Green Energy and Technology

Sachin Kumar
Suresh Sundaramurthy
Deepak Kumar
Anuj K. Chandel *Editors*

Clean Energy Transition-via-Biomass Resource Utilization

A Way to Mitigate Climate Change

Springer

Green Energy and Technology

Climate change, environmental impact and the limited natural resources urge scientific research and novel technical solutions. The monograph series Green Energy and Technology serves as a publishing platform for scientific and technological approaches to “green”—i.e. environmentally friendly and sustainable—technologies. While a focus lies on energy and power supply, it also covers “green” solutions in industrial engineering and engineering design. Green Energy and Technology addresses researchers, advanced students, technical consultants as well as decision makers in industries and politics. Hence, the level of presentation spans from instructional to highly technical.

Indexed in Scopus.

Indexed in Ei Compendex.

Sachin Kumar · Suresh Sundaramurthy ·
Deepak Kumar · Anuj K. Chandel
Editors

Clean Energy Transition-via-Biomass Resource Utilization

A Way to Mitigate Climate Change

Springer

Editors
Sachin Kumar
Biochemical Conversion Division
Sardar Swaran Singh National Institute
of Bio-Energy
Kapurthala, Punjab, India

Suresh Sundaramurthy
Department of Chemical Engineering
Maulana Azad National Institute
of Technology
Bhopal, Madhya Pradesh, India

Deepak Kumar
College of Environmental Science
and Forestry
State University of New York
New York, NY, USA

Anuj K. Chandel
Department of Biotechnology
Engineering School of Lorena
University of São Paulo (USP)
Lorena, São Paulo, Brazil

ISSN 1865-3529 ISSN 1865-3537 (electronic)
Green Energy and Technology
ISBN 978-981-97-6320-7 ISBN 978-981-97-6321-4 (eBook)
https://doi.org/10.1007/978-981-97-6321-4

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

The bioresources have tremendous potential to mitigate global warming. Also, biomass is expected to play a multifunctional role including food production, source of energy and fodder, biodiversity conservation, and yield of goods and services to society. Clean energy transition via utilizing biomass resources has been projected as an important climate change mitigation strategy. A vital characteristic of biomass is its localized nature; therefore, bioenergy utilization should follow decentralized planning.

This book consists of 12 chapters that highlight different biomass resource utilization for clean energy transition objectives. A few of them are described here. Sustainable utilization of biomass resources focuses on the potential of biomass to mitigate climate change, enhance energy security, and promote rural development. Algal feedstocks are the key component of the 3G biorefinery that strengthens the bio-renewables industry.

Policies for systematizing biomass collection, handling, storage, and transport to have a robust supply chain, improved product yields, and quality would drastically bring down the huge investment needed for separation and further upgradation and in turn, boost the competitiveness of the processes.

Among the sources used for biomaterials and related products, the use of vegetable oil seeds as a biomass resource is of great prominence due to the availability of a wide range of sources and varieties of plant-based seeds. Utilization of castor seed oil and its products (an agricultural-based feedstock) as a biomass source for a wide range of oleochemical products for potential applications ranging from bio-lubricants to biomaterials. Management, processing, and value addition of fish waste in the sense of supplying different agricultural leftovers as a co-digesting medium to a floating drum biogas plant. The slurry from the bio-digester has been analyzed with respect to N, P, and K content and treated properly for utilization as manure for eco-farming. Perspectives on industrial symbiosis, biomass banking, and a government-funded co-operative also covered the view of bioenergy society to promote indigenous biofuel production and improve a nation's gross domestic product value.

One of the chapters focuses on the mechanisms of production of biohydrogen by microalgae, microalgal cultivation methods, types of reactors used for cultivation of microalgae, parameters influencing the production of biohydrogen by microalgae, metabolic limitation and bottlenecks and economic evaluation for the biohydrogen produced by microalgae.

Biofuels such as ethanol and biodiesel produced from different feedstocks as promoted in the National Biofuel Policy 2018 of India are critically discussed and economic feasibility is of great importance considering the application of the non-edible oil of *Jatropha curcas* process at an industrial scale. Furthermore, it explores the cost-effective and sustainable technologies associated with this sector. These factors, when combined, could have a positive impact on the local or regional economy availability and cost of biomass feedstocks, the efficiency and cost of conversion technologies, and the market demand for biomass-derived energy.

UN Sustainable Development Goals associated with biomass utilization, emphasizing the importance of policy frameworks for the social inclusion of minorities. It highlights the need for transparent and accountable reporting mechanisms to ensure the credibility of biomass utilization practices, promoting informed decision-making and responsible resource management. The integration of social accounting principles into the assessment of biomass resource utilization provides a holistic understanding of its impacts, beyond traditional economic and environmental metrics. By recognizing the social dimensions and involving stakeholders, the credibility of biomass applications can be significantly enhanced and can mobilize a renewable biomass-based economy, which is the need of the day.

Satinder Kaur Brar, Ph.D.
Professor and James and Joanne Love
Chair in Environmental Engineering
Department of Civil Engineering
Lassonde School of Engineering
York University
Toronto, ON, Canada

Preface

Nowadays energy is a big crisis in all sectors for which there is a big change to store and optimize its uses. Energy usage in industrial, domestic, and transportation accounts for an overwhelming proportion of greenhouse gas emissions. The cost of fossil fuels is increasing and fluctuating due to depleting resources and growing concerns for climate change that require an immediate solution. Globally, the determination to achieve 'net carbon-neutral' targets by 2050, requires new clean energy sources and efficient energy systems. Green Energy and Technology focus on energy and power supply, it also covers 'green' solutions in industrial engineering and engineering design. The Clean Energy Transition-via-Biomass Resource Utilization will uplift the focus on Green Energy and Technology which addresses researchers, advanced students, technical consultants as well as decision-makers in industries and politics.

This book consists of 12 chapters that highlight different biomass resource utilization for clean energy transition objectives. This book highlights the clean energy transition via sustainable utilization of biomass resources, viz. forestry, agriculture, agroforestry, grassland, and seaweeds to climate change mitigation. Bioresources have tremendous potential to mitigate global warming. Also, biomass is expected to play a multifunctional role including food production, source of energy and fodder, biodiversity conservation, and yield of goods and services to society. This book was elaborated on considering the biological and physiochemical characteristics of these bioresources—the major criteria on which the choice of application(s) could be reserved for each biomass. Sustainable utilization of biomass resources focuses on the potential of biomass to mitigate climate change, enhance energy security, and promote rural development. Algal feedstocks are the key component of the 3G biorefinery that strengthens the bio-renewables industry. Policies for systematizing biomass collection, handling, storage, and transport to have a robust supply chain, improved product yields, and quality would drastically bring down the huge investment needed for separation and further upgradation and in turn, boost the competitiveness of the processes. Among the sources used for biomaterials and related products, the use of vegetable oil seeds as a biomass resource is of great prominence due to the availability of a wide range of sources and varieties of plant-based seeds.

Utilization of castor seed oil and its products (an agricultural-based feedstock) as a biomass source for a wide range of oleochemical products for potential applications ranging from bio-lubricants to biomaterials. Fish waste management, processing, and value addition in the sense of feeding to a floating drum biogas plant with various agro-residues as a co-digesting medium. The slurry from the bio-digester has been analyzed with respect to N, P, and K content and treated properly for utilization as manure for eco-farming. Perspectives on industrial symbiosis, biomass banking, and a government-funded co-operative also covered the view of bioenergy society to promote indigenous biofuel production and improve a nation's gross domestic product value. One of the chapters focuses on the mechanisms of production of biohydrogen by microalgae, microalgal cultivation methods, types of reactors used for cultivation of microalgae, parameters influencing the production of biohydrogen by microalgae, metabolic limitation and bottlenecks, and economic evaluation for the biohydrogen produced by microalgae.

Presently, the global economy is based on the fossil fuel economy, which is referencing the global hydrocarbon industry. The energy used mostly comes from fossil fuels like crude oil, natural gas, and coal. Problems of using these fossil fuels are the emission of greenhouse gases (GHGs), price fluctuation, issues with supply/distribution network, etc., these problems can be minimized by adopting clean energy or alternative clean fuels such as Hydrogen. The hydrogen economy relies on the use of hydrogen as a low-carbon commercial fuel in the transportation sector, alternative industrial feedstock, power generation, energy storage, etc. A few strategies were covered that could help to reduce greenhouse gas emissions and achieve the net carbon neural target are:

- Increase or optimise the energy efficiency of existing/new energy systems.
- Biofuels with Carbon Capture, Utilization, and Storage.
- Shift to clean energy as H_2 from conventional energy systems.

This book covers energy transition for various industries and techno-economic analysis. This book content will be informative to all industrial and research professionals along with academicians.

We sincerely hope that our contribution throughout this book will be a valuable asset to researchers, instructors, decision-makers, practising professionals, senior undergraduate and graduate students, and others interested in clean energy production and storage using renewable and low-cost bioresources. The book could even be used as a reference book for researchers teaching courses dealing with biomass valorisation. All the chapters were contributed by professionals from academia and government laboratories from various countries. The editors thank Springer for believing in our book project. We gratefully acknowledge all the authors who have contributed to this book for sharing their views and research findings with the scientific and

professional communities through our book. The views or opinions expressed in each chapter of this book are those of the authors.

Kapurthala, India — Dr. Sachin Kumar
Bhopal, India — Dr. Suresh Sundaramurthy
New York, USA — Dr. Deepak Kumar
Lorena, Brazil — Dr. Anuj K. Chandel

Contents

About the Editors

Dr. Sachin Kumar is a Deputy Director in the Biochemical Conversion Division at the Sardar Swaran Singh National Institute of Bio-Energy (Formerly Sardar Swaran Singh National Institute of Renewable Energy), Kapurthala, India. He obtained his Ph.D. in Chemical Engineering from the Indian Institute of Technology Roorkee, India. He has more than 12 years of research experience in Biochemical Conversion of Biomass to Biofuels including lignocellulosic ethanol, biogas, biohydrogen, etc. During his career at SSS-NIBE, he has developed state-of-the-art laboratory facilities for Biochemical Conversion of Biomass to Biofuels. His research interests are in biofuels, including bioethanol, biogas, biobutanol, biohydrogen, algal biomass, bioprocess engineering, enzyme technology, metabolic engineering, etc.

