BIOENERGY SOLUTIONS FOR CLIMATE CHANGE

THE KEY TO A SUSTAINABLE FUTURE

Editors:
Ashootosh Mandpe
Maulin P. Shah
Sonam Paliya

Bentham Books

Bioenergy Solutions for Climate Change: The Key to a Sustainable Future

Edited by

Ashootosh Mandpe
Department of Civil Engineering
Indian Institute of Technology Indore, Indore 453552
Madhya Pradesh, India

Maulin P. Shah
Industrial Wastewater Research Lab
Division of Applied & Environmental Microbiology
Enviro Technology Limited, Ankleshwar 393002
Gujarat, India

&

Sonam Paliya
Institute for Geology and Geochemistry of Petroleum and Coal
RWTH Aachen University, Aachen 52062
North Rhine-Westphalia, Germany

Bioenergy Solutions for Climate Change: The Key to a Sustainable Future

Editors: Ashootosh Mandpe, Maulin P. Shah and Sonam Paliya

ISBN (Online): 979-8-89881-765-7

ISBN (Print): 979-8-89881-766-4

ISBN (Paperback): 979-8-89881-767-1

Published by Bentham Science Publishers Pte. Ltd. Singapore,

in collaboration with Eureka Conferences, USA.

First published in 2026.

Bentham Science Publishers Pte. Ltd.
No. 9 Raffles Place
Office No. 26-01
Singapore 048619
Singapore
Email: subscriptions@benthamscience.net

BENTHAM
SCIENCE

CONTENTS

FOREWORD

The threat of climate change continues to dominate global discussions, making the transition to sustainable and renewable energy sources an urgent priority. In this context, bioenergy has surfaced as a critical element in the fight against environmental degradation. It offers not only a path to reduced dependence on fossil fuels but also provides innovative opportunities for waste management, energy security, and economic development. The complexities of modern energy challenges require a multi-dimensional approach that bioenergy uniquely delivers, making it a key player in the broader framework of climate change mitigation and adaptation.

Bioenergy Solutions for Climate Change: The Key to a Sustainable Future arrives at a time when the world is in dire need of actionable, scientifically grounded solutions to its energy crisis. This book brings together a wealth of knowledge from experts across different disciplines, offering comprehensive insights into the latest advancements and trends in bioenergy technologies. From microbial bioenergy generation to carbon capture integration, and from waste valorization to the socio-economic impacts of bioenergy, this volume covers the spectrum of approaches needed to address today’s energy challenges.

The editors, Dr. Ashootosh Mandpe, Dr. Maulin Shah, and Dr. Sonam Paliya, have curated a selection of works that illustrate both the vast potential and the real-world applicability of bioenergy. Their vision in assembling this volume highlights the importance of bridging scientific research with practical solutions, fostering innovation that can be scaled globally. The inclusion of interdisciplinary perspectives from researchers and practitioners worldwide enhances the relevance and impact of the book.

This publication not only informs readers about cutting-edge technologies but also serves as a roadmap for integrating bioenergy into climate action strategies. It emphasizes the role of bioenergy in circular economies, providing sustainable waste management and energy generation solutions that align with environmental and economic objectives. Moreover, the book emphasizes the need for strong policy frameworks and strategic planning to ensure that bioenergy fulfills its promise as a key player in the transition to a sustainable future.

As we face an unprecedented climate emergency, it is imperative that we take decisive action. Bioenergy, with its versatility and renewability, offers a beacon of hope in this challenge. I am confident that this book will inspire researchers, policymakers, and industry leaders to explore and adopt bioenergy solutions that are pivotal for a sustainable future. The collective knowledge presented in this volume reflects the depth and breadth of research in this area and offers practical insights into how bioenergy can transform our energy systems, reduce environmental impacts, and pave the way for a resilient and sustainable world.

I commend the editors and authors for their dedication and contributions to this timely and essential publication. It is my hope that Bioenergy Solutions for Climate Change: The Key to a Sustainable Future will serve as both an inspiration and a resource for the global community in its pursuit of a sustainable, energy-efficient, and climate-resilient future.

Suvasish Mukhopadhyay
Former Associate Professor
College of Engineering Pune (COEP)
Pune 411005, Maharashtra
India

PREFACE

The global fight against climate change demands urgent, innovative, and sustainable solutions. In this context, bioenergy stands as a beacon of hope, offering renewable energy alternatives that can help mitigate the damaging effects of greenhouse gas emissions. As the world grapples with the energy transition, bioenergy has emerged as a key pillar in the pursuit of a sustainable future, providing a versatile and reliable source of clean energy derived from biological materials. This book, Bioenergy Solutions for Climate Change: The Key to a Sustainable Future, aims to explore the vast potential of bioenergy technologies and their role in advancing global sustainability goals.

As climate change continues to exert pressure on ecosystems, economies, and societies, there is a growing recognition that traditional energy systems must evolve to include renewable sources. Bioenergy, with its ability to transform waste into valuable energy and reduce carbon footprints, presents a promising avenue for achieving both environmental and economic resilience. This volume brings together cutting-edge research from diverse disciplines to explore various bioenergy pathways, from microbial energy generation to carbon capture, biofuel production from agro-food waste, and strategic planning frameworks for bioenergy projects.

The chapters in this book span the fundamentals of bioenergy, advanced technologies, and policy perspectives. Contributions from leading experts and emerging researchers around the world highlight the interdisciplinary nature of bioenergy, addressing technical, economic, and socio-environmental challenges and opportunities. Each chapter delves into innovative bioenergy applications, offering insights into sustainable development, circular bioeconomy strategies, and climate resilience.

Our objective in compiling this volume is to present a comprehensive and multidisciplinary approach to bioenergy that can guide policymakers, researchers, industry professionals, and students alike. The solutions discussed herein offer not only pathways to mitigate climate change but also means to foster sustainable development, reduce waste, and enhance global energy security.

We extend our heartfelt gratitude to all the contributors for their valuable insights and hard work in advancing bioenergy research. Their collective efforts have made this book a rich resource for anyone interested in the intersection of energy, environment, and sustainability. We also thank the institutions and teams that have supported the research and publication process.

We hope that this book will serve as a valuable reference and inspire continued innovation in bioenergy solutions that are integral to addressing the pressing challenges of our time.

Ashootosh Mandpe
Department of Civil Engineering
Indian Institute of Technology Indore, Indore 453552
Madhya Pradesh, India

Maulin P. Shah
Industrial Wastewater Research Lab
Division of Applied & Environmental Microbiology

Enviro Technology Limited, Ankleshwar 393002
Gujarat, India

&

Sonam Paliya
Institute for Geology and Geochemistry of Petroleum and Coal
RWTH Aachen University, Aachen 52062
North Rhine-Westphalia, Germany

List of Contributors

Ajantha S.	Environmental Technology Division, CSIR – National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram 695019, Kerala, India
Ch Bhanupriya	Department of Microbiology, MS Ramaiah College of Arts, Science and Commerce, Bangalore 560054, Karnataka, India
Doyel Bhattacharya	Department of Chemistry, Dada Ramchand Bakhru Sindhu Mahavidyalaya, RTM Nagpur University, Nagpur 440001, Maharashtra, India
Deepak Singh Baghel	Department of Civil Engineering, SVKM's Institute of Technology, Dhule 424001, Maharashtra, India CSIR-4pi, NAL Belur Campus, Bengaluru 560037, Karnataka, India Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, Uttar Pradesh, India
Krishnakumar Bhaskaran	Environmental Technology Division, CSIR – National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram 695019, Kerala, India
Neeraj Dwivedi	Council of Industrial Innovation and Research, Sector-6, Noida 201301, Uttar Pradesh, India
Prasann Kumar	Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara 144411, Punjab, India
Pratik Vilas Deore	Department of Civil Engineering, SVKM's Institute of Technology, Dhule 424001, Maharashtra, India
Priyanshu Sao	Faculty of Sciences, ISBM University, Gariyaband 493996, Chhattisgarh, India
Poonam Verma	Faculty of Sciences, ISBM University, Gariyaband 493996, Chhattisgarh, India
Rohit Maind	PG & Research Department of Chemistry, Hislop College, RTM Nagpur University, Nagpur 440001, Maharashtra, India
Reshma Anil S.	Environmental Technology Division, CSIR – National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram 695019, Kerala, India
Surya Prakash Dwivedi	Council of Industrial Innovation and Research, Sector-6, Noida 201301, Uttar Pradesh, India
Shweta Singh	Council of Industrial Innovation and Research, Sector-6, Noida 201301, Uttar Pradesh, India
Saurabh Sakhre	Environmental Technology Division, Academy of Scientific and Innovative Research, Ghaziabad 201002, Uttar Pradesh, India
Shubhajit Halder	PG & Research Department of Chemistry, Hislop College, RTM Nagpur University, Nagpur 440001, Maharashtra, India
Suyog Gupta	Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, Jharkhand, India

Yogesh Bafna	Department of Civil Engineering, SVKM's Institute of Technology, Dhule 424001, Maharashtra, India
Yogeesh N.	Department of Mathematics, Government First Grade College, Tumkur 572201, Karnataka, India INTI International University, Nilai 71800, Negeri Sembilan, Malaysia

CHAPTER 1

Fundamentals of Bioenergy

Ch Bhanupriya[1,*]

[1] *Department of Microbiology, MS Ramaiah College of Arts, Science and Commerce, Bengalore 560054, Karnataka, India*

Abstract: The world's trend towards industrialization, the increasing global population, and faster economic growth have resulted in a growing demand for a consistent and reliable energy supply. However, the fluctuations in oil prices, the decline in oil reserves, the significant effect of harmful gases on global warming, and the overconsumption of fossil fuels have made it crucial to explore and develop alternative sources of energy that can effectively meet the world's ever-growing energy needs. In this context, bioenergy emerges as a beacon of hope, a crucial and excellent energy source obtained from biomass produced by absorbing carbon. Biomass, the world's largest renewable energy source, results from photosynthesis and includes wood and its residues, energy crops, non-edible crops, crops grown on marginal lands, and crop residues. Even the seemingly less significant materials, such as organic waste/residues from industry, agriculture, landscape management, and households, play a significant role in bioenergy generation. By unlocking the potential of biomass, we can transform it into solid, liquid, or gaseous fuel, creating a renewable, non-petroleum-based, and net-zero-emission energy source. This not only meets the energy needs but also significantly reduces harmful emissions. It constitutes up to 55% of the world's energy supply, with a growing demand in countries such as the United States, Brazil, Europe, Indonesia, and India for the production of ethanol, biodiesel, renewable diesel, and bio-jet fuel. By 2050, biomass use will shift from traditional to transportation, electricity, industries, and infrastructure, thus significantly impacting global energy consumption and potentially revolutionizing the energy sector.

Keywords: Bioenergy, Biomass, Global industrialization, Renewable energy.

INTRODUCTION

Over the course of its existence, the Earth has experienced significant changes in its climate. The changes we are witnessing have been brought about by a myriad of natural factors, including orbital variations and volcanic eruptions. Furthermore, the feedback processes inherent to the climate system have also significantly contributed to these transformations. These natural forces are at play,

* **Corresponding author Ch Bhanupriya:** Department of Microbiology, MS Ramaiah College of Arts, Science and Commerce, Bengalore 560054, Karnataka, India; E-mail: ch.hemapriya@gmail.com

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

driving the changes we observe in our environment. These natural climate forcings have resulted in periodic and episodic shifts in Earth's climate across various time scales, ranging from short-term fluctuations to long-term alterations [1]. However, it is essential to note that in addition to natural changes, there is increasing evidence from independent investigations that human activities, particularly since the Industrial Revolution, have had significant changes in Earth’s climate [2]. This underscores the importance of our responsibility for the current state of the environment and our actions in shaping the climate.

The current phase of climate change is undeniably more than just another natural variation. It is an unprecedented acceleration, surpassing any pace seen in the history of modern civilization. This rapid change, a result of complex interactions between environmental factors and human activities, is outstripping ecosystems' ability to adapt to the constantly changing environment. The pressing issue of rapid climate change demands swift action to safeguard the health of our planet. We must curb these impacts and prevent irreparable harm [3, 4].

The Earth’s energy budget, a delicate equilibrium between the solar energy the Earth absorbs and the energy it emits back into space, is a crucial regulator of the planet's climate. Any disturbances to this balance, as we are witnessing due to human activities, can have far-reaching and devastating consequences for our climate [5, 6]. Activities like the combustion of non-renewable fuels, industrial by-products, deforestation, and changes in Land use and Land Cover (LULC) release significant Greenhouse Gases (GHGs) like Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), and aerosols into the atmosphere, contributing to increased global warming. Furthermore, Aerosols, those minuscule particles floating in the atmosphere, reflect the sunlight into space and indirectly lead to a cooling effect [7]. However, this cooling effect is not enough to offset the warming effect of GHGs, making aerosols a significant contributor to climate change. Therefore, it is essential to transition to using renewable energy, improving energy efficiency, implementing sustainable land use practices, and reducing waste.

Bioenergy, derived from biological sources, is a beacon of hope in the fight against climate change. Among renewable sources, biomass is an organic material that contains chemical energy from the Sun, stored in plants through photosynthesis. It can come from various sources, including plants, agricultural crops or residues, municipal wastes, and algae [8, 9]. It is an essential and excellent energy source for producing solid, liquid, and gaseous fuels. Among the liquid fuels, bioethanol is being used as an alternative to fossil fuels by blending with petrol. Biofuel derived from plant materials represents one of the most rapidly advancing renewable energy technologies. The process involves converting biomass into liquid fuel and tapping into various plant sources to bolster domestic energy reserves. This emphasis on bioenergy's potential should instil optimism in our ability to find sustainable solutions.

The History and Evolution of Bioenergy

"Biomass existed before humans." The history of biomass dates back to ancient times, long before humans emerged. Biomass energy has been an integral part of human development, persisting throughout history and playing a fundamental role in all societal life [10]. Even in the pursuit of clean energy sources, biomass and bioenergy remain essential, accounting for 98% of the renewable energy sources humans have used throughout history. It is important to note that fossil fuels became popular in the 20^{th} century. Before that, biofuels like wood and charcoal were the primary fuel sources from the caveman era until the early Industrial Revolution. It is essential to understand that fossil fuels and biofuels contain sequestered carbon, while biofuels are derived from renewable carbon sources. Both types of fuel are derived from biomass. This highlights biofuels' sustainable and environmentally friendly nature, making them a compelling choice for the future [11].

Since ancient times, humans have been utilizing biomass as an energy source. The first way of using biomass was to burn it using fire. They used branches, dried grass, and wood for various purposes such as heating, illumination, driving out dangerous animals, or ripening food. The use of biomass energy has been prevalent for centuries, mainly for heating and cooking. The ancient civilizations of Egypt, Babylon, and Greece used straw to burn fires in ceramic furnaces and burned wood for steel production. The history of biomass energy saw a dramatic transformation in the 1800s as innovative technologies emerged, enabling more efficient energy harnessing from biomass sources.

During the Industrial Revolution in 1760, coal usage increased significantly, contributing to growth and development. In 1826, ethanol was first used to power an engine, and in 1876, Nicolaus Otto used it to power an early engine. Ethanol was first used to power an engine in 1826 [12], and in 1876, Nicolaus Otto, the inventor of the modern four-cycle internal combustion engine, used ethanol to power an early engine. Ethanol was also used as a lighting fuel in the 1850s, but its use declined when it was taxed as liquor to help pay for the Civil War. In response to fuel shortages during World War II in the 1920s and 1930s, the first ethanol was blended with gasoline to boost octane levels, a practice that continues to this day [13]. In India, the first anaerobic digestion plant was constructed at a leper colony in Bombay in the year 1859 [14]. Anaerobic digestion reached England in 1895 when biogas was recovered from the well-designed sewage

CHAPTER 2

Exploring the Potential of Microorganisms for Renewable Bio-energy Generation

Priyanshu Sao[1] and **Poonam Verma**[1,*]

[1] *Faculty of Sciences, ISBM University, Gariyaband 493996, Chhattisgarh, India*

Abstract: To address the increasing global energy needs and environmental issues, microbial fuel cells leverage the distinctive capabilities of microorganisms to produce bioenergy. This research provides a detailed analysis of the fundamental concepts underlying Microbial Fuel Cells (MFCs), focusing on the mechanisms that enable the transfer of electrons and bioenergy production, as well as the factors influencing MFC performance. It examines the synergistic integration of MFCs with other renewable energy systems and further analyses their many applications, including toxic waste remediation and biofuel recovery. This review emphasises current advancements designed to enhance the efficacy, stability, and profitability of MFC research, while recognising the limitations of scalability, cost-effectiveness, and optimisation despite these promising developments. This paper provides a comprehensive overview of the evolving domain of MFCs, highlighting the barriers to widespread adoption and evaluating their potential to transform bio-energy production.

Keywords: Bio-energy, Employs, Feasibility, Microbial fuel cells, Pollutants, Sustainability problems, Specialised authority.

INTRODUCTION

The depleting and harmful fossil fuels are mostly to blame for the world's acute energy problems [1]. Investigating and developing eco-friendly, sustainable, and renewable alternative energy sources is becoming more and more necessary in response [2]. Bioenergy, originating from natural or biological sources, represents a feasible alternative. Its renewable nature is advantageous, as it depends on ongoing development and regeneration, unlike petroleum and coal, which are depleting [3]. Amid the rising energy use and heightened environmental consciousness, the use of MFCs has emerged as the forefront of bio-energy research. MFCs occupy a unique position in this burgeoning sector, potentially

* **Corresponding author Poonam Verma:** Faculty of Sciences, ISBM University, Gariyaband 493996, Chhattisgarh, India; Tel: +91-9752588321; E-mail: poonamverma8624@gmail.com

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

addressing both power generation and environmental enhancement demands. Efficient utilisation of natural substance which is crucial for MFC performance. The management of these substrates is crucial to a raw material, and the efficacy of MFC depends extensively on it. The relationship between conducting materials and organic substrates significantly influences the efficacy of MFCs. A thorough analysis of this relationship is necessary for optimal results. Recent developments in MFC research highlight the complexity and potential of this subject. A recent article in the Journal of Chemistry highlights the importance of long-term stability in the management of innately unstable chemical substrates [4]. A paper published in RSC Advances discusses efforts to increase energy production while reducing component and plant operational costs [5]. Despite these commendable advancements, several challenges remain, particularly in operational optimisation, economic feasibility, and scalability. The current generation of MFCs, characterised by high running costs and little stability, renders them economically unfeasible for large-scale production. MFCs possess many uses, including the effective utilisation of bioenergy, wastewater treatment, and the management of energy and waste issues [6]. Their capacity to provide broad options for producing clean energy is further augmented by their seamless interaction with other forms of renewable energy, warranting investigation. Despite their considerable promise, MFCs encounter many challenges regarding flexibility, cost-effectiveness, and operational enhancement in practical applications [7]. Authors emphasise recent advancements that enhance the effectiveness, strength, and profitability of MFC research. Innovations that convert solar energy into power for appliances, including registered hybrid structures that incorporate bio-battery science and technology with living organisms, have the potential to transform renewable energy generation. Bio-Photoelectrochemical Cells (BPECs) illustrate the potential integration of MFCs with living organisms, facilitating energy generation from light. BPECs facilitate the generation of clean, sustainable energy through integration with diverse biological systems, such as plants [8], seaweed, and single-cell photosynthetic bacteria. The development of bio-solar cells, grounded in the principles of photosynthesis, exemplifies this concept. Using succulent plants as catalysts offers novel research at the nexus of biology and renewable energy sources [9].

