THE WASTE TO ENERGY NEXUS

TECHNOLOGIES FOR INDUSTRIES OF THE FUTURE

Editors:
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FOREWORD

As we stride deeper into the 21st century, humanity faces a dual-edged challenge: managing ever-increasing waste and securing sustainable energy sources. With a burgeoning global population and rapid industrialization, the mounting pressure on our planet's finite resources is undeniable. At the same time, our relentless pursuit of energy has driven innovation toward solutions that are both sustainable and environmentally conscious. The relationship between waste management and energy generation holds transformative potential in shaping a sustainable future. By extracting energy from waste materials, we not only reduce environmental harm but also preserve existing resources while creating clean, renewable energy. This integrated vision aligns seamlessly with the global commitment to the United Nations' 17 Sustainable Development Goals (SDGs), particularly the goal of achieving affordable and clean energy by 2030.

This book explores cutting-edge technologies and methodologies at the intersection of waste management and energy valorization. It presents an in-depth investigation into innovative processes and practical solutions designed to inspire a new generation of thinkers, researchers, and engineers. Each chapter meticulously unpacks the intricacies of various approaches, offering insights for both specialized readers and those new to the subject.

The journey begins with an exploration of waste-to-energy technologies, including incineration, gasification, pyrolysis, and anaerobic digestion, alongside renewable energy sources such as solar, wind, and biomass. Subsequent chapters explore the role of biorefineries in advancing circular economy principles, the immense potential of biomass and biochar in energy storage applications, and the revolutionary possibilities of hydrogen technology.

The book also sheds light on emerging fields, such as composite material recycling and CO_2 capture, offering practical insights into processes including chemical absorption, adsorption, and microbiological methods. The potential of alternative fuels, exemplified by India's Ethanol 100 initiative, is addressed, alongside strategies to embed circular economy principles into the lifecycle management of solar panels, wind turbines, and battery systems.

In addition to these innovative themes, this work emphasizes the importance of regional perspectives, particularly India's role in managing Municipal Solid Waste (MSW) and advancing renewable energy solutions, such as wind power and bioethanol derived from algal biomass. Together, these chapters provide a holistic framework for tackling global sustainability challenges.

It is my privilege to present this remarkable work to readers from diverse backgrounds, including graduate and postgraduate students, researchers, engineers, and policymakers. The comprehensive insights offered in this book ensure that even non-specialist readers can grasp the complexities of each topic and stay abreast of the latest advancements.

This book is a testament to the power of human ingenuity and collaboration in solving some of the most pressing challenges of our time. By bridging the gap between waste management and energy generation, it offers hope for a cleaner, greener, and more sustainable future.

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PREFACE

As the world enters the 21st century, waste management, coupled with energy security, remains a serious challenge. With a growing global population and fast-paced industrialization, the rate of waste generation has skyrocketed, putting tremendous pressure on planetary resources. At the same time, an unbridled quest for energy has propelled innovation towards solutions that are not only effective but also sustainable and environmentally benign. In 2015, all 193 countries finally resolved to work together towards making the world healthier by committing to 17 Sustainable Development Goals for 2030. One of the goals addresses sustainability in terms of affordable and clean energy. The relationship between waste and energy remains a promising avenue for achieving a sustainable future. This encompasses all aims within a single framework: realizing the energy potential of wasted materials while reducing environmental harm, conserving resources, and generating clean energy. This book examines cutting-edge technologies that significantly transform approaches to waste management and energy valorization processes.

This book will be beneficial for graduate and postgraduate students, research scholars, and engineers. Even non-specialist readers have the opportunity to grasp the intricacies of each topic and access the latest content in this book.

Chapter 1 explores various waste-to-energy technologies, including incineration, gasification, pyrolysis, and anaerobic digestion, as well as renewable energy sources such as solar, wind, and biomass. This chapter also explores the optimization of these systems, including process improvements, lifecycle assessments, smart grid integration, and supportive policies.

Chapter 2 explains the role of biorefineries in waste valorization within the circular economy, offering significant potential for advancing sustainability.

Chapter 3 provides information on biomass and its derivatives, which offer great potential as renewable energy sources, making them excellent alternatives for sustainable energy.

Chapter 4 explores the Biomass-derived biochar emerges as a sustainable and efficient material for energy storage applications in supercapacitors.

Chapter 5 introduces the research on hydrogen production, which is crucial for the development of sustainable energy alternatives. Hydrogen technology, which has the potential to revolutionize various industrial applications and significantly contribute to a sustainable, low-carbon economy, is gradually gaining recognition.

Chapter 6 introduces new technologies for recycling composite materials, as well as improvements to existing procedures and their adaptation for alternative applications.

Chapter 7 presents an overview of the primary methods for MSW utilization, aiming to elucidate the current state of MSW management and to assess and compare the environmental impacts of different MSW utilization pathways.

Chapter 8 explores methods for capturing CO_2, including chemical absorption, adsorption using solid-phase porous materials, membrane separation, cryogenic separation, hydrate-based methods, and microbiological methods.

Chapter 9 explores "Ethanol 100: A New Approach for the Transportation Industry in India." This chapter outlines the policy initiatives undertaken, particularly in India, to develop and promote various alternative fuels for road transportation, highlighting the progress made in comparison to global advancements.

Chapter 10 presents the integration of circular economy ethics into the lifecycle management of solar panels, wind turbines, and battery storage systems, thereby ensuring a sustainable energy future.

Chapter 11 investigates the potential of algal biomass for bioethanol production and outlines a model for the complete conversion process.

Chapter 12 provides a comprehensive review of the characteristics, production, collection, disposal, and effective treatment technologies of MSW practiced in India. Incineration, pyrolysis, bio-refining, biogas facilities, recycling, and composting are among the waste management and treatment processes currently used.

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CHAPTER 1

Environmental Waste and Renewable Energy Optimization

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Abstract: The growing challenge of industrial waste management and the increasing global demand for sustainable energy solutions have driven the evolution of Waste-to-Energy (WtE) technologies. This chapter explores integrating environmental waste management with renewable energy generation, focusing on optimizing WtE systems. It covers various renewable energy sources, including solar energy, biomass energy, and wind energy, and examines their potential synergy with waste management practices. Promising WtE technologies are discussed, and successful implementations across different sectors are presented through case studies, showcasing both the benefits and challenges. Additionally, this chapter identifies barriers to the widespread adoption of WtE, suggests future research directions to improve efficiency, and addresses the economic and environmental sustainability of these technologies.

Keywords: Environmental remediation, Energy optimization, Renewable energy.

INTRODUCTION

Global discussions are increasingly dominated by two critical issues: Environmental concerns from industrial waste and the urgent need for renewable and sustainable energy systems. The escalating global waste generation, projected to reach nearly 4 billion tons within the next three decades, underscores the pressing need to transition to circular economy principles [1]. The increasing waste problem, caused by industrialization, consumerism, and population growth, is severely impacting our ecosystems and public health [2]. It offers a favorable

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solution to address these issues by converting waste into usable energy while minimizing environmental impact. Different types of waste are produced by industries, including gaseous, solid, and liquid types, and each poses a unique challenge for disposal and management. For example, solid waste contributes significantly to landfills, and through methods such as open burning and unregulated dumping, approximately 70% of municipal solid waste globally is being inadequately managed. This unhealthy mismanagement contributes to the emission of greenhouse gases and environmental hazards, making it necessary to adopt sustainable waste treatment strategies [3, 4].

Sustainable waste management emphasizes the role of WtE conversion. Space scarcity due to landfilling, substantial energy demands, and environmentally harmful CH_4 emissions represent an increasingly unsustainable approach [1]. Various WtE techniques, namely incineration, pyrolysis, gasification, and anaerobic digestion, offer a dual benefit comprising waste reduction and producing electricity (clean energy), contributing to the global shift towards renewable energy sources. The steel industry, renowned for its substantial waste generation, presents a unique opportunity for transformation. Slag, a residual material from steel manufacturing processes, presents an opportunity for industrial waste to contribute to a circular economy through its extensive utilization in construction and road infrastructure projects [5]. By decreasing dependence on traditional fossil fuels, blast furnace gas contains gases such as CO, H_2, and CH_4, offering opportunities for energy recovery through advanced combustion systems [6]. Toxic heavy metals pose a significant challenge to the effective management of industrial wastewater. Industries such as electroplating, battery manufacturing, and textile production contribute substantially to water contamination by releasing hazardous metals, including lead, cadmium, and mercury, which contaminate aquatic ecosystems and threaten environmental health [5]. The effective reduction of this pollution is achieved through innovative approaches, such as using industrial by-product ash as a low-cost adsorbent [2, 7]. However, the widespread implementation of WtE technologies faces challenges. The widespread adoption of WtE technologies faces several challenges, including substantial initial investment costs, regulatory obstacles, and the imperative for technological improvements to enhance efficiency and environmental compatibility. Furthermore, the integration of WtE systems with sustainable and renewable energy sources, such as solar, wind, and biomass, necessitates sophisticated infrastructure and a supportive policy framework to optimize energy output while minimizing ecological harm. This chapter explores the relationship between waste management and renewable energy optimization, focussing on the role of WtE technologies and their practical applications.

This chapter discusses successful WtE implementations across various industries and outlines promising directions for future research and development based on case studies. By identifying shortcomings in existing practices and proposing groundbreaking approaches, this chapter seeks to drive progress toward sustainable industrial and environmental solutions. To understand the potential of integrating waste management with renewable energy, it is essential to examine key renewable energy sources and how they align with waste-to-energy objectives.

Integration of Renewable Energy with Waste-to-Energy Technologies

To develop effective Waste-to-Energy (WtE) strategies, it is crucial to consider how renewable energy sources, such as solar, wind, and biomass, can complement WtE technologies. Integrating these renewables can help optimize energy output, reduce reliance on fossil fuels, and create more sustainable hybrid systems. The following sections explore each of these energy sources in this context. Currently, the most effective sustainable energy resources are solar, wind, and biomass, which offer potential replacements for hydrocarbon-based fuels and provide sustainable solutions to the energy crisis and climate change. These energy sources not only help to decrease the environmental effects of energy production but also align with waste management practices by transforming waste into a useful resource. The subsequent sections provide an in-depth exploration of each energy source, highlighting their advantages, technologies, and applications in the renewable energy landscape.

Solar Energy

Notably, the Earth receives 173,000 terawatts (TW) of solar radiation daily, 17,000 times more than the current global energy consumption [8, 9]. This indicates that solar energy is an abundant and environmentally friendly energy source. This makes solar power a key player in meeting the escalating global energy needs. Solar energy can be effectively harnessed to generate electricity by employing photovoltaic cells or concentrated solar power systems. Recent advancements in technology, such as the development of multi-junction photovoltaic cells, have significantly increased their efficiency, with some reaching approximately 34.1% [9]. Solar energy also benefits from its minimal environmental impact, as it uses little to no water, making it a sustainable energy source [8]. Around the globe, many countries can generate electricity using solar energy during the daytime. However, a key limitation is that the energy generated during peak periods must be stored for use during times of low solar energy production. Hence, we need efficient batteries that can store the excess solar energy produced during the day for use at night. Efficient batteries can provide a

CHAPTER 2

Valorizing Waste: The Role of Biorefineries and Bioproducts in the Circular Economy

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Abstract: In the rising quest for a sustainable future, the circular economy has emerged as a transformative model that prioritizes the continuous use of resources, minimizing waste and environmental impact. Central to this model are biorefineries, which offer an innovative solution for valorizing waste streams by converting them into valuable bioproducts and bioenergy. This chapter explores the pivotal role of biorefineries in the circular economy, examining their ability to transform agricultural residues, industrial by-products, and municipal waste into a diverse array of bio-based products, including biofuels, biochemicals, and biomaterials. The chapter opens with an overview of the circular economy framework, emphasizing the shortcomings of traditional linear production models and the environmental burden posed by escalating waste accumulation. It then delves into the principles and technologies underlying biorefineries, with particular attention to the integrated processes that enable the efficient conversion of biomass into a variety of high-value products. Special attention is given to selecting feedstocks, pre-treatment methods, and bioconversion techniques that maximize resource efficiency and product yield. Through case studies and real-world examples, the chapter demonstrates how biorefineries are actively contributing to the circular economy by closing resource loops, decreasing dependence on fossil fuels, and generating new economic opportunities. The discussion also addresses the scalability of biorefinery technologies and the financial, regulatory, and technological barriers that must be overcome to realize their full potential. By valorizing waste, biorefineries help to decouple economic growth from resource depletion, paving the way for a more sustainable and resilient industrial future.

Keywords: Biorefineries, Bio-based products, Bioconversion, Circular economy, Sustainable production, Waste valorisation.

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INTRODUCTION

The world is confronting the severe consequences of massive waste generation resulting from a wide range of human activities. Growing population demands have intensified environmental challenges, including resource depletion, climate change, and rising pollution levels. Therefore, there is a dire need for urgent and innovative solutions to overcome these challenges, and it also requires shifting from a 'take-make-use-dispose' economic model to a circular economic model [1]. In the current context, the circular economy framework emerges as a transformative paradigm for promoting resource efficiency, minimizing waste, and fostering sustainability, while recovering value-added products from various waste streams [2]. Within this framework, biorefineries play a crucial role in transforming waste into various value-added bioproducts that can be utilized for multiple applications. Biorefineries are integrated facilities that convert waste biomass derived from plants, animals, and microbial resources into various products, including biofuels, bioplastics, and biochemicals [3]. These facilities utilize renewable biological resources to produce valuable bioproducts, paving the way for reduced reliance on fossil fuels and generating wealth from waste. Adopting biorefineries facilitates sustainable production, reduces the emission of greenhouse gases, and promotes economic independence by managing various biological wastes. The application of advanced technologies, such as fermentation, anaerobic digestion, and gasification, for optimizing biomass into high-value products highlights the crucial role of technology and innovation in achieving sustainable development. Biorefineries play a significant role in job creation and economic growth by transforming waste into valuable bioproducts [4]. They stimulate the emergence of new industries and markets, thereby bolstering local economies while simultaneously tackling global sustainability challenges. Therefore, it is essential to evaluate the role of biorefineries in valorizing waste. This chapter will therefore explore the diverse array of bioproducts generated from waste, with a focus on their applications across various sectors, including agriculture, packaging, and pharmaceuticals. The case studies demonstrating successful implementations, cutting-edge technologies, and the socio-economic advantages of integrating biorefineries in local and global contexts have been included. Ultimately, this investigation seeks to underscore the pivotal role of biorefineries and their associated bioproducts in advancing the circular economy. It emphasizes that waste should not be regarded merely as a burden to be managed, but as a valuable resource capable of enhancing sustainability and resilience in modern societies.

The Concept of Circular Economy

The circular economy is a sustainable production and consumption model that emphasizes reducing waste, reusing materials, and recycling resources to extend the lifecycle of products. Thus, the circular economy aims to recover resources through a regenerative use cycle that traditional waste management techniques would otherwise discard. It aims to tackle global challenges such as climate change, biodiversity loss, and pollution, and paves the way for a future that supports ecological balance, social equity, and economic prosperity. It replaces the linear economy that relies on "take, make, dispose of" (Fig. (**1**) through conceptual design, new technology approaches, scale-up, and commercialization, emphasizing and proposing waste design from the outset and maintaining a balance between progress and sustainability [5]. According to the UNECE (2024), waste valorization has played a crucial role in promoting the circular economy. This approach encourages a more sustainable and efficient use of resources by converting waste into secondary raw materials. According to a survey by the United Nations Industrial Development Organization (UNIDO, 2021), global trade in various types of waste experienced steady growth between 2002 and 2019, indicating the existence of an active and expanding market for these materials. In recent years, worldwide, it has been observed that there is a tremendous acceleration toward a circular economy. The market is predicted to reach USD 517.79 billion in 2025 and USD 798.3 billion by 2029, with a remarkable compound annual growth rate of 11.4%. This surge highlights not only increasing awareness but also strong policy support, technological innovation, and private-sector investment aimed at reducing waste and maximizing the production of valuable products [6].

The circular economy is based on three core pillars:

Creative process design: It focuses on redesigning the production system to reduce waste and pollution.

Circular Experimental Data: This involves experimental data or design that keeps resources in use longer through reuse, repair, and remanufacturing, thereby reducing the need for new raw materials.

Regenerating Modelling and analysis: The circular model aims to restore and enhance natural ecosystems, ensuring long-term environmental sustainability and resilience. Utilizing methods such as LCA and system dynamics enables data-driven decision-making, optimizes resource utilization, and facilitates the design of an efficient circular system.

CHAPTER 3

Biomass-Derived Biochar Materials as Sustainable Energy Resources and Their Assessment

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Abstract: The rise in global warming, environmental pollution, and population growth has significantly increased energy consumption, leading to greater dependence on fossil fuels. Biomass and its derivatives offer substantial potential as renewable energy sources, making them promising alternatives for sustainable energy conversion, storage, and production. Through pyrolysis, biomass produces a porous, carbon-rich solid material called biochar. A green and sustainable platform for preparing various functional carbon materials is provided by biochar materials derived from biomass. The various types of biomass exhibit distinct physical and chemical properties. In this chapter, a summary of various methods used for preparing different types of biomass-derived biochar materials is provided. An investigation into the numerous potential applications of biomass in environmental reduction and its mechanisms has been conducted. Further assessment of these materials, including their properties and the challenges involved, is also discussed.

Keywords: Biomass, Biochar, Cellulose, Hemicellulose, Hydrothermal carbonization, Lignin, Organometallic compounds.

INTRODUCTION

Oil, natural gas, and coal are among the primary fossil fuels used to power various sectors, and they have significantly contributed to meeting the growing global

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energy demand. However, the rapid depletion of these resources, along with their environmental impact and the escalating demand for energy, underscores the urgent need for clean and sustainable alternatives [1]. Renewable energy systems—such as wind, hydrothermal, geothermal, and solar—often rely on intermittent sources, making efficient energy storage devices essential for storing surplus energy during peak production periods and supplying it when demand increases [2, 3]. Among all the elements, carbon is the fourth most plentiful element in the cosmos and the second highest component in the biosphere. Carbon is a fundamental element that underpins all life on Earth, including plants and animals, and plays a vital role in the energy supply chain through the formation of carbohydrates, which consist primarily of carbon, hydrogen, and oxygen atoms. In addition to the usable portions of plants and animals, the remaining or unused parts constitute biomass—a term that refers to natural organic materials, including plant matter, animal matter, and their wastes [4, 5]. Biomass primarily comes from forests and crops, as well as their post-harvest residues, which are among the most abundant resources, including plants and their residues. Generally speaking, these wastes are frequently burned in areas that pose a significant environmental threat due to pollution and greenhouse gas emissions. However, when biomass is processed into bioethanol, biogas, or solid pellets, it serves as an effective feedstock for energy generation and a valuable source of carbon-based raw materials for producing various commodities [6]. Biomass, used as a renewable source for the production of biochar, (*i.e.* carbon and advanced carbon materials) has recently attracted a lot of research interest in the development of materials that may be important in a variety of applications, including dye degradation, environmental remediation, energy storage devices, hydrogen storage, photovoltaics and carbon (CO_2) capture and storage [7 - 13]. Rapid population growth, along with economic and industrial development in recent years, has contributed to significant environmental and energy-related challenges. Over the past few decades, fossil fuel usage has increased due to the outdated waste management system and the growing energy demands of industry and communities. Even while fossil fuels have many benefits, including affordability, compatibility, and ease of access, they are non-renewable resources that could potentially run out in the future and produce significant greenhouse gas emissions [14]. Therefore, turning waste into eco-friendly and efficient products, and creating eco-friendly and renewable technologies for the production of energy, its storage, and use, are crucial worldwide concerns that must be addressed. However, throughout the pollutant's degradation process, the chemical energy present in pollutants is disregarded and wasted, while traditional waste treatment procedures primarily concentrate on eliminating or destroying the pollutant molecules [15]. To achieve carbon neutrality, the wasted energy is manifested in increased power consumption, higher costs in physicochemical processes or biomass generation, and additional costs throughout the life cycle. Finding appropriate technology to meet the growing demand for sustainable energy and waste treatment on a worldwide scale is therefore crucial. The heated disintegration of biomass, obtained from plants or animals, decomposed thermally without oxygen, produces biochar —a carbonaceous solid substance that is porous, with aromatization on the higher side, and is resistant to degradation [16]. Due to its diverse applications in various industrial and agricultural processes, it has garnered considerable attention recently. The numerous physicochemical properties of biochar have a substantial influence on its diverse range of uses [17]. According to the latest data, the material and production process have a significant impact on the properties of biochar, including density, porosity, pH, and concentrations of elemental ingredients. These properties collectively determine the suitability of biochar for various applications. It is widely used in waste treatment across multiple sectors to remove organic and inorganic contaminants, including pigments and dyes from textile effluents [18, 19].

It is used in agriculture to improve the soil's quality. It improves the quality of the soil by slowing down the rate at which nutrients degrade [20, 21]. Due to its high carbon content, biochar can be advantageous for generating power, as it can be used as a fuel [22]. It has been determined that biomass is a good source of minerals, chemicals, and renewable energy [23]. Biomass of any kind might be used to manufacture bio-oil and biochar [24]. However, the abundance of feedstock is reduced by the high cost of manufacturing and regulatory restrictions [25].

Sources of Biomass

The primary sources of biomass feedstock include digestate, energy crops, crop residues, animal waste, agricultural waste, algae biomass, and activated sludge [26, 27]. Biomass can be categorized based on its composition, source, and properties, as outlined below:

Forestry

Forest biomass has historically played a vital role in the development of human society through the utilization of various forest components, including timber, bark, branches, leaves, and roots. Traditional forest biofuels, including firewood and charcoal, are still widely used in many regions around the world.

One of the primary sources of forest biomass is the material obtained from harvesting trees and their by-products. Additionally, energy crops represent another significant source. These crops are cultivated specifically for energy production and are considered cost-effective and low-maintenance. Energy crops

CHAPTER 4

Biomass-Derived Biochar for Supercapacitor Applications: A Sustainable Approach to Energy Storage

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Abstract: Biochar is a carbonaceous material derived from biomass through pyrolysis. It can be used to serve as a sustainable platform for producing various functional carbon materials, such as porous carbon, carbon nanotubes, heteroatom-doped biochar, carbon quantum dots, and graphene. These materials are synthesized through physical and chemical activation processes, taking advantage of biochar's versatile physicochemical properties for electrochemical energy storage applications, particularly supercapacitors. Biochar exhibits a high specific surface area (> 1000 m^2/g), large pore volume (> 0.5 cm^3/g), and high electrical conductivity (10-100 S/m). These characteristics enhance supercapacitor performance metrics, including capacitance, energy density, power density and cycling stability. Studies show that biochar obtained from various feedstocks like agricultural residues and municipal waste can boost supercapacitor's performance while also helping with waste management and carbon sequestration. However, challenges like scalability, cost and optimization of biochar properties persist. Future research will focus on the integration of biochar with advanced materials like graphene and MXenes to further improve its electrochemical performance, showing its potential as a viable and eco-friendly material for next-generation energy storage technologies.

Keywords: Biochar, Electrochemical performance, Energy storage, Supercapacitors, Sustainability.

INTRODUCTION

As global energy demands increase and the environmental impacts of fossil fuels become more evident, the need for sustainable and efficient energy storage solutions has gained unprecedented urgency. Among the promising materials under investigation, biomass-derived biochar has emerged as a compelling and

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eco-friendly option for enhancing energy storage technologies, particularly in supercapacitors. This article provides an in-depth exploration of biochar, its production, and applications in supercapacitors, supported by recent research and practical examples that highlight its potential.

Biochar is a carbon-rich material produced through the pyrolysis of organic biomass, such as agricultural residues, forestry by-products, or municipal waste [1, 2]. Pyrolysis is a thermochemical decomposition process carried out in the absence of oxygen that converts biomass into a stable form of carbon. The resulting biochar has a high surface area, significant porosity, and excellent electrical conductivity, making it highly suitable for various applications, including energy storage. The production of biochar typically involves heating the biomass to temperatures ranging from 300-800°C [3 - 5]. During this process, volatile compounds are released, leaving behind a solid carbonaceous material. The specific pyrolysis conditions, such as temperature, heating rate, and duration, affect the properties of the resulting biochar [3]. For instance, higher temperatures generally lead to increased carbon content and enhanced electrical conductivity of biochar, while lower temperatures tend to increase surface area and porosity [6 - 8]. The production of biochar offers significant environmental advantages, converting waste materials into a valuable resource while simultaneously sequestering carbon and reducing greenhouse gas emissions. Research has shown that biochar can store carbon in a stable form for hundreds or even thousands of years, thereby playing a role in mitigating climate change [1]. Recent studies have focused on the doping of biochar with heteroatoms such as boron (B), phosphorus (P), sulfur (S), and nitrogen (N) to enhance its performance as a supercapacitor electrode material [9, 10]. Fig. (**1**) illustrates the preparation methods for heteroatom-doped biochar, which typically involve a two-step process: carbonization followed by pyrolysis in an inert atmosphere [6]. This approach allows for the incorporation of heteroatoms into the biochar structure, thereby improving its electrical conductivity, surface area, and electrochemical properties, ultimately leading to enhanced supercapacitor performance.

Supercapacitors and Their Energy Storage Mechanism

Supercapacitors, also known as ultracapacitors or Electric Double-layer Capacitors (EDLCs), are advanced energy storage devices characterized by high power density, rapid charge/discharge capabilities, and long cycle life [2]. Unlike conventional capacitors and batteries, supercapacitors store energy through electrostatic charge accumulation rather than relying on chemical reactions. A typical supercapacitor consists of two electrodes, an electrolyte, and a separator. When a voltage is applied, ions from the electrolyte accumulate on the electrode surfaces, forming an electric double layer that stores energy, which can be discharged rapidly when needed. The performance of supercapacitors is largely determined by the properties of the electrode material, including surface area, conductivity, and porosity [7, 9]. In comparison to batteries, supercapacitors offer higher power density and faster charge/discharge rates but generally have lower energy density. Batteries, conversely, provide higher energy density but are typically characterized by slower charge/discharge rates and shorter cycle lives. As a result, supercapacitors are particularly well-suited for applications that require rapid bursts of energy and frequent cycling, such as regenerative braking in electric vehicles and power backup systems.

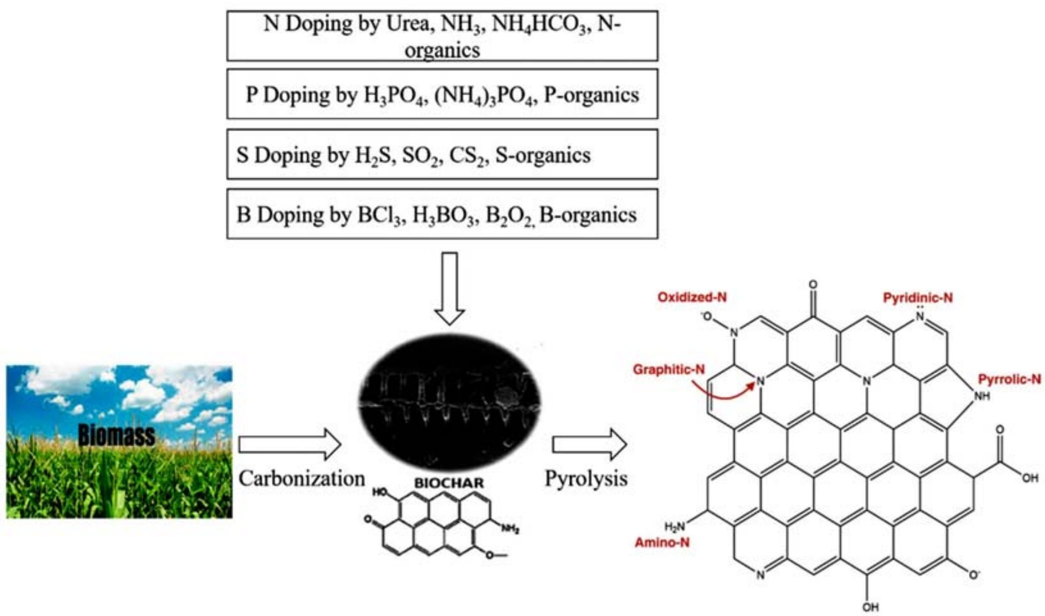

Fig. (1). Schematic diagram to prepare heteroatom doped biochar. Reprinted from ref [6]. Copyright 2020, with permission.

The unique physical and chemical properties of biochar make it an attractive candidate for use in supercapacitor electrodes (Fig. **2**) [1]. Its high surface area, porosity, and electrical conductivity significantly enhance its performance in energy storage applications. The porous structure and extensive surface area of biochar are crucial for increasing the capacitance of supercapacitors, as they enable a greater accumulation of charge. For instance, a study by Ray *et al.* demonstrated that hierarchical porous biochar derived from rice husks treated with NaOH exhibited a specific surface area (307.42 m^2/g) and high porosity, leading to a high capacitance value of 112 F/g at a current density of 0.5 A/g in supercapacitor applications [2]. Furthermore, the electrical conductivity of biochar is a critical factor in its performance as an electrode material. The carbon

CHAPTER 5

Hydrogen Technology and Its Industrial Applications

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Abstract: The potential of hydrogen technology to revolutionize different industrial applications and contribute considerably to a sustainable, low-carbon economy is gradually being acknowledged. Research in hydrogen production is crucial for the development of sustainable energy alternatives. Hydrogen is in high demand because of its significant heating value, which makes it well-suited for a variety of uses, such as aircraft fuel, steel manufacturing, and power storage in fuel cells. The progress in green hydrogen generation systems is highly encouraging, as they provide a means to fulfill future energy needs while reducing environmental harm. Hydrogen-generating technology can be classified into two primary categories. The methods used for producing hydrogen from fossil fuels include partial oxidation, steam reforming, and autothermal reforming. Renewable sources-based hydrogen production encompasses many biomass processes, including bio-photolysis, photo-fermentation, dark fermentation, pyrolysis, gasification, combustion, and liquefaction. Additionally, water splitting methods, such as thermolysis, photolysis, and electrolysis, are utilized. Hydrogen technology has favourable prospects for reducing carbon emissions. However, it is crucial to acknowledge that we should use hydrogen in conjunction with other renewable energy technologies rather than relying solely on it as a standalone solution. Its industrial uses are found in the chemical industry, metallurgical sector, transport, and energy storage. Although there are several positive attributes, there are also challenges associated with investment, infrastructure, and technological advancements.

This chapter discusses the production technologies for hydrogen, like electrolysis, reforming, and photocatalysis, and also briefly discusses various methods for storing hydrogen. The main focus of this chapter is its industrial applications across various domains, including power generation, aviation, and various industrial processes. Despite these advantages, hydrogen production and applications have some limitations, which we also discuss with a future perspective.

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Keywords: Applications of H_2, Compressed hydrogen storage, Electrolysis, Hydrogen (H_2), Liquid hydrogen storage, Medical, Photocatalysis, Steam methane reforming, Storage of hydrogen, Solid-state hydrogen storage.

INTRODUCTION

Hydrogen technology signifies a promising advancement in the pursuit of sustainable and carbon-free energy. H_2 serves as an energy carrier in several forms, presenting the opportunity to decarbonize businesses and mitigate greenhouse gas emissions. This chapter concentrated on the generation, storage, and use of hydrogen, especially for industrial and energy purposes, as shown in Fig. (**1**). Hydrogen is produced through various means, like electrolysis, steam methane reforming, and photocatalysis, with electrolysis being the predominant technique.

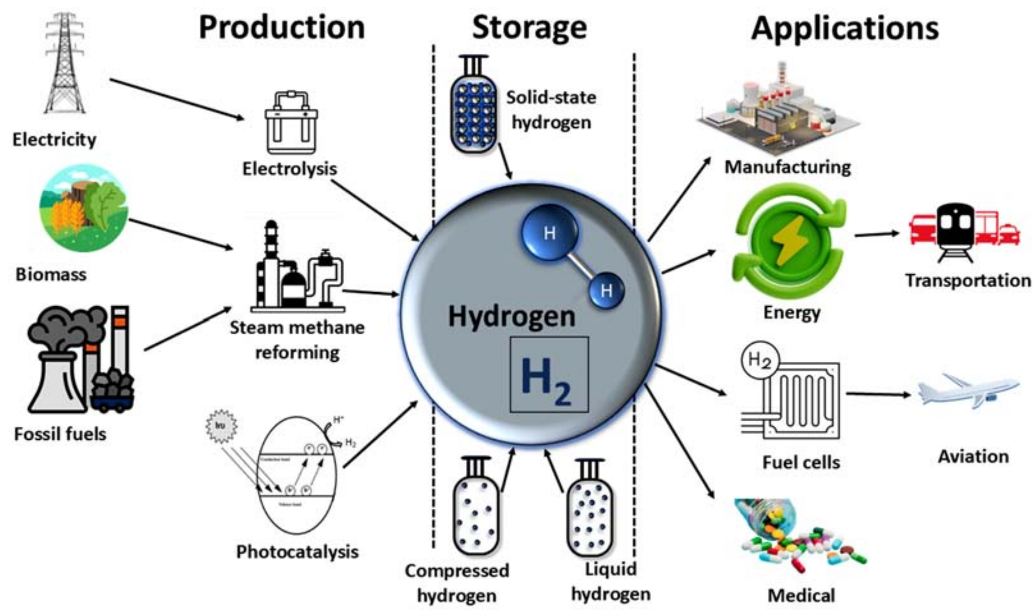

Fig. (1). Schematic diagram of hydrogen production, storage, and applications [14 - 16].

Production and Storage of Hydrogen

The production of H_2 is primarily divided into three technologies: electrolysis, steam methane reforming, and photocatalysis. Electrolysis is a viable method for generating carbon-free hydrogen. In electrolysis, electrical energy is used to decompose water into its constituent elements, oxygen and hydrogen. This process occurs within a device known as an electrolyzer. Electrolyzers have a cathode and an anode divided by an electrolyte. Various electrolyzers operate distinctly, depending on the electrolyte materials utilized and the type of ions they conduct.

Under elevated pressure and temperature conditions, SMR uses methane to generate hydrogen. Methane is a chemical molecule represented by the formula CH_4 and is a key component of natural gas. The conventional steam methane reforming process has four primary units: the desulfurization unit, the reforming unit, the shift reactor, and the separation unit.

Photocatalytic H_2 generation is a technique that utilizes photons to dissociate water molecules into oxygen and hydrogen. A photocatalyst, often a semiconductor, is suspended in water and exposed to light irradiation. The light generates electron-hole pairs that dissociate water into oxygen and hydrogen. Photocatalytic hydrogen generation is regarded as a promising, cost-effective, and eco-friendly method. Titanium dioxide (TiO_2) is a widely utilized photocatalyst due to its non-toxicity, chemical stability, and cost-effectiveness. Recent hydrogen-generating techniques include photoelectrochemical (PEC) water splitting and biological hydrogen synthesis. PEC water splitting electrolyzes water with semiconductors and solar energy. Solar energy generates hydrogen, making it a renewable energy source. To make PEC systems commercially viable, titanium dioxide (TiO_2) and other hybrid materials are being studied for their efficiency and scalability. Biochemical hydrogen production employs algae, bacteria, and fungi. This method is popular since it employs organic waste and operates under mild conditions. Scalability and efficiency concerns require additional investigation to enhance these systems for large-scale hydrogen production.

There are primarily three different kinds of hydrogen storage methods. Compressed hydrogen storage is the predominant process, entailing the containment of H_2 gas within high-pressure cylinders. It is economical and facilitates swift charging and discharging, although it possesses low volumetric density [1]. Liquid hydrogen storage, in which hydrogen is cooled to cryogenic temperatures to get a liquid state, hence providing excellent storage efficiency [2 - 4]. Compressed hydrogen storage is an essential technology for hydrogen fuel applications, especially in automotive contexts. This approach has shown notable improvements in safety, efficiency, and cost-effectiveness, rendering it a feasible candidate for commercialization [5]. The current hydrogen refueling infrastructure primarily utilizes compressed gas stations, thereby simplifying market entry. Material innovations comprise Contemporary tanks that are fabricated from high-strength carbon-composite materials, which improve safety and performance [6, 7].

CHAPTER 6

State-of-the-Art Recycling Technologies for Composite Materials

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Abstract: There is a lot of interest in the development of new technologies for composite materials recycling, as well as in the improvement of the existing procedures and their adaptation for alternative applications. Since numerous sorting techniques have been developed and tested to recover recyclable components from a waste stream, this chapter aims to elucidate the state-of-the-art materials identification technologies for waste sorting. The survey revealed that, aside from the commonly used set of identification methods for analyzing the quantitative and qualitative elemental compositions of the inspected materials (X-ray fluorescence, XRF) and their molecular structure (near-infrared spectroscopy, NIR) assisted by visual (VIS) spectroscopy, some of the less conventional methods, such as Raman spectroscopy, Laser-induced breakdown spectroscopy (LIBS), and even X-ray transmission (XRT) spectroscopy (traditionally employed for the mining and mineral processing industry), have been proposed either as individual or supplementary techniques for advanced hybrid technologies. The evolution of machine learning and artificial intelligence tools has already contributed to the improvement of material classification accuracy based on measurement data. This chapter contains a brief description of the adopted and prospective identification technologies with their principal illustrations and a presentation of the latest advances in their implementation for waste sorting.

Keywords: Composite materials, Materials identification, Plastics, Spectroscopy, Sorting, Waste recycling.

INTRODUCTION

Municipal Solid Waste (MSW) represents a mixture of paper, plastics, clothing, metals, glass, food, and other types of household waste. The world's annual production of MSW constitutes over 2 billion tons and, according to forecasts, will skyrocket up to about 4 billion tons by 2100. Thus, the increasing amount of Municipal Solid Waste (MSW) has gradually become one of the acute problems that hampers the global movement toward economic, environmental, and social

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prosperity. To address this issue and promote the development of a circular economy and sustainable cities, it is essential to prioritize the sorting of recyclable materials, particularly plastics [1, 2].

At present, the predominant sorts of commonly used plastics include polyethylene terephthalate (PET), polypropylene (PP), high-density polyethylene (HDPE), and low-density polyethylene (LDPE)—altogether contributing over 50% of the plastic residues present in municipal solid waste, as well as polystyrene (PS), polyvinyl chloride (PVC), and some other sorts of plastic. The listed polymers are widely used as one-part materials as well as components of composite and multi-layer materials. The problems associated with Plastic Waste (PW) handling are that it is often represented by mixtures of different plastics with unknown compositions and can contain organic contaminants or other materials (paper, metal, *etc*.). Packaging waste accounts for over 61% of PW, with the following shares of individual plastics: PE > PP > PET> PS > PVC [3].

The current alternatives for PW handling include recycling, incineration, and burying at landfills (Fig. **1**). In 2020, over 29 million tons of post-consumer PW were collected in European Union countries. As much as 23.4% of that amount went to landfills, 34.6% was subjected to recycling, and 42% was utilized through incineration with energy recovery [4]. Recycling is the most rational approach to plastic waste handling, which employs a variety of chemical, mechanical, and thermochemical methods to convert PW into either raw materials with their properties close to those of the original ones, or into valuable substances (gaseous and liquid fuels, monomers, *etc*.), or some functional composite materials by their combining with different additives. However, a relatively low level of PW recycling has been observed so far, and the major reasons for this typically include the unsatisfactory quality of the resulting products, high energy demand, and the complexity of the processing methods.

Sorting

Effective waste recycling requires the execution of certain preparatory procedures, the first of which is the reliable sorting of the waste streams in order to extract recyclable components. Automated waste sorting encompasses both direct and indirect sorting methods. Direct sorting can be performed through air separation, magnetic separation, magnetic levitation, Eddy Current Separation (ECS), the dense medium method, and the electrostatic method. It is intended for direct solid waste separation using electromagnetic force, buoyancy, electric field force, and other methods. In the case of indirect sorting, the separation of the supplied stream into recyclable items and the remaining waste mass is preceded by the identification of the former ones by their material. Materials identification can be performed by a variety of methods, which comprise Delayed and Prompt Gamma Neutron Activation Analysis (DGNAA and PGNAA), Neutron Radiography (NR), X-ray fluorescence (XRF), dual-energy X-ray transmission (DE-XRT) scanning, dual-energy γ-ray transmission (DE-γRT), X-ray luminescence (XRL), Raman spectroscopy, laser-induced fluorescence spectroscopy (LIFS), Laser-induced breakdown spectroscopy (LIBS), visual (VIS) spectroscopy, infrared (IR) – visible to near-infrared (VNIR), Near-infrared (NIR), short-wavelength infrared (SWIR), Mid-wavelength infrared (MWIR), Long-wavelength infrared (LWIR), Far-infrared (FIR) – spectroscopy, terahertz (THz) spectroscopy, Microwave Imaging (MWI), radiofrequency radiation based techniques, electric conductivity, Thermal Imaging (TI), Impact Acoustic (IA) method, and their combinations [5 - 8]. Since existing techniques are continually updated and new ones are constantly introduced and adapted, it would be helpful to survey the current state of the art methods in this domain of knowledge.

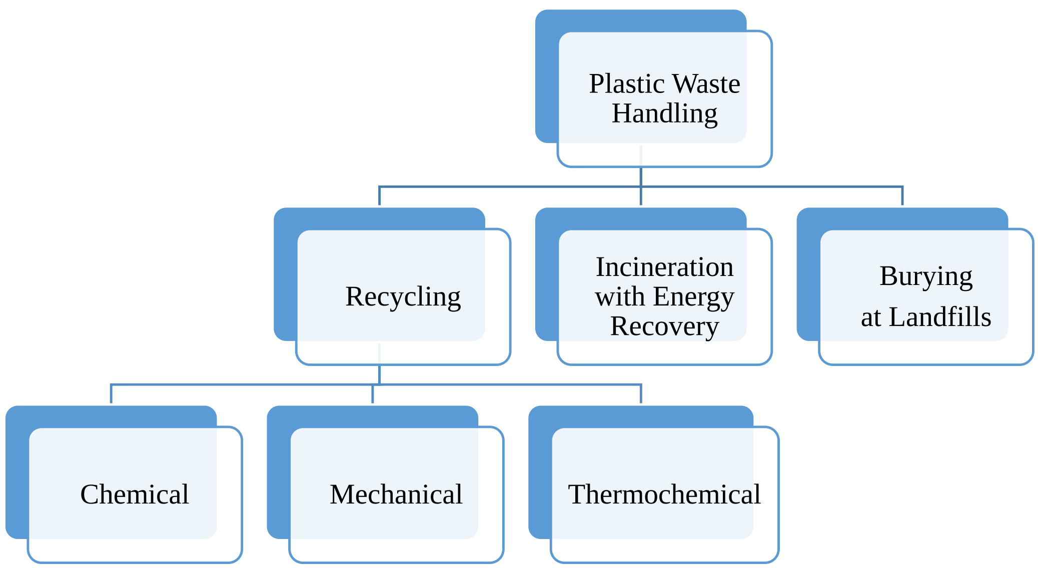

Fig. (1). Conventional approaches to waste handling.

Neutron and γ-Ray Based Methods

Delayed and Prompt Gamma Neutron Activation Analysis

Delayed and Prompt Gamma Neutron Activation Analysis (DGNAA and PGNAA) are the methods designed initially for scanning radioactive waste packages for non-radioactive substances, with the typical sample masses on the order of 0.001–1 g. PGNAA is based on the measurement of γ-radiation (wavelength, $\lambda < 10^{-11}$ m) emitted promptly (after 10^{-16}–10^{-12} s) due to the de-

CHAPTER 7

Approach for Smart Municipal Solid Waste Management and a Sustainable Circular Economy

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Abstract: The global increase in Municipal Solid Waste (MSW) presents a significant challenge to the sustainable development of humanity. The waste generation rate continues to increase with population growth, urbanization, and economic development. The presented chapter overlooks the main methods of MSW utilization in order to elucidate the current state of MSW management as a whole and to assess and compare the environmental impact of different MSW utilization pathways. Consideration includes references to regional aspects. The current state of MSW management worldwide and the assessment of environmental impact from different MSW utilization pathways are described in the presented work. Analysis is based on the collection of data on MSW and its component properties determined experimentally.

Keywords: Classification, Composting, Chemical composition, Generation rate, Heating value, Incineration, Landfill, Municipal solid waste, Management, Recycling, Utilization.

INTRODUCTION

Today, the waste utilization problem is one of the main challenges on the path to the sustainable development of the economy and society as a whole. Humanity forms waste through both its economic activities and household life. Municipal Solid Waste (MSW) is a type of waste generated primarily by the urban population. MSW requires special attention, such as sustainable management practices, due to its proximity to people. The primary methods for MSW utilization today are landfill disposal, composting, recycling, and incineration. A

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considerable portion of Municipal Solid Waste (MSW) is currently managed through landfill disposal, where the decomposition processes release landfill gases containing methane, a potent greenhouse gas contributing significantly to global warming. One of the key thermochemical methods utilized for MSW management is incineration. MSW incineration also leads to the emission of greenhouse gases into the atmosphere, but it is accompanied by useful energy generation and should reduce the consumption of primary energy resources.

The presented paper overlooks the main methods of MSW utilization in order to elucidate the current state of MSW management as a whole and to assess and compare the environmental impact of different MSW utilization pathways. Consideration includes references to regional aspects.

MSW management in different regions of the world varies from one another. It depends on many factors, including the economic development of a region, its degree of urbanization and industrialization, culture, and climate, among others. Modern methods of MSW utilization are primarily implemented in high-income countries, whereas in developing countries, only one or two main methods dominate the MSW management system [1, 2]. The conversion of MSW into valuable secondary materials or energy represents a central focus of global research and development initiatives in the field of waste management. Efforts are increasingly being directed towards diversifying waste-to-energy technologies through alternatives such as gasification, pyrolysis, and torrefaction [3 - 5]. Nevertheless, these methods encounter various challenges due to the heterogeneous nature of MSW, its low density, high Moisture Content (MC), and the presence of potentially hazardous substances. Therefore, knowing or predicting the properties of MSW is crucial for the effective application of any thermochemical or mechanical treatment method. One of the main objectives of this work is to study MSW characterization data to estimate the recycling level and energetic potential of MSW and to evaluate its environmental impact. This work includes the study of the main properties of MSW of different regions of the world, as well as separate components and ingredients that are usually presented in MSW.

MSW Definition

Solid waste streams are categorized based on their origins, methods of generation, production rates, compositions, and physical characteristics. According to the World Bank, there are eight primary sources of solid waste: residential, industrial, commercial, institutional, construction and demolition, municipal services, agricultural, and process-related sources. The specific types of waste produced by each of these sources are summarized in Table **1**. It is important to note that the term "municipal solid waste" is used variably in the literature to describe waste derived from diverse sources, which can lead to inconsistent reporting of MSW quantities for the same region. In practical application, MSW incorporates waste from multiple sources, depending on the region, often including residential, industrial, commercial, institutional, construction, municipal services, and process-related waste. Often, only residential waste is referred to as MSW, and in high-income countries, it accounts for 25-35% of the total solid waste [6].

Table 1. Major waste sources and waste compositions according to the World Bank classification [6].

Waste Sources	Waste Producers	Waste Composition
Residential	Single and multifamily dwellings	Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, metals, ashes, special wastes (*e.g.*, bulky items, consumer electronics, white goods, batteries, oil, tires), and household hazardous wastes.
Industrial	Light and heavy manufacturing, fabrication, construction sites, power, and chemical plants.	Housekeeping wastes, packaging, food wastes, construction and demolition materials, hazardous wastes, ashes, and special wastes.
Commercial	Stores, hotels, restaurants, markets, office buildings, etc.	Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes.
Institutional	Schools, hospitals, prisons, and government centers	Same as commercial.
Construction and demolition	New construction sites, road repairs, renovation projects, and demolition of buildings.	Wood, steel, concrete, dirt, etc.
Municipal services	Street cleaning, landscaping, parks, beaches, other recreational areas, water, and wastewater treatment plants.	Street sweepings; landscape and tree trimmings; general wastes from parks, beaches, and other recreational areas; sludge.
Process	Heavy and light manufacturing, refineries, chemical plants, power plants, mineral extraction, and processing.	Industrial process wastes.
Agriculture	Crops, orchards, vineyards, dairies, feedlots, farms.	Spoiled food wastes, agricultural wastes, and hazardous wastes (*e.g.*, pesticides).

CHAPTER 8

Sustainable Carbon Dioxide Capture Technologies

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Abstract: This study presents a comparison of the primary methods for capturing CO_2, followed by an examination of CO_2 utilization techniques. Special attention is given to the bioutilization of CO_2, particularly the use of microalgae. The potential of microalgae for CO_2 capture and as a source of renewable energy is emphasized.

Keywords: Biofuel, Biomass, CO_2 capture, Greenhouse effect, Microalgae.

INTRODUCTION

Over the past two centuries, the world's population has grown from 1 billion to 8 billion, and the average life expectancy has nearly doubled. To provide energy for such a large population and support economic development, it is essential to have access to appropriate energy resources. For the past few decades, fossil fuels have been the primary source of energy. According to 2021 data, over 80% of all the energy consumed globally comes from fossil fuels, including coal, oil, and natural gas [1]. However, the extraction and use of these traditional energy sources are not environmentally sustainable, as they release gases into the atmosphere that contribute to the greenhouse effect. The greenhouse effect refers to the increase in temperature of the Earth's lower atmosphere compared to its thermal radiation balance, driven by a rise in the concentration of specific gases. Greenhouse gases include CO_2, CH_4, N_2O, NO, NO_2, O_3, water vapor, and certain chemical industry products, such as halogenated hydrocarbons and hydrofluorocarbons [1]. NO_2, O_3, water vapor, and certain chemical industry products, such as halogenated hydro-

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carbons and hydrofluorocarbons [1]. To account for the wide range of potential greenhouse gases, a simplified model is often used, measuring them in units of Gt CO_2, as CO_2 is the most prevalent. In 2020, CO_2 emissions totaled 35 gigatons (Gt), while overall greenhouse gas emissions were 60 gigatons (Gt) in CO_2 equivalents [2]. The increase in these concentrations in the atmosphere has led to a significant rise in global temperatures. Notably, the average temperature deviation during the peaks of 2016 and 2020 was +1.66 °C above the baseline established in 1862 [3].

Research on the greenhouse effect has led to the formation of various advisory groups, national political programs, and international meetings involving representatives from many countries. The to establish plans, criteria, and targets for reducing greenhouse gas emissions and transitioning toward a net-zero greenhouse gas policy. The first major intergovernmental agreement on this issue was the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992. Since its inception, the agreement has been frequently updated as new data have become available, such as with the Kyoto Protocol in 1997, which serves as a supplementary agreement to the original UNFCCC. The most recent significant intergovernmental initiative on greenhouse gas reduction is the "Fit for 55" package, adopted by the European Union in 2022. This initiative aims to reduce greenhouse gas emissions by 55% compared to 1990 levels by 2030 [4]. However, current data indicate that these agreements, like others before them, have yet to result in significant reductions in greenhouse gas emissions. Notably, the only periods during which emissions decreased since 1992 were 2009, due to the global financial crisis, and 2020, due to the COVID-19 pandemic [3].

CO_2 Capture Methods

To address the challenges of reducing the greenhouse effect, several CO_2 capture technologies are being developed [2]. These technologies can be divided into 3 groups. Before considering them in more detail, it is worthwhile to examine their advantages and disadvantages, as presented in Table **1**. Due to the substantial investment required, pre-combustion and oxyfuel combustion technologies have undergone limited applied research and development. In contrast, post-combustion capture is widely used in the industry and is considered a relatively mature technology, offering high selectivity and efficient CO_2 capture [5]. The following sections will provide a brief overview of the various CO_2 capture methods, with a primary focus on those employed to capture CO_2 after the combustion of hydrocarbon fuels.

Methods of CO_2 Capture

Chemical Absorption

The chemical absorption method typically involves the use of solvents, such as weak alkaline solutions, to react with carbon dioxide, resulting in a compound that contains CO_2 in a bound form. The absorbent can be regenerated by desorption, which is achieved by altering the temperature or pressure of the reaction [6]. Commonly used absorbents include solutions of organic amines, ammonia, or sodium hydroxide. Among these, organic amines are considered the most widely used and effective for chemical absorption [6].

Table 1. Comparison of CO_2 capture methods [2, 5]

Capture Methods	Advantages	Disadvantages
Pre-combustion Capture	Small size of CO_2 capture equipment, and higher energy output.	Operational limitations and high investment costs.
Oxyfuel combustion	High CO_2 concentration in combustion products, and lower emissions of NO_X and SO_X.	High energy and investment costs.
Post-combustion capture	Low investment costs, rapid technology deployment, and flexible operations to reduce expenses. High technology deployment speed and lower investment requirements.	Large equipment size for CO_2 capture.

Adsorption by Solid-Phase Porous Materials

Adsorption with solid-phase porous materials relies on electrostatic or Van der Waals interactions between the adsorbent (solid-phase porous material) and the adsorbate (CO_2) [7]. This method is characterized by a high adsorption capacity and low cost of chemical processes [5, 8]. These advantages are achieved through the use of adsorbents with high capacity and selectivity for carbon dioxide, along with the ease of regenerating the adsorbent for repeated use [9, 10]. The most studied and widely used adsorbents include metal-organic frameworks (MOFs), Covalent Organic Frameworks (COFs), zeolites, mesoporous materials, and activated carbon [10, 11].

Membrane Separation

This method is based on gas separation due to the varying rates of gas permeation through membranes [12]. Organic membranes, primarily made of polymers, are widely used in the industry for gas separation (especially CO_2), but their selectivity is not optimal [13, 14]. In contrast, inorganic membranes offer improved selectivity, greater stability, and higher efficiency. However, their

CHAPTER 9

Ethanol 100: A New Approach for the Transportation Industry in India

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Abstract: The chapter "Ethanol 100: A New Approach for the Transportation Industry in India" delves into the potential of adopting 100% ethanol as the primary fuel source for India's transportation sector. It outlines the pressing issues of air pollution, fossil fuel dependency, and energy security that necessitate a shift toward alternative energy sources. The chapter highlights ethanol's advantages, including its role in reducing carbon emissions, enhancing energy independence, and supporting rural agricultural economies through increased demand for ethanol production. The discussion covers the technical, economic, and logistical aspects of implementing Ethanol 100 in India. It reviews the current infrastructure for ethanol production and distribution, vehicle compatibility, and necessary modifications to support a transition to a full ethanol system. Comparative case studies from other countries that have successfully integrated ethanol into their fuel mix offer valuable lessons and strategies. This chapter outlines the policy initiatives undertaken, particularly in India, to develop and promote various alternative fuels for road transportation, highlighting the progress made in comparison to global advancements. Innovations in ethanol production, distribution, and flex-fuel vehicle technologies make the adoption of E100 viable. With adequate investment in research, the required technologies can be developed to ensure the efficient and sustainable use of E100.

Keywords: Energy independence, Ethanol 100, Fossil fuel, Global advancements.

ENVIRONMENTAL AND ECONOMIC JUSTIFICATION FOR E100

The transportation subsector in the Indian economy is very crucial as it facilitates movement and trade throughout a large area of the country. But the sector also

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comes with challenges, primarily environmental sustainability, dependency on fossil fuels, or more broadly, energy security. These concerns make it clear that safer and better energy options are long overdue.

Overview of India's Transportation Sector Challenges

A large part of India's population is exposed to severe air pollution due to the Indian transport sector. This is mostly in urban areas that are relatively crowded. Pollution from vehicles leads to the degradation of the air with contaminants such as PM2.5 and PM10, NO_x, and VOCs. In major cities like Delhi alone, transport emissions account for as high as 30% of PM2.5 levels as per the findings of a study by Guttikunda and Goel (2019), which exerts a very negative impact on human health and the environment [1, 2]. The World Health Organization (WHO) has identified many Indian cities as the most polluted in the world, directly linking vehicle emissions to respiratory diseases, heart diseases, and premature death [3].

India's transportation energy dependence on fossil fuels, particularly gasoline and diesel, is a major problem for the country's carbon emissions. This dependency also poses economic risks due to the high availability of petroleum products, which account for about 80% of India's fuel needs [4]. The fluctuations in global oil prices further increase economic vulnerability, as seen in recent years. These fluctuations further create trade imbalances and affect currency stability. Moving towards alternative fuels can help reduce India's carbon footprint while reducing the risk of fluctuations in the global oil market [5].

Emerging demands for transportation services make energy security of utmost importance. Fossil fuels are finite resources, and their destruction poses a threat to energy security, along with the disruption of supply. With India's commitment to the Paris Agreement and focus on renewable energy, there is an urgent need to diversify energy sources in the transportation sector [6]. Switching to renewable and clean fuels, such as ethanol, biodiesel, and hydrogen, can increase energy security, reduce emissions, and support sustainable development goals.

Ethanol as an Alternative Fuel: Benefits and Global Context

Renewable biofuels, mostly derived from biomass sources, such as corn, sugar, and other crops, offer a promising alternative to fossil fuels. Their use as a transportation fuel is widespread in countries such as Brazil and the United States, where they have been observed to reduce greenhouse gas emissions and improve air quality. Ethanol emits less pollution than gasoline and diesel, particularly in terms of carbon monoxide, particulates, and greenhouse gases. Studies show that ethanol can reduce lifetime greenhouse gas emissions by 20–30% compared to natural gas [7]. Its use can also reduce smog production due to reduced nitrogen oxide and hydrocarbon emissions, which is especially beneficial in urban areas with high air pollution [8].

As a domestically produced fuel, ethanol can reduce India's dependence on imported fossil fuels, thereby contributing to energy security and economic stability. Ethanol production can also support the rural economy by creating employment in agriculture and biofuel processing. The Indian government has recognized the potential of ethanol and set an ambitious target to increase the blending of ethanol with gasoline to achieve a 20% blending target by 2025 [9]. The change is expected to save billions of dollars on oil imports and support energy independence. The enhanced production of ethanol can bring significant change in the rural economy with the increasing demand for agricultural products, such as sugarcane and maize. This can further create new job opportunities in rural areas, decrease the release of agriculture waste, and provide a new revenue stream for people residing in rural areas [10]. Importing a significant portion of oil makes the Indian economy vulnerable to the fluctuating global oil prices. The use of ethanol in the transportation sector is able to reduce dependency on imported oil. Scaling up ethanol production can act as double edge sword by providing both economic security and environmental sustainability. It can prevent India from an economic meltdown that could be threatened by the volatility of global oil markets.

Countries like Brazil have long supported ethanol as a primary fuel. Brazil's Proálcool program, launched in the 1970s, enabled the country to replace most of its fuel consumption with ethanol, reducing domestic emissions and creating a viable biofuel market [10]. Similarly, the United States has introduced ethanol into transportation fuels, mostly from corn-based ethanol, and this currently accounts for approximately 10% of the U.S. gasoline consumption [11]. These international events demonstrate the feasibility and quality of ethanol as a viable transportation fuel. By analyzing current policies, implementation challenges, and future prospects, this chapter aims to understand how ethanol can play a significant role in the transition to a cleaner and more sustainable transportation industry in India.

ETHANOL PRODUCTION AND FEEDSTOCKS

Ethanol can be produced through two primary processes: fermentation and chemical synthesis.

Fermentation

The most common method of producing ethanol is fermentation, in which sugar is

CHAPTER 10

Sustainable Future: Integrating Circular Economy Strategies into Renewable Energy for Effective Recycling and Resource Management

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Abstract: The critical need to address climate change and implement circular economy principles is the driving force behind the background and motivation of this chapter. Numerous researchers have extensively published on circular economy strategies within the contexts of sustainability, recycling, resource management, and productivity. Simultaneously, debates on the impacts of climate change and mitigation strategies have intensified. The dwindling supply of limited fossil fuels and their harmful environmental impacts have prompted a global shift towards clean and renewable energy sources. This chapter also discusses the crucial role of circular economy principles in enhancing the sustainability of renewable energy systems, for example, wind turbines, solar panels, and Battery Energy Storage Systems (BESS). The primary focus is on how circular economy approaches can reduce costs, minimize environmental impacts, and promote a more sustainable energy future. We analyse the economic and environmental implications of these practices and offer recommendations to encourage stakeholders to adopt circular economy strategies. A comprehensive review of current practices, future trends, and approaches to integrating circular economy strategies into renewable energy systems will ultimately promote sustainable development and help achieve long-term environmental goals.

Keywords: BESS, Circular economy, Renewable energy systems, Sustainable development.

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INTRODUCTION

Climate change is caused by the burning of fossil fuels for energy, deforestation, and industrial activities. Its negative effects include rising global average temperatures, extreme climate events, such as droughts and heavy rains, storms, melting of ice caps and glaciers, and impacts on agriculture. Due to the existence of these problems, countries around the world are considering how to mitigate the effects of climate change and have identified efforts to reduce emissions or adopt advanced technologies to limit greenhouse gas emissions [1 - 4].

Over time, the economies of countries have been growing, and the living standards of people have also been improving, resulting in increased consumption of goods, services, electronics, appliances, various consumer products, automation, and advanced manufacturing technologies, which have led to a significant increase in efficiency and productivity. As consumption increases, driving economic growth while reducing costs, it has also led to an increase in the volume of municipal solid waste, scrap metal, chemicals, and e-waste. The linear "take-make-leave" model, which has dominated industrial and economic practices, is no longer viable due to the lack of recyclable or reusable materials, environmental pollution, resource depletion, economic inefficiency, and the scarcity of rare earth metals and fossil fuels [5 - 7].

A multi-pronged approach is needed to effectively address environmental issues, achieve eco-efficiency that benefits both humans and the biosphere, and realize a self-sustaining future. One of the strategies is to incorporate the C2C (popularly called circular economy, (Fig. **1**) principles into the renewable energy sector, which can ensure significant changes and advancements in areas, such as bio-prospecting, bio-sorption, bio-leaching, bio-reduction, bio-flotation, microbial electrochemical technologies, recycling, and resource management to extract metals from e-waste [8].

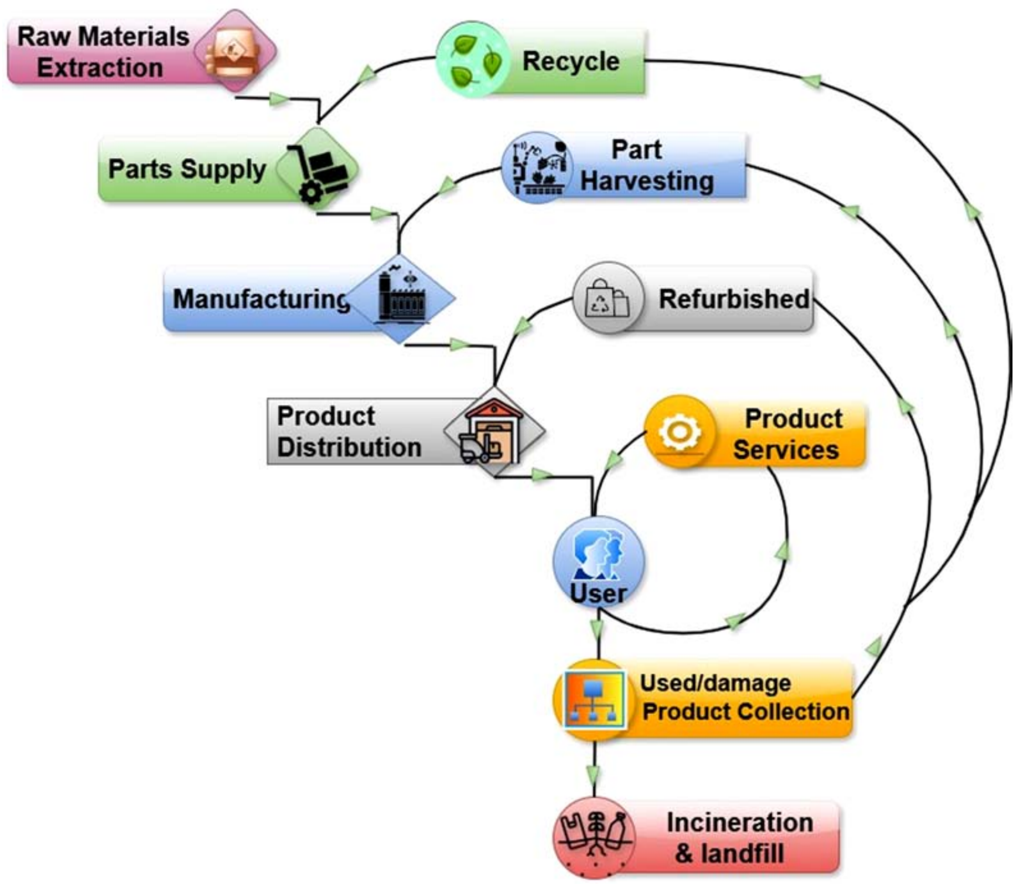

Fig. (1). Circular economy principles in the renewable energy sector [8]

The demand for Electric Vehicles (EVs) is increasing, and many countries are enacting legislation to promote the adoption of hybrid and fully electric vehicles. Global battery demand is expected to increase from 185 GWh in 2020 to over 2,000 GWh by 2030. One of the most popular choices is systems powered by lithium-ion batteries. As a result, the growing number of lithium-ion batteries will need an effective and sustainable end-of-life management program to manage their end-of-life, including recycling, reuse, landfill disposal, or incineration.

Recent research is focused on more sustainable approaches, such as remanufacturing, reusing, and reprocessing battery components for future use, as well as developing recycling methods for the sustainable disposal of large quantities of batteries in the near future. As the world moves towards renewable energy plants, it is important to integrate circular economy strategies to ensure

CHAPTER 11

Smart Bioethanol Production System From Algal Biomass Harvested From River Water

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Abstract: Researchers emphasize that prioritizing sustainable and renewable energy sources is essential for mitigating the rapid progression of global warming driven by excessive fossil fuel consumption. Bioethanol presents a promising alternative to fossil fuels, as it can be used in engines without modification, helping to reduce carbon emissions and air pollution. This study investigates the potential of algal biomass for bioethanol production and outlines a model for the complete conversion process. To achieve this, the research developed a smart bioethanol production system with variable production rates that effectively reduced energy consumption. This system effectively reduced contaminants in bioethanol by utilizing an automated inspection framework. The impure bioethanol undergoes a purification process to enhance its quality. The developed mathematical model accounts for both upstream and downstream processes, providing flexibility and adaptability for bioethanol production. This study aims to reduce the total cost of an algal-based bioethanol production system, thereby achieving the optimal quantity of bioethanol. The model's findings highlight that the main economic challenges arise from the high costs of harvesting and extracting algal biomass, particularly from riverbanks. This research contributes to the body of knowledge on sustainable energy production and underscores the need for targeted policy measures to transition from conventional fossil fuels to renewable biofuels.

Keywords: Algal biomass, Autonomation, Bioethanol, Smart production.

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INTRODUCTION

When it comes to the generation of second-generation bioethanol, it is noted that such feedstock could be potentially produced from lignocellulosic materials and is beneficial in several ways . Several feedstock pre-treatments have presented various yield and product inhibitory processing challenges. However, the pre-treatment of lignocellulosic biomass is a critical step in bioethanol production due to the inherently recalcitrant nature of these materials. The most prevalent carbonous fuel is biomass, which is ultimately derived from both microorganisms and plants. It is also recognized as lignocellulose-based biomass, which has now become a common biomass to facilitate the better production of bioethanol. The most common constituents of plant tissue cells are the cellulosic components, which are composed of cell structural carbohydrates, including cellulose, hemicellulose, and other unbranched structures, such as lignin. The contents of these components may vary significantly depending on the species, variety, and climatic conditions. In addition, several pre-treatment methods, including physical, chemical, biophysical, and biological [1, 2], have been developed to enhance enzyme access to cellulosic fibers. Ethanol is produced through a series of key steps, including the hydrolysis of cellulose and hemicellulose into fermentable reducing sugars, the fermentation of these sugars into ethanol, the separation of lignin residues, and the recovery and purification of ethanol to meet fuel-grade specifications [3]. Glucose and xylose are fermented in separate reactors in the traditional bioethanol production process, yielding a substantial amount of ethanol. This procedure significantly increases the yield and productivity of ethanol and can be carried out in a bioreactor using hydrolysate fractions rich in glucose and xylose [4 - 7].

Lignocellulosic biomass has a complex structure that includes both fermentable and non-fermentable sugars. With a compositional analysis of 33–47%, cellulose is the most abundant component of lignocellulosic biomass (LCB). Another abundant component is hemicellulose, which accounts for 19–27% of the LCB. The surface area that is available for enzyme activation, preventing degradation, and forming a barrier against external entry [8, 9].

The appropriate industrial use of biomass requires a well-planned and controlled production infrastructure. By making deliberate decisions about the production structure, modes of transportation, environmental impacts, social benefits, and node locations, it is possible to industrialize a bioethanol production system [10, 11]. Several researchers have examined the traditional process of producing bioethanol. Since labour and production problems are frequently caused by the traditional techniques used in bioethanol production, an innovative manufacturing system is vital. As traditional manufacturing methods often generate defective goods, intelligent production systems should strive to reduce their production. Consequently, implementing an energy-efficient bioethanol production system that reduces bioethanol pollutants is essential [12]. The smart production system uses automation techniques to identify any contaminants in the bioethanol. The impure bioethanol undergoes a purification process after each in-house production of bioethanol. After purification and asmart inspection process, the purified form of bioethanol is transferred to the bioethanol marketplaces.

Compared to typical ethanol systems, they have lower yields, require less land-use change, and emit fewer CO_2 emissions (like corn or sugarcane). Higher biomass yields, the ability to utilize non-arable land, and the potential for net CO_2 capture make microalgae-based systems more sustainable overall (Table **1**).

Table 1. Comparative study of traditional ethanol with algal-based ethanol

Parameters	**Algal-based ethanol**	**Traditional ethanol**
Yield	5000-10000 gallons/acre/ year	400-500 gallons/acre/year
C-absorptivity	Captures	Emit during processing
Feedstock	Macro/micro, Sunlight, $CO_{2,}$ and nutrients	Food Crops
Land use	Can also flourish on marginal	Need fertile land

Mathematical Model

This study develops a mathematical model to minimize the total production cost of algal-based bioethanol. The model focuses on optimizing the allocation of algal biomass to the biorefinery after its harvest from a freshwater river, as well as the distribution of purified bioethanol to market demand zones. A liquid extraction process, utilizing the Soxhlet method, is employed to extract bioethanol from the algal biomass. Key cost components considered in the model include the collection of algal biomass, interim storage, and loading the biomass into transport equipment. The model also determines the variable production cost of bioethanol, which includes expenses such as purification (the process of converting impure bioethanol into pure bioethanol), autonomous inspection, and inventory maintenance at the biorefinery. Transportation costs for moving algal biomass from riverbanks to the biorefinery, as well as the distribution of bioethanol to market demand zones, are also accounted for in the total cost minimization. The bioethanol inventory behaviour in the biorefinery is shown in Fig. (**1**).

CHAPTER 12

Understanding Municipal Solid Waste Volatility in India

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Abstract: In addition to health and environmental concerns, the growing volume of Municipal Solid Waste (MSW) and the pursuit of Sustainable Development Goals (SDGs) highlight the need for sustainable MSW management. Improper waste disposal poses significant risks to public health and the environment. Due to the economic and ecological challenges associated with environmentally sound disposal methods, alternative waste management strategies are essential. Studies indicate that nearly 90% of MSW is improperly disposed of in landfills or open dumps, leading to environmental degradation, health hazards, and contamination of the food chain. In India, Urban Local Bodies (ULBs) face difficulties in managing large quantities of MSW due to high population density and inadequate infrastructure. Among the challenges are door-to-door garbage collection, MSW recycling techniques, and scientific waste treatment methods. Given these realities, the new Solid Waste Management Rules (SWM), 2016, were announced by the Union Ministry of Environment, Forests, and Climate Change (MoEF&CC) of India, aiming to modernize solid waste management nationwide. Several steps of waste management/treatments are being adopted, including incineration, pyrolysis, bio-refining, biogas plants, recycling, and composting. Composting is a sustainable, low-cost option for MSW management; however, a very small amount, 6–7% of MSW, was recycled through it. The present study emphasized a comprehensive review of the characteristics, production, collection, disposal, and effective treatment technologies of MSW practised in India. Some of the waste management/treatment processes used in India include incineration, pyrolysis, bio-refining and biogas facilities, recycling, and composting. Composting is a low-cost and sustainable method for managing Municipal Solid Waste (MSW); however, only 6–7% of MSW in India is currently recycled through this method. The present study focuses on a comprehensive examination of the characteristics, generation, collection, disposal, and treatment technologies associated with MSW in the Indian context.

Keywords: Development, Goals, Municipal, SDG, Solid waