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Review Article

Biomass and organic waste conversion for sustainable bioenergy: A comprehensive bibliometric analysis of current research trends and future directions

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Abstract. The rising demand for renewable energy sources has fueled interest in converting biomass and organic waste into sustainable bioenergy. This study employs a bibliometric analysis (2013-2023) of publications to assess trends, advancements, and future prospects in this field. The analysis explores seven key research indicators, including publication trends, leading contributors, keyword analysis, and highly cited papers. We begin with a comprehensive overview of biomass as a renewable energy source and various waste-to-energy technologies. Employing Scopus and Web of Science databases alongside Biblioshiny and VOSviewer for analysis, the study investigates publication patterns, citation networks, and keyword usage. This systematic approach unveils significant trends in research focus and identifies prominent research actors (countries and institutions). Our findings reveal a significant increase in yearly publications, reflecting the growing global focus on biomass and organic waste conversion. Leading contributors include China, the United States, India, and Germany. Analysis of keywords identifies commonly used terms like "biofuels," "pyrolysis," and "lignocellulosic biomass." The study concludes by proposing future research directions, emphasizing advanced conversion technologies, integration of renewable energy sources, and innovative modelling techniques.

Keywords: Bibliometric analysis, Biomass, Bioenergy, Renewable energy, VOSviewer, Organic waste conversion

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1. Introduction

In today's world, one of the most pressing issues is securing a sustainable and reliable energy future. Transitioning to sustainable energy sources is essential as we grapple with pressing climate change concerns and ever-growing energy demands. Bioenergy, produced from biomass and organic waste conversion, emerges as a promising and environmentally friendly alternative (Holechek *et al.,* 2022; Kabeyi and Olanrewaju, 2022b). As the world's most prevalent renewable energy source globally, bioenergy plays a significant role in the energy transition (IEA, 2020).

Biomass, primarily consisting of agricultural residues, forestry waste, and urban organic matter, is an extensive and largely untapped resource with substantial potential for energy generation (Anvari *et al.*, 2024; Blasi *et al.,* 2023a; Qin *et al.,* 2021; Salleh *et al.,* 2020; Singh *et al.,* 2023). Biomass conversion, the process of transforming this organic matter into usable energy through thermochemical and biochemical methods, offers numerous benefits. It helps mitigate greenhouse gas emissions, reduce reliance on fossil fuels, and create employment opportunities, fostering economic growth (Garba, 2020; Kataya *et al.,* 2023; Rashidi *et al.,* 2022a). Advancements in bioenergy research are driving progress in conversion technologies, making them more efficient and cost-effective. Bioenergy currently stands as the world's most prevalent renewable energy source, contributing over 55% of all renewable energy and supplying over 6% of the world's total energy needs (Bennett and Buckley, 2022). In 2019, the International Renewable Energy Agency (IREA) reported that bioenergy employed more than 3.1 million individuals worldwide. Furthermore, biomass conversion offers substantial waste reduction advantages and promotes a circular economy (REN21, 2020). Efficient utilization of biomass resources and sustainable organic waste management practices can contribute to achieving a sustainable bioenergy system, waste reduction, and circular economy goals.

However, high production costs and environmental concerns hinder the immediate widespread use of biomass residues and waste as a bioenergy source. The viability of bioenergy relies on the prudent management of resources. Efficient and affordable biomass conversion technologies are essential for scaling up biomass and organic waste conversion

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to produce sustainable bioenergy (Tshikovhi and Motaung, 2023).

Despite these challenges, advancements in feedstock preprocessing, biorefinery integration, and advanced conversion technologies are dramatically enhancing the efficiency and adaptability of bioenergy (Tshikovhi and Motaung, 2023; Yamakawa *et al.,* 2018). The bioenergy sector presents a promising future, providing renewable energy alternatives, economic opportunities, and the potential for waste reduction (Chung, 2013). With ongoing efforts to combat global warming and explore alternative energy options, bioenergy plays a crucial role in promoting a more environmentally friendly and sustainable future. As countries strive to achieve net-zero emissions by 2050, the demand for bioenergy is expected to increase (Junginger, 2013). Biofuels are predicted to reduce emissions across various transportation sectors, including road transport, aviation, and maritime transport (Kabeyi and Olanrewaju, 2022b). Hence, the need for biomass resources is likely to persist in the coming years.

Advancements in bioenergy research are expected to revolutionize the energy sector, making it more attractive and environmentally friendly. The proliferation of bioenergy innovations attracts considerable attention because it can change the energy sector by providing renewable energy alternatives, creating economic prospects, and minimizing waste generation (Jaiswal *et al.,* 2022; Strielkowski *et al.,* 2021). The continuous improvement in the efficiency of biomass conversion techniques and their combinations has provided the renewable energy industry with more environmentally friendly, advanced bio-energies and biofuels (Hasan *et al.,* 2023).

These advancements are crucial as bioenergy research generates a massive amount of data through academic publications. Researchers can utilize a powerful tool called bibliometrics to effectively analyze these vast amounts of information and gain valuable insight (Donthu *et al.,* 2021; Fakruhayat and Rashid, 2023). Bibliometrics is a technique that leverages statistical methods to examine patterns and trends within bibliographic data, such as academic publications. It allows researchers to assess the research volume objectively, identify key focus areas, and map the contributions of different countries and institutions. This approach offers a unique perspective, comprehensively evaluating the current state of biomass and organic waste conversion research.

By applying bibliometric analysis to bioenergy research, we hope to achieve several key objectives. Firstly, we aim to identify emerging trends and research focus. Analyzing this data will provide valuable insights into areas of active investigation and potential knowledge gaps that warrant further exploration. Secondly, we will assess the volume of research output to gauge global interest in bioenergy development. This analysis can help us understand the intensity with which researchers pursue this renewable energy source. Thirdly, bibliometrics allows us to map the contributions of various countries and institutions. Analyzing the challenges and solutions in bioenergy research can reveal leading players and potential areas for collaboration. Finally, by analyzing publication trends over time, we can comprehend the evolution of the bioenergy research landscape. This historical perspective sheds light on how research priorities have shifted and identifies areas of continuous focus.

This study first provides a comprehensive overview of biomass as a renewable energy source, covering its types, sources, benefits, and challenges. We then examine waste-to-energy technologies, their efficiencies, and environmental impacts. Following this, we present our methodology for bibliometric analysis and discuss the results, highlighting significant trends and contributions. The paper concludes with insights into future research directions and the broader implications of our findings for the sustainable bioenergy sector.

1.1 Biomass as a Renewable Energy Source

Biomass, as a renewable energy source, has a crucial role in the worldwide effort to achieve sustainable and environmentally friendly energy solutions. Bioenergy utilizes the energy contained in organic substances, usually plant material, to generate electricity, heat, or fuel. Organic material from plants and animals comprises biomass (Garba, 2020; Malode *et al.,* 2021). Through photosynthesis, plants transform light energy from the sun into chemical energy, which helps form biomass. We can then burn or decompose this biomass to provide energy in various ways. Through burning or biological processing, biomass releases its stored energy, which can be used directly or transformed into other energy sources like electricity or biofuels (Osman *et al.,* 2021). The key feature that makes biomass a renewable energy source is its ability to be used directly as energy or converted into other energy forms. Unlike fossil fuels, which take millions of years to form, biomass resources can be rapidly replenished through sustainable agricultural practices or natural processes. A steady supply of biomass material can be guaranteed by repeatedly growing and harvesting trees, crops, and other plants (Department of Energy, 2015).

Biomass is categorized into various types, such as woody biomass, agricultural biomass, algal biomass, and urban waste biomass. As depicted in Figure 1, these diverse biomass waste streams hold immense potential as feedstock for bioenergy generation through waste-to-energy conversion processes. These waste streams can be converted into bioenergy through various technologies, offering a sustainable alternative to fossil fuels. Agricultural biomass combines crops and their byproducts, such as corn stalks, soybean residues, and sugar cane bagasse. In contrast, woody biomass consists of wood and waste from wood processing. Cities generate urban waste biomass from waste products like sewage, food scraps, and solid waste. Algal biomass, on the other hand, comes from algae. Various technologies, such as gasification, fermentation, and direct combustion, can convert diverse biomass sources into energy (Ben-Iwo *et al.,* 2016). The renewable, sustainable, and adaptable nature of biomass makes it a desirable resource for producing energy.

It's important to note, however, that the conversion efficiency of biomass to usable energy can be lower compared to fossil fuels. Despite its potential as a renewable energy source, biomass production faces environmental and economic challenges. A key concern is the competition between biofuel crops and food production, often called the "food vs. fuel" debate. Dedicating land to energy crops can increase food prices and threaten food security in vulnerable regions, particularly those already facing food shortages. Additionally, even with dedicated land, increased demand for biofuels can indirectly cause deforestation elsewhere to grow more food crops, further exacerbating the issue. Biomass utilization can also significantly impact land use through deforestation for wood biomass, leading to biodiversity loss, habitat destruction, and disruption of natural carbon storage. Converting ecosystems to grow energy crop fields can also contribute to habitat loss for wildlife and disrupt ecological balance.

Furthermore, biomass production can be water and nutrient-intensive, straining local resources and potentially leading to soil degradation if not managed sustainably. Intensive production practices can deplete soil nutrients and lead to erosion, impacting long-term agricultural productivity. Addressing these challenges through careful management and

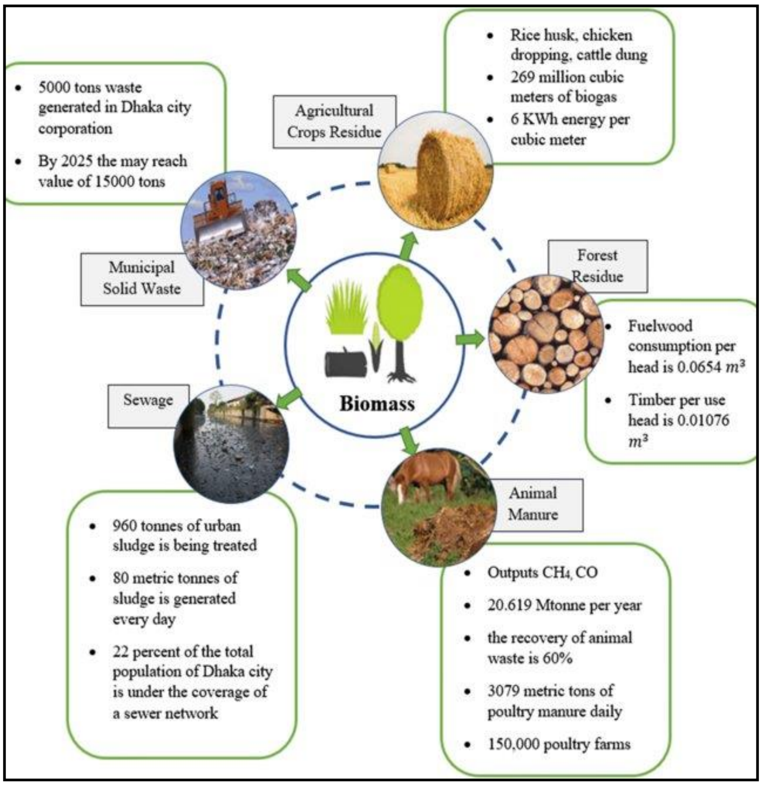


Fig 1. Diverse Sources of Biomass and their Conversion Pathways for Renewable Energy Generation through Waste-to-Energy Processes (Olatoyan *et al.,* 2023).

innovative agricultural practices is crucial to maximizing land use efficiency and ensuring that biomass remains a viable and sustainable energy source.

This illustrates the vast potential of biomass, ranging from agricultural residues and forestry waste to municipal solid waste and wastewater treatment byproducts, to be converted into valuable renewable energy sources. The depicted conversion pathways, including direct combustion, gasification, and anaerobic digestion, showcase the versatility of waste-to-energy technologies in harnessing the embedded energy within various biomass feedstocks.

Biomass emerges as a promising renewable energy source due to its rapid replenishment and diverse forms, including agricultural residues, woody biomass, algal biomass, and urban waste biomass. However, it's crucial to acknowledge that challenges associated with cost, potential land-use conflicts, and conversion efficiency must be addressed for widespread adoption.

1.2. Bioenergy: Advantages, Challenges, and Technological Advancements

Biomass, a versatile and renewable energy source, is positioned to have a crucial impact on the worldwide transition to cleaner energy models. Biomass has a wide range of uses beyond just producing energy. It plays a vital role in sustainable development by supporting environmental conservation, fostering economic stability, and contributing to social well-being (Seboka *et al.,* 2023). Biomass is a sustainable substitute for fossil fuels, aiding in mitigating carbon emissions and providing a dependable electricity supply. Nevertheless, it is imperative to tackle obstacles such as maintaining a consistent supply chain and implementing sustainable farming practices to fully capitalize on the advantages of bioenergy (Clauser *et al.,* 2021). Moreover, using biomass for energy generation can reduce waste and alleviate the environmental consequences of conventional energy sources. Although there are advantages and disadvantages to utilizing biomass as an energy source, its renewable characteristics and ability to minimize waste make it a promising element of the worldwide energy framework (Saleem, 2022).

1.3. Advantages of Biomass as a Sustainable Energy Source

Biomass plays a crucial role in the renewable energy industry, providing diverse advantages beyond its function as an alternative energy source. It not only meets the immediate requirement for sustainable energy but also contributes to the preservation of the environment, advancement of the economy, and progress of society. Table 1 presents a concise overview of the key benefits of biomass, highlighting its role in promoting a sustainable energy infrastructure and facilitating wider societal advantages.

However, to fully harness the potential of biomass as a sustainable energy source, it's essential to address certain challenges. These challenges are not insurmountable, and advancements in technology are playing a crucial role in mitigating them. The following section explores these challenges and the promising solutions emerging from the field of bioenergy research.

1.4. Challenges in Biomass Utilization and Conversion

Bioenergy holds immense potential as a renewable and sustainable energy source. However, achieving widespread adoption requires navigating various technical, economic, and environmental challenges.

Improving the efficiency of conversion methods like gasification, combustion, and anaerobic digestion is crucial, as these methods directly impact the amount of usable energy obtained from biomass. Advancements are needed in pretreatment technologies to enhance bioenergy density,

Table 1
Multifaceted Benefits of Biomass as a Renewable Energy Source

Category	Advantage	Description
Environmental Advantages	Carbon Neutrality	Plants absorb CO_2 during their growth, compensating for the emissions produced by burning biomass and helping maintain an equilibrium in carbon emissions (Sharew *et al.,* 2022).
	Waste Management	By harnessing organic waste for biomass, the emission of methane and the amount of waste disposed in landfills are reduced, decreasing environmental impact (How *et al.,* 2019; Williams *et al.,* 2016).
	Biodiversity Preservation	Biomass utilization aids in conserving natural habitats and preserving biodiversity by diminishing dependence on fossil fuel extraction (Alex, 2023).
Economic Benefits	Renewable Job Creation	Biomass supply chains generate employment opportunities, especially in rural regions, promoting local economies (Catherine, 2023; Nunes and Silva, 2023).
	Energy Cost Stability	Biomass-derived energy exhibits reduced vulnerability to fluctuations in the international fuel market, resulting in more predictable energy pricing (Saleem, 2022).
	Local Economic Development	Establishing novel biomass-derived supply chains and industries fosters regional economic expansion (Catherine, 2023).
Social and Energy Security Advantages	Reduced Energy Poverty	Bioenergy initiatives have the potential to offer energy accessibility to communities that are not connected to the main power grid, thereby enhancing living standards and mitigating energy deprivation (Zhao, 2022).
	Diversification of Energy Sources	Integrating biomass into the energy blend diminishes the country's dependence on imported fuels, enhancing energy security (Khurram *et al.,* 2023).
Technological and Innovation Advantages	Advancements in Conversion Technologies	Advancements in conversion technologies are crucial to address some of the challenges associated with biomass utilization, such as improving efficiency and reducing environmental impact (Tshikovhi and Tshwafo, 2023).
	Integration with Other Renewables	Integrating biomass with solar and wind power can enhance the dependability and consistency of renewable energy systems (Speirs *et al.,* 2015).
Policy and Climate Change Advantages	Alignment with Climate Policies	Biomass utilization aligns with global initiatives such as the Paris Agreement by aiding in achieving targets for reducing greenhouse gas emissions (Sütterlin and Siegrist, 2017).
	Incentives for Renewable Energy	Governments may provide financial assistance and rewards to encourage the use of biomass as part of a sustainable energy plan, thereby promoting its widespread adoption (EUBA, 2023a; Rashidi *et al.,* 2022b).

optimize conversion for different feedstock types, and seamlessly integrate bioenergy systems with existing infrastructure. These advancements necessitate collaboration between researchers, policymakers, and investors to navigate the complexities of implementing renewable energy and establish biomass as a viable contributor to the global energy mix.

The high initial costs associated with bioenergy infrastructure and competition from established energy sources pose significant hurdles. Utilizing waste products or dedicated energy crops grown on non-arable land can help manage feedstock costs, an essential aspect of sustainable bioenergy practices. Policy interventions like subsidies, tax breaks, and financial innovations like carbon credits or public-private partnerships can further incentivize investment and improve the economic competitiveness of bioenergy projects.

While bioenergy can contribute to reducing greenhouse gas emissions, it's important to note that bioenergy production may not always lead to the desired environmental benefits. Potential drawbacks include deforestation, biodiversity loss, and increased carbon emissions from land-intensive crops used for biofuel production. Sustainability standards, life cycle assessments, and promoting public awareness about responsible bioenergy practices are crucial to mitigating these environmental risks. Implementing sustainable practices throughout the bioenergy life cycle, from cultivation to conversion, is essential to minimize net greenhouse gas emissions and protect biodiversity.

Table 2 classifies these challenges, providing a comprehensive summary of the barriers that must be overcome to fully utilize biomass as a viable and sustainable energy source. This subject is crucial for stakeholders, policymakers, and researchers promoting and implementing bioenergy solutions.

By acknowledging and addressing these technical, economic, and environmental challenges, bioenergy can become a more sustainable and viable contributor to the global energy landscape. Continued research and development efforts focused on improving conversion technologies, exploring sustainable feedstock options, and promoting responsible practices are essential for realizing the full potential of bioenergy as a renewable energy source. These advancements hold the key to unlocking solutions that can mitigate the challenges outlined above, paving the way for a more sustainable and efficient bioenergy sector.

1.5. Current Technological Developments in Bioenergy Generation

Technological developments in bioenergy generation are bringing about significant improvements in cost reduction, environmental impact minimization, and efficiency. Enhancing conversion technologies, making the best use of feedstock, and incorporating bioenergy into current energy systems are the main goals of recent developments. Some of the critical significant technological advancements in the production of bioenergy in this area include:

Table 2
Key Challenges in Biomass Utilization and Conversion

Category	Challenges	Description
Technical Challenges	Conversion Efficiency	Bioenergy conversion exhibits lower efficiency than fossil fuels, necessitating a larger quantity of biomass to generate an equivalent amount of energy, resulting in heightened resource consumption (Sharew *et al.,* 2022).
	Technology Maturity	Several sophisticated biomass technologies are currently in the experimental or developmental phases and have not yet been fully implemented commercially (How *et al.,* 2019).
	Feedstock Quality and Consistency	Differences in biomass feedstock, such as the amount of water present and the amount of energy it contains, can impact the efficiency of converting it into energy and the stability of energy production processes (Williams *et al.,* 2016).
Economic and Financial Challenges	High Initial Capital Costs	Establishing biomass processing facilities requires substantial initial capital, discouraging potential investments (Alex, 2023).
	Competition with Fossil Fuels	High production costs often prevent bioenergy from competing effectively with cheaper fossil fuels. (Catherine, 2023).
	Supply Chain and Infrastructure	Establishing a dependable biomass supply chain encompassing biomass gathering, processing, and transporting biomass is multifaceted and expensive (Nunes and Silva, 2023).
Environmental and Social Challenges	Sustainable Sourcing	It is imperative to acquire biomass in a manner that does not cause harm to ecosystems or exhaust soils, thus preserving environmental integrity (Saleem, 2022).
	Food vs Fuel Debate	The contrast of utilizing land for energy crops instead of food production raises ethical and resource allocation concerns (Catherine, 2023).
	Emissions and Air Quality	The combustion of biomass can generate emissions that have the potential to impact air quality, thus requiring meticulous management and advanced technology to mitigate the consequences (Zhao, 2022).
Policy and Regulatory Challenges	Lack of Supportive Policies	The lack of comprehensive policy frameworks to promote bioenergy development impedes its expansion (Khurram *et al.,* 2023).
	Regulatory Uncertainty	The volatility of regulations and incentives creates an ambiguous investment environment, impacting the ability to make long-term plans and implement projects (Speirs *et al.,* 2015).
	Public Acceptance	Misconceptions and a lack of awareness about bioenergy's benefits contribute to public resistance and slow adoption (Sütterlin and Siegrist, 2017).
Research and Development Challenges	Innovation Requirement	Sustained research and innovation are crucial for improving the effectiveness and competitiveness of biomass technologies (EUBA, 2023b).
	Skilled Workforce	Proficient human resources are essential for efficiently managing and operating biomass facilities, necessitating specialized education and training initiatives (Rashidi *et al.,* 2022b).

A. Normal Conversion Technologies:

Normal or conventional biomass converion technologies encompass well-established and widely used methods that have been a mainstay of bioenergy production for many years. The following items are included:

- Direct Combustion: Direct combustion is the most basic and ancient technique for converting biomass into energy (Greenvolt, 2023; Luo and Zhou, 2012; Tursi, 2019). The process entails combusting biomass material, such as wood, agricultural residues, or municipal solid waste, in the presence of oxygen to generate heat (Amalina *et al.,* 2022; Kalak, 2023; Yaashikaa *et al.,* 2020). Subsequently, we can then use this thermal energy directly for heating applications or convert it into electrical power through steam generation. Steam turbines, turbo generators, and boilers represent cutting-edge technology by utilizing combustion to convert mechanical energy into electricity (National Environment Agency, 2019). The process entails combusting biomass at temperatures between 800 and 1000 °C, requiring the burned materials to have a moisture content below 50% by weight to achieve optimal efficiency (Chen *et al.,* 2021; Zeng and Han, 2023). The net efficiency of power generation from biomass combustion ranges from 20% to 40%. However, increasing the scale of operations to exceed 100 MWe or incorporating 10% co-firing with coal can significantly improve this efficiency (Zamri *et al.,* 2022). Coal-algae co-combustion combines microalgae biomass with coal for direct combustion (Ye *et al.,* 2020). This approach enhances energy efficiency and provides a sustainable solution by potentially decreasing CO_2 emissions. The process entails diverting CO_2 from the combustion reaction to stimulate microalgae growth, thus facilitating carbon capture in a beneficial cycle (Li *et al.,* 2023; Tarafdar *et al.,* 2023).

  Additional research is required to evaluate the feasibility of coal-algae co-firing despite its potential thoroughly. In the global context of addressing climate change, implementing carbon credit schemes is a timely approach to encourage the reduction of greenhouse gas emissions. The utilization of biomass in boilers through direct combustion, as described in Green Energy reports, serves as evidence of the effectiveness of this method in producing steam at high pressure. Steam generation systems use the produced steam to power turbines connected to electric generators, functioning similarly to conventional fossil fuel power plants but with the advantage of being renewable. Furthermore, the concept of co-generation exemplifies the effective use of waste heat and secondary steam in biomass power plants (Abbas *et al.,* 2020). Co-generation facilities significantly improve the overall energy efficiency of direct combustion by utilizing these byproducts for heating and industrial processes, such as ethanol production or drying chemicals and wood products (Deshmukh *et al.,* 2013). This comprehensive approach optimizes power generation and enhances the sustainability and energy efficiency of the industrial environment.
- Anaerobic Digestion: Anaerobic digestion is a complex biological process where specialized microorganisms break down organic materials in oxygen-free

environments (Adekunle and Okolie, 2015; Anukam *et al.,* 2019; Harirchi *et al.,* 2022; Mata-Álvarez *et al.,* 2000). The production of biogas, a renewable energy source primarily consisting of methane (CH_4) and carbon dioxide (CO_2), is heavily reliant on this process (Kabeyi and Olanrewaju, 2022a; Sara, 2017). It also contains small quantities of other gases. Anaerobic digestion relies on the lack of oxygen to efficiently decompose biodegradable substances by specialized microorganisms that thrive in oxygen-deprived environments (Samir *et al.,* 2022).

The European Union's Green Paper on Bio-Waste Management highlights anaerobic digestion as a crucial technology, particularly for treating biomass unsuitable for burning. The adoption of this technology for treating various organic waste streams is growing at an impressive rate of 25% annually, leading to a remarkable expansion (EEA, 2020). Despite its long history of use, the understanding of anaerobic digestion is still incomplete, primarily because of the intricate interaction between physicochemical and microbiological factors. Gaining a deeper understanding of these fundamental mechanisms through theoretical simulations and control models is crucial for future research focused on maximizing the efficiency of the process.

Anaerobic digestion transforms a substantial amount of organic material into biogas, a highly abundant energy resource. This process is highly adaptable and capable of handling diverse organic materials, including municipal solid waste (MSW), wastewater sludge, and various industrial wastes such as oils, fats, grease (FOG), energy crops, and agricultural residues (Wang *et al.,* 2023). The process commences with decomposing intricate organic molecules into less complex compounds such as proteins, lipids, and carbohydrates via extracellular enzymatic hydrolysis. This results in the production of both short-chain and long-chain fatty acids, amino acids, and simple sugars. Microorganisms, whether in suspension or attached to solid particles, produce these enzymes. Afterwards, acidogenic bacteria transform these soluble substrates into organic acids and alcohols, metabolized by acetoclastic methanogens into acetate, methane, and carbon dioxide (Ali Shah *et al.,* 2014; Harirchi *et al.,* 2022; Wainaina *et al.,* 2019).

Hydrogenotrophic methanogens are vital in producing methane, as they combine carbon dioxide and hydrogen to generate methane, accounting for approximately 30% of the overall methane output (Kurth *et al.,* 2020; Megonigal *et al.,* 2014). Several factors, such as retention time, influence the composition of biogas. Retention time strongly correlates with the substrate's methane content and carbon oxidation state (Czekała *et al.,* 2023). The reactor configuration also influences biogas output. Continuous digestion methods promote lower CO_2 levels by expelling dissolved CO_2. Additionally, temperature affects gas solubility and reaction rate (Ceron-Chafla *et al.,* 2020). The concentration of dissolved hydrogen has a significant influence on the acid-genesis/acetogenesis and hydrogenotrophic methanogenesis stages, highlighting its crucial role in the process of digestion.

Nevertheless, the reaction network is significantly complex, involving supplementary processes such as methanol and formate oxidation, nitrate and sulfur reduction, siloxane disintegration, and lactic acid production, among various others. It is essential also to consider factors such as the transfer of mass between vapour and liquid, the equilibrium between acids and bases, and the growth and decay of microorganisms. Anaerobic digestion enables the generation of renewable methane and provides a substitute for traditional fossil fuels, thereby addressing environmental concerns such as acid rain and global warming (Werkneh, 2022a).

Despite the higher cost of bioenergy than fossil fuel-derived energy, regulatory measures such as emission caps, carbon taxes, and incentives for bioenergy are expected to improve its cost competitiveness. Anaerobic digestion of biomass produces methane, heat, synthesis gases, and ethanol, all of which have similar efficiency and cost (IEA, 2020). The study conducted by Kitessa *et al.,* (2022) investigates the enhancement of biogas production from a combination of wastewater and microalgae through anaerobic digestion. The research shows that specific ratios of these blends significantly increase the amount of methane produced and decrease the levels of total solids (TS), volatile solids (VS), and chemical oxygen demand (COD), and this demonstrates that co-digestion of these substances is indeed feasible. These findings establish the foundation for additional investigation into feasible energy production applications.

- Fermentation: Fermentation is a biotechnological procedure that converts biomass into bioethanol, a sustainable biofuel, through the fermentation of sugars derived from plants (Adegboye *et al.,* 2021; Bušić *et al.,* 2018; Chin and Hng, 2013; Sindhu *et al.,* 2019). This process utilizes the inherent metabolic capabilities of yeast and specific bacteria to enzymatically convert sugars, such as glucose, fructose, and sucrose, into ethanol and carbon dioxide (Maicas, 2020). The underlying principle of fermentation is similar to that used in brewing beer, where yeast converts sugars in grains into alcohol. However, the process for bioethanol production is optimized and adapted for large-scale fuel production rather than beverage making.

The conversion of biomass into biofuels involves a complex series of processes, with pre-treatment, fermentation, and critical stages of hydrolysis (Osman *et al.,* 2021). Fermentation is a crucial anaerobic process that ingeniously converts glucose in organic matter into acids or alcohols through chemical reactions (Britannica, 2023). Adding bacteria or yeast to biomass enables conversion, as they efficiently consume sugars to produce ethanol and carbon dioxide. The ethanol obtained is subjected to distillation and dehydration processes to attain the desired level of concentration and purity, rendering it suitable for use as a fuel in automobiles. Notably, the waste product of this process, such as bagasse derived from the fermentation of sugar cane, is effectively used as a fuel for gasification or boilers and can even be used as feed for cattle, showcasing the efficient and cyclical utilization of biomass.

Conventional crops such as corn and sugarcane, which are crucial for bio-ethanol production, have limitations because they are also important for food and animal feed, making it challenging to meet the worldwide demand for bio-ethanol (Sarkar *et al.,* 2012). The restriction on certain materials makes lignocellulosic materials, like abundant and renewable agricultural waste, even more attractive as alternative feedstocks. Their plentiful nature and ability to be replenished contribute to their cost efficiency (Mujtaba *et al.,* 2023). They offer a practical solution for sustainably producing bio-ethanol. Nevertheless, converting biomass into biofuel is not difficult; notable obstacles include challenges in biomass handling and transportation, specifically in the pre-treatment for effective removal of lignocellulosic lignin (Antunes *et al.,* 2019). Improved pre-treatment methods enhance the process of breaking down complex carbohydrates into simple sugars using enzymes, resulting in higher amounts of sugars that can be fermented into bio-ethanol, ultimately improving the overall efficiency of bio-ethanol production (Bušić *et al.,* 2018).

For efficient and cost-effective biofuel production, it is necessary to develop innovative fermentation technologies that can efficiently convert glucose and xylose into ethanol (Li *et al.,* 2019). The wide range of microbial cultures, which includes pure strains such as Clostridium species and mixed cultures, provides various fermentation options (Du *et al.,* 2020). An example is the *bacterium Clostridium aceto-butylicum*, which is well-known for its exceptional hydrogen production rates (Son *et al.,* 2021). Moreover, Serratia marcescens and diverse food wastes have exhibited encouraging hydrogen yields, underscoring the potential of waste components in municipal solid waste for bio-hydrogen production (Dong *et al.,* 2009; Haque and Azad, 2023). Anaerobic fermentation offers a straightforward method for hydrogen production from diverse feedstocks, including waste materials and microalgae.

Recent studies have shown that Enterobacter aerogenes can convert microalgae species such as Anabaena and Scenedesmus obliquus into biofuel (Batista *et al.,* 2018; Khan *et al.,* 2023). Combining microaerobic dark fermentation and photo-fermentation processes using *Rhodobacter capsulatus* JP91 has significantly increased hydrogen production (Silva *et al.,* 2019; Su *et al.,* 2009). These findings emphasize the impact of factors such as oxygen, inoculum, and substrate concentration on bio-hydrogen production, which can lead to more efficient fermentation techniques. When producing ethanol from lignocellulosic materials, the industry considers two main methods: separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) (Garver and Liu, 2014; Xue and Cheng, 2019). SHF enables the separate optimization of hydrolysis and fermentation conditions but encounters obstacles such as enzyme inhibition caused by hydrolysis products. On the other hand, SSF combines the processes of cellulose hydrolysis and glucose fermentation processes in one container, reducing the harmful effects of end-product inhibition and allowing for more effective ethanol production *(Beluhan et al.,* 2023; Kotarska *et al.,* 2019). The combination of enzymatic hydrolysis and microbial fermentation in SSF increases ethanol yields and speeds up the bioconversion process, demonstrating the interactive relationship between these two processes in the production of biofuels.

B. Advanced Conversion Technologies:

Advanced biomass conversion technologies boast increased complexity to achieve several goals: enhanced efficiency, minimized emissions, and the ability to convert a wider range of biomass materials, which include:

- Gasification: Gasification works by subjecting carbonaceous materials, organic or fossil-derived, to high temperatures (over 700°C) in an oxygen-limited environment with a controlled amount of steam. This process transforms the materials into a mixture of carbon dioxide, hydrogen, and carbon monoxide (Lam *et al.,* 2019a; Shadle *et al.,* 2020). Modern gasifiers have undergone notable advancements in their design and operation, improving efficiency. They can generate cleaner, more energy-dense syngas (synthesis gas), mainly hydrogen and carbon monoxide (Sikarwar *et al.,* 2017). Gasification produces a synthetic gas (syngas) that can be used in various ways. It can be combusted directly to heat or generate electricity. Alternatively, it can undergo additional processing to produce liquid biofuels, chemicals, or hydrogen. Gasification is a precious process in the bioenergy sector due to its versatility (Erdiwansyah *et al.,* 2023).
- Pyrolysis: Pyrolysis refers to breaking down biomass through the application of heat without the presence of oxygen. It takes place at elevated temperatures, usually ranging from (300-600°C) to (600-1300°C) (Al-Haj Ibrahim, 2020; Dawod, 2021; Devi and Rawat, 2021; Dhawane *et al.,* 2022; Pahnila *et al.,* 2023; Zaman *et al.,* 2017). The process converts biomass into three main products: bio-oil, syngas, and biochar. Technological advancements have enhanced pyrolysis efficiency (Gupta *et al.,* 2021). Pyrolysis produces a concentrated, liquid energy carrier called bio-oil when performed in modern units. This bio-oil can be used directly as fuel or upgraded into chemicals and fuels. Additionally, these units are designed to optimize bio-oil yield while simultaneously generating syngas and high-quality biochar (Al-Rumaihi *et al.,* 2022). Biochar, a residue produced through pyrolysis, possesses various uses in agriculture as a substance added to soil to enhance its quality, aid in the retention of carbon, and promote the growth of plants. Syngas, as utilized in gasification, can serve as a source of energy or raw material for synthesizing various chemicals (Yaashikaa *et al.,* 2020).
- Improvements in Anaerobic Digestion: The process by which microorganisms break down organic matter in the absence of oxygen is known as anaerobic digestion (Jarvie, 2023; Mourshed *et al.,* 2023; Ngan *et al.,* 2020; Uddin and Wright, 2023). Anaerobic digestion widely treats organic waste and wastewater, producing digestate and biogas (primarily methane and carbon dioxide). Current advancements prioritize improving the anaerobic digestion process's effectiveness, which involves optimizing the composition of microbial populations to expedite the decomposition of intricate organic compounds. Scientists are developing advanced bioreactors to handle diverse forms of biomass, such as decomposition-resistant lignocellulosic (plant-derived) and algal biomass (Sarwer *et al.,* 2022). Biogas, a highly adaptable energy resource, can be used on-site for heating and electricity generation or purified and injected into the natural gas grid. Additionally, the nutrient-rich digestate, a byproduct of the process, can be utilized as fertilizer (Farghali *et al.,* 2022).

C. Biofuel Production Improvements:

- Cellulosic Ethanol: Cellulosic ethanol is a biofuel derived from lignocellulose, a plant material that makes up a significant portion of its mass. Non-food biomass sources, such as agricultural residues (e.g., corn stover, straw), forest residues, and grasses, contain lignocellulose (Aboudi *et al.,* 2021; Blasi *et al.,* 2023b). This procedure entails decomposing intricate carbohydrates (cellulose and hemicellulose) in biomass into more basic sugars. Biotechnological advancements have created highly efficient enzymes capable of effectively decomposing these carbohydrates, even from resilient, lignocellulosic biomass. After the sugars are released, they undergo fermentation to generate ethanol (Li *et al.,* 2022).

Recent advancements have concentrated on enhancing the fermentation procedure, which involves employing genetically modified yeasts or bacteria capable of fermenting sugars with greater efficiency and enduring higher levels of ethanol (Ahmad and Qazi, 2014; Khan *et al.,* 2018; Malode *et al.,* 2021; Sharma *et al.,* 2020). Contemporary cellulosic ethanol production facilities progressively incorporate hydrolysis and fermentation processes to lower expenses and enhance yields (Liu *et al.,* 2019). An integration method known as simultaneous saccharification and fermentation (SSF) can be employed, wherein hydrolysis and fermentation processes occur simultaneously in a single step (Patel and Shah, 2021).

- Biodiesel from Algae: Algae are a wide-ranging collection of water-dwelling organisms that can carry out photosynthesis (Andersen and Lewin, 2023). Some specific species of algae contain a significant amount of lipids or oils, which makes them well-suited to produce biodiesel (Akubude *et al.,* 2019; Bošnjaković and Sinaga, 2020). Algae can thrive in diverse environments such as freshwater, wastewater, and marine (Ebrahimzadeh *et al.,* 2021). Studies have concentrated on enhancing the growth conditions of algae to achieve the highest possible lipid productivity (Alishah Aratboni *et al.,* 2019; Mulgund, 2022; Udayan *et al.,* 2023). Successful algal biofuel production relies on carefully choosing appropriate algae strains, enhancing growth mediums, and regulating environmental variables such as light, temperature, and CO_2 levels.

An obstacle associated with algae is the efficient extraction of minute organisms from substantial quantities of water (Daneshvar *et al.,* 2021). Implementing flocculation, centrifugation, and filtration techniques in harvesting has increased the process's feasibility and cost-efficiency (Fasaei *et al.,* 2018). After the algae is collected, the lipid content needs to be extracted. Methods such as solvent extraction, mechanical pressing, and supercritical fluid extraction are being improved to optimize the amount of oil obtained (Zhou *et al.,* 2022). The oil that has been extracted is subsequently converted into biodiesel through the process of transesterification. Algae-based biodiesel is a sustainable alternative because algae can be cultivated on infertile land and used as wastewater, avoiding competition with food crops and minimizing environmental harm (Chhandama *et al.,* 2023).

C. Efficiency Optimization:

- Combined Heat and Power (CHP) Systems: Combined Heat and Power, or cogeneration, is a system that produces electricity and captures the heat generated during this process for practical use (Radovanović, 2023). Combined heat and power systems employ biomass as a primary fuel source within bioenergy. Conventional power plants frequently squander a substantial portion of the energy they generate as heat. Unlike traditional methods, Combined Heat and Power systems utilize the excess heat for other purposes, resulting in energy efficiencies of up to 80% or higher, as opposed to the 40-50% efficiency of conventional systems (IEA and OECD, 2011). The thermal energy produced in combined heat and power systems can be utilized for various purposes, such as industrial operations, building space, or district heating systems that distribute heat to residential areas (Fuentes-Cortés *et al.,* 2017). Combined Heat and Power systems situated near biomass power plants offer advantages to industries and communities. Combined Heat and Power systems minimize fuel consumption and the resulting greenhouse gas emissions by optimizing energy extraction from biomass (Celebi *et al.,* 2019; Pariasamy *et al.,* 2022). They play a crucial role in enhancing the sustainability of bioenergy generation.
- Process Integration and Optimization: This approach entails amalgamating various biomass conversion techniques to enhance efficiency and decrease expenses. The objective is to establish a continuous and uninterrupted transition from the initial biomass feedstock to the ultimate energy output (Garba, 2020; Tshikovhi and Motaung, 2023). Combining gasification and pyrolysis processes makes it possible to utilize different biomass feedstocks and generate diverse products, such as syngas, bio-oil, and biochar (Zhou *et al.,* 2022). We can efficiently extract significantly more energy from a given amount of biomass through synergistic process optimization. Following the initial conversion processes, such as gasification or pyrolysis, additional refining or upgrading of the fuels can be incorporated into the system, including tasks like cleaning and improving the quality of syngas or bio-oil, and this optimizes the production process, enhancing its efficiency and cost-effectiveness. Integrating different phases of biomass conversion allows facilities to decrease operational expenses related to energy input, equipment, and labour (Bolívar Caballero *et al.,* 2022).

Additionally, synergistic process optimization reduces waste and enhances the production of superior final products. Continuous advancements in process control, materials handling, and conversion techniques are crucial for successful integration and optimization (Bähner *et al.,* 2021). These advancements encompass reactor design, thermal process management, and catalyst development.

D. Feedstock Diversification and Pretreatment

The latest developments in bioenergy generation have greatly expanded the range of viable raw materials while improving the efficiency of their transformation into energy (Chen *et al.,* 2021; Rashidi *et al.,* 2022b). Technological developments have made it possible to use a variety of biomasses, including agricultural residues, industrial byproducts, and municipal solid waste. This diversification diminishes reliance on conventional biomass sources and provides sustainable waste management solutions and local economic advantages (Clauser *et al.,* 2021).

Researchers have developed advanced pretreatment methods like steam explosion and acid hydrolysis to improve the breakdown of lignocellulosic materials and increase overall energy output. These techniques are crucial for analyzing the complex compositions of various biomass types (Mujtaba *et al.,* 2023). Steam explosion disrupts biomass structure using high-pressure steam, while acid hydrolysis breaks down cellulose and hemicellulose into fermentable sugars with acids. These advancements in pretreatment are crucial because they enable more efficient, cost-effective, and environmentally friendly biomass conversion (Bandyopadhyay-Ghosh *et al.,* 2015). By implementing these sustainable practices, bioenergy becomes a more feasible and sustainable contributor to the renewable energy mix.

E. Integration with Renewable Energy Systems.

Integrating bioenergy systems with other renewable energy sources and smart grid technologies is a pivotal advancement in the renewable energy industry (GGI, 2023; Østergaard *et al.,* 2023). This integration is vital for improving the effectiveness and dependability of renewable energy provision. Smart grids embody sophisticated electricity networks that facilitate the bidirectional exchange of electricity and data (Kabeyi and Olanrewaju, 2023). These grids can effectively regulate the demand and supply of electricity by integrating different energy sources and storage systems. Integrating bioenergy systems into intelligent grids can have a crucial impact on grid balancing (Tan *et al.,* 2021). Smart grids become the bridge between bioenergy's dependable power and the fluctuating nature of renewables (Khan *et al.,* 2023). With its advanced software forecasting energy patterns, this integration optimizes bioenergy generation and distribution, guaranteeing a reliable and uninterrupted flow of electricity.

Ultimately, bioenergy represents a significant step towards a sustainable energy future. However, to fully realize its potential, we must address challenges related to feedstock availability, environmental impact, and technological advancements. By fostering innovation and implementing effective policies, we can overcome these hurdles and maximize bioenergy's contribution to a cleaner and more secure energy landscape. Integrating bioenergy and smart grids paves the way for exploring other promising renewable energy sources, such as waste-to-energy technologies. These technologies can further optimize resource utilization and revolutionize waste management in energy production.

2. Waste-to-Energy Technologies

Waste-to-energy technologies are crucial in contemporary waste management and energy production strategies. Their solution combines waste reduction and energy generation, positively contributing to sustainability and environmental protection (Alao *et al.,* 2022; Rezania *et al.,* 2023). Waste-to-energy transforms waste materials, particularly those that cannot be recycled, into different types of energy. The energy generated can manifest as electricity, heat, or fuel and is obtained through various processes that handle and decompose waste (Palacio *et al.,* 2018).

Waste-to-energy technologies possess the capacity to manage a wide range of waste types, including municipal solid waste, industrial waste, agricultural waste, and even specific hazardous wastes. The appropriateness of waste for Waste-to-Energy processes is contingent upon its calorific value and composition (Alao *et al.,* 2022). Landfills, which are the prevailing method of waste disposal, have notable environmental consequences, such as the utilization of land, the release of methane gas, and the potential pollution of soil and water.

Waste-to-energy technologies minimize the waste that is ultimately deposited in landfills (Abubakar *et al.,* 2022). Specific Waste-to-energy processes facilitate the retrieval and reutilization of materials, including metals. Not only does this practice help preserve resources, but it also enhances the efficiency of waste management. Although the term 'renewable' is commonly linked to natural resources such as wind and solar, Waste-to-energy also plays a role in renewable energy portfolios (Abdel-Shafy and Mansour, 2018). A vast array of waste materials hold the potential to be converted into energy. Integrating these waste-to-energy processes into the energy portfolio reduces reliance on fossil fuels, ultimately facilitating a shift towards a more environmentally sustainable energy landscape (ADB, 2020). The potential of waste-to-energy to reduce reliance on fossil fuels makes it a critical tool in global efforts to mitigate climate change.

2.1 Overview of Biomass Conversion Methods

Biomass conversion methods refer to the procedures employed to convert biomass into practical forms of energy, such as heat, electricity, or biofuels (Fiala and Nonini, 2018; Garba, 2020; Junginger, 2013; Osman *et al.,* 2021; Pande and Bhaskarwar, 2012). These methods are crucial for harnessing biomass from organic materials such as plant and animal matter for energy generation. Comprehending these techniques is essential for utilizing biomass as a renewable and sustainable energy resource. There are various biomass conversion methods, which can be broadly categorized into two main groups: thermal and biochemical technologies.

2.1.1 Thermal Technologies

Thermal technologies play a crucial role in the conversion of biomass into energy. These processes utilize heat to convert organic matter into practical forms of energy such as electricity, heat, or syngas (synthesis gas). The three leading thermal technologies used in biomass conversion are:

a. Incineration

Biomass incineration, or direct combustion, is the controlled burning of biomass to produce heat (Gumisiriza *et al.,* 2017). This method is essential for converting organic matter into usable energy and is crucial in sustainable waste management and energy generation. During incineration, organic material combustion occurs, generating heat, carbon dioxide, and water vapour (Amulen *et al.,* 2022). The effectiveness of this process is contingent upon the calorific value of the biomass, which fluctuates based on its type and moisture content. The main objective of incineration is to harness the generated heat for diverse purposes, such as warming structures via district heating systems, supplying industrial process heat in sectors like chemical manufacturing, food processing, and paper production, and producing electricity (Traven, 2023). Electricity utilizes the thermal energy from biomass combustion to generate steam, which powers turbines connected to electricity generators.

Modern incineration facilities are outfitted with sophisticated emission control technologies aimed at minimizing pollutants, including particulate matter, nitrogen oxides (NOx), Sulphur oxides (SOx), and dioxins, thereby enhancing their environmental safety (Sabin Guendehou *et al.,* 2006; Schwartz *et al.,* 2020). These technologies are crucial for reducing incineration's ecological effects and meeting strict air quality regulations. While burning biomass releases CO_2, the process is considered carbon neutral because plants continuously absorb atmospheric CO_2 as they grow, offsetting the emissions from biomass-based energy production (EIA, 2022). However, the environmental impact assessment must also consider the procurement and processing of biomass.

Municipal Solid Waste (MSW) incineration utilizes a well-established thermal treatment technique: deliberate combustion in a furnace with a plentiful oxygen supply. The process typically operates between 800°C and 1000°C for at least two seconds, generating heat and residual ash (bottom and fly ash) (Alao *et al.,* 2022). This technology is widely recognized as the most advanced and extensively implemented method for global waste management.

An inherent benefit of incineration is its notable capacity to decrease waste volume by 80–90% and mass by 70–80% (Ding *et al.,* 2022). The high-efficiency level in waste volume reduction greatly reduces the land required for landfilling, thus prolonging the lifespan of current landfill sites. Annually burning 1 million tonnes of Municipal Solid Waste (MSW) requires less than 100,000 square meters of land over an average lifespan of 30 years. In contrast, landfilling the same amount of MSW requires roughly 300,000 square meters of space in the area (Abubakar *et al.,* 2022).

Regarding land utilization, a standard incineration facility that handles 300 tonnes per day is projected to necessitate roughly 0.8 hectares, underscoring the process's efficiency in terms of spatial demand (Yong *et al.,* 2019). In addition to significantly reducing waste mass and volume, the high incineration temperatures effectively neutralize hazardous materials, enhancing environmental safety (Tsui and Wong, 2019). Moreover, incineration technology stands out for its adaptability in handling various waste forms. It also boasts relatively modest requirements for both technological complexity and human resource expertise.

b. Gasification

In contrast to incineration, which directly burns biomass for heat, gasification offers a thermochemical process that partially oxidizes biomass, transforming it into syngas (synthesis gas). This process typically operates between 700°C and 1300°C and involves simultaneous exothermic oxidation and endothermic pyrolysis. A finite oxygen supply facilitates the conversion of solid biomass into combustible gas mixtures (often called syngas) (Canabarro *et al.,* 2013; Gao *et al.,* 2023; Lam *et al.,* 2019b; Sankaran *et al.,* 2018; Hussain *et al.,* 2023). By transforming biomass into products with additional value, such as charcoal, energy, fertilizers, heat, syngas, and biofuels, biomass gasification helps to reduce the adverse environmental effects of conventional waste management methods. Advanced biofuels, which include dimethyl ether, B. methanol, or Fischer-Tropsch diesel, can be manufactured in customizable ways through the syngas process (Alnouss *et al.,* 2019). The partial oxidations of air, water vapour, or oxygen cause gasification to typically occur at high temperatures between 800 and 1000 °C (Lam *et al.,* 2019b). Gasification sometimes utilizes steam as a burning agent. The process produces a gas by-product that can be directly used in gas engines and gas turbines for energy generation (Salami and Skála, 2015).

Biomass gasification offers a promising thermochemical technique for converting organic material into a valuable fuel source: syngas. This combustible gas mixture, containing primarily hydrogen, carbon monoxide, and methane, has applications in electricity generation and heat production (Gao *et al.,* 2023). As illustrated in Figure 2, the gasification process involves drying the biomass feedstock to remove moisture. Then, the dried biomass is heated in a controlled environment with a limited amount of oxygen (Molino *et al.,* 2016). This oxygen-starved environment triggers decomposition instead of combustion, generating syngas along with char, tar, and other byproducts. The specific composition of syngas can vary, with hydrogen, carbon monoxide, and methane concentrations ranging from 6% to 53% (Lam *et al.,* 2019b).

However, the moisture content of the biomass feedstock can significantly impact the efficiency and quality of the syngas produced. Studies have shown that using biomass with a lower moisture content (around 15%) leads to better results compared to feedstock with higher moisture levels (up to 40%) (Raheem *et al.,* 2015). Higher moisture content in the biomass can reduce the gasification efficiency and result in syngas with a lower calorific value (heating potential).

c. Pyrolysis

Another thermochemical conversion technology is pyrolysis. Unlike gasification, which utilizes a limited oxygen supply, pyrolysis efficiently decomposes carbonaceous

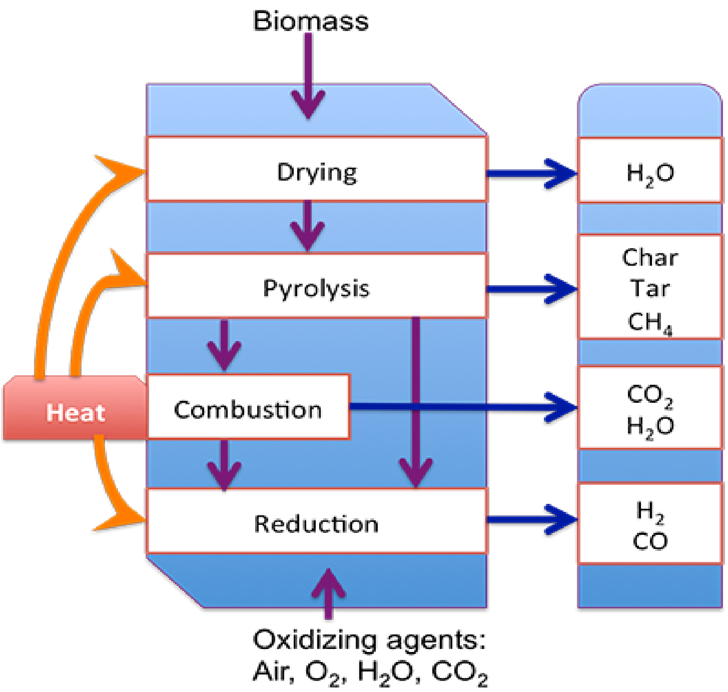


Fig. 2. A schematic diagram of the key stages of biomass gasification, a thermochemical process that converts organic material into a combustible gas mixture called syngas (Molino *et al.,* 2016). Biomass is fed into the gasifier, where it undergoes thermal decomposition in a controlled environment with limited oxygen. This process generates syngas (gaseous products), char (solid residue), and condensates (liquids), all of which have various potential applications like electricity generation, biofuel production, or industrial heat.

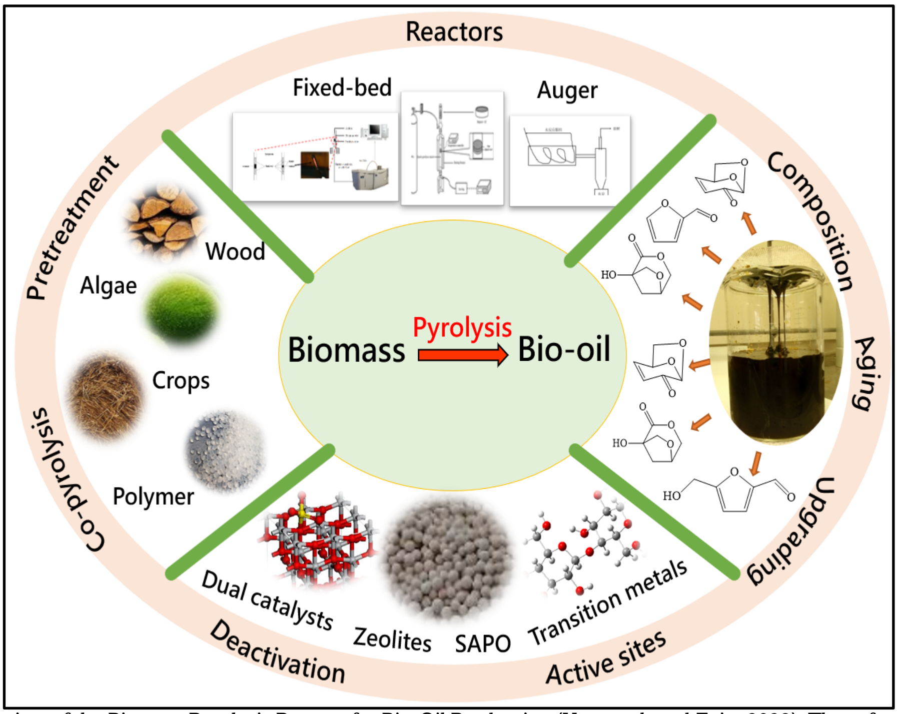


Fig 3. Schematic Overview of the Biomass Pyrolysis Process for Bio-Oil Production (Yansaneh and Zein, 2022). These fundamental steps depict biomass pyrolysis, a thermochemical conversion process that breaks down organic material in the absence of oxygen. Biomass feedstock is introduced into a reactor and heated to temperatures ranging from (400-900°C). Under these conditions, the biomass decomposes into various gaseous products (bio-gas), a liquid bio-oil fraction, and a solid charcoal residue. Bio-oil, the primary product of interest, is a complex mixture of oxygenated hydrocarbons that can be further upgraded into valuable biofuels or chemicals.

biomass, such as cellulose, lignin, and hemicellulose, through a thermochemical process in an oxygen-free environment or with very limited oxygen to prevent complete gasification. This method is widely recognized as a prevalent thermochemical technique (Suresh *et al.,* 2020; Urrutia *et al.,* 2022). The process usually operates at elevated temperatures, typically 600 to 900 °C, with moderate rates of heating and extended periods, which helps create syngas enriched with hydrogen (Gao *et al.,* 2023; Yaashikaa *et al.,* 2020).

Biomass conversion offers a pathway to sustainable biofuels through various thermochemical processes. Pyrolysis, for instance, utilizes high temperatures (400-900 °C) to decompose organic materials such as cellulose, lignin, and hemicellulose in an oxygen-limited environment, typically achieved within a reactor (Yansaneh and Zein, 2022). This process, as depicted in Figure 3, breaks down complex biomass molecules into bio-oil, a potential renewable fuel source further refinable into valuable chemicals and transportation fuels. This illustrates the key steps of pyrolysis: heating biomass in a limited-oxygen reactor, which breaks down the material to produce bio-oil alongside syngas and biochar byproducts. Bio-oil's potential as a renewable fuel exemplifies the versatility of biomass conversion technologies.

Prior research has primarily concentrated on generating bio-oil from microalgae such as *Tetraselmis chuii and Chlorella sp.* using slow pyrolysis, which produces compounds like amides, phenol, and alkenes (Grierson *et al.,* 2011). Conversely, *Chlorella protothecoides* has demonstrated the ability to produce significant quantities of bio-oil through fast pyrolysis (McIntosh *et al.,* 2021). Nevertheless, information concerning syngas generation through the catalytic pyrolysis of microalgae is scarce.

Pyrolysis, however, is not limited to microalgae. Researchers have additionally investigated the potential of pyrolyzing various agricultural biomasses, including rice straw, rice husk, wheat straw, and maize straw (Bian *et al.,* 2016). The process reached its peak completion temperature of 400 °C. The results indicate that biochar derived from rice straw has great potential for modifying nutrient-poor, acidic soils. With a yield of 43.8%, rice straw produced the most biochar. Moreover, biochar, a byproduct of pyrolysis used to make biofuel, has many uses and is always coming up with new ones (Bolan *et al.,* 2021).

While thermal conversion technologies offer advantages in terms of simplicity and high processing rates, biochemical conversion methods provide a more targeted approach for producing specific biofuels and chemicals. Biochemical processes leverage biological processes such as enzymes and microorganisms to break down biomass and convert it into desired products.

2.1.2 Biochemical Technologies

Biochemical conversion technologies for biomass encompass converting biomass into targeted products through physical, chemical, and biological pretreatments (Adams *et al.,* 2018; Gnanasekaran *et al.,* 2023). The purpose of these pretreatments is to enhance the conversion process's efficiency rather than directly producing the final products. This approach differentiates biochemical conversion from solely physical or chemical biomass conversion methods. Moreover, biochemical conversion processes are typically less severe and more moderate than physical and chemical alternatives (Kumar and Sharma, 2017a). These techniques prioritize biomass preparation to ensure efficient conversion, thus laying the foundation for the subsequent production of the desired final products.

Through careful selection of microorganisms, biochemical conversion of biomass can yield a diverse range of products, including xanthan gum, xylitol, mannitol, hydrogen, biogas, ethanol, acetone, butanol, and various organic acids (such as

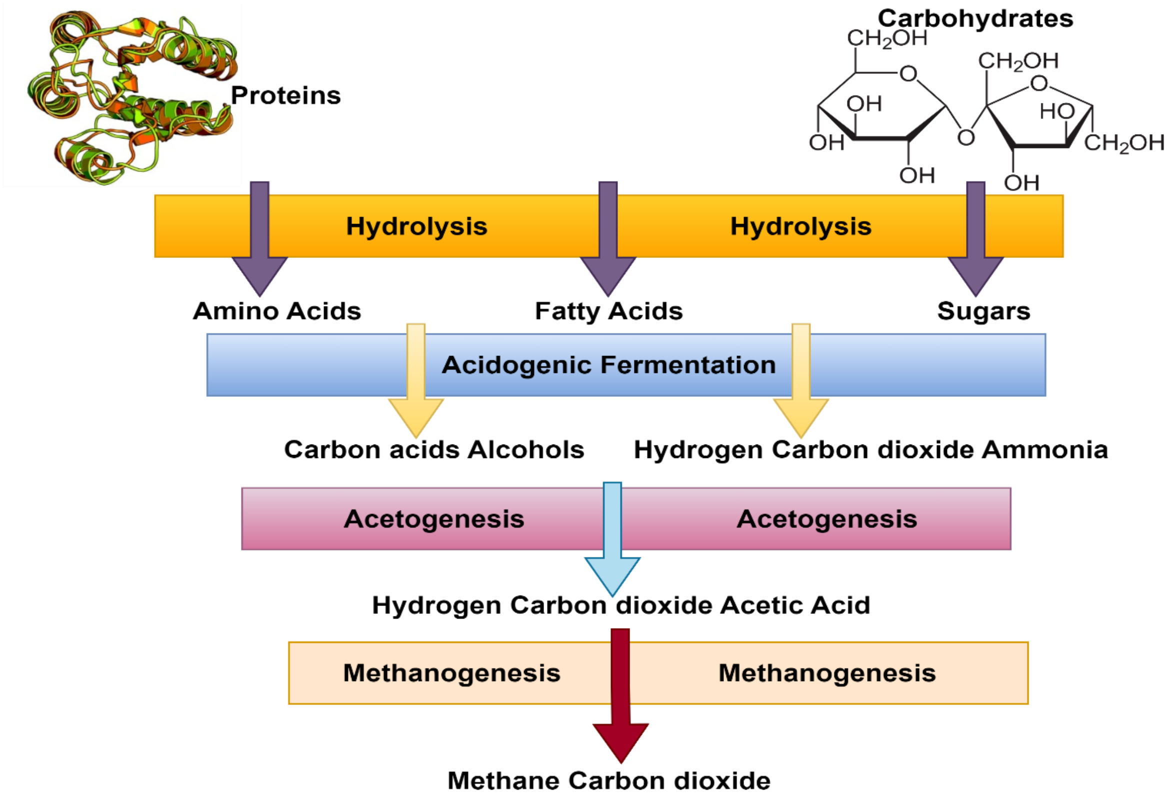


Fig. 4. Multi-Stage Process of Anaerobic Digestion for Biomass Conversion (Gnanasekaran *et al.,* 2023).

pyruvate, lactate, oxalic acid, levulinic acid, and citric acid) (Chen and Wang, 2017). These products have two advantages: they can replace grain-derived products like ethanol and act as environmentally friendly substitutes for petroleum-based products.

Biochemical technologies excel in biomass conversion compared to other methods due to their moderate, clean, and efficient nature. Additionally, these technologies enable producing various intermediate products from biomass through the strategic selection of specific enzymes or microbes (Tshikovhi and Tshwafo, 2023). Numerous platform materials necessary to create materials, fuels, and chemicals using renewable resources are made possible by this versatility. As a result, biomass biochemical conversion technologies are seeing a lot of attention and investment.

a. Anaerobic Digestion

Anaerobic digestion offers a sustainable solution for waste management and renewable energy production. This oxygen-depleted process decomposes organic matter, primarily animal dung, agricultural waste, or energy crops, into biogas (Masud *et al.,* 2023). Biogas, a fuel composed mainly of methane and carbon dioxide, can be directly burned or upgraded to biomethane for use in engines (Tsigkou *et al.,* 2022). Figure 4 illustrates the various stages of anaerobic digestion, potentially depicting the breakdown of complex organic matter into biogas by distinct microbial communities. The resulting soluble organics are then converted into volatile fatty acids by acidogenic bacteria. These acids are further transformed into acetate by acetogenic microbes. Finally, methanogenesis, facilitated by a distinct microbial group, utilizes the acetate to produce the valuable biogas. This breakdown of complex organic matter into a clean-burning fuel highlights the potential of anaerobic digestion for a circular economy.

Anaerobic digestion, a biological process that breaks down organic matter by microorganisms in an oxygen-free environment, involves four key stages: the first stage, hydrolysis, involves the breakdown of complex organic molecules into simpler sugars and organic acids. The second stage, acidogenesis, further ferments these products into volatile fatty acids, alcohols, and carbon dioxide. In the third stage, acetogenesis, the intermediate products are converted into acetate, hydrogen, and carbon dioxide. Finally, the fourth stage, methanogenesis, utilizes the acetate and hydrogen to produce the final product – methane, also known as biogas – alongside carbon dioxide and water. This multi-stage process allows for the conversion of various biomass feedstocks into a clean-burning renewable fuel source (biogas) and a nutrient-rich digestate byproduct.

In the second phase of anaerobic digestion, called acidogenic fermentation, specialized microorganisms decompose the less complex compounds obtained from hydrolysis, such as simple sugars, fatty acids, and amino acids, into volatile fatty acids with short carbon chains. These volatile fatty acids include butyric and propanoic acids, acetic acids, alcohol, and carbon dioxide. During this stage, approximately 70% of these compounds undergo conversion into acetate, carbon dioxide, and hydrogen, while the remaining 30% are transformed into a variety of volatile fatty acids (VFAs) and alcohols (Gnanasekaran *et al.,* 2023; Wainaina *et al.,* 2019).

Acetogenic bacteria convert fermentation products unsuitable for direct methane production by methanogens. This process involves oxidizing volatile fatty acids (VFAs) and

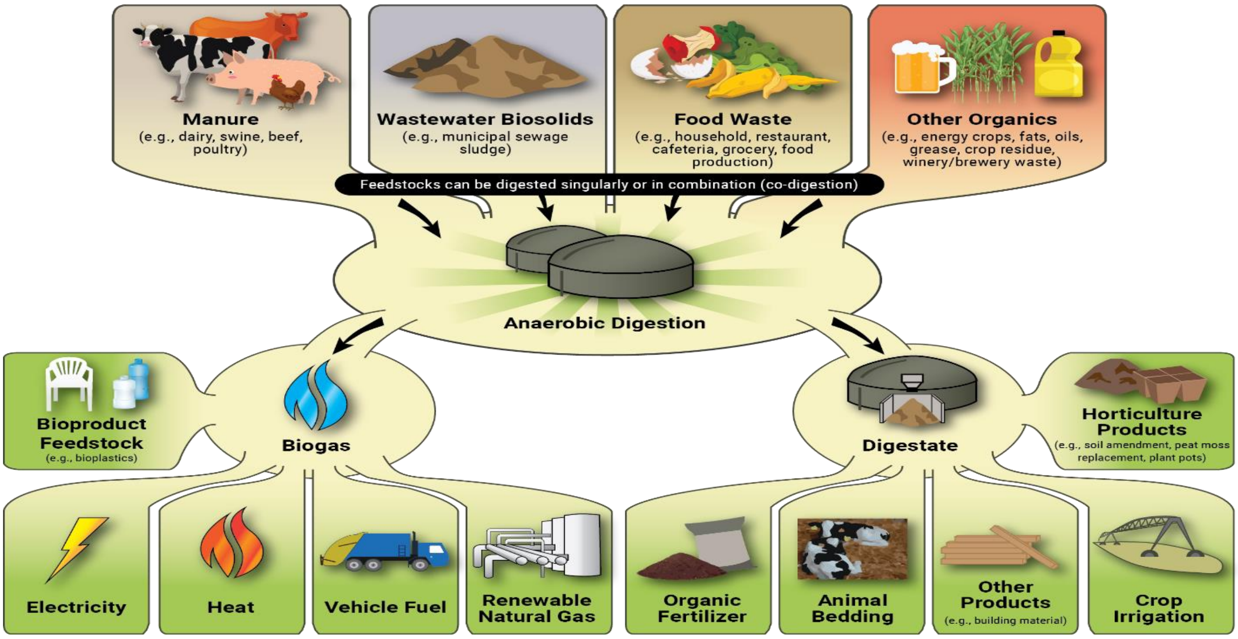


Fig. 5. Anaerobic Digestion Process Flowchart: From Biomass to Energy and Products (Serfass, 2018).

alcohols, primarily yielding acetate, hydrogen, and carbon dioxide (CO_2). This collaboration between oxidizing bacteria and methane-producing archaea in the subsequent methanogenesis stage is crucial (Nandi *et al.,* 2023).

The final stage is methanogenesis, where methanogenic bacteria generate methane and CO_2. Acetate contributes roughly 70% of the methane produced, while the remaining 30% stems from the conversion of hydrogen and CO_2. Methanogenesis is a critical but rate-limiting step in anaerobic digestion due to its slow pace. This bottleneck arises from the complex interplay required between multiple mesophilic bacterial species for efficient conversion (Ali Shah *et al.,* 2014).

Anaerobic digestion emerges as a compelling technology for generating renewable methane, a clean-burning biogas, as depicted in Figure 5. This process leverages microorganisms to decompose organic matter, like biomass, in an oxygen-depleted environment. The resulting product, biogas, is primarily composed of methane (CH_4) and serves as a clean-burning alternative to conventional fossil fuels (Werkneh, 2022b). This shift towards bioenergy has the potential to mitigate environmental issues like acid rain and global warming associated with fossil fuel combustion. While the initial cost of bioenergy production might be higher compared to fossil fuels, trends are shifting towards making bioenergy more cost-competitive. Regulations like emission limits and carbon taxes on fossil fuels, alongside incentives for bioenergy production, are contributing to this change.

It's important to note that anaerobic digestion produces a variety of bioenergy forms beyond just methane. These include heat, syngas (a mixture of gases used for fuel production), and ethanol. Notably, research by Kitessa *et al.,* (2022) explored the potential of co-digesting wastewater (WW) and microalgae (MA) to enhance biogas production. Their findings demonstrated that combining wastewater (WW) and microalgae (MA) in specific ratios yielded significant methane production. For example, a 3:2 mixture of wastewater to microalgae resulted in 44 mL of CH_4 per gram of COD (Chemical Oxygen Demand), a measure of organic matter content. However, this value was lower than the theoretical maximum of 350 mL CH_4/g COD achievable under standard temperature and pressure (STP) conditions.

Fig 5 illustrates the key steps involved in anaerobic digestion, a biological process that utilizes microorganisms to decompose organic matter in an oxygen-free environment. Biomass feedstock enters the system and undergoes pre-treatment processes, such as size reduction and mixing, to enhance biodegradability. The organic material then enters the digester, where a consortium of microbes breaks it down through a series of interlinked stages. The process ultimately yields biogas, a clean-burning renewable fuel composed primarily of methane, alongside a nutrient-rich digestate byproduct. The digestate can be further processed into fertilizer or soil amendments, maximizing resource recovery and contributing to a circular bioeconomy.

b. Fermentation

Bioethanol production relies on fermentation to convert sugars from organic waste into a usable fuel (Bibra *et al.,* 2023; Bušić *et al.,* 2018; Tse *et al.,* 2021). These sugars can come from various waste sources, including food scraps (Chow *et al.,* 2020), agricultural by-products (Petrovič *et al.,* 2023), and sewage sludge (Battista *et al.,* 2019). To facilitate fermentation, certain types of waste may necessitate saccharification or hydrolysis processes to break down intricate carbohydrates into glucose-enriched solutions enzymatically (Bardhan *et al.,* 2022).

The fermentation of glucose to produce ethanol involves the utilization of microorganisms such as *Saccharomyces cerevisiae, E. coli, Zymomonas mobilis, Pachysolen tannophilus, and Candida shehatae* (Aditiya *et al.,* 2016). Although fermentation and anaerobic digestion have similarities, fermentation primarily produces alcohols or organic acids rather than methane. The presence of cellulose, hemicellulose, and lignin in waste directly impacts the efficiency of ethanol production. Variables such as pH, oxygenation, and temperature exert a substantial influence on the bioethanol fermentation process

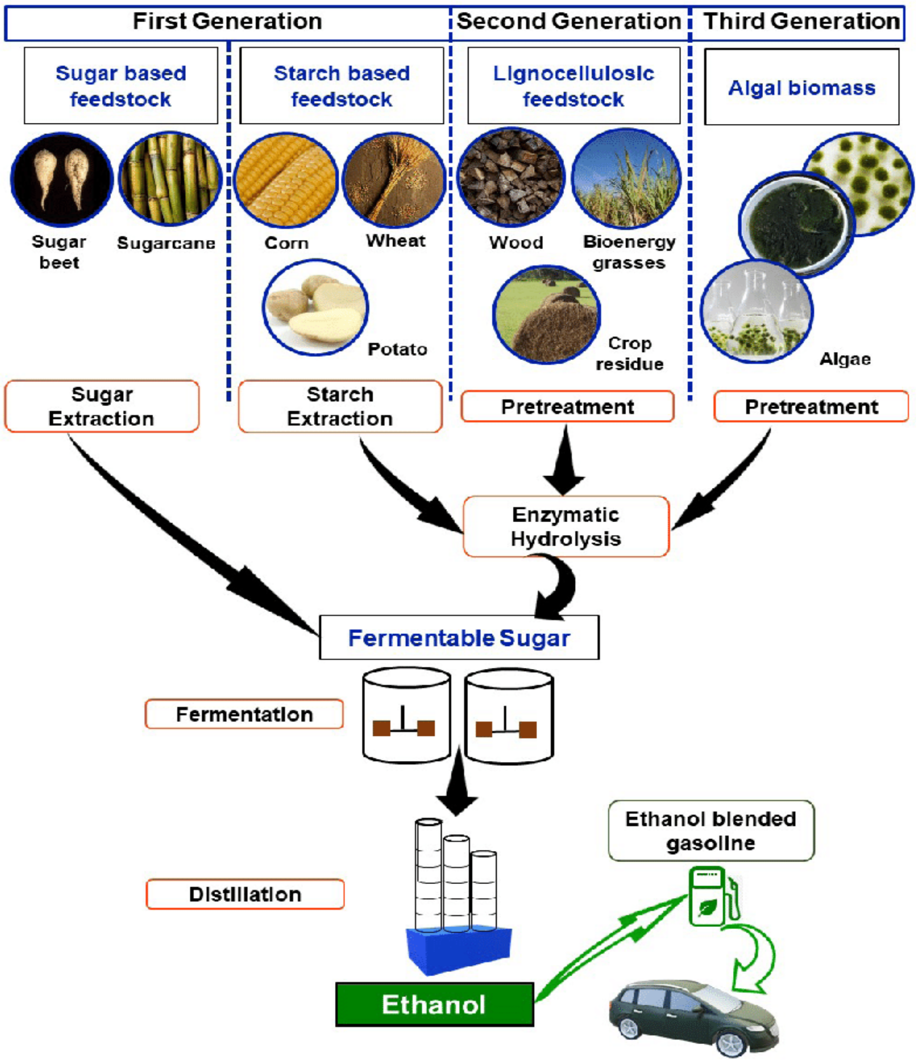


Fig. 6. Bioethanol Production Process: From Feedstock to Biofuel and Byproducts (Bera *et al.,* 2020).

(Blasi *et al.,* 2023b). Figure 6 illustrates the key stages involved in converting diverse feedstocks, like sugarcane or cornstalks, into bioethanol fuel. The process begins with a pretreatment stage, potentially depicted using equipment such as hammer mills or steam explosion chambers. This pretreatment breaks down complex molecules in the feedstock, making them accessible for microorganisms during fermentation.

Following the pretreatment stage, fermentation tanks come into play. Here, these accessible sugars are converted into ethanol by microorganisms. Finally, a distillation process, potentially represented by distillation columns, separates the ethanol from the fermentation broth, yielding bioethanol fuel as the final product. Commercial bioethanol production typically utilizes sugar-rich crops, starch-based substrates, and lignocellulosic biomass as its primary feedstocks. Additionally, bioethanol often undergoes further distillation to meet the requirements of vehicle fuel (Broda *et al.,* 2022; Bušić *et al.,* 2018).

The process in large-scale operations involves multiple stages: sugar fermentation for ethanol production, distillation for ethanol-water separation, dehydration for eliminating residual water, and denaturation to render the ethanol unsuitable for human consumption (Amornraksa *et al.,* 2020). At first, intricate organic molecules undergo hydrolysis to form simpler ones (Youcai and Tao, 2021). Microorganisms ferment the sugars into ethanol and other byproducts (Mohd Azhar *et al.,* 2017). Fractional distillation then separates the ethanol from the water. This technique leverages the difference in their boiling points. Fractional distillation and condensation achieve an ethanol purity of around 95% (Monceaux, 2019).

Fig 6 depicts the key steps involved in bioethanol production, a biological process that converts sugary or starchy biomass into a clean-burning biofuel. The process begins with the selection of a suitable feedstock, such as corn, sugarcane, or cellulosic materials. The feedstock undergoes pre-treatment processes to enhance its digestibility by enzymes. Subsequently, fermentation is carried out using specific microorganisms that convert the sugars in the feedstock into bioethanol. The fermentation broth is then distilled to separate and purify the bioethanol. Finally, co-products like animal feed distillers' grains can be recovered, maximizing resource utilization and contributing to a sustainable biorefinery approach. Bioethanol derived from biomass offers a renewable alternative to fossil fuels and can be used in transportation fuels or industrial applications.

The overview of biomass conversion methods presented delineates the array of strategies employed to transform biomass into viable forms of energy, emphasizing thermal and biochemical technologies. From incineration and gasification to pyrolysis and anaerobic digestion, each method offers specific benefits and operates under distinct conditions to facilitate the conversion of organic material into energy. These processes highlight the versatility of biomass as a renewable energy source and underscore the ongoing technological advancements aimed at improving efficiency and reducing environmental impacts.

2.2 Efficiency, Environmental Impact, and Advancements

Waste-to-energy (WtE) processes play a crucial role in modern waste management by simultaneously reducing waste volume and generating energy. These processes encompass many methods, including traditional incineration and advanced bioconversion techniques (Gumisiriza *et al.,* 2017; Sadeghi *et al.,* 2015). Evaluating the effectiveness of waste-to-energy technologies is crucial for optimizing energy recovery and maximizing the environmental and economic advantages. Maximizing efficiency involves extracting more energy from each unit of waste processed, essential for mitigating waste disposal expenses and ecological consequences (Alao *et al.,* 2022).

Waste-to-energy (WtE) processes require careful management and regulation of emissions to ensure efficient energy conversion from waste materials (Brunner and Rechberger, 2015). These emissions, including greenhouse gases and contaminants like particulate matter, dioxins, and furans, can have significant health and environmental consequences (Zikhathile *et al.,* 2022). Contemporary waste-to-energy (WtE) facilities are outfitted with sophisticated emission control systems engineered to capture and process these emissions, guaranteeing adherence to stringent environmental regulations. Furthermore, waste-to-energy processes aid in reducing waste by redirecting waste away from landfills (Yong *et al.,* 2019). By engaging in this action, they contribute to reducing methane emissions commonly linked to the decomposition of waste, thereby alleviating a significant contributor to greenhouse gas emissions. Landfill diversion helps conserve land and mitigates the environmental disruptions caused by landfill expansion (Abubakar *et al.,* 2022).

The waste-to-energy (WtE) industry is rapidly advancing in various technological areas. These advancements encompass enhancements in thermal conversion efficiencies, such as refining combustion conditions and devising waste pre-treatment techniques that augment calorific value (Yong *et al.,* 2019). Progress in bioconversion technologies, such as anaerobic digestion and fermentation, has led to significant improvements. These include the modification of microorganisms to improve their ability to utilize substrates more efficiently and produce higher yields of biogas (Das *et al.,* 2023). Integrating waste-to-energy solutions into a more comprehensive and environmentally friendly waste management strategy is key for the sector's future (Yong *et al.,* 2019). This approach entails developing adaptable processing facilities to handle diverse waste streams and generate various outputs, such as electricity, heat, liquid fuels, and chemical precursors (Mukherjee *et al.,* 2020).

To thoroughly assess the technical aspects of efficiency, environmental impact, and advancements in the waste-to-energy (WtE) sector, we must analyze the intricate factors contributing to these processes' effectiveness and long-term viability.

a. Efficiency

The efficiency of waste-to-energy (WtE) processes is complex and involves more than just converting waste into energy (Ferdoush *et al.,* 2024; Klinghoffer *et al.,* 2013). It also includes optimizing process parameters to reduce energy input and increase energy output. Advanced thermal technologies, such as plasma arc gasification, achieve greater energy conversion efficiencies by operating at excessively high temperatures (Li *et al.,* 2022; Ray *et al.,* 2012; Tamošiūnas *et al.,* 2023). These high temperatures effectively break down complex waste molecules into simpler syngas components, surpassing the effectiveness of conventional methods (Fiore *et al.,* 2020). Furthermore, incorporating waste pre-treatment methods like torrefaction, which entails the gentle pyrolysis of biomass to enhance its energy content and grinding characteristics, can significantly improve the overall effectiveness of thermal conversion processes (Tumuluru *et al.,* 2021).

b. Environmental Impact

Regarding the environment, the technical discussions go beyond simple emission controls and involve the implementation of innovative carbon capture and storage technologies. These technologies can effectively reduce the carbon footprint of waste-to-energy (WtE) plants (Bisinella *et al.,* 2021; Wienchol *et al.,* 2020). Integrating carbon capture and storage technology into waste-to-energy (WtE) facilities, particularly those processing carbon-rich waste streams, could transform them into net-negative emitters, aligning them with global climate goals (Sara Budinis *et al.,* 2023). In addition, the application of biochar, a residue produced through pyrolysis, as a soil additive not only stores carbon for long periods but also improves soil productivity and decreases reliance on synthetic fertilizers, thereby minimizing the environmental consequences (Oni *et al.,* 2019).

c. Advancements

Research in the waste-to-energy sector is currently focused on enhancing the catalytic efficiency of gasification and pyrolysis processes to improve the quality and quantity of syngas produced (Al-asadi *et al.,* 2020; Lisbona *et al.,* 2023). Developing new catalysts that can endure the severe conditions of gasification and pyrolysis while improving the selectivity towards desired syngas components is a crucial area of innovation (Bolívar Caballero *et al.,* 2022). In addition, the progress in anaerobic digestion technologies, including high-rate digesters and the co-digestion of multiple substrates, is enhancing biogas production and ensuring a more stable process (Rajendran *et al.,* 2020). As a result, this biological conversion process is becoming more feasible for a wider variety of waste streams.

The concept of poly-generation, which involves designing a single waste-to-energy facility to produce multiple outputs such as electricity, heat, and liquid fuels or chemicals, is becoming increasingly popular in process integration. This strategy not only optimizes the usefulness of the waste materials but also improves the financial feasibility of waste-to-energy plants by expanding sources of income (Subramanian *et al.,* 2022). Furthermore, the drive towards digitalization and integrating intelligent technologies into Waste-to-Energy (WtE) operations will profoundly transform the industry. Implementing advanced sensors, data analytics, and machine learning algorithms to monitor and optimize processes in real-time can greatly enhance the efficiency and adaptability of

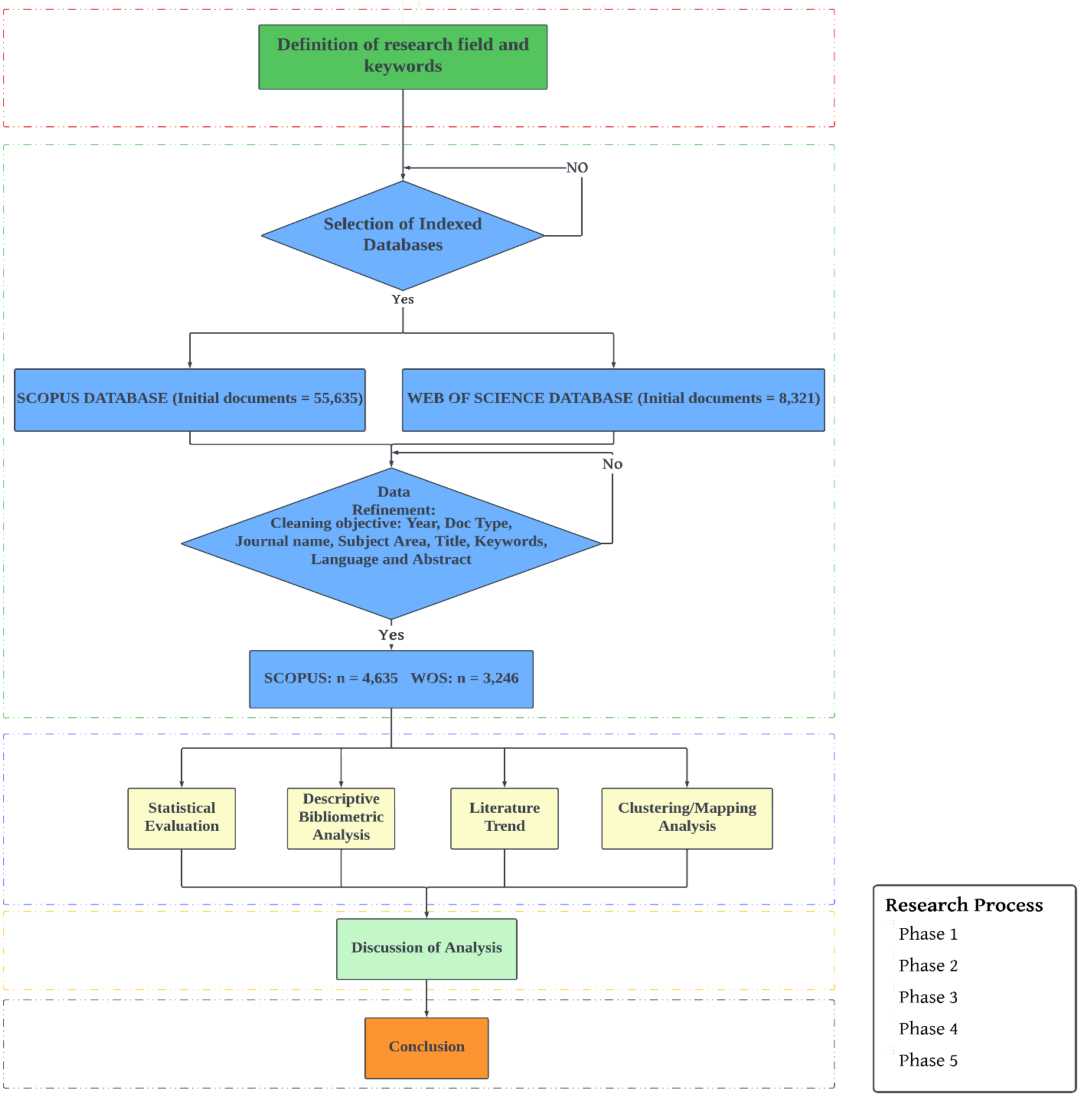


Fig. 7. Flowchart of the Research Process.

waste-to-energy (WtE) processes, and this, in turn, allows for more effective and efficient waste management practices (Said *et al.*, 2023).

The interplay between efficiency, environmental impact, and waste-to-energy (WtE) technology advancements has been explored. Optimizing energy recovery and minimizing environmental consequences is crucial. Advancements in thermal and biological conversion processes and innovative technologies such as carbon capture and storage (CCS) offer promising solutions for a more sustainable waste-to-energy future. The emphasis on poly-generation and digitalization further underscores the industry's commitment to resource recovery and efficient waste management.

3. Methodology

Bibliometric analysis is a valuable tool for researchers to assess academic and technological contributions and their impacts (Donthu *et al.*, 2021; Fakruhayat and Rashid, 2023; Moral-Muñoz *et al.*, 2020; Rejeb *et al.*, 2023). This multi-stage process begins with a crucial step: selecting the most appropriate bibliometric software for the analysis. Next, researchers actively gather data from relevant search engines, ensuring the chosen databases align with their study's thematic focus. Once collected, this data is imported into the selected software. In this study, we employed VOSviewer for their bibliometric analysis.

This study gathered relevant literature from bibliographic databases, accessing over 34,522 and 25,000 Web of Science and Scopus journals, respectively. Biblioshiny and VOSviewer were the primary software tools used for analysis. Biblioshiny facilitated the creation of science maps and performance analyses, while VOSviewer excelled in visualizing research trends (AlMallahi *et al.*, 2023; Aria and Cuccurullo, 2017; Moral-Muñoz *et al.*, 2020). Notably, both tools generated informative and illustrative graphics that aided in understanding the research landscape.

This study employed a six-step methodology encompassing statistical analysis of the literature, scientific research source mapping, citation analysis with word cloud creation, examination of citations and contributions by country, institutional research to identify top contributors, and finally, identification of research gaps and areas of great attention.

The keywords "biomass conversion" OR "biomass and organic waste," OR "waste-to-energy technologies, "OR "bioenergy, production," OR "sustainable bioenergy systems," OR "energy recovery from waste" were included in the list of terms used to find the most relevant publications. The search spanned from 2013 to 2023. The collected data included information such as the year of publication, language, journal name, title, author(s), affiliation(s), keywords, document type, abstract, and the citation count for each document. There were 8,321 publications found in the Web of Science database and 55,635 in the Scopus database that are relevant to this topic.

After additional filtration removed duplicate and irrelevant publications, reducing the numbers to 3,246 and 4,635 respectively, the research process is visualized in Figure 7 as a structured flowchart. This flowchart outlines the five key phases of a research study: Phase 1 focuses on selecting appropriate keywords and terminology to ensure data relevance. Phase 2 involves data acquisition and purification, followed by Phase 3 where the data is transformed into meaningful insights. Phase 4 entails a comprehensive evaluation and investigation of these insights, culminating in Phase 5 with a comprehensive summary and present

This flowchart outlines the key stages involved in a comprehensive research process. Phase 1: Literature Review and Keyword Selection emphasizes identifying relevant keywords and search terms to ensure retrieved data aligns with the research objectives. Phase 2: Data Acquisition and Purification focuses on gathering data from credible sources and potentially applying techniques to refine the data quality and remove irrelevant information. Phase 3: Data Analysis and Interpretation involves transforming the data into meaningful insights through techniques like statistical analysis or qualitative coding. Phase 4: Evaluation and Refinement entails critically examining the derived insights to ensure their validity and potentially refining them based on further investigation or consultation with experts. Phase 5: Conclusion and Reporting culminates in a comprehensive summary of the research findings, highlighting significant observations and potential contributions to the field.

4. Results and Discussions

An analysis of data from the past ten years reveals a persistent and steady increase in research focused on converting biomass and organic waste. Table 3 showcases this trend, indicating that Scopus and Web of Science databases yielded 3,246 and 4,635 studies on biomass and organic waste conversion between 2013 and 2023.

4.1 Annual Publication Trends

Figures 8a and 8b illustrate the publication trends in biomass and organic waste conversion from 2013 to 2024. These figures depict line graphs, showcasing the steady increase in publications from both Web of Science (3,246 publications, peaking at 728 in 2022) and Scopus (4,635 publications), reflecting the growing research interest in this field.

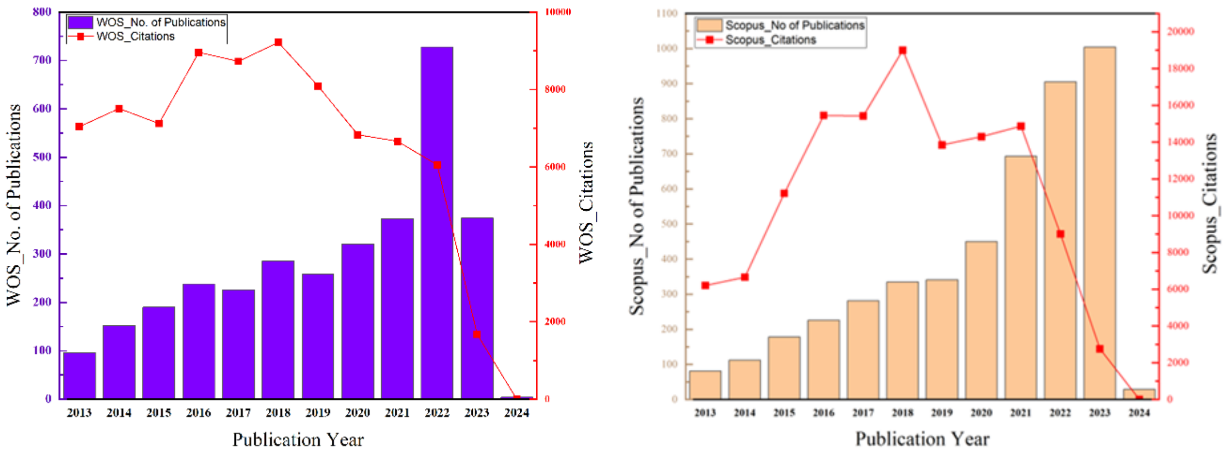
Nevertheless, there is a significant decline to 374 publications in 2023, followed by a mere four publications in 2024, suggesting incomplete data for the latter year. The high number of citations in 2016 (8,961) suggests significant referencing to research published during that period. After 2016, there has been a noticeable decrease in citation figures despite the rising number of publications. The decline in citation numbers after reaching the peak, significantly the significant decrease observed in recent years (2022-2023), can be attributed to the fact that newer publications have not yet accumulated a substantial number of citations. The significantly diminished figures for 2024 in terms of publications and citations suggest that the data collection for that particular year was incomplete, potentially because it was either the present or a forthcoming year at the time of data retrieval.

The publication count for Scopus begins at 81 in 2013 and steadily increases to 1004 in 2023, demonstrating a consistent growth in research within the topic area throughout the years. The significant number of citations in 2016 (15,452) suggests that research published during that period has been extensively referenced. Following 2016, despite the rise in publication quantity, there is a noticeable variability in citation counts. There is a peak in 2018 with 18,999 citations, followed by a decrease, a slight rise in 2020 and 2021, and a substantial decline in 2022 and 2023. The significant reduction of citations during 2022-2023, along with the notably low numbers for 2024, could be attributed to the insufficient time for the publications from these years to accumulate citations.

The data for 2024 exhibits a significant decline in publications and citations, potentially attributable to the year's incompleteness or a delay in the indexing process. Both the Web of Science and Scopus databases show an increasing research focus on biomass and organic waste conversion from 2013 to 2024. The web of science data exhibits a notable surge in publications in 2022, followed by a subsequent decrease. This pattern indicates a potential change in research emphasis or the

Table 3
Obtained data from the primary sources of the examined publications.

Parameters	Web of Science	Scopus
Search String	Results for ALL=("biomass conversion" OR "biomass and organic waste" OR "Waste-to-energy technologies" OR "Bioenergy production" OR "Sustainable bioenergy systems" OR "Energy recovery from waste")	ALL("biomass conversion" OR "biomass and organic waste" OR "Waste-to-energy technologies" OR "Bioenergy production" OR "Sustainable bioenergy systems" OR "Energy recovery from waste") AND PUBYEAR > 2012 AND PUBYEAR < 2025
Number of documents after filtration	3,246	4,635
Top publication journal	Biomass conversion and biorefinery	Energies
Top publication country	China	United States
Top publication author in the citation	Li, hu	Ragauskas, Arthur, J
Keywords with the highest occurrences	Biomass	Biomass
Most relevant affiliation	University of Chinese Academy of Science, Beijing, China	School of Chemical and Processing Engineering, University of Leeds, United Kingdom



(a) (b)

Fig 8. Number of Publications and Citations Indexed by Web of Science (a) and Scopus (b) from 2013 to 2024. This shows the publication trends and citation impact of research output in the field of biomass and organic waste conversion over an eleven-year period (2013-2024), as indexed by both the Web of Science and Scopus databases. This allows for a valuable comparison of publication trends across these two major bibliographic databases.

possibility of incomplete data for the most recent years. Scopus consistently rises in research productivity, reaching its highest point in 2023. Analysis of citations across both databases reveals a peak around 2016, indicating researchers heavily referenced earlier publications during that period. The recent decline in citations stems from newer publications having limited time to accumulate citations.

The conversion of biomass and organic waste presents a compelling strategy for achieving several sustainable development goals (SDGs) established by the UN General Assembly in 2015. This approach transcends environmental benefits, fostering economic development and social well-being.

Fossil fuels remain a dominant energy source, contributing significantly to greenhouse gas emissions. Biomass conversion offers a renewable and sustainable alternative. Providing a clean energy source can significantly reduce dependence on fossil fuels and their associated emissions (Aidonojie *et al.*, 2023; Blair *et al.*, 2021) – directly addressing SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Biomass also contributes to a sustainable carbon cycle by promoting carbon sequestration through plant growth, effectively balancing carbon emissions and absorption (Gabrielli *et al.*, 2023).

The bioenergy sector is a powerful economic driver, particularly in rural areas. Cultivating feedstock (plants used for energy) and operating conversion plants create numerous job opportunities (Review of SDG Implementation and Interrelations among Goals Discussion on SDG 8-Decent Work and Economic Growth, 2019). Furthermore, this industry stimulates economic growth (SDG 8) by providing new revenue streams for farmers and landowners. Investments in renewable energy technologies further drive development by fostering innovation and infrastructure creation.

Biomass conversion tackles the growing organic waste problem, contributing to SDG 12 (Responsible Consumption and Production). By utilizing agricultural residues or waste as feedstock, we minimize the need for landfills and their associated environmental burdens (Mohd Hanafiah *et al.*, 2022; Muscat *et al.*, 2020). Biomass cultivation can sustainably contribute to land-use sustainability and biodiversity preservation (SDG 15). Practices like crop rotation and responsible land management ensure long-term benefits for ecosystems.

Studies estimate that biomass could contribute 20-30% of global energy needs by 2050, significantly impacting SDG 7 (Affordable and Clean Energy). The bioenergy sector also employs millions globally, with projections for continued growth (IRENA, 2022). These figures highlight the significant potential of biomass conversion for achieving multiple SDGs.

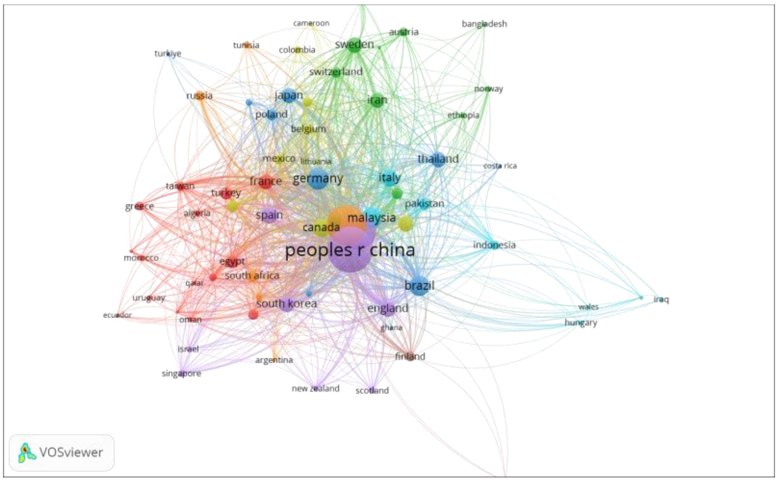
While promising, challenges exist. Competition for land and water resources requires careful management to ensure responsible use and avoid impacting SDG 6 (Clean Water and Sanitation). Sustainable practices such as utilizing marginal lands and efficient water management are crucial. Responsible forestry practices are essential to avoid deforestation, protect ecosystems, and contribute to SDG 15 (Life on Land).

Biomass conversion, when implemented thoughtfully, serves as a powerful tool for achieving multiple SDGs. It promotes clean energy (SDG 7), fosters economic growth (SDG 8), minimizes waste (SDG 12), and contributes to climate change mitigation (SDG 13) and biodiversity preservation (SDG 15). By addressing challenges and adopting sustainable practices, we can unlock the full potential of this technology for a more secure and sustainable future.

4.2 Analysis of Major Contributing Countries

Between 2013 and 2023, contributions from 109 countries in Web of Science and 122 countries in Scopus were made to biomass and organic waste conversion. According to the data from Web of Science (Fig. 9a), China has the highest number of publications with 708, followed by India with 535, USA with 442, Germany with 177, Brazil with 153, Malaysia with 152, Canada with 122, Italy with 107, Spain with 101, and South Korea with 97. The countries with the highest number of citations are China (16,450), the USA (15,635), India (9,635), Germany (4,348), Canada (4,084), Malaysia (3,785), Sweden (3,277), France (3,119), England (3,075), South Korea (2,861), and Japan (2,600) (Table 4).

According to the data from Scopus (Fig. 9b), the United States has the highest number of publications with 813, followed by China with 640, the United Kingdom with 478, Spain with



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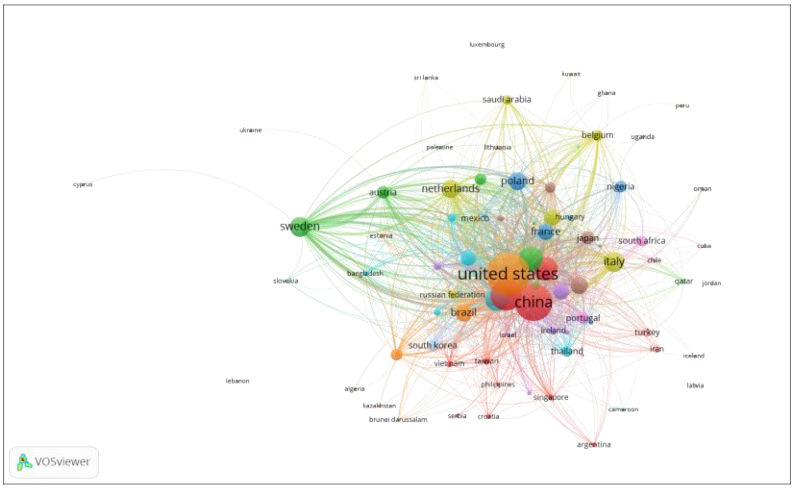


(b)

Fig. 9. Top Research Countries in Web of Science (a) and Scopus (b). This figure unveils the most prolific countries in biomass and organic waste conversion research. It analyzes publications indexed by the Web of Sciences and Scopus database from 2013 to 2023, offering a glimpse into publication trends within this specific field on the Web of Sciences and Scopus platform during this timeframe.

Table 4
Major contributing countries based on citations (Web of Science)

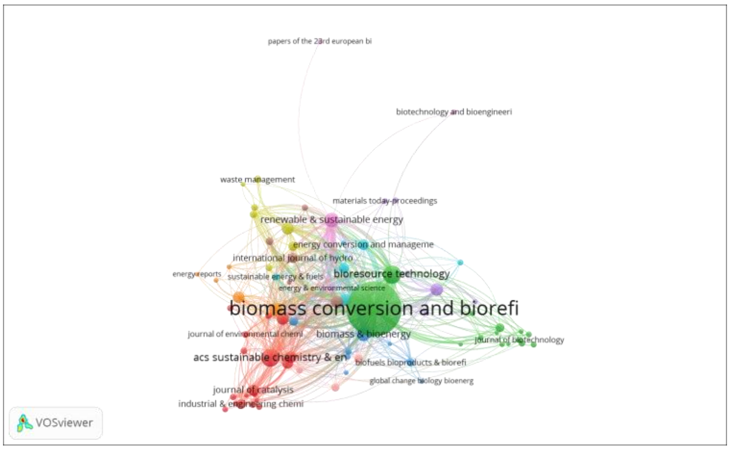
Rank	Countries	Citations
1	China	16450
2	United States	15635
3	India	9635
4	Germany	4348
5	Canada	4084
6	Malaysia	3785
7	Sweden	3277
8	France	3119
9	England	3075
10	South Korea	2861
11	Japan	2600

320, India with 311, Germany with 298, Sweden with 238, Italy with 234, the Netherlands with 203, Poland with 201, and Malaysia with 187. The nations with the highest number of

Table 5
Major contributing countries based on citations (Scopus)

Rank	Countries	Citations
1	United States	34069
2	United Kingdom	22280
3	China	19849
4	India	11335
5	Spain	10203
6	Germany	9729
7	Australia	9337
8	Netherlands	7302
9	Sweden	6727
10	France	6158
11	Malaysia	5966

citations are as follows: USA (34,069), UK (22,280), China (19,849), India (11,335), Spain (10,203), Germany (9,729), Australia (9,337), Netherlands (7,302), Sweden (6,727), France



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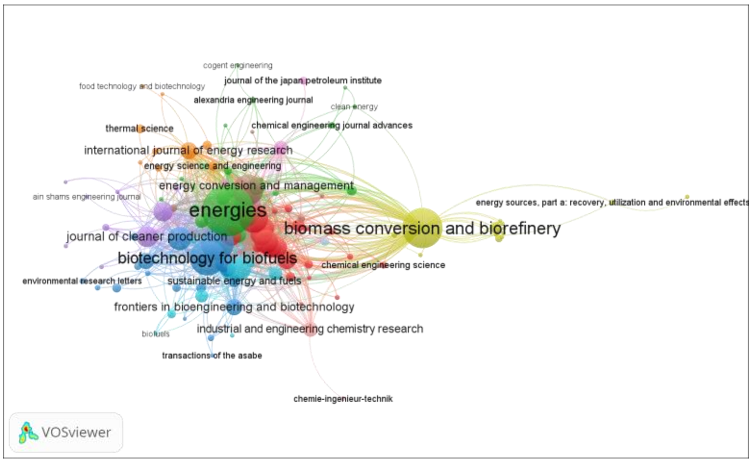


(b)

Fig. 10. Bibliometric Network of Journals. This presents a ranking of the most prolific journals in biomass and organic waste conversion research based on the Web of Sciences (a) and Scopus (b) database from 2013 to 2023. This network established the relationship between the past studies.

(6,158), and Malaysia (5,966) (Table 5). Asian countries collectively contribute to 49% of the highest-ranked publications in Web of Science, whereas North America, specifically the USA, contributes to 24% of the most referenced research in Scopus. Both databases emphasize the worldwide involvement in this research field, with numerous countries making substantial contributions.

4.3 Analysis of Scientific Mapping Sources

3,246 and 4,635 papers were published in 359 and 322 journals, respectively, in both the Web of Science and Scopus databases from 2013 to 2023. Figures 10a and 10b focus on the most prolific journals in this field, presenting a ranking or list format. These figures reveal the journals with the highest publication counts in biomass and organic waste conversion research. The Journal of Biomass Conversion and Biorefinery has been the leading publication over the past decade, with 1335 papers indexed in the Web of Science. The Journal of Energies held the top position in Scopus with 567 papers. The source with the highest publishing output among the sources in the Web of Science, as indicated in Table 6, is Biomass Conversion and Biorefinery, accounting for 41.1% of the total. Following are Bioresource Technology at 3.39%, ACS Sustainable Chemistry and Engineering at 3.20%, Renewable and Sustainable Energy Reviews at 1.97%, Biomass and Bioenergy at 1.79%, Fuel at 1.79%, and Biotechnology for Biofuels at 1.48%. The source with the highest publishing output among the sources in Scopus, as indicated in Table 7, is Energies, accounting for 12.23% of the total and this is followed by Biomass Conversion and Biorefinery (7.36%), Biotechnology

Table 6
Top 10 sources in terms of publications and citations (Web of Science)

Rank	Source (Journals)	Citations	Documents
1	Biomass Conversion and Biorefinery	13985	1335
2	Bioresource Technology	5804	110
3	ACS Sustainable Chemistry and Engineering	3284	104
4	Renewable and Sustainable Energy Reviews	5476	64
5	Biomass and Bioenergy	1941	58
6	Fuel	1322	58
7	Biotechnology for Biofuels	2071	48
8	Renewable Energy	1657	48
9	Chemical Engineering Journal	818	45
10	Journal of Cleaner Production	1619	44

Table 7
Top 10 sources in terms of publications and citations (Scopus).

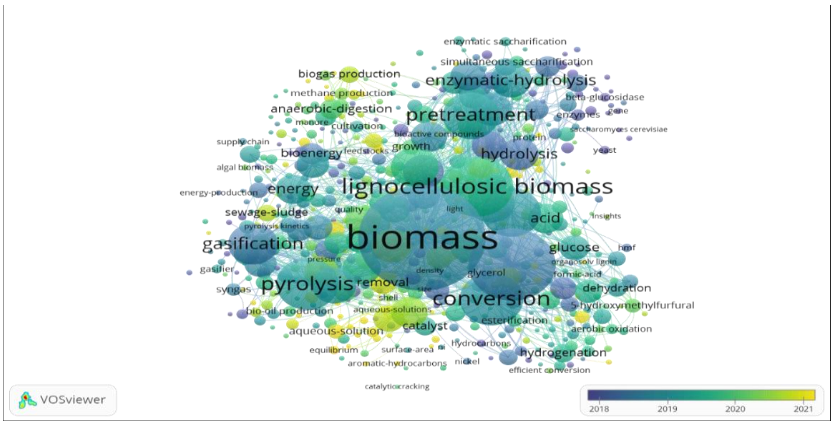
Rank	Source (Journals)	Citations	Documents
1	Energies	7862	567
2	Biomass Conversion and Biorefinery	3424	341
3	Biotechnology for Biofuels	11523	257
4	Bioresource Technology	11698	230
5	Sustainability (Switzerland)	1936	196
6	Fuel	3991	173
7	Biomass and Bioenergy	4007	115
8	ACS Sustainable Chemistry and Engineering	3868	113
9	Renewable and Sustainable Energy Review	9384	110
10	Journal of Analytical and Applied Pyrolysis	2557	102

for Biofuels (5.54%), Bioresource Technology (4.96%), Sustainability (Switzerland) (4.23%), Fuel (3.73%), and Biomass and Bioenergy (2.48%).

According to our data from the Web of Science, over 50% of the papers were published in prestigious journals focusing on biomass and bioenergy, while 40% were published in Scopus. The field of study received its most significant contributions from publications on biomass and journals covering various disciplines. Biomass and organic waste conversion have been extensively covered in scientific journals on biomass conversion and biorefinery. This research is motivated by the worldwide necessity to shift from fossil fuels to sustainable energy sources.

4.4 Analysis of Keywords

Keywords are crucial indicators of the central themes of a research paper (Tullu, 2019). Performing a keyword analysis assists in uncovering the main areas of focus, patterns of trends, and thematic paths within a specific field (Donthu *et al.,* 2021; Rejeb *et al.,* 2023). This systematic approach can analyze specific time intervals within a given period, allowing for a thorough examination of the changing research landscape. A keyword investigation was conducted on 3,246 articles from the Web of Science and 4,635 articles from Scopus between 2013 and 2023.



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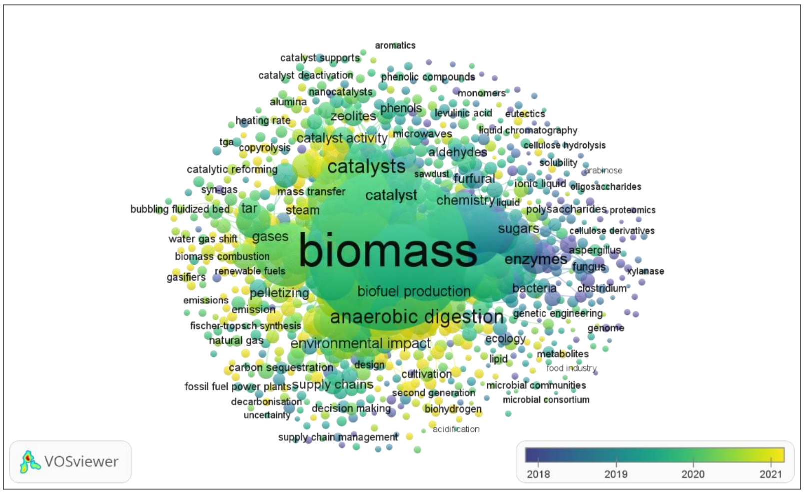

(b)

Fig. 11. Bibliometric Analysis of Keywords in Web of Sciences (a) and Scopus (b) Publications. This figure utilizes a word cloud to depict prominent keywords associated with biomass and organic waste conversion research, based on the Scopus database. The size of each word reflects its relative frequency within the analyzed publications.

Table 8
Top 10 keywords used in biomass and organic waste research.

Rank	Keywords (WOS)	Occurrences	Keywords (SCOPUS)	Occurrences
1	biomass	828	biomass	2304
2	biomass conversion	494	pyrolysis	855
3	lignocellulosic biomass	384	biofuels	698
4	conversion	319	cellulose	592
5	pyrolysis	312	bioconversion	579
6	cellulose	291	gasification	562
7	pretreatment	271	biofuel	554
8	gasification	230	lignin	554
9	optimization	219	feedstocks	454
10	lignin	207	lignocellulosic biomass	436

Figures 11a and 11b demonstrate the most frequently used keywords over the past decade, potentially highlighting terms like 'biomass,' 'pyrolysis,' and 'gasification.' This aligns with Table 8, which shows 'biomass' as the most common term in Web of Science (WOS) and Scopus databases, with 828 and 2,304 instances, respectively. This strong emphasis on 'biomass' suggests a robust research focus on this renewable energy source.

The prominence of 'biomass conversion' and 'pyrolysis' as keywords indicates a specific research interest in these areas. Notably, 'pyrolysis' appears more frequently in the Web of Science data, suggesting a potential research strength in this biomass conversion technology. The term 'Lignocellulosic biomass' is prominently featured in both databases, highlighting the significant role of these raw materials in research. The terms 'biofuel,' 'pretreatment,' and 'optimization' indicate the diverse methodologies and processes that form the foundation of this field. This keyword analysis identifies the main substances and methods used in research on converting biomass and organic waste and demonstrates the wider strategies employed in developing renewable energy solutions.

4.5 Analysis of Highly Cited Papers

The Web of Science and Scopus databases' top-cited papers in biomass and organic waste conversion from 2013 to 2023 are shown in Tables 9 and 10, along with further information such as journal, number of citations received, and country. The study with the most citations in Web of Science is " A comprehensive review on the pyrolysis of lignocellulosic biomass" by Dhyani and Bhaskar, published in Renewable Energy Journal in 2018. The study examined and assessed recent advancements in lignocellulosic biomass pyrolysis efficiency. Additionally, examining publications with many references points out areas

Table 9
Top 10 cited publications in biomass and organic waste conversion in Web of Science.

Rank	Ref.	Country	Journal	Total citations
1	(Dhyani and Bhaskar, 2018)	India	Renewable Energy	822
2	(López Barreiro *et al.,* 2013)	Belgium	Biomass and Bioenergy	536
3	(Zhang *et al.,* 2016)	United States	Bioresource Technology	515
4	(Singhania *et al.,* 2013)	France	Bioresource Technology	453
5	(Ruiz *et al.,* 2013)	Portugal	Renewable and Sustainable Energy Reviews	451
6	(Zeng *et al.,* 2014)	United States	Current Opinion on Biotechnology	413
7	(Cai *et al.,* 2017)	China	Renewable and Sustainable Energy Reviews	387
8	(Yu and Tsang, 2017)	China	Bioresource Technology	370
9	(Yoo *et al.,* 2020)	United States	Bioresource Technology	331
10	(Dimitriadis and Bezergianni, 2017)	Greece	Renewable and Sustainable Energy Reviews	325

Table 10
Top 10 cited publications in the biomass and organic waste conversion field in Scopus.

Rank	Ref.	Country	Journal	Total citations
1	(Bui *et al.,* 2018)	United Kingdom	Energy and Environmental Science	2213
2	(Mariscal *et al.,* 2016)	United States	Energy and Environmental Science	1161
3	(Porosoff *et al.,* 2016)	Spain	Energy and Environmental Science	900
4	(Kumar and Sharma, 2017b)	India	Bioresources and Bioprocessing	836
5	(Sikarwar *et al.,* 2016)	China	Energy and Environmental Science	791
6	(Gollakota *et al.,* 2018)	United Kingdom	Renewable and Sustainable Energy Reviews	756
7	(Elliott *et al.,* 2015)	United States	Bioresource Technology	696
8	(Destek and Sinha, 2020)	Turkey	Journal of Cleaner Production	631
9	(Sheldon, 2018)	Netherlands	ACS Sustainable Chemistry and Engineering	586
10	(Baruah *et al.,* 2018)	India	Frontiers in Energy Research	585

Table 11
Top eight affiliations in the chosen research string in Web of Science

No	Affiliations	Country	Documents
1	Chinese Academy of Sciences	China	92
2	Huaiyin Institute Technology	China	47
3	National Renewable Energy Lab	United States	37
4	University Sao Paulo	Brazil	37
5	Technology University	Denmark	37
6	University of Chinese Academy of Sciences	China	31
7	Aalborg University	Denmark	29
8	Universiti Teknologi Malaysia	Malaysia	29

Table 12
Top eight affiliations in the chosen research string in Scopus

No	Affiliations	Country	Documents
1	University of Leeds	United Kingdom	13
2	University of Chinese Academy of Sciences	China	13
3	Hamad bin Khalifa University	Qatar	13
4	Best-bioenergy and Sustainable Technologies, GmbH	Austria	12
5	Iowa State University	United States	12
6	Iowa State University	United States	12
7	Iowa State University	United States	10
8	National Renewable Energy Laboratory	United States	10

needing further research and gaps that need to be filled. The article "Carbon capture and storage" by Mai Bui, published in the Energy and Environmental Science Journal in 2018, is also the most cited in Scopus. The most recent developments in carbon capture and storage were also examined in the study.

4.6 Analysis of Institutions and Authors

The number of publications from the top 8 most cited institutions was evaluated using data from Web of Science and Scopus records, as depicted in Figures 11 and 12. The assessment was conducted for the period spanning from 2013 to 2023. This phenomenon can be attributed to the substantial level of interest in biomass within Asian and United States countries.

In comparison, the top eight institutions have collectively published over 339 documents in Web of Science and 95 documents in Scopus. Most of the eight affiliations presented in Tables 11 and 12 are attributed to China and the United Kingdom. China and Malaysia are the primary Asian nations in terms of publications in this research field, with 199 documents combined in Web of Science. On the other hand, the United States is the leading North American country in this field, with 44 documents in Scopus.

4.7 Research Gaps

The highly cited publications discussed in this study serve a valuable purpose for researchers, not only by identifying prominent areas within related scientific fields but also by offering insights and methodologies that can enhance the recognition and visibility of new research, particularly for early-career scholars. This can be achieved by strategically adopting relevant keywords within the same research domain. Furthermore, the sources mentioned in this study offer an extensive platform for publishing research findings in biomass

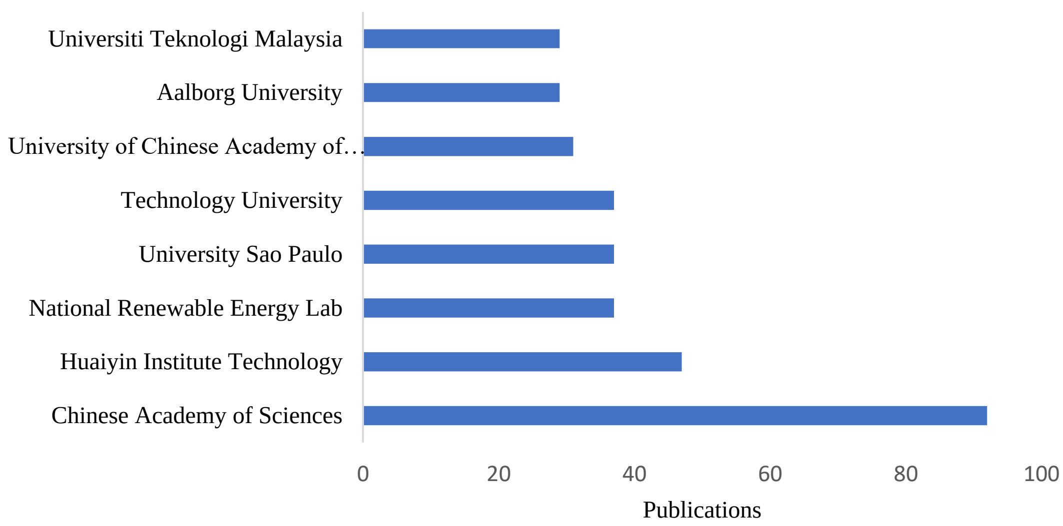

Fig. 11. Progress of Top Affiliations in Biomass and Organic Waste Conversion Research. This shows the publication output of the eight leading affiliations in biomass and organic waste conversion research according to the Web of Science database. This visualization allows researchers to compare the publication productivity of different affiliations within this field.

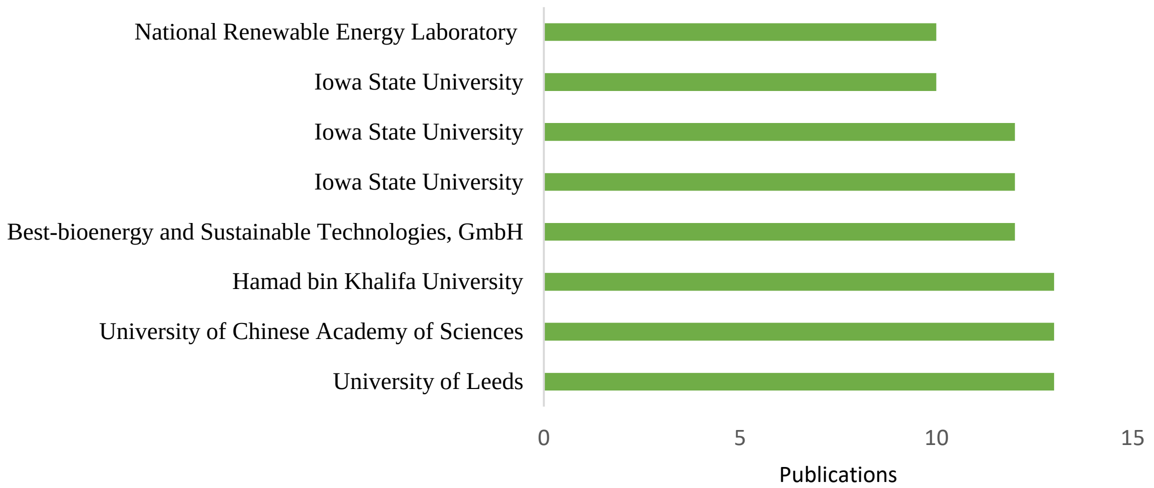

Fig. 12. Progress of Top Affiliations in Biomass and Organic Waste Conversion Research. This depicting the publication output of the eight leading affiliations in biomass and organic waste conversion research, based on the Scopus database. This visualization allows researchers to compare the publication productivity of different affiliations within the field according to Scopus data and potentially identify trends in institutional research output over time.

and organic waste conversion due to their established reputations.

The study's findings unveil numerous exciting avenues for future biomass and organic waste conversion research. A key focus should be developing sustainable and integrated systems that transform these materials into valuable products like energy or commodities. Such systems could involve investigating innovative biomass processing approaches, such as exploring novel pretreatment techniques (e.g., microwave, ultrasonic) to enhance digestibility or employing advanced oxidation processes to break down complex molecules for efficient conversion. Waste treatment approaches prioritizing ecological sustainability and economic efficiency should also be explored. This could involve investigating the integration of biological processes like composting or anaerobic digestion alongside thermochemical conversion technologies for a holistic waste management strategy.

Further research should prioritize improvements in biomass conversion technology, such as developing novel catalysts for thermochemical conversion processes or optimizing enzymatic hydrolysis techniques to enhance the efficiency of breaking down lignocellulosic biomass into fermentable sugars for biofuel production. Additionally, exploring the integration of renewable energy sources like solar or geothermal power into these systems holds promise for establishing more environmentally friendly and self-sufficient processes. Energy and cost analysis modeling is a crucial field of study in this context. Research in this domain can significantly improve biomass and organic waste conversion systems by minimizing operational expenses while maximizing production output. These involve investigating novel approaches to decrease energy consumption during conversion, such as optimizing reaction conditions or exploring the use of waste heat for preheating purposes, and developing more economical materials and technologies for reactor design and construction.

Finally, broadening the research agenda to encompass the social and environmental impacts of biomass and organic waste conversion is critical. This expanded scope could involve investigating the societal ramifications of large-scale implementation, such as potential land-use changes or economic impacts on local communities. Evaluating the sustainability of conversion processes throughout their lifecycle assessments is crucial. This includes analyzing factors such as water usage, greenhouse gas emissions, and potential air or soil pollution throughout the entire process, from feedstock cultivation to final product disposal. Researching the environmental footprint of converted products is also important to ensure their overall sustainability. By adopting a holistic approach, we can ensure that technologies for converting organic waste and biomass are developed responsibly and sustainably, meeting the needs of both present and future generations.

4.8 Research Limitations

This study aimed to comprehensively review biomass and organic waste conversion literature, focusing on development patterns and emerging research hotspots. However, the review has limitations. Firstly, the literature review is confined to the Web of Science and Scopus databases. This selection was made due to their extensive coverage of peer-reviewed scientific literature, but it inevitably excludes potentially relevant studies on other platforms such as Google Scholar. These limitations restrict the scope of our analysis, particularly in capturing grey literature or the latest unpublished research.
Additionally, our study primarily focuses on publications in English, which omits significant contributions in other languages. These limitations suggest that while our findings provide valuable insights into the current state of research in this field, they may not fully encapsulate the global research landscape. Future research could include a broader range of databases and languages, offering a more holistic view of the subject matter.

5. Future Directions for Research and Development

Biomass, organic matter such as plants and animal waste, offers a promising renewable energy solution capable of generating electricity, heat, or transportation fuels sustainably. However, limitations such as low efficiency, feedstock specificity, and high processing costs hinder widespread adoption and necessitate technological advancements to overcome these barriers.

The future of biomass energy lies in embracing innovation. New technologies such as advanced gasification, which offers high thermal conversion efficiency and syngas production suitable for further conversion into liquid fuels, and fast pyrolysis, which efficiently breaks down biomass into bio-oil usable for direct combustion or upgrading to fuels, are emerging. Other promising areas include enzymatic conversion, which utilizes enzymes to break down biomass into fermentable sugars for biofuel production, and microbial fuel cells, which harness the power of microorganisms to directly convert biomass into electricity. These technologies offer improved efficiency, broader feedstock compatibility, and a more environmentally friendly approach to biofuel production. However, scaling up these new technologies requires further research and development, focusing on economic feasibility and technical challenges associated with large-scale implementation. Integration with existing infrastructure, such as power grids and transportation networks, and utilizing waste biomass streams like agricultural residues and municipal solid waste, can further improve viability and economic feasibility.

Sustainable biomass utilization requires a holistic approach. While these technologies hold immense potential, environmental concerns such as greenhouse gas emissions and land-use change must be addressed. Advanced gasification with carbon capture and storage (CCS) technologies can mitigate emissions by capturing carbon dioxide produced during the process and storing it underground. Dedicated energy crops grown on non-arable land and prioritizing waste biomass sources can minimize land-use change. Life cycle assessments are crucial for understanding the overall environmental impact of biomass energy systems, including cultivation, processing, transportation, and emissions.

Several key areas require further exploration to unlock the full potential of biomass energy. Research and development efforts should focus on developing more efficient and cost-effective conversion technologies that can handle diverse feedstock types, including agricultural residues, forestry waste, and energy crops. Integrating biomass energy systems with existing grids is essential for efficient distribution and utilization of the generated biofuels. Exploring novel feedstock sources like algae and dedicated energy crops with minimal environmental impact holds promise for the future. Additionally, research on advanced biomass harvesting, transportation, and storage techniques is needed for optimal supply chain management. By focusing on these key areas, we can pave the way for a future where biomass energy plays a significant role in a sustainable and clean energy future. Investing in research and development of biomass technologies is not just about innovation; it's about creating a cleaner environment, reducing our reliance on fossil fuels, and ensuring energy security for future generations, while also considering the social and economic implications of large-scale implementation.

6. Conclusions

The conversion of biomass and organic waste offers a crucial solution to the pressing challenge of energy scarcity. This challenge is further amplified by factors such as population growth, rising living standards, and industrial expansion. These factors contribute to a decline in the availability of conventional energy sources while simultaneously driving up energy demand. Traditional energy production heavily relies on fossil fuels, which exacerbate global warming and environmental degradation. Consequently, there's a growing focus on exploring renewable energy sources such as solar, wind, and geothermal for power generation.

Among these renewable options, biomass and organic waste conversion stands out due to its ability to effectively utilize agricultural residues, municipal waste, and other organic materials. The substantial increase in research activity in this field, particularly over the past five years, underscores the growing interest in this environmentally friendly energy solution. This shift is driven by a heightened awareness of the tangible effects of climate change and the urgent need to reduce dependence on fossil fuels for energy production.

This study aimed to comprehensively analyze biomass and organic waste conversion technologies, explore emerging trends, and highlight key areas of potential and innovation. The analysis revealed that China, the United States, India, and several European countries are leading contributors to research in this field. A bibliometric analysis of research publications identified "biomass," "biomass conversion," "lignocellulosic biomass," "conversion," and "pyrolysis" as the top five keywords in the Web of Science database. Scopus results yielded "biomass," "pyrolysis," "biofuels," "cellulose," and "bioconversion" as the leading keywords. The prominence of "biomass" as the most frequent keyword across both databases emphasizes the research community's focus on biomass and its conversion processes.

The study also examined the most highly cited papers published between 2013 and 2023, providing details such as journal, citation count, country of origin, and contribution. It further evaluated the top universities contributing the most publications. This analysis effectively maps the evolving themes and trends in biomass and organic waste conversion research over time. The performed bibliometric analysis offers valuable insights into potential future research directions, sheds light on the current areas of focus in this field, and serves as a roadmap for researchers pursuing future advancements in organic waste and biomass conversion. This comprehensive review highlights significant progress made in this field and suggests promising avenues for future research, contributing to a deeper understanding of the evolution and direction of this important area of study.

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Authors contributions

K.T. Alao: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Proofreading. SIU Gilani: Writing – review & editing, Supervision, K Sopian: Proofreading and grammar, T.O. Alao: Writing – review & editing, D.S. Oyebamiji: Writing – review & editing, T.L. Oladosu: Writing – review & editing, Proofreading.

Conflicts of Interest

The authors declare no conflict of interest.

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