In the areas of energy generation and ecological sustainability, we hope to illuminate their potential as revolutionary forces. Taking into consideration many aspects influencing MFC performance, the authors carried out an exhaustive examination of the complex processes behind electron transport and bio-energy generation. It seeks to further our knowledge by looking at the complicated interactions that happen among microorganisms' organic substrates, and electrodes, we can learn more about MFCs and their important part in moving towards a safe and energy-rich future. In the global effort to transition to environmentally friendly, sustainable energy sources, MFCs may play a major role.

METHODS BY WHICH BIO-ENERGY IS PRODUCED

Laminaria and *Ulva* species are two examples of microalgae that have the potential to produce energy. Micro algae drying for biodiesel requires a lot of energy because of the high quantities of unsaturated fatty acids. A range of non-lethal techniques, including physical, biological, and thermolytic methods, are employed to address these issues [10]. Microalgae experiencing nutritional stress, particularly due to nitrogen deficiency, exhibit increased oil production. By merging autotrophic and heterotrophic metabolism, a photosynthesis-fermentation model lowers CO_2 emissions and boosts lipid output. Micro algae with complex polysaccharides, such as *Laminaria spp. and Ulva spp*., have the potential to produce biogas but require specialized processing [10]. Chemical quality protection is required throughout the dry process because it uses a lot of energy and financially demanding operation. Microalgae's high levels of unsaturated fatty acids provide difficulties for the etherification of lipids with alcohol, a critical step in the synthesis of biodiesel [10]. This provides a number of techniques for processing microalgae biomass for the generation of biofuel, including extraction using chemicals, living things, heat, and not killing, as shown in Table **1**. Though some sea species may produce more phospholipids than the optimal amount of triglycerides, high-lipid algae are prioritised for biodiesel production. Furthermore, ethanol and butanol may be produced using fermentation techniques and osmotic shock. Adding fresh water to fermentation can make it better by freeing cell parts and changing the salt content. Pyrolysis, along with other thermolytic processes, can turn waste into biofuels, but they use a lot of energy and may not be practical for all situations, producing hazardous byproducts [11]. Often called "milking," non-lethal extraction techniques focus on certain chemicals to increase productivity and lessen their negative effects on the environment [12]. However, additional technological developments are needed to use microalgae more effectively [13]. Microbial oxidation represents the starting point in the several stages involved in the formation of MFCs, wherein microorganisms break down organic materials and release electrons. Electrons are transferred from the anode to the source *via* extracellular electron transfer mechanisms. This can occur either through direct contact or *via* conductive materials such as oxides of metal or carbon nanotubes. Electrons are particles that travel from the anode to the cathode *via* an external connection during reduction processes. In that context, they combine *via* oxygen as well as protons to form water [14]. The rate and efficiency of both of these processes are influenced by various factors, including the composition of organic matter, temperature, pH, microbial population, and the accessibility of electron acceptors. The production

CHAPTER 3

Carbon Capture and Bioenergy Integration: A Sustainable Approach for Mitigating Climate Change

Suyog Gupta[1,*]

[1] *Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, Jharkhand, India*

Abstract: This chapter summarizes the present position and development of Bioenergy with Carbon Capture and Storage (BECCS) technologies and stresses. Its positive aspects are environmental and economical, not only waste, but also sustainable land use and rural development. Simultaneously, it tackles some of the technical, economic, and regulatory obstacles that threaten the realization of the BECCS concept, such as the establishment of a durable biomass supply chain, the high cost of Carbon Capture and Storage (CCS) deployment, and the dependence on policy frameworks and social acceptance. By providing an extensive review of published case studies and pilot projects, this paper demonstrates practical examples of energy retrofits with BECCS. It examines their technical and economic potential in the future. It further highlights the need for interdisciplinary research and innovation in BECCS and a variety of BECCS-positive law and policy interventions to remove inhibitors of BECCS development at scale globally. This method provides a unique means of delivering large-scale climate solutions without rapid changes in energy practices while strengthening energy security and advancing cleaner energy opportunities by integrating CCS and bioenergy. The findings and recommendations provided in this chapter aim to inform policymakers, researchers, and stakeholders about the critical role of BECCS in sustainable management.

Keywords: Bioenergy, Carbon capture, Carbon storage, Rural development, Sustainable management.

INTRODUCTION

Global ecosystems, human health, and economies are highly vulnerable to climate change due to the high concentration of Greenhouse Gas (GHG). There is a need for robust mitigation policies to control the rise in global temperatures and prevent catastrophic environmental events [1, 2]. Traditional containment theories like decreasing fossil fuel consumption and upgrading energy efficiency levels

* **Corresponding author Suyog Gupta:** Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, Jharkhand, India; E-mail: suyog.iitdh@gmail.com

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

have reached their limits [3, 4]. Climate change poses an immense threat to the biosphere [3, 5, 6]. The Intergovernmental Panel on Climate Change (IPCC) has underlined the urgency of active mitigation policies to keep global temperatures below critical levels and avoid potentially irreversible impacts on our environment. Thus, new solutions need to provide significant, lasting reductions in emissions [4, 7, 8].

Bioenergy is a renewable energy source derived from biomass, which is converted through various processes (*e.g.*, thermal, chemical, or biological) into heat, electricity, and liquid fuels, providing a sustainable alternative to fossil fuels [9, 10]. However, Carbon Capture and Storage (CCS) is a promising technology to reduce emissions from existing fossil fuel infrastructure by transporting and storing captured carbon in geological formations [11, 12]. Bioenergy with Carbon Capture and Storage (BECCS) combines these two approaches, leveraging biomass's carbon-absorption capacity during growth and integrating CCS to capture CO_2 emissions from bioenergy conversion [13, 14]. BECCS has the potential to achieve net harmful emissions, where more CO_2 is removed from the atmosphere than is emitted, making it a vital strategy for meeting stringent climate targets [15, 16].

This chapter aims to provide an inclusive overview of the integration of Bioenergy with Carbon Capture (BECC) in climate change mitigation strategies. It highlights innovations in CCS and bioenergy technologies, the associated environmental and economic benefits, and the challenges to their global adoption. Additionally, this chapter will highlight the prospects of BECCS through current case studies and pilot projects, offering examples and recommendations for policies to develop these options. We hope to educate policymakers, scientists, and stakeholders about the important role of BECCS in achieving climate commitments and meeting sustainable energy practices through the discussion of technology and socioeconomics.

CARBON CAPTURE AND STORAGE (CCS)

Description of CCS Technology

CCS technologies are a set of advanced techniques intended to decrease CO_2 emissions from industrial sources by capturing, transporting, and securely storing CO_2 emissions underground (Fig. **1**) [10, 17, 18].

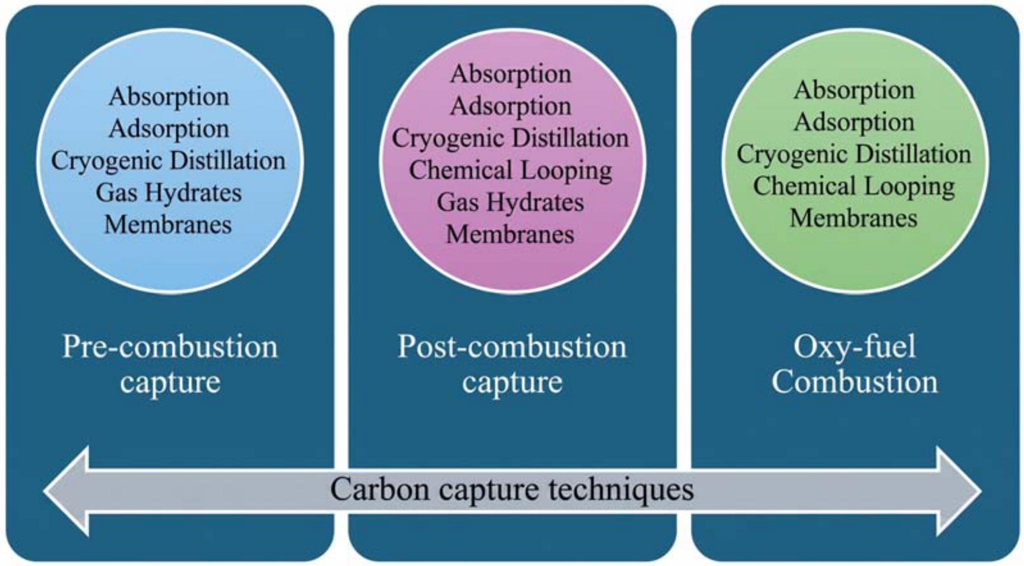

Fig. (1). Types of carbon capture techniques.

Pre-combustion Capture

CCS involves gasifying fossil fuels (*e.g.*, coal, natural gas) to produce a synthesis gas (syngas), *i.e.*, a mixture of hydrogen and CO. The CO reacts with water to produce CO_2 and hydrogen. CO_2 is then separated and captured [19, 20]. It is frequently used in Integrated Gasification Combined Cycle (IGCC) plants.

Post-combustion Capture

This process captures CO_2 from flue gases produced after fossil fuels are burned. This is done using solvents (*e.g.*, chemical solvents like amines absorb CO_2 from flue gases), adsorbents (*e.g.*, materials like zeolites or activated carbon capture CO_2), or membranes (selective barriers allow CO_2 to pass through while retaining other gases). It can be retrofitted to existing power plants and industrial facilities [21, 22, 23].

Oxy-fuel Combustion

Fossil fuels are burned in pure oxygen during this procedure, emitting CO_2 and water vapour as flue gases. Water vapour is condensed, leaving nearly pure CO_2 for capture. It suits new power plants designed with this technology [24, 25].

CHAPTER 4

A Hybrid Fuzzy-SWOT Analysis for Strategic Planning in Bioenergy Projects

Yogeesh N.[1,2,*]

[1] *Department of Mathematics, Government First Grade College, Tumkur 572201, Karnataka, India*

[2] *INTI International University, Nilai 71800, Negeri Sembilan, Malaysia*

Abstract: Background/Purpose: Bioenergy projects have high uncertainty in biomass supply, technology performance, market dynamics, and regulatory frameworks. Traditional SWOT analysis cannot capture these nuances quantitatively. This chapter proposes a Hybrid Fuzzy-SWOT methodology integrating triangular fuzzy sets with standard SWOT to support strategic planning in complex bioenergy contexts.

Materials/Methods: We (i) define fuzzy membership functions for four SWOT categories, (ii) aggregate and defuzzify internal/external scores *via* the centroid method, and (iii) apply the model to two case studies: the hypothetical Green Energy biofuel plant (USA) and the Kolar Agro-Biofuel pilot (India).

Results: The defuzzified internal score (D_{int} = 0.72), indicating robust in-house strengths but moderate external threats. Government incentives and market demand emerged as top opportunities, while initial CAPEX and policy shifts were key threats. Comparative analysis shows ~18% more decision clarity than traditional SWOT.

Conclusion: The Hybrid Fuzzy-SWOT framework delivers a quantitative, uncertainty-aware tool for bioenergy strategy. Its interdisciplinary insights spanning environmental impact (LCA), socio-economic benefits, and engineering design equip stakeholders to prioritize actions, allocate resources, and navigate risk. Future work should standardize membership-function elicitation and integrate real-time AI analytics.

Keywords: Bioenergy, Decision support, Fuzzy-SWOT analysis, Fuzzy mathematics, Sustainability, Strategic planning, Uncertainty management.

[*] **Corresponding author Yogeesh N.:** Department of Mathematics, Government First Grade College, Tumkur 572201, Karnataka, India & INTI International University, Nilai 71800, Negeri Sembilan, Malaysia;
E-mail: yogeesh.r@gmail.com

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

INTRODUCTION

Background and Significance of Bioenergy Projects

The use of bioenergy projects in sustainable energy development is increasingly recognized as they present renewable energy sources that are capable of reducing dependency on fossil fuels [1] and greenhouse gas(es) emissions. The importance of bioenergy lies in the utilization of biomass, which can be effective in various forms, such as agricultural residues, forestry by-products, and organic waste, leading to energy generation through processes such as combustion, anaerobic digestion, and gasification [2]. The growing global focus on reducing emissions and increasing the reliability of renewable energy, in turn, has given bioenergy projects a valuable role in fields such as energy security, carbon reduction, and rural development [3].

Challenges in Strategic Planning for Bioenergy

Planning bioenergy projects necessitates a strategic approach to addressing challenges across environmental, economic, and social domains. Some of the environmental challenges include sustainable biomass sourcing and reducing land-use change and emissions [4]. Economically, bioenergy projects need to be cost-competitive with conventional, established energy supplies while remaining financially viable in the long term [5, 6]. The latter must gain social acceptance and provide a benefit to residents (section 6). Moreover, the uncertainties in their inherent availabilities and variabilities of biomass, but also in market conditions and market fluctuations, and those of technology advancements make the strategic planning even more challenging [7].

Limitations of Traditional SWOT Analysis

SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is a classic strategic planning approach that offers a structured evaluation of internal and external characteristics that may affect a project [8]. Nevertheless, the use of SWOT analysis in bioenergy projects is limited by difficulties in dealing with the inherent uncertainties and subjective judgments of these projects [9]. The traditional SWOT analysis is unable to provide weights for each of these factors, which can create bias and oversimplify the analysis [10]. Firstly, it fails to consider the interactions and dependencies among factors that are necessary in a complex decision-making context [11].

Objectives of the Study

This specifically addresses the fetters of the conventional SWOT analysis approach, and the effort in this context is to develop a new framework that wedges Fuzzy Logic with SWOT analysis to create a Hybrid Model (Fuzzy-SWOT). The goals are:

i. Design of a Fuzzy-SWOT analysis model for bioenergy projects, where rough set theory is applied to the strategic planning in bioenergy projects.
ii. The implementation of the hybrid model for a bioenergy project in the real world is to show the applicability and robustness of the proposed approach.
iii. Comparing the outcome of the hybrid Fuzzy-SWOT analysis with traditional SWOT analysis and establishing the convergence of the fuzzy method over the traditional one.
iv. Strategic guidance on obtaining policy leverage, given recommended pathways identified. Agenda setting based on identified research needs and informing policy dialog and stakeholder communication around bioenergy project planning, based on findings on carbon balance.

Comparative Positioning

Unlike classical SWOT analysis, which depends entirely on qualitative assessments of strengths, weaknesses, opportunities, and threats [2], recent fuzzy-SWOT variants introduce fuzzy membership functions to model expert uncertainty. However, most of these approaches employ a mean-of-bounds defuzzification, simply averaging each fuzzy interval's lower and upper limits, an operation that can obscure fine distinctions when different factors share similar ranges.

In contrast, our hybrid methodology uses centroid-based defuzzification, computing the center of gravity of each aggregated fuzzy set to produce crisp strategic scores. By preserving the full shape of the underlying membership functions, this approach yields more discriminating and robust prioritizations of strategic dimensions, enhancing decision-makers' ability to rank and select actions under uncertainty.

LITERATURE REVIEW

Overview of SWOT Analysis in Strategic Planning

A SWOT analysis is a strategic planning tool used to evaluate and understand the framework of internal AND external factors that can directly impact the success of a project OR organization [12]. It organizes these factors into 4 groups:

CHAPTER 5

Strategies for Clean Biofuel Production from Agro-Food Waste: The Journey to Environmental Sustainability

Shubhajit Halder[1,*], **Doyel Bhattacharya**[2] and **Rohit Maind**[1]

[1] *PG & Research Department of Chemistry, Hislop College, RTM Nagpur University, Nagpur 440001, Maharashtra, India*

[2] *Department of Chemistry, Dada Ramchand Bakhru Sindhu Mahavidyalaya, RTM Nagpur University, Nagpur 440001, Maharashtra, India*

Abstract: The environment and economic growth have been significantly impacted by the indiscriminate use of traditional energy sources. Waste disposal has also led to environmental hazards such as the release of greenhouse gases, contributing to global warming, pollution of natural resources, and habitat fragmentation. Biofuels offer a viable alternative to conventional fossil fuels due to their environmental friendliness, lower pollution levels, easy availability, and renewability. Blending biofuels with petroleum can result in reduced emissions of toxic gases and less depletion of fossil fuels, leading to lower environmental pollution compared to non-biofuel-containing fuels. Clean biofuel sources can be primarily derived from waste materials such as agro-food byproducts, municipal solid waste, sewage sludge, and various organic materials found on Earth. Agro-food waste, a significant biomass feedstock, is a key source for biofuel production. Organic biomass with a high carbon content, obtained from agro-food waste through appropriate processing, has the potential for sustainable use in industries such as medicine, cosmetics, and energy production. Balancing energy needs and waste utilization is crucial for achieving sustainability and promoting a circular economy. This chapter aims to discuss research and development strategies, limitations, and potential sustainable policies related to the production of biofuels from agro-food waste. The review will contribute to the concept of a circular economy, which focuses on generating value from waste to improve waste management practices effectively.

Keywords: Agro-food waste, Clean biofuels, Circular economy, Environmental pollution, Traditional energy sources, Waste management.

[*] **Corresponding author Shubhajit Halder:** PG & Research Department of Chemistry, Hislop College, RTM Nagpur University, Nagpur 440001, Maharashtra, India; Tel: +919175490338; E-mail: suvochem.halder@gmail.com

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

INTRODUCTION

Environmentally adaptable materials have a greater demand for promoting a circular and sustainable economy than natural storage, which cannot go back to its original form. Long-term sustainable and value-added economies are broadly dependent on the co-existence of social, economic, and environmental balances [1]. One of the major purposes of the circular economy is to convert the leftover agro-materials into value-added products such as biofuels, bioenergy, and bio-hybrid materials [2]. Co-operation between resource management and market consumption throughout industries is utmost needed for policy implementation related to the circular economy and the maximum utilization of surplus agro-food waste. Environmental and energy crises have been mainly accelerated due to uncontrolled industrial development and population expansion [3]. The bulk of the total energy requirements worldwide is substantially provided by fossil fuels and their derivatives [4]. Non-renewable sources such as natural gas, crude oil, coal, and other derivatives are the backbone for many industries in terms of total energy production [5]. Storage of these resources is limited and continuously diminishing with increasing demand worldwide. The generation of greenhouse gases is the adverse effect of fossil fuels, which causes substantial climate change, destruction of ecosystems, and overall damage to mankind in the long run. Wastes derived from agriculture and food leftovers, *viz*., vegetable peels, crops, and fruits, can generate biomass waste, which must be effectively disposed of to deter environmental and economic damage [6]. The sustainable use of agro-food waste can be used to generate renewable energies in the form of biofuels, and it can also promote the advancement of the circular economy. Agro-waste can produce high-end value-added products and promote the generation of biofuels to meet global energy demand. The ample availability of worldwide production of agro-waste is a spontaneous choice for valuable biofuel production. Biofuel production from agro-waste can be processed mainly through three main stages: pretreatment, hydrolysis, and fermentation technology. Various petroleum-based products can also be synthesized from the precursors of agro-food wastes. New-age bio-composites have important applications in additive manufacturing technology, medical applications, and the fabrication of environmentally benign materials [7]. Production of bio-composites can be effectively processed from agro-food waste, which is eco-friendly in nature. Other applications of agro-food waste are mainly to incorporate fiber matrix into the upgraded automobile industry, such as the production of car seats and mats, *etc*. Agro-food waste has been proposed as a probable alternative to produce clean energy sources, and byproducts can also be a good source of value-added products. One of the richest resources for producing biofuel and electrical energy is biomass [8]. Biomass can produce highly valued chemical precursors, *viz*., furfural and levoglucosan. Biomass is a sustainable raw material for the cost-effective preparation of ethanol and biodiesel. Leftovers from industry, agricultural products, wood, and animal wastes are the major sources of biomass. Biomass can be classified into four major components as per its chemical constituents: sugar, triglycerides, starch, lignocellulose, and hydrocarbons.

The composition of biomass may vary depending on its origin [9]. The high calorific efficiencies of lignocellulosic biomass are valuable resources for biomass production and the synthesis of environmentally friendly value-added products. It also strategically eliminates the large loads produced during the production process. Lignocellulosic biomass is abundantly available, and its main constituents are cellulose, lignin, and hemicellulose. Fewer inorganic materials and organic phytoextracts are present in the composition of lignocellulosic biomass. Agro-food waste requires special attention as a major resource for biofuel production. Agro-food waste is commonly produced by humans, and millions of tons can be strategically utilized to build a circular, sustainable economy. Economic loss due to uncontrolled agro-food waste can be converted into profitable biofuel production. A common practice has been developed in various countries to dispose of food waste at dumping sites and incinerate this waste along with other solid waste. The production of detrimental environmental pollutants is one of the major drawbacks of these common practices. Biofuels, which can also be produced from waste cooking oil, are a regular item in the food industry. A substantial apprehension regarding waste cooking oil is the disposal method, which involves blockage in drains and dangerous impacts on water pollution [10]. Renewable energy, as a sustainable resource for long-term use, can be produced from the waste derived from the agriculture sector and can be an alternative solution to fossil fuels. Biomass and feedstock are in different compositions with respect to the synthesis methods, chemical characteristics, and execution parameters. Biomass is organic in nature and derived from photosynthesis, either directly or indirectly [11]. The last few decades have been known for industry growth related to the consumption industry, where the food industry has occupied a large market area. Hence, waste derived from food and agro-food creates an extensive amount of waste globally. It has been approximately calculated that overall production, dispersion, and use of food account for nearly 20 percent of waste globally, out of 20 MMT generated waste per year [12]. Food waste is the most common waste generated from a global perspective. Various intermediate processes, *viz*., business production, management, loading, packaging, circulation, and ingesting of food, mostly contribute to the extent of global food waste production. Proper food waste management requires the effective isolation of edible and non-edible fractions at the time of disposal [13]. The agro-food industry produces extra waste compared to other food processing domains, approximately 35% of the entire waste, which covers primarily peels and other parts of compositions [14]. Improper disposal of

CHAPTER 6

Assessing the Sustainability of Bioenergy

Surya Prakash Dwivedi[1,*], **Neeraj Dwivedi**[1] and **Shweta Singh**[1]

[1] *Council of Industrial Innovation and Research, Sector-6, Noida 201301, Uttar Pradesh, India*

Abstract: A feasible path towards a sustainable energy structure is provided through bioenergy, which is composed of natural resources. Assessing sustainability involves analyzing the results with the environment, the economy, and society. This chapter provides a radical framework for assessing bioenergy sustainability, focusing on socioeconomic factors, ecological offerings, and "Life Cycle Analysis" (LCA). Life cycle analysis evaluates the environmental effects of biomass production, power conversion, and consumption. Among the critical factors that are protected are changes in energy output, land use, and particularly greenhouse gas fuel use. A thorough assessment of sustainability must include environmental services related to water resources, soil health, and in particular, biodiversity conservation. The bankruptcy highlights how important it is to strike a balance between renewing environmental regulations and producing biofuels. The socio-economic assessment considers societal acceptance, energy conservation, and especially rural development. It focuses on how laws and rules impact the creation of sustainable biofuel paths. The sustainability potential of a number of bioenergy feedstocks, which include forestry by-products, agricultural residues, and specialized strengthening products, has been classified. The chapter also discusses the results for the sustainability of technological developments in bioenergy conversion methods such as gasification, pyrolysis, and anaerobic digestion. Recommendations for feasibility studies and coverage guidelines to enhance bioenergy sustainability are presented in the conclusion of the chapter.

Keywords: Bioenergy, Bioenergy feedstocks, Ecosystem services, Lifecycle Analysis (LCA), Sustainability, Socio-economic assessment.

INTRODUCTION

The term "bioenergy" describes energy produced from biodegradable materials, including agricultural leftovers, plant matter, and natural waste. These materials are transformed into heat, biofuels, electricity, and other types of energy. In the shift to a more comprehensive and environmentally friendly renewable power program, bioenergy plays a crucial role as a renewable energy source.

* **Corresponding author Surya Prakash Dwivedi:** Council of Industrial Innovation and Research, Sector-6, Noida 201301, Uttar Pradesh, India; E-mail: drsuryadwivedy@gmail.com Contact No. +91-9690316293

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

It is impossible to exaggerate the significance of bioenergy. It offers a flexible and perhaps low-carbon substitute for fossil fuels, lowering greenhouse emissions from gasoline and slowing down global warming. By diversifying the energy mix and lowering reliance on imported petroleum and natural gas, bioenergy promotes resilience. It also has enormous potential to boost agricultural economies and provide employment in industry, energy generation, and agriculture.

Bioenergy can be obtained from many sources. Wood, waste, or agricultural waste are examples of biomass that can be burned simultaneously to offer energy and heat. Biofuels are liquid fuels made from biodegradable materials consisting of ethanol and biodiesel. While biodiesel is a product of animal fats, vegetable oils, or recycled food fats, next to being used as a diesel substitute, ethanol is usually produced from crops such as corn and sugarcane and then used as an additive in gasoline. Another type of bioenergy is biogas. It is a methane-rich fuel produced by anaerobic digestion of herbaceous residues. It can be converted into biomethane to replace fossil fuels or used to generate heat and power. More sustainability and less rivalry with food resources are provided by advanced biofuels, which use non-food sources of biomass, such as agricultural leftovers, algae, and wood chips.

Bioenergy offers a number of benefits. It is a form of environmentally friendly energy that replenishes rapidly, in contrast to finite fossil fuels. Bioenergy has the potential to be low carbon since CO_2 absorbed with the aid of biomass over time can balance the emissions produced by the energy conversion process, which has decreased carbon emissions. By diversifying fuel sources, bioenergy increases energy security and lessens vulnerability to geopolitical issues in the supply of fossil fuels. The bioenergy firm may strengthen the agricultural economy by creating jobs in producing goods, energy generation, and agriculture.

Bioenergy also brings up a variety of issues and worries. Even if it could be sustainable, it must be properly managed to prevent negative environmental effects, including biodiversity loss, deforestation, and soil deterioration. The conflict between feeding people and producing bioenergy for resources like water as well as land may give rise to ethical and sustainable concerns. The high premature costs along with technical issues must be resolved in order to increase the efficiency and environmental sustainability of bioenergy systems.

Bioenergy is a viable component of a renewable energy sources portfolio with a number of advantages for lowering carbon emissions while improving power security. Meticulous handling, along with technological innovation, is needed to maximize sustainability along with minimize any detrimental effects. This chapter will include in-depth analyses of several facets of bioenergy, along with a technical, financial, and environmental sustainability evaluation.

Importance of Sustainability in Energy Production

Sustainability in power generation is essential to addressing the social, economic, and environmental issues brought up by conventional fossil gasoline-based power infrastructure. Sustainable strength production aims to fulfill current strength demands without sacrificing the capacity of future generations to satisfy their own needs in order to ensure long-term environmental health, financial balance, and social well-being. Traditional energy sources, including oil, coal, and vegetable fuels, are major contributors to air pollution, greenhouse gas emissions, and environmental degradation brought on by declining biodiversity, problems with fitness, and climate change [1, 2]. Switching to sustainable energy sources like wind, water, and solar, in addition to bioenergy, makes it simpler to minimize carbon emissions as well as adopt clean air and water. Sustainable electrical systems may cut power costs, boost energy security, and generate employment by expanding the supply of electricity and decreasing dependency on foreign fuels [3]. Socially, they may promote community resilience, provide fair access to energy, along with improving public health. Implementing global sustainability targets and building a resilient, lower-carbon future depend on the transition to sustainable energy generation [4].

Objectives and Scope of the Chapter

The primary purpose of this chapter is to offer readers a radical take on bioenergy. It attempts to offer a thorough assessment of bioenergy, including its types, resources, and site conversion methods. The chapter lays the foundation for understanding the broader context and the necessity of bioenergy within the renewable energy landscape by clarifying the fundamentals.

The chapter aims to assess the sustainability of bioenergy across the environment, the financial system, and society. To obtain a compelling assessment of the advantages and disadvantages of bioenergy, this includes assessing life cycle GHG emissions, economic opportunities, and social consequences of bioenergy production and use. Exploring coverage frameworks and manufacturing improvements is another critical direction. The bankruptcy provides insight into the present and potential future of bioenergy technology by highlighting the latest technological developments and examining the effectiveness of coverage in aiding sustainable bioenergy.