Dr. Suresh Sundaramurthy is the Faculty & Head, Department of Chemical Engineering, Maulana Azad National Institute of Technology (MANIT) Bhopal, India. He has received Ph.D. in Chemical Engineering from the Indian Institute of Technology Roorkee, India. Prof. Suresh was the recipient of Postdoctoral Fellow awarded by IUSSTF, Govt. of India, and at that time, he was associated at The City University of New York, USA. He was also the recipient of Visiting Faculty and Researcher awarded by Govt. of India. During this award, he was deputed to the Asian Institute of Technology Thailand and the International Centre for Materials Science (JNCASR) Bengaluru, India. He has also worked at Pondicherry University and Indian Institute of Technology Kanpur. He has supervised 09 Ph.D. students, 60 M.Tech. students, more than 145 B.Tech./project students, and a few students along with co-supervisors. His total number of research journal publications are more than 120 in the areas of Environmental Biotechnology, New sorbents & Catalysts, Reactor Design, Waste-to-Energy, Nanoengineered materials, biofuels and intermediates from CO_2 and Biomass Decarbonization, Energy Transition, Technical Textiles, Gas separation, Air pollution abatement, Sensing of toxic gases, and Process Safety. He has more than 75 publications in international and national conference proceedings and few with co-authored. He has undertaken 23 R&D and consultancy projects. He has published 01 Indian patent and 01 technology synchronized and many more in progress, 04 textbooks, and more than 33 book chapters, and 06 edited books and proceedings.

In recognition of his research contributions, he has received a number of awards and honors including the National Innovation-Rashtrapati Bhavan, office of the President of India, and DST-Young Scientist Award; Visiting Research Fellowship; and Prof. R C Singh Medal and IEI Young Engineers Award.

Dr. Deepak Kumar is an Assistant Professor in the Chemical Engineering Department at the State University of New York College of Environmental Science and Forestry (SUNY-ESF). Dr. Kumar received his Ph.D. in Biological and Ecological Engineering from Oregon State University. His research focuses on the development of sustainable bioprocess technologies for the production of high-value bioproducts, bioplastics, and biofuel from agro-food processing waste and forest residues using integrated experimental and modeling approaches. He has authored more than 90 peer-reviewed research articles and 15 book chapters, with over 3200 citations and an H-index of 32. He has received several awards, including the Bioenergy Society of Singapore (BESS) Achievement Award 2016. He is listed as one of the top 2% cited scientists in the field of energy by the research conducted by Stanford University in collaboration with Elsevier-Scopus for the years 2022 and 2023.

Dr. Anuj Kumar Chandel is a Professor in the Department of Biotechnology, Engineering School of Lorena, University of São Paulo, Brazil. He has over 22 years of experience working on various aspects of industrial biotechnology (production of industrial enzymes, biofuels, and bio-based products) and membrane-based separation of fats, proteins, and viruses. He obtained his Ph.D. in 2009 and then did three post-doctoral fellowships at Stellenbosch University, South Africa, Engineering School of Lorena, University of São Paulo, Brazil, and University of Arkansas, Fayetteville, USA. Dr. Chandel has worked in three biotech industries for 7 years at large-scale operations. His primary research interest is to develop sustainable processes for the bioconversion of lignocellulosic biomass into renewable fuels and biochemicals by bridging the gap between research laboratories and industries. Dr. Chandel has published more than 116 peer-reviewed scientific papers, edited 15 books, and wrote 56 book chapters. He has one Brazilian patent to his credit.

Sustainable Utilization of Biomass Resources

V. Varalakksmi, S. Sudalai, and A. Arumugam

Abstract The chapter explores the sustainable utilization of biomass resources, focusing on the potential of biomass to mitigate climate change, enhance energy security, and promote rural development. It highlights the global need to transition away from fossil fuels and reduce greenhouse gas emissions. The chapter also discusses various biomass feedstock forms and their applications, including bioenergy production, biofuels, biochemicals, and bioproducts. It emphasizes the importance of sustainable practices like crop rotation, agroforestry, and waste-to-resource conversion. It also highlights the role of policy frameworks and regulatory incentives in promoting sustainable biomass utilization. The chapter also addresses challenges such as resource availability, logistical constraints, and competition for land use. Strategies for mitigating these include efficient supply chain management and integrating biomass into circular economies. The chapter offers valuable insights for policymakers, researchers, industry stakeholders, and environmentalists seeking to harness biomass's full potential while safeguarding our planet's natural resources and ecosystems.

Keywords Sustainable utilization · Biomass · Climate mitigation · Bioenergy · Bioproducts · Policies

1 Introduction

In an era characterized by the dire consequences of unchecked industrialization and fossil fuel consumption, the urgency to transition toward cleaner, more sustainable energy sources has reached unprecedented levels. Biomass, in its diverse forms

V. Varalakksmi · A. Arumugam (✉)
Advanced Biorefinery & Catalysis (ABC) Lab, Centre for Bioenergy, School of Chemical and Biotechnology, SASTRA Deemed University, Thirumalaisamudram, Thanjavur 613401, India
e-mail: aruchemxl@scbt.sastra.edu

S. Sudalai
Centre for Pollution Control and Environmental Engineering, School of Engineering and Technology, Pondicherry University, Puducherry 605014, India

S. Kumar et al. (eds.), *Clean Energy Transition-via-Biomass Resource Utilization*, Green Energy and Technology, https://doi.org/10.1007/978-981-97-6321-4_1

ranging from agricultural residues and forest byproducts to organic waste, presents an invaluable alternative with the potential to revolutionize our approach to energy production, waste management, and carbon sequestration [1].

Biomass, originating from a wide array of sources such as crops, forest residues, algae, and even organic waste, embodies the solar energy captured through photosynthesis. By converting this stored energy into various forms, such as heat, electricity, biofuels, and biogas, societies can significantly reduce their reliance on fossil fuels and consequently mitigate the release of greenhouse gases into the atmosphere [2]. Biomass resource utilization involves harnessing energy stored within organic materials through various processes such as combustion, fermentation, anaerobic digestion, etc. [53]. Unlike finite fossil fuels, biomass is a renewable resource that can be continually replenished through responsible land management and sustainable farming practices. Furthermore, its utilization emits significantly fewer greenhouse gases compared to conventional fossil fuels, making it a crucial component of strategies aimed at curbing global warming and meeting emission reduction targets outlined in international agreements like the Paris Agreement [3].

Beyond its contributions to climate change mitigation, the responsible use of biomass offers a range of other benefits. By leveraging agricultural residues and forestry waste that might otherwise go unused or contribute to environmental problems, societies can simultaneously reduce waste disposal challenges and generate valuable energy. This, in turn, bolsters energy security and supports local economies by creating jobs along the biomass supply chain [4].

Biomass resource utilization also aligns with circular economy principles, where waste is minimized, resources are maximally utilized, and environmental impacts are reduced. By diverting organic waste from landfills and incineration, biomass utilization minimizes methane emissions and concurrently generates clean energy [5]. Furthermore, innovative technologies enable the extraction of biogas, biofuels, and valuable biochemicals from biomass, paving the way for a sustainable transition in sectors ranging from transportation to chemical manufacturing [61].

The socio-economic benefits of biomass utilization are equally compelling. Localized biomass energy systems can stimulate rural economies by creating jobs in agriculture, forestry, and energy production. Moreover, biomass-derived energy can enhance energy security by diversifying energy portfolios, reducing dependence on imported fossil fuels, and enhancing energy self-sufficiency at various scales [22]. Moreover, biomass resource utilization has the potential to aid in land restoration and conservation efforts. In cases where deforestation or land degradation has occurred, strategically managed biomass production can aid in soil rehabilitation, prevent erosion, and promote reforestation. These efforts contribute to the preservation of biodiversity, enhance ecosystem services, and safeguard vital natural habitats.

As we navigate the complexities of climate change mitigation, the exploration of biomass resource utilization becomes more imperative than ever. However, it is essential to approach this strategy with caution and consider resource management to avoid potential negative impacts such as competition with food production or ecosystem disruption. By coupling scientific innovation, policy support, and community engagement, societies can tap into the immense potential of biomass while safeguarding the delicate balance of our planet's ecosystems [6].

In this chapter, we will delve deeper into the various facets of biomass resource utilization, examining its different applications, technological advancements, policy implications, and ways for successful integration into sustainable energy systems. Through these insights, we will illuminate the path forward for biomass as a promising avenue in the fight against climate change, offering a bridge to a more environmentally conscious and resilient future.

2 Biomass Utilization—Prospects and Challenges

Biomass utilization holds immense promise as a means to mitigate climate change by providing renewable energy, waste management solutions, and economic growth opportunities. The synergy between the prospects and challenges of biomass utilization underscores the need for a holistic and interdisciplinary approach [7]. By capitalizing on the benefits while navigating the complexities, societies can harness biomass's potential to contribute meaningfully to climate change mitigation, energy security, waste reduction, and economic growth (Fig. 1).

Fig. 1 Prospects of biomass utilization [42]

2.1 Prospects

2.1.1 Renewable Energy Source

Biomass is a renewable energy source as it can be produced and replenished relatively quickly compared to fossil fuels. Biomass energy can be harnessed through various processes, including combustion, gasification, and fermentation, to produce heat, electricity, and biofuels like biodiesel and bioethanol [5].

2.1.2 Reduction in Greenhouse Gas Emissions

Biomass can play a role in reducing greenhouse gas emissions when used for energy production, as it is considered carbon–neutral. The carbon dioxide released during biomass combustion is offset by the carbon dioxide absorbed by plants during their growth [47]. Biomass can replace fossil fuels in many applications, helping to mitigate climate change.

