestion	Reactor	Microbial inoculum	Feed ratio	HRT	Biogas /Methane yield	References
Pig manure, Chicken manure, Cow dung	Co-digestion	Three stage anaerobic digester	*Pichia kudriavzevii*	1:1	12 days	0.442 L/g VS	[121]
Prosopis juliflora seeds, dry water hyacinth, dry leaves, and cow manure	Co-digestion	Two stage digester	Cow manure based microbial inoculum	1:10	60 days	396 L/kg VS	[122]
Azolla pinnata biomass	Batch digestion	Single stage digester	Cow dung manure microbial inculum	1:4	28 days	Biogas – 3571.14 mL Methane – 55.62 %	[13]
Baltic seaweeds, wheat straw and straw pellets	Co-digestion	Single Digester	Sewage sludge		31 days	395–470 mL/g	[123]
Chlorella sorokiniana biomass	Batch digestion	Single stage batch digester	Digested anaerobic sludge	3 g/L	42 days	0.253–0.388 L/g VS	[124]
Chicken manure	Full scale anaerobic digestion	Single stage digester	Codigested pig slurry	-	217 days	508 mL/g VS	[125]
Food waste and Maize husk	Batch flow anaerobic digestion	Batch digester	Anaerobic reactor effluent	1	44 days	99.7 L/g VS	[126]
Microalgae biomass with wastewater	Batch digestion	Upflow anaerobic sludge blanket reactor	-	7 mL/s	10–20 days	0.14 to 0.23 Nm^3/kg VS	[127]
Brewery spent grain	Mesophilic digestion	Solid-state anaerobic digester	Brewery seed sludge	-	10 days	414 L/kg	[128]
Laminaria digitata biomass	Batch anaerobic digestion	Two-stage anaerobic digester	Dark fermentation sludge	2:1	21 days	Biohydrogen – 57.4 mL/g	[129]
Chlorella sp.	Integrated anaerobic digestion	Two stage digester	Anaerobic granular sludge	5–25	-	47.2 mL/g VS	Phanduang et al., 2019
Food waste	Continuous digestion	Continuous stirred tank digester	-	-	30 days	79 NL/kg VS	[130]
Sugarcane filter cake	Co-digestion	Two stage digester	Anaerobic sludge	4:1	5 days	130.5 mL/g VS	[131]

fuels generated from petroleum, including comparatively high combustion efficiency and low levels of combustion wastes in comparison to traditional firewood [133]. Having a high MC in a pile of biomass chips can cause the pile to self-combust because of the higher temperatures brought on by the enhanced microbial activity. Low MC will also produce pellets with a low survivability quality. If the MC of the chips being supplied into the pellet press is too low, the tension between the particles as well as the die will significantly raise the necessary energy to expel the substance from the die or cause blockages leading to an increase in pelletizer downtime [134,135]. The amount and quality of combustion are impacted by the ash concentration (AC) of solid biofuels. The primary components of biomass combustion ash are inorganic substances such potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg). The ash melting point of solid biofuels is lowered by high K and Ca content, which can cause combustion issues such fouling, slagging, and corrosion [136]. Comparative analysis of different biomass conversion process based on reaction conditions and efficiency has been listed in Table 4.

5. Applications and challenges

5.1. Applications

Biogas produced by anaerobic digestion can be exploited to engender heat or electricity, furthermore it can be ameliorated to produce biomethane that can be consumed as fuel for vehicles. Biological cleaning process can be employed through biogas applications [139]. Bioethanol has a certain molecular formula and performs in a predictable manner which makes it a feasible aviation biofuel. The most popular application for bio-based ethanol (bioethanol) is as an extender in gasoline (petrol) that contains a high percentage of ethanol. Over 95 % of ethanol produced by fermentation of biomass is utilized for fuel cell applications. These ethanol fuel cells have the application of commercialization like other bioproducts production. Partial oxidation of ethanol leads to the production of acetic acid and acetaldehyde. The wide applications of bioethanol such as power generation, fuel cell applications, and chemical regeneration has promoted its research interest [140,141].

Biooils: Multiple bio-oils have so far been subjected to testing and have proved to operate significantly in boilers and turbines. Likewise, bio-oils could certainly be processed into premium fuels and served as a feedstock for the manufacture of chemicals. In case of biodiesel, many nations explicitly support the utility of biodiesel blends with combining percentages ranging from 5 to 100 %. Considering rapeseed which is predominantly cultivated, the preponderance of biodiesel is made from edible oil crops like those. Waste cooking oil and animal fat obtained from the restaurant, fast food, and food processing industries can also be repurposed into biodiesel [142,143]. Biohydrogen being a clean source for alternate vehicle fuels, requires less energy input during its processing. The potentiality of hydrogen has enabled it to be used in fuel cell for electricity generation. In combination with biogas, biohydrogen enhances the combustive processes of biomass. In the refining industries, biohydrogen plays an influential role in the process of desulphurization, hydrocracking, and hydrotreating [144]. The other applications of hydrogen includes methanol and ammonia production.

The advancement of biofuels is regarded to be among the most significant strategies for reducing global warming by substituting for traditional carbon fuels. Nevertheless, expanding the production of bioethanol might have negative consequences for the environment in the form of water stress, environmental degradation, and bigger greenhouse emissions. Several areas' water footprints are governed by a variety of soil types and climates. By principle, the three characteristics of blue ocean, clear water, and untreated wastewater may be used to classify the water footprint (WF) of bioenergy during the phases of crop growth and factory transformation. According to reports, the production process of bioenergy is often dominated by greywater usage. According to recent research, J. curcas has a water footprint in China that ranges from 64.7 to 182.3 L per MJ of biofuel produced, from plants to biofuel [145,146]. With values of 60 % and 40 %, correspondingly, the cultivation stage has been recognised as the major contributor to carbon emissions and power requirements. Furthermore, the consequences can be reduced by 35–60 % by utilising leftover biomaterials created throughout the various steps in the production process. Biomass production may lead to biological product scarcity and cultivation of biomass may affect the sustainable production of biofuel and may increase the demand for both biomass and biofuel [147].

5.2. Technological challenges

In the thermochemical method of bioenergy production, feedstock variability remain as one of the biggest challenges due to the versatility in biomass feedstock. Variability in feedstock is largely associated with harvest volumes and conditions for harvest timing. Variation in chemical composition lead to fluctuations in energy yield and reduce the process efficiency. For instance, high moisture content in feedstock hinders the thermochemical conversion process whereas the variability in the chemical composition affects the biochemical composition. Addressing the challenge requires robust process designs and integration of multiple conversion techniques enhancing resource utilization and bioenergy production. Most of the biomass requires intensive pre-treatment process due to the presence of lignocellulosic compounds. These pre-treatment processes requires high energy that increases the total cost of the bioenergy production process. One of the significant technological challenge is the high operational and capital cost linked with the conversion system. For instance, thermochemical processes such as pyrolysis, combustion, and gasification require optimal control of residence time and temperature alongside demanding the need of

Table 4
Comparative analysis of different biomass conversion process based on reaction conditions and efficiency [137,138].

Parameter	Thermochemical			Biochemical			Physico-chemical
	Gasification	Pyrolysis	Combustion	Fermentation	Photosynthesis	Anaerobic digestion	Pelleting/ Briquetting
Operating temperature (°C)	500 - 1400	300 - 700	800 - 1000	25 - 40	20 - 30	30 - 60	100 - 200
Reactive conditions	Partial oxygen	Oxygen absence	Complete oxidation	Anaerobic conditions	Aerobic and presence of sunlight	Anaerobic	High pressure
Production efficiency	High	Moderate	Low	Moderate	Very low	Moderate	-
Capital cost	High	Moderate to High	Low to moderate	Moderate	Very low	Low	Low
Processing time	Minutes	Minutes	Minutes	Hours to days	Months to years	Days to months	Minutes
Products	Syngas	Bio-oil and biochar	Heat and electricity	Bioethanol Biobutanol	Biomass	Biogas	Solid fuels
Environmental impact	Need emission control	Controlled emissions	High emissions	Very low emissions	Zero emissions	Low emission	Very low impact

advanced materials which leads to high cost. In the biochemical conversion process like anaerobic digestion, conversion efficiency is hindered by low reaction rates demanding advanced pre-treatment processes [122]. Another major technological hurdle is the scalability as many processes perform efficiently in the laboratory scale and encounter difficulties during the scale-up process such as high energy demand. To overcome the challenges, prolonged multi approach is required. Thermochemical and biochemical reactor design can be modified and advanced to facilitate better scale-up. Development of adaptive control systems using artificial intelligence addresses the issues associated with feedstock variability. Hybrid conversion systems might enhance the overall product efficiency. Also, stronger policy framework is requisite to bridge the gap between pilot scale study and industrial implementation.

6. Sustainability and life cycle assessment

The transition towards sustainable energy system necessitates the environment impact and assessment of bioenergy production pathways. Life cycle assessment (LCA) serves as a crucial tool in quantifying the impact of climate change impact. In the context of LCA without carbon capture, evaluation of biomass systems offer valuable insights into environmental advantages. A study focused on remote communities of Canada where the prominent use of diesel is found. LCA conducted in the study using SimaPro with Ecoinvent data included different stages like harvesting, transportation, combustion, and pelletization. Non-carcinogenic impacts have been observed with pelletization process highlighting the potential of biomass system in providing sustainable energy solutions even in the absence of carbon capture [148]. Conventional bioenergy systems does not impart carbon capture are most commonly studied in life cycle assessment. Indirect emission from land and transport use are not accounted in conventional LCA without carbon capture.

When carbon capture and storage is integrated into bioenergy system, process – Bioenergy with carbon capture and storage (BECCS) can lead to net negative emissions in the environment. Life cycle assessment of BECCS is vital for the quantification of environmental performance and reduction of negative emissions. Negative emissions apart from requiring the capture and storage of greenhouse gases (GHGs) needs overall LCA from biomass cultivation to fuel production and GHGs storage. In a recent study by Krogh et al. [149], LCA analysis with carbon capture has been performed for the bioenergy production from forestry residues. Using feed centric LCA, combined heat and power with carbon capture storage (CCS) has been compared. All production pathways exhibited savings between −111 and −1742 kg CO_2eq/tonne residue. Moreover, the performance of CCS has been more sensitive with a threshold limit of 44 kg CO_2eq/kWh [149]. Expanding further, a recent assessment by Saharudin et al. [150] focussed on the LCA for the utilization of palm oil waste for BECCS in Malaysia. The study inferred that the system with CCS could achieve negative GHG emissions per tonne of CO_2. However, the other environmental impact categories raised by 217 % emphasizing the impact of multi-impact LCA [150]. These studies collectively underscores the crucial role of comprehensive LCA in evaluation of BECCS. Thus, in overall, although both systems contribute to decarbonisation, BECCS represent a better climate change potential through comprehensive LCA analysis.

7. Future perspectives

Next-generation biofuels are more advanced industrially than first-generation varieties; while this energy is also made from renewable material, referring to different fuels, it does not often imitate food sources. Usually, these kinds of fuel sources are not intended for human consumption. In other words, the second-generation feed is not designed for human feeding. Despite being a plant for nourishment, they are no more fit for human consumption. Due to the difficulty of extracting gasoline from this resource, second-generation biodiesel is referred to as "advanced biofuels." For second-generation biofuels, quasi-resources of bioenergy include timber, crop residues, green matter, food scraps, and some biomass plants together with cellulosic, hemicelluloses, or lignin [151]. Although second-generation ethanol have not yet been produced commercially, a large percentage of experimental and demonstration facilities have been announced or established in recent years, with study operations primarily taking place in the United States, European, and a few developing nations. Significant volumes of biofuel must be delivered in order to produce the second generation, necessitating a review of current and future bioenergy supplies well in advance of the commencement of huge quantities of production [151]. Vegetable oil waste has little nutritional value, however, it may aid in increasing air quality. Certain internal combustion engines are built specifically so that the biodiesel produced from this biomass may be employed straight away sans mixing or purifying. Geography is the key factor affecting grassland farming. On precarious terrain, this biomass develops swiftly and harvests of plants are acquired often throughout the year. It takes less fertiliser to cultivate and may be utilised right away as biomass without any further treatment [152]. Crop seed biomass can be grown in significant quantities on degraded lands, but its calorific value is substantially lower than that of biofuels made from biomass from soy. Next-generation biofuels provide a variety of benefits and are superior to first-generation products for a plethora of purposes: (A) They utilise a quasi feedstock, such as lignocellulose material (such byproducts from earth plants, timber production, or quickly expanding cover crops). Therefore, second generation biofuels differ from first-generation biofuels in that they wouldn't originate from meal crops such as wheat and soybeans; (b) the energy is a phasing substitute for traditional crude oil fuels, which means there is no restrictions on combining or they can be used directly in current cars (without mixture); d) they do not create by-products like livestock feed; c) biofuels of the second generation are more ecologically friendly and emit fewer carbon output [153].

8. Conclusion

Since there will always be a demand for energy, finding a power source large enough to meet our requirements is a difficulty. Additionally, this source of energy needs to be stable, sustainable, consistent, and global warming free. The transition to a greener, sustainable power may be seen in first-generation biofuels in economically and cost - effective way. The technical advancement of renewable energy sources has both positive and negative implications. However, since they do not really conflict with foodstuff, the next generation of biofuels offers the best prospect to have a chance for a gas replacement. Compared to other biofuels, it has a higher capacity for Carbon dioxide collection and a higher production rate. The wide availability of biomass has prompted its usage for bioutilization in different fields. Biomass has much potentiality to be utilized as a feedstock for bioenergy production. An increase in bioenergy yield has been observed with simultaneous biochemical and thermochemical conversion of biomass. The high temperature range of thermochemical conversion has elicited interest on biochemical conversion techniques. Fermentation and anaerobic digestion are the well suited biochemical processes for the production of biohydrogen and biomethane. However, there remain significant difficulties to overcome in making them more commercially feasible. Technological advancements in pre-treatment process such as catalytic efficiency and process integration might significantly lower operational costs and improve yields. Continuous research and policy overcomes the limitations associated with the biomass conversion techniques.

CRediT authorship contribution statement

A. Saravanan: Visualization, Resources, Data curation. **Y.P. Ragini:** Writing – review & editing, Supervision, Conceptualization. **S Karishma:** Resources, Methodology, Investigation. **R.V. Hemavathy:**

Visualization, Resources, Investigation. **Marie Jyotsna:** Validation, Resources, Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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