Furthermore, the chapter attempts to demonstrate successful bioenergy tasks and the hours obtained through case studies and real-world examples. For stakeholders

CHAPTER 7

Bioenergy Solutions for Climate Change: The Key to a Sustainable Future

Prasann Kumar[1,*]

[1] *Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara 144411, Punjab, India*

Abstract: The chapter "Bioenergy Solutions for Climate Change: The Key to a Sustainable Future" delves into the pivotal role of bioenergy in mitigating climate change and advancing sustainable development. It begins by defining bioenergy and exploring its various forms, including biomass, biofuels, and biogas. The chapter examines bioenergy's environmental, economic, and social impacts, emphasising its potential to reduce greenhouse gas emissions and enhance energy security. It discusses current technologies and innovations in bioenergy production, highlighting successful case studies worldwide. The chapter also addresses challenges such as land use competition, sustainability concerns, and policy frameworks needed to promote bioenergy adoption. This chapter aims to underscore its critical importance in achieving a sustainable future and combating climate change by providing a comprehensive overview of bioenergy's benefits and challenges.

Keywords: Agriculture, Bioenergy, Climate, Diverse, Emission, Economics, Innovation, Sustainable.

INTRODUCTION

Bioenergy from organic sources is a crucial renewable energy resource in the pursuit of sustainable energy. By biomass, an array of energies may be understood to be virtually represented by organic substances. Bioenergy plays a crucial role in reducing reliance on oil, mitigating greenhouse gas emissions, and enhancing environmental sustainability and energy security. Bioenergy feedstocks encompass a range of materials, including plants, agricultural residues, animal waste, and the organic portion of municipal solid waste. These feedstocks are converted into bioenergy products (such as biofuels, biogas, and bioelectricity). To understand bioenergy, it is essential to understand its structure and the characteristics that differentiate its primary components: biomass, biofuels, and

[*] **Corresponding author Prasann Kumar:** Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara 144411, Punjab, India; E-mail: prasann0659@gmail.com

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

biogas [1 - 3]. Bioenergy is primarily based on converting organic materials and biomass into feedstock for producing biofuels through the use of microbial organisms that can transform these substances. However, the biomass sources to produce energy are diverse (wood, agricultural residues, energy crops, such as switchgrass and miscanthus, among others). Biomass can be converted into heat and other forms of bioenergy through combustion, as well as *via* chemical and biological processes. The flexibility of biomass is a crucial aspect of the bioenergy area. Bioenergy also includes another significant type of biofuel: biofuels produced from biomass. These are biofuels, also known as liquid and gaseous fuels. Bioethanol and biodiesel are the major biofuels. Ethanol has historically been produced by fermenting sugars in crops such as corn and sugarcane. Biodiesel is produced through a process known as transesterification, where vegetable oils or animal fats are converted into a fuel. Biofuels offer sustainable alternative energy sources, replacing non-renewable fossil fuels and reducing carbon footprints and dependence on imported oil in the Southern Hemisphere. A significant type of bioenergy is biogas produced from the Anaerobic Digestion (AD) of organic matter. This process involves breaking down organic materials, including farm waste, manure, and food waste, by microorganisms in a non-oxygen environment, which generates methane-rich biogas. Biogas can be burned directly for cooking and heating, but it also has other potential uses. Alternatively, it can be further processed to remove impurities and used as a substitute for natural gas [4]. As an alternative renewable energy source, biogas mitigates waste by reducing methane (landfill gas) released by the decay of organic waste deposited at disposal sites. Biomass, biofuels, and biogas have different physical forms and applications. Biomass refers to untreated organic material, and biofuels and biogas are differentiated forms of energy derived from the processing of biomass in various ways. Its primary use is as a transport fuel, a renewable alternative to petrol and diesel [5]. Unlike biogas, however, it is a versatile energy source that can be used for heat, power, and power-to-gas (*i.e.*, replacing renewable natural gas). Each member of the bioenergy team has a specific role to play, which makes our energy profile remarkably diverse. There are diverse and advanced technological processes for bioenergy production. For instance, biomass can be burned directly to produce heat and electricity at biomass power plants. Thermochemical and biochemical processes can convert it into solid, liquid, and gaseous fuels. Thermochemical processes, including pyrolysis, gasification, and hydrothermal liquefaction, involve the dissociation of biomass at high temperatures to form syngas, bio-oil, and other added-value by-products. Bacteria and other organisms are used for similar processes (anaerobic digestion, fermentation) to produce biofuels and biogas as fermentation products. Progress in bioenergy technologies depends on several key factors, including the availability of resources, technological development, economic conditions, and environmental considerations. Sustainable bioenergy crop production requires careful management of feedstock resources to avoid impacts on food security, land use, and biodiversity [6]. Additionally, technological and infrastructural developments are crucial for optimizing efficiency and cost-effectiveness in bioenergy systems. Bioenergy also offers significant environmental benefits. It helps address greenhouse gas emissions by replacing fossil fuels and sequestering CO_2 during the growth of biomass feedstock. Furthermore, bioenergy can contribute to waste treatment and reduce methane emissions from the decomposition of organic waste. However, the environmental impacts of bioenergy production need to be carefully examined to ensure that they do not outweigh the benefits [7 - 12]. Unsustainably managed large-scale bioenergy can lead to deforestation, soil loss, and unsustainable water use. Bioenergy is a versatile and environmentally friendly energy source derived from organic matter. He said the different sources, including biomass, biofuels, and biogas, have their respective and specific place in the energy mix. Biomass is the feedstock, while biofuels and biogas are energy carriers produced through various conversion pathways. The need to reduce reliance on fossil fuels and emissions of greenhouse gases, and enhance energy security calls for accelerated technical development of bioenergy. However, sustainable management is necessary to ensure that bioenergy production is environmentally friendly and socially viable. With ongoing technological advancements, bioenergy can be a key component in the global renewable energy portfolio, providing significant support for sustainable and secure futures. Bioenergy is crucial for climate change mitigation because it offers a renewable alternative to fossil fuels and can effectively reduce greenhouse gas emissions. In the face of the global challenges posed by climate change, the transition to sustainable energy production becomes increasingly imperative. Bioenergy from biomass, including plants, agricultural waste, and organic matter, offers a flexible and efficient solution to this challenge by enabling decarbonization of the energy sector. Renewable goals are achieved by integrating these technologies into a diverse energy portfolio, resulting in a greener and more resilient energy future. The primary way bioenergy contributes to climate change mitigation is by reducing GHG emissions. Traditional fossil fuels, upon combustion, release large amounts of Carbon Dioxide (CO_2) and other Greenhouse Gases (GHGs) into the atmosphere, contributing to the acceleration of global warming. In contrast, bioenergy operates in a closed carbon cycle. During photosynthesis, plants absorb Carbon Dioxide (CO_2) from the atmosphere. Since the carbon dioxide released when we burn these plants or their byproducts is roughly equal to the amount they absorb as they grow, they are said to be 'carbon neutral'. In the case of sustainable land management, this steady state implies no net increase in CO_2 in the atmosphere. In this way, bioenergy can further reduce GHG emissions from waste. When biodegradable organic waste is

CHAPTER 8

Water Resources and Bioenergy in India: Navigating the Future with Statistical Insights and Strategic Frameworks

Pratik Vilas Deore[1], **Deepak Singh Baghel**[1,2,3,*] and **Yogesh Bafna**[1]

[1] *Department of Civil Engineering, SVKM's Institute of Technology, Dhule 424001, Maharashtra, India*

[2] *CSIR-4pi, NAL Belur Campus, Bengaluru 560037, Karnataka, India*

[3] *Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, Uttar Pradesh, India*

Abstract: India's water resources face pressure from rapid population growth, urbanization, and increased agriculture despite receiving 4,000 billion cubic meters of rainfall annually. The bioenergy landscape in India has great potential for expansion using non-food biofuel crops, urban organic waste, and agricultural residues. The country's annual potential for bioenergy from surplus crop residue is estimated to be in the range of 1500-1700 petajoules (PJ). There is a fundamental connection between the production of bioenergy and water resources in terms of utilizing water-efficient techniques in the growing and processing of crops used to produce biofuel. However, several issues arise at the intersection of water conservation and bioenergy. These issues include the water-intensive character of some biofuel crops and their potential effects on India's water security system. These issues are uncovered through statistical insights of methods such as Water Footprint Assessments & Life Cycle Assessments (LCAs). India needs to develop strategic frameworks to meet its sustainable bioenergy targets and promote sustainable farming practices. They include technological advancements for water-efficient bioenergy processes, regulatory proposals, and community engagement tactics. India's sustainable growth depends on developing a stakeholder-engaged strategy, investing in water-saving technologies, and integrating policy-making to traverse the challenges of guaranteeing water security while moving towards energy self-sufficiency. This chapter identifies the difficulties in managing India's water resources and the possibility for the nation to use bioenergy as a sustainable energy source. This study also provides a thorough review of solutions for sustainable resource management by providing India with options for utilizing its bioenergy potential without jeopardizing its water supplies. The analysis provides a clear picture of India's current water availability, usage trends, and bioenergy output by

* **Corresponding author Deepak Singh Baghel:** Department of Civil Engineering, SVKM's Institute of Technology, Dhule 424001, Maharashtra, India; CSIR-4pi, NAL Belur Campus, Bengaluru 560037, Karnataka, India; Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, Uttar Pradesh, India; Tel: +91-9561476047; E-mail: deepaksingh.baghel@svkm.ac.in

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

integrating a wide range of statistical data, highlighting the crucial balance between water sustainability and energy needs.

Keywords: Agricultural residues, Bioenergy, Biofuel, Biomass power generation, Climate change, Crop residue, Drip irrigation, Drought-resistant crops, Genetic modification, Groundwater depletion, Life Cycle Assessments (LCAs), Organic waste, Policy framework, Stakeholder engagement.

INTRODUCTION

Overview of India's Water Resources and Bioenergy Potential

India's water resources are vast yet unevenly distributed, both spatially and temporally. The country relies heavily on its monsoon season to replenish its water supplies, which are crucial for agriculture, industry, and domestic use [1] (Table **1**).

Table 1. Sector-wise projected water demand in India [1 - 3].

Sector	Water Demand in Billion Cubic Meter (BCM)					
	2010		2025		2050	
-	High	Low	High	Low	High	Low
Irrigation	557	543	611	561	807	628
Drinking Water	43	42	62	55	111	90
Industry	37	37	67	67	81	81
Energy	19	18	33	31	70	63
Other	54	54	70	70	111	111
Total	710	694	843	784	1180	973

India's water resources are under considerable strain due to the country's burgeoning population and increasing industrial activity. India accounts for about 18% of the world's population but has only 4% of the world's freshwater resources [2]. The annual per capita availability of water has significantly decreased from about 5,177 cubic meters in 1951 to around 1,486 cubic meters in 2021, and is projected to fall below 1,400 cubic meters, placing India among water-stressed nations [3] (Fig. **1**).

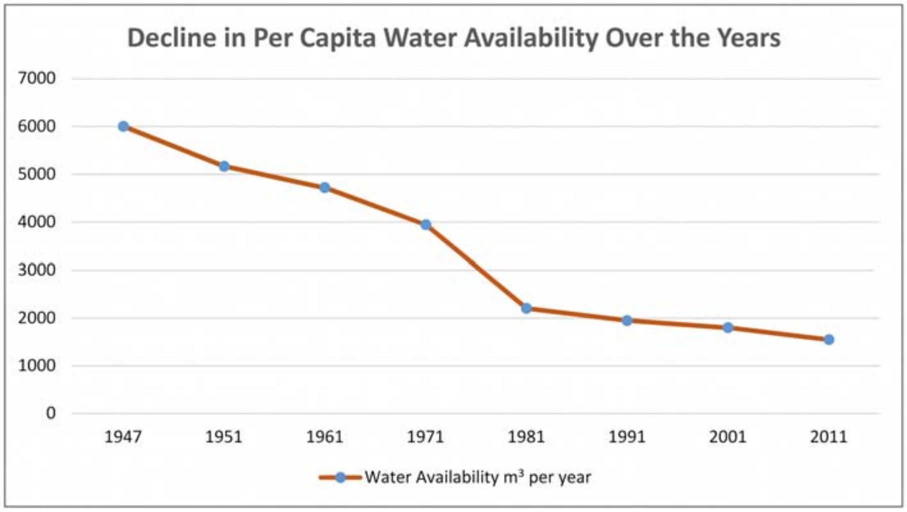

Fig. (1). Decline in per capita water availability over the years [3].

On the bioenergy front, India has a theoretical biomass potential of about 28,446 MW from agricultural residue and, through bagasse cogeneration in sugar mills, around 13866 MW. The agricultural sector produces an estimated 228 million metric tonnes of surplus agricultural residues every year, with only a fraction currently being utilized for energy production [4].

Importance of Addressing the Water-energy Nexus for Sustainable Development

The interdependence between water and energy resources is crucial to shaping sustainable development strategies, especially in a densely populated and rapidly developing country like India. The concept of the water-energy nexus recognizes that water is essential for energy production and, conversely, energy is crucial for water extraction, treatment, and distribution. Understanding and managing this nexus is pivotal for ensuring efficient use of resources, minimizing environmental impacts, and supporting sustainable economic growth.

In India, the agriculture sector, which consumes about 70% of the country's freshwater resources, also produces vast amounts of agricultural residues that can be converted into bioenergy [3]. However, inefficient water use in agriculture strains the limited water supply and reduces the availability of biomass for energy production, due to degraded agricultural productivity.

Furthermore, energy production, particularly from conventional sources, is a significant water consumer. For instance, thermal power plants, which account for

CHAPTER 9

Temperature Variation of Aqueous Faecal Sludge and Its Impact on the Rate of Degradation of Organic Matter: A Short-term Study

Reshma Anil S.[1], **Ajantha S.**[1], **Krishnakumar Bhaskaran**[1] and **Saurabh Sakhre**[2,*]

[1] *Environmental Technology Division, CSIR – National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram 695019, Kerala, India*

[2] *Environmental Technology Division, Academy of Scientific and Innovative Research Ghaziabad 201002, Uttar Pradesh, India*

Abstract: The present study provides the findings of the experimental studies conducted across all three trials on the reduction in Chemical Oxygen Demand (COD) with changes in temperature. The experimental trials are conducted on fresh faecal matter before it goes into the septic tank. As temperature is one of the crucial parameters that affect almost all processes in the environment, including wastewater treatment, the experiments were carried out to examine the variation in temperature with reductions in COD. The study aims to investigate the degradation of organic matter in faecal sludge under different temperature conditions. Faecal sludge, a mixture of human excreta, water, and solids, poses significant challenges for effective treatment and management. The experiment investigated the impact of temperature variations on the degradation of organic pollutants by measuring COD as an indicator of organic matter content. The system's temperature is measured with a temperature probe. The temperatures varied systematically to observe the corresponding changes in COD levels. The findings indicate an inverse relationship between temperature and COD: as temperature increased, COD decreased. This suggests that higher temperatures enhance the degradation rate of organic matter within the faecal sludge. All three trials showed a decrease in COD with an increase in temperature. The coefficient of correlation in all three trials was found to be 0.8805, 0.857, and 0.9177, respectively. Overall, the study mimics the inherent processes that would have been occurring in a septic tank and provides an idea of the optimal temperature.

Keywords: Chemical oxygen demand, Faecal sludge, Organic matter, Septic tank, Temperature.

[*] **Corresponding author Saurabh Sakhre:** Environmental Technology Division, Academy of Scientific and Innovative Research Ghaziabad 201002, Uttar Pradesh, India; Tel: +9168078008; E-mail: saurabh@niist.res.in

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

INTRODUCTION

The role of temperature in wastewater and waste management is crucial for various processes and outcomes in environmental sustainability. Temperature significantly influences waste management by affecting processes such as decomposition, chemical reactions, and microbial activity. Changes in temperature can impact the biochemical processes within waste, influencing the rate of decomposition and the production of byproducts [1]. Temperature variations in waste management systems can affect the efficiency of waste treatment processes and the quality of effluents [2]. Understanding the temperature dynamics of municipal solid waste is essential for developing effective waste management strategies and protocols [3]. Temperature monitoring in landfills is crucial to assess the progress of waste decomposition, gas generation, and leachate quality [4]. Improper temperature management in landfills can lead to uncontrolled temperature increases, changes in gas composition, and other environmental issues [5, 6, 7].

Faecal Sludge (FS), a byproduct of human waste, poses significant challenges to sanitation and public health due to its diverse harmful microorganisms [8]. The composition of FS, characterised by high moisture content and bacterial biomass, necessitates effective treatment strategies to mitigate environmental and health risks [9]. Understanding the physicochemical characteristics of FS is crucial for developing sustainable management practices, such as its potential use as a feedstock for green energy production [10]. Inadequate management of FS, often discharged untreated into the environment, can lead to water contamination and public health hazards [11]. The presence of pathogens in FS underscores the importance of temperature-dependent treatment processes to ensure pathogen inactivation and safe disposal [8].

The impact of temperature on pathogens in FS is a critical aspect of sanitation and public health. Research has shown that increased temperatures can be effective in inactivating FS pathogens, such as *Escherichia coli* and *Salmonella spp* [12]. Studies have indicated that thermal treatment processes, such as composting and thermal pretreatment, can lead to the destruction of contamination indicators and pathogens like faecal coliforms and *Salmonella spp* [13, 14]. Moreover, the time-temperature relationship has been highlighted as a key factor in the inactivation of pathogens in FS, with specific temperature ranges and exposure times proving effective in reducing pathogen levels [12]. In the past decade, several studies have delved into the impact of temperature on wastewater treatment and the treatment of FS. The influence of sludge conditioning temperature on polymer performance for sludge thickening and dewatering aimed to optimize polymer efficacy under varying temperature conditions [15].

Investigating the microbial safety of heat-treated FS for black soldier fly larvae, production underscored the importance of temperature in the treatment process [16]. The relationship between total organic carbon content and the heating value of sewage sludge samples has been examined, emphasizing the role of temperature in determining sludge energy potential [17]. Research on various sanitizing methods for FS highlights the critical role of temperature in the method's effectiveness [18]. A study [19] concentrated on a semi-decentralised mobile system for septic sludge treatment, emphasizing temperature control for high-quality treated liquid streams. A super high-frequency irradiation method for communal liquid waste treatment, showcasing the temperature's impact on liquid waste treatment in urban settings, is proposed [20]. These studies collectively underscore the pivotal role of temperature in liquid waste management practices, demonstrating its significant influence on treatment processes in wastewater and faecal sludge management.

The chapter aims to provide a comprehensive understanding of the role of temperature in various environmental processes, with a specific focus on wastewater treatment and FS management. It begins by introducing the concept of temperature and its significance in environmental contexts. The chapter then explores the diverse impacts of temperature on environmental processes, highlighting its effects on organic matter decomposition, nutrient cycles, and carbon emissions. Subsequently, the role of temperature in different stages of wastewater treatment systems is discussed, with a specific emphasis on anaerobic and aerobic treatment processes. Furthermore, the chapter delves into the experimental works conducted at the study area (CSIR-NIIST), focusing on temperature-dependent degradation processes in faecal sludge. By examining the results of these experimental studies, the chapter aims to provide valuable insights for developing efficient treatment methods and regulatory frameworks to address the challenges of faecal sludge management in India.

Study Area

The study was carried out in the CSIR-National Institute for Interdisciplinary Science and Technology (NIIST), Thiruvananthapuram, staff quarters area. It is situated in the Industrial Estate ward of Thiruvananthapuram city. Fig. (**1**) illustrates the index map of the study area.

Temperature

Temperature is a physical quantity that measures the hotness or coldness of an object or a substance. It is a fundamental parameter in thermodynamics and plays a crucial role in various scientific disciplines, including physics, chemistry, and meteorology. Temperature is typically measured using a thermometer and is

CHAPTER 10

A Critical Review on Socio-Economic Impacts of Bioenergy

Suyog Gupta[1,*]

[1] *Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, Jharkhand, India*

Abstract: This chapter will explore the socio-economic advantages of bioenergy systems in the context of sustainable development. It evaluates the potential of bioenergy in reducing energy poverty, offering employment, enhancing local livelihood, and retarding rural-urban migration through decentralized energy access. The chapter highlights the advantages of various biomass resources: agricultural residues, forestry residues, and organic municipal waste, and bioenergy technologies facilitating their conversion into electricity, heat, and fuels like biogas and bioethanol. The chapter highlights essential case studies demonstrating successful implementation in India, including improved cookstove programs, biogas plants, and biomass power systems. In addition, the study mentions financial benefits such as income generation and enhanced fossil fuel independence, as well as environmental co-benefits like reduced greenhouse gas emissions and improved waste management practices. In addition, the chapter analyses the problems associated with bioenergy development, including innovation adoption barriers, resource constraints, policy limitations, and community-level capacity-building needs. It concludes by recommending policy integration, stakeholder involvement, and enhanced investment in research and infrastructure to realize the development potential of bioenergy in rural India. This chapter positions bioenergy at the centre of the policy agenda as a renewable energy source and as a lead driver of all-round socio-economic change in rural India.

Keywords: Bioenergy, Carbon neutrality, Employment, Income generation, Energy access, Environmental sustainability.

INTRODUCTION

Bioenergy, derived from biomass such as lignocellulosic residues, organic municipal solid waste, and animal manure, has emerged as a key renewable energy source [1, 2, 3]. As a carbon-neutral energy within the biogenic carbon cycle, its lifecycle Greenhouse Gas (GHG) emissions, typically 10-90 gCO_2eq/kWh, are significantly lower than those of fossil fuels (>400 gCO_2

* **Corresponding author Suyog Gupta:** Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, Jharkhand, India; E-mail: suyog.iitdh@gmail.com

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

eq/kWh) [4, 5]. Although net emissions can approach zero when biomass regrowth offsets combustion output, practical outcomes are influenced by factors such as land-use change, feedstock processing, and logistics [1, 5].

Bioenergy applications span transportation (*e.g.*, bioethanol, biodiesel), heating (*e.g.*, pellet stoves), and electricity generation through Combined Heat and Power (CHP) systems. It enhances energy security by decentralizing supply and utilizing locally available feedstocks, reducing dependence on volatile fossil fuel imports. Its Energy Return on Investment (EROI) ranges from 2:1 to 10:1, depending on the conversion technology used, such as anaerobic digestion or gasification [5, 6]. Additionally, co-products like biochar, heat, and digestate contribute to circular economy goals and resource efficiency [6, 7, 8].

Beyond environmental benefits, bioenergy contributes significantly to socio-economic development. It utilizes organic matter that would otherwise become waste, such as agricultural residues and wood waste, thereby improving resource efficiency and waste management [9, 10, 11]. It also stimulates rural economies by creating employment opportunities and opening new markets for agricultural and forest products [10, 12, 13]. These activities promote rural development and help diversify the energy mix, strengthening national energy security [14, 15, 16, 17].

Research indicates that bioenergy can address both climate and socio-economic challenges. For instance, studies in Nigeria have shown that expanding bioenergy production creates agricultural employment and boosts regional income [18]. Similarly, in Europe, farmers and landowners benefit economically by supplying biomass for energy projects [19].

This review critically examines the socio-economic impacts of bioenergy, with a focus on its roles in energy generation, rural development, and environmental sustainability. It aims to systematically evaluate the benefits and drawbacks of bioenergy deployment, particularly in terms of employment, income generation, poverty reduction, social equity, and rural well-being. By analysing these aspects, the review seeks to offer insights into how bioenergy can support the achievement of sustainable development goals and inform energy policy and planning.

TRANSITION OF BIOENERGY AND RENEWABLE ENERGY

Bioenergy in the Renewable Energy Mix

Bioenergy's integration into the global renewable energy mix is critical. Technologically, it supports baseload demand through dispatchable power and can be hybridized with intermittent renewables (*e.g.*, PV, wind). Gasification, pyrolysis, and Fischer-Tropsch synthesis represent advanced thermochemical pathways with >50% conversion efficiency. Biofuels like HVO (Hydrotreated Vegetable Oil) and drop-in fuels are compatible with existing ICE infrastructure, lowering transition costs.

The International Energy Agency (IEA) classifies bioenergy as a vital component of net-zero strategies, particularly through BECCS. Under BECCS, net-negative emissions (up to -200 gCO_2/kWh) are achievable when combined with carbon storage in geological formations (*e.g.*, saline aquifers) [20, 21]. Including bioenergy in the energy mix diversifies the energy sources, improving overall energy resilience and reducing susceptibility to supply disruptions in fossil fuel markets [20, 22, 23]. It can stimulate rural economies, create jobs, and support sustainable land management practices. By converting agricultural residues, forestry, and municipal solid waste into energy, bioenergy reduces waste and promotes resource efficiency.

Moreover, it can also be used for electricity generation and heating, offering flexibility in its application. It can be integrated into existing energy systems, providing a reliable and dispatchable renewable energy source. Biofuels, *i.e.*, biodiesel and bioethanol, can be utilised as alternatives to fossil fuels in transportation [24]. They can diminish greenhouse gas emissions and improve air quality compared to fossil fuels. Bioenergy production can be integrated into sustainable land use practices, such as agroforestry and crop rotation, promoting biodiversity and soil health. It plays a crucial role in transitioning to a sustainable energy system, offering a renewable substitute for fossil fuels and contributing to environmental, economic, and social sustainability (Fig. **1**).

Carbon Neutrality and Climate Change Mitigation

Due to its unique carbon cycle dynamics, bioenergy plays a significant role in carbon neutrality and climate change mitigation strategies. When managed sustainably, bioenergy can offer a carbon-neutral or even carbon-negative pathway compared to fossil fuels (Fig. **2**). The carbon released in bioenergy combustion is part of the carbon cycle. Plants absorb CO_2 from the atmosphere during photosynthesis, incorporating carbon into their tissues. When these plants are used as biomass for energy and burned, the CO_2 released is equivalent to the amount previously absorbed, maintaining a carbon balance. This cycle makes bioenergy carbon-neutral over time, provided the biomass is replenished through sustainable management practices.

SUBJECT INDEX

A

B

Ashootosh Mandpe, Maulin P. Shah & Sonam Paliya (Eds.)

C

D

E

G

H

L

M

S

T

W

Ashootosh Mandpe

Dr Ashootosh Mandpe is an Indian academician, researcher, and environmental engineer known for his contributions to solid waste management, waste-to-energy systems, anaerobic digestion, and circular economy–based resource recovery, working as an Assistant Professor at the Indian Institute of Technology Indore. He has actively worked in areas such as biogas and biohydrogen production, landfill emission mitigation, decentralized waste management, and sustainable urban sanitation systems. Dr. Mandpe has authored and edited several scholarly books and research articles with reputed international publishers and journals, focusing on sustainability, climate resilience, and emerging digital approaches such as AI-driven decision support for environmental infrastructure. He is recognized for promoting interdisciplinary research, mentoring young researchers, and fostering innovation in environmental engineering and circular resource utilization for sustainable development and net-zero transitions.

Maulin P. Shah

Dr. Maulin P. Shah is an Indian academician, researcher, and editor known for his contributions to environmental biotechnology, industrial microbiology, and sustainable bioprocessing. He has actively worked in areas such as bioremediation, wastewater treatment, circular bioeconomy, and microbial valorization of waste. Dr. Shah has authored and edited several scholarly books and research articles with reputed international publishers, focusing on sustainability and emerging technologies like artificial intelligence in microbiology. He is recognized for promoting interdisciplinary research, mentoring young scientists, and fostering innovation in environmental and industrial applications for sustainable development and resource recovery.

Sonam Paliya

Dr. Sonam Paliya is an Alexander von Humboldt Fellow at RWTH Aachen University, Germany, with over eight years of research experience in Biological and Environmental Sciences. She earned her Ph.D. from the Academy of Scientific and Innovative Research (AcSIR) while conducting research at CSIR-National Environmental Engineering Research Institute (CSIR- NEERI), Nagpur. Her research focuses on the bioremediation of persistent organic pollutants and emerging contaminants, wastewater treatment, bio-valorization of waste, life cycle assessment, and environmental impact assessment. A recipient of prestigious fellowships including the Alexander von Humboldt Fellowship, DST-SERB National Postdoctoral Fellowship, and UGC- NET JRF, she has received several national awards recognizing her research excellence. Dr. Paliya has published extensively in leading SCI-indexed journals. She is also an accomplished editor and author, contributing to several international books on environmental sustainability, waste management, climate resilience, and bioenergy.