2.1.3 Waste Management

Biomass utilization can help manage organic waste materials, including agricultural residues, forestry waste, and food scraps, diverting them from landfills and reducing methane emissions. By converting these wastes into energy or biofuels, biomass can contribute to a more sustainable waste management system [58].

2.2 Economic Benefits

Biomass projects can stimulate local economies by creating jobs in biomass production, harvesting, transportation, and processing. Biomass can provide economic opportunities for rural communities, particularly in agriculture and forestry regions.

2.2.1 Energy Security and Storage

Biomass can contribute to energy security by diversifying energy sources and reducing dependence on imported fossil fuels. It can be used as a reliable source of baseload or intermittent power generation. Biomass can be used as a form of energy storage when converted into biofuels or bioenergy carriers like biogas or hydrogen [1]. This can help balance intermittent renewable energy sources such as wind and solar.

2.2.2 Technological Advancements

Ongoing research and development in biomass conversion technologies are leading to increased efficiency and cost-effectiveness. Advanced biomass processing techniques, such as torrefaction, pyrolysis, and anaerobic digestion, are being developed to enhance biomass utilization [32].

2.2.3 Carbon Sequestration

Biomass utilization contributes to carbon sequestration indirectly by promoting sustainable forestry and land management practices, such as reforestation. When biomass is used for energy or biofuel production, it can reduce net CO_2 emissions compared to fossil fuels, as long as the biomass source is managed sustainably [19]. Biomass can also be integrated with carbon capture technologies to further reduce emissions from biomass-based energy production.

2.3 Challenges

2.3.1 Competing Land Uses

The demand for biomass resources may compete with food production, raising concerns about food security [41]. Striking a balance between energy and food production is critical to prevent exacerbating existing food scarcity issues.

2.3.2 Environmental Impact

Unsustainable biomass extraction can lead to deforestation, habitat loss, and soil degradation [18]. Careful ecosystem management and land-use planning are necessary to avoid environmental harm and ensure the long-term sustainability of biomass resources. Biomass combustion can release pollutants such as particulate matter, nitrogen oxides (NOx), and carbon monoxide (CO), which can contribute to air quality issues. Careful emission control and monitoring are necessary to mitigate these effects.

2.3.3 Resource Availability and Variability

While biomass is renewable, its availability varies by region and season [50]. Balancing resource demand with supply requires sophisticated logistics and infrastructure to ensure a consistent and reliable energy supply. Different types of biomasses (e.g., wood, agricultural residues, algae) have varying compositions and

Fig. 2 Challenges of biomass utilization [15]

properties. This variability can affect the efficiency and performance of biomass conversion processes, requiring customized solutions for different feedstocks (Fig. 2).

2.3.4 Policy and Regulation

Establishing comprehensive regulatory frameworks is crucial to prevent overexploitation, ensure responsible sourcing, and maintain environmental integrity. Policies that incentivize sustainable practices and guide the responsible growth of the biomass industry are vital. Biomass utilization is subject to various regulations and policies that vary by region. These can impact the feasibility and profitability of biomass projects, so a clear and supportive regulatory environment is important [54].

2.3.5 Energy Conversion Efficiency and Density

Biomass conversion technologies, such as combustion, gasification, and fermentation, often have lower energy conversion efficiencies compared to fossil fuel technologies. This means that a significant portion of the energy in the biomass may be lost during conversion [12]. Biomass generally has a lower energy density compared to fossil fuels like coal and natural gas. As a result, a larger volume of biomass is required to generate the same amount of energy, which can pose challenges for transportation, storage, and handling [10].

3 Sustainable Factors of Biomass Utilization

In the context of the escalating climate crisis, the imperative to mitigate greenhouse gas emissions and transition to sustainable energy sources has never been more pressing. Among the array of options available, “Biomass Resource Utilization” stands out as a versatile and sustainable strategy that offers a multifaceted approach to address climate change while promoting socio-economic development (Fig. 3). The sustainable factors that underscore the potential of biomass utilization as a pivotal way to mitigate climate change are as follows.

3.1 Renewability and Carbon Neutrality

Central to the sustainability of biomass resource utilization is its renewable nature. Unlike fossil fuels, which are finite and contribute to the release of sequestered carbon into the atmosphere, biomass originates from organic matter that can be replenished through responsible land management and agricultural practices [46]. When biomass is combusted for energy, the carbon dioxide released is equivalent to the carbon dioxide absorbed during the plant’s growth through photosynthesis. This closed-loop carbon cycle renders biomass energy generation nearly carbon–neutral, making it a crucial tool for reducing net emissions and achieving climate goals [15].

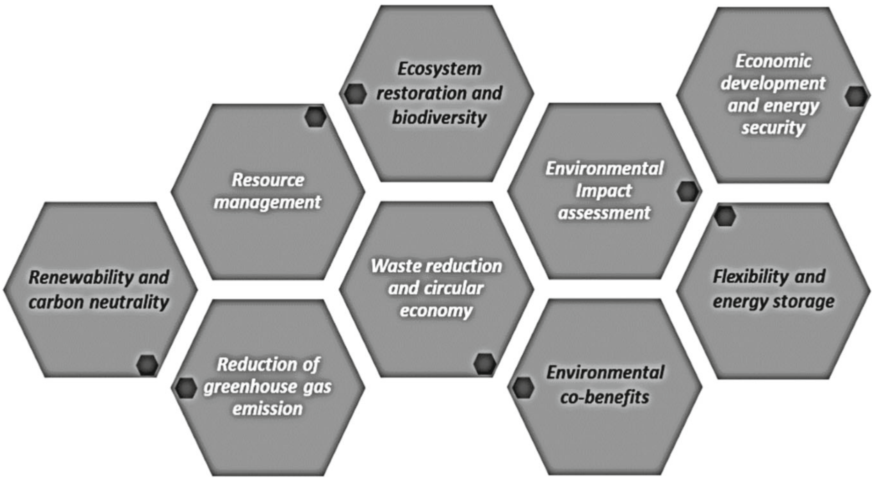

Fig. 3 Sustainable factors of biomass utilization [57])

3.2 Resource Management

Sustainable biomass utilization starts with responsible resource management. This involves ensuring that the biomass feedstocks, such as wood, crop residues, and organic waste, are harvested or collected in a manner that does not deplete the resource. Practices like selective logging in forestry and efficient waste collection and recycling systems contribute to sustainable resource management [20].

3.3 Reduction of Greenhouse Gas Emissions

The combustion of fossil fuels is a significant contributor to the accumulation of greenhouse gases in the atmosphere, resulting in global warming and climate disruptions. Biomass utilization offers a sustainable alternative by releasing significantly lower levels of carbon dioxide compared to fossil fuel combustion [35]. This reduction in emissions not only directly mitigates climate change, but also fosters cleaner air quality and improved public health, further enhancing the societal benefits of biomass energy.

3.4 Waste Reduction and Circular Economy

Biomass utilization aligns seamlessly with the principles of the circular economy by converting organic waste into valuable resources. Agricultural residues, food waste, and other organic byproducts can be diverted from landfills or incineration, preventing the release of methane and other harmful gases. Instead, these materials can be transformed into biogas, biofuels, and biochemicals through anaerobic digestion, fermentation, and other innovative processes. This waste-to-energy paradigm not only addresses waste management challenges, but also reduces the need for fossil fuel extraction [31].

3.5 Ecosystem Restoration and Biodiversity Preservation

Sustainable biomass utilization practices underscore the importance of responsible land management to avoid ecosystem degradation. By utilizing waste biomass and residues, the pressure on natural habitats and forests is reduced, which in turn safeguards biodiversity and promotes ecosystem health [27]. Moreover, strategic biomass production can aid in reforestation efforts, soil rehabilitation, and the prevention of erosion, contributing to the restoration of critical ecosystems and enhancing their resilience to climate impacts.

3.6 Environmental Impact Assessment

Before commencing biomass utilization projects, thorough environmental impact assessments (EIAs) should be conducted. These assessments evaluate potential adverse effects on air quality, water quality, soil health, and ecosystems [4]. They also identify mitigation measures to ensure that the project aligns with sustainability goals.

3.7 Economic Development and Energy Security

The integration of biomass resource utilization into energy systems has significant economic implications. Localized biomass energy production can stimulate rural economies by creating jobs in agriculture, forestry, and energy production [44]. It provides a decentralized energy solution that enhances energy security, reduces reliance on imported fossil fuels, and empowers communities to take control of their energy future.

3.8 Flexibility and Energy Storage

Biomass resource utilization offers a flexible energy source that can contribute to balancing the intermittency of renewable energy systems such as solar and wind. Biomass facilities can be ramped up or down relatively quickly to respond to changes in energy demand. Additionally, biomass-derived biofuels can serve as a form of energy storage, allowing for the stockpiling of energy during periods of low demand and its release when demand surges [8]. This flexibility enhances the stability of energy grids and supports the integration of variable renewable sources.

3.9 Environmental Co-benefits

Sustainable biomass utilization can offer various environmental co-benefits beyond climate change mitigation [25]. For instance, it can reduce the need for conventional fertilizers by recycling nutrient-rich organic waste back into the soil. This practice promotes soil health, minimizes water pollution, and conserves resources. In the broader context of combating climate change, the sustainable factors of biomass resource utilization extend far beyond carbon reduction. They touch on various dimensions of sustainability, including economic viability, social equity, ecosystem health, and technological innovation. By embracing these factors, societies can leverage biomass as a potent tool to mitigate climate change, drive sustainable development, and forge a path toward a more resilient and harmonious coexistence with our planet [22].

4 Policies for Sustainability

4.1 Renewable Energy Standards (RES) or Renewable Portfolio Standards (RPS)

These policies require utilities to obtain a certain percentage of their energy from renewable sources, including biomass. They create a reliable market for biomass-based energy, incentivizing its production and utilization. States and countries often set specific targets and deadlines for increasing the share of renewable energy in their energy mix.

4.2 Feed-in Tariffs (FiTs)

FiTs guarantee a fixed, premium price for renewable energy producers, making biomass energy projects financially attractive [24]. These incentives encourage private investments in biomass power plants, biofuel production facilities, and other biomass-based energy projects. FiTs provide predictability and stability in revenue for biomass energy producers.

4.3 Tax Incentives and Credits

Governments offer tax incentives, credits, or grants to biomass producers and users to promote sustainable practices and technology adoption [43]. Examples include investment tax credits, production tax credits, and accelerated depreciation for biomass-related investments. These financial incentives help offset the initial capital costs of biomass projects.

4.4 Carbon Pricing Mechanisms

Carbon pricing policies, such as carbon taxes and cap-and-trade systems, put a price on carbon emissions, making fossil fuels more expensive. Biomass, when sustainably managed and utilized, is considered carbon–neutral, as the carbon emitted during combustion is offset by the carbon absorbed during growth. This makes biomass a financially attractive option in carbon pricing markets.

4.5 Environmental Regulations

Governments impose environmental regulations on biomass utilization to minimize air and water pollution [56]. Emission limits, air quality standards, and wastewater treatment requirements ensure that biomass energy production and processing are environmentally responsible. Compliance with these regulations is crucial for the sustainability of biomass projects.

4.6 Sustainable Forest Management Standards

For woody biomass, sustainable forest management standards ensure that forests are harvested responsibly [16]. Selective logging, reforestation, and protection of sensitive ecosystems are essential components of these standards. Sustainable forestry practices maintain a healthy forest ecosystem and a sustainable supply of wood biomass.

4.7 Land Use Policies

To prevent conflicts with food production and habitat preservation, policies can limit the conversion of natural ecosystems or agricultural lands into biomass plantations. Sustainable land use practices help safeguard food security and biodiversity.

4.8 Bioenergy Certification Systems

Certification programs like the Roundtable on Sustainable Biomaterials (RSB) and Forest Stewardship Council (FSC) verify that biomass is sourced and processed sustainably [29]. Certified biomass products have a market advantage, as they demonstrate adherence to rigorous sustainability criteria.

4.9 Research and Development Funding

Governments allocate funds for research and development in biomass technology, sustainable practices, and innovation. These investments accelerate the adoption of advanced biomass utilization methods, improving efficiency and sustainability.

4.10 Waste-to-Energy Policies

Policies promoting the conversion of organic waste into energy, such as anaerobic digestion or gasification, reduce waste sent to landfills [34]. Organic waste-to-energy processes can provide a sustainable source of biomass feedstock and reduce methane emissions.

4.11 Community Engagement and Benefit Sharing

Policies encourage biomass projects to engage with local communities, create jobs, and share economic benefits. Benefit-sharing mechanisms, such as revenue sharing or community development funds, promote social sustainability and acceptance of biomass projects [17].

4.12 Monitoring and Reporting Requirements

Governments implement reporting and monitoring requirements for biomass utilization projects. These requirements ensure compliance with sustainability criteria, environmental standards, and emissions limits. Monitoring helps identify areas for improvement and assesses the ongoing sustainability of biomass projects.

5 Biomass Supply Chain

The biomass supply chain is a complex network that encompasses the entire journey of biomass, from its origination as organic matter to its conversion into energy, biofuels, or other valuable products. A well-designed and sustainable biomass supply chain is crucial for ensuring that biomass utilization effectively contributes to climate change mitigation while minimizing environmental and social impacts. This section delves into the intricate components of the biomass supply chain, focusing on

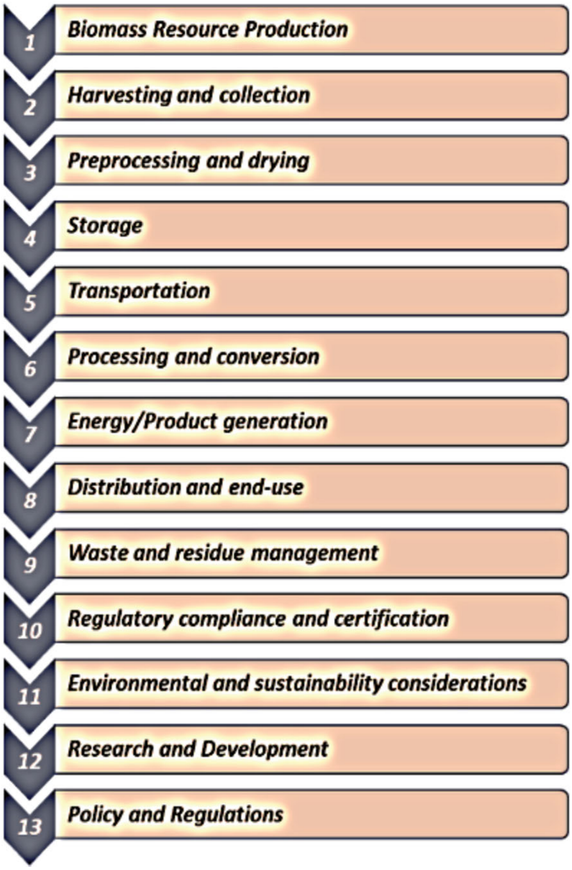

Fig. 4 Biomass supply chain [45]

its stages, challenges, and the sustainable practices necessary to achieve climate mitigation goals (Fig. 4).

5.1 Biomass Resource Production

The supply chain begins with the production of biomass resources, which can include crops (e.g., corn, sugarcane), forestry (e.g., wood, wood residues), agricultural residues (e.g., straw, corn stover), and organic waste materials (e.g., food waste, yard trimmings). Sustainable agricultural and forestry practices are crucial to ensure a continuous and environmentally friendly supply of biomass.

5.2 Harvesting and Collection

After biomass resources reach maturity or become available, they are harvested or collected. This stage involves the use of appropriate machinery and equipment, such as combine harvesters for crops or logging equipment for woody biomass [45]. Sustainable practices, like selective logging or crop residue management, are employed to minimize environmental impact.

5.3 Preprocessing and Drying

Biomass materials often require preprocessing to reduce moisture content, increase energy density, and improve storage and handling characteristics. Drying, grinding, and chipping are common preprocessing steps [26]. Reducing moisture content is particularly important for biomass used in combustion or gasification processes.

5.4 Storage

Biomass feedstock is stored in appropriate facilities, such as silos, bunkers, or covered areas. Proper storage prevents degradation, moisture uptake, and the growth of molds or fungi. Storage facilities should be designed to minimize losses and maintain feedstock quality.

5.5 Transportation

Biomass is transported from the production or collection sites to processing facilities or end-users. Transportation methods can include trucks, rail, ships, or even pipelines for certain types of biomasses. Efficient logistics and transportation planning are essential to minimize costs and environmental impacts [58].

5.6 Processing and Conversion

Biomass can undergo various processing and conversion methods depending on its intended use. This includes combustion for heat and power generation, gasification for syngas production, fermentation for biofuels, or chemical processes for bioproducts [38]. Advanced technologies like pyrolysis, torrefaction, or enzymatic hydrolysis may also be used to optimize biomass conversion.

5.7 Energy or Product Generation

Biomass is converted into energy (electricity, heat) or bioproducts (biofuels, chemicals) at processing facilities. These facilities can range from small-scale operations to large power plants and biofuel refineries. Combustion, gasification, anaerobic digestion, and biochemical processes are some of the common methods used for biomass utilization [55].

5.8 Distribution and End-Use

The energy or bioproducts generated from biomass are distributed to end-users through established distribution networks (e.g., electrical grids, and fuel distribution networks). End-users can include residential, commercial, industrial, and transportation sectors.

5.9 Waste and Residue Management

During the biomass conversion process, there may be byproducts or residues generated. These need to be managed properly, whether it's utilizing them for co-products, disposing of them responsibly, or returning them to the soil as agricultural or forestry residues [37].

5.10 Environmental and Sustainability Considerations

Throughout the supply chain, environmental sustainability practices, such as sustainable sourcing, carbon neutrality, and reduced emissions, are essential to ensure that biomass utilization has a positive impact on the environment and mitigates climate change.

5.11 Regulatory Compliance and Certification

Compliance with local, regional, and national regulations related to environmental standards, land use, and emissions is crucial. Some biomass supply chains may seek certification from organizations like the Forest Stewardship Council (FSC) or Roundtable on Sustainable Biomaterials (RSB) to demonstrate sustainable practices.

5.12 Research and Development

Ongoing research and development efforts are essential to improve the efficiency and sustainability of the biomass supply chain, as well as explore innovative technologies and feedstock sources.

5.13 Policy and Regulation

Government policies and regulations at various levels influence the biomass supply chain by addressing issues such as land use, environmental standards, incentives for renewable energy, and sustainability requirements [36].

6 Biomass Processing

6.1 Thermochemical Conversion

Biomass combustion is a widely used technique where organic materials are burned in the presence of oxygen to produce heat energy. This process is commonly used in biomass power plants and industrial boilers

$$\text{CxHyOz (biomass)} + O_2 \rightarrow CO_2 + H_2O + \text{heat}$$

During combustion, biomass releases carbon dioxide, water vapor, and heat energy. The heat is typically used to produce steam, which drives turbines to generate electricity or to provide heat for industrial processes [23].

Gasification is a process where biomass is heated in a controlled environment with limited oxygen (partial oxidation) or steam to produce a gas mixture called syngas (synthetic gas) [62]

$$C_6H_{10}O_5 + 2\,H_2O \rightarrow 6\,CO + 15\,H_2 + 2\,CO_2$$

Syngas consists of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and traces of other gases. Syngas can be used for various applications, including electricity and heat generation, as well as for the production of biofuels and chemicals.

Pyrolysis involves heating biomass in the absence of oxygen, resulting in the decomposition of biomass into three primary products biochar (a solid carbon-rich material), bio-oil (a liquid), and syngas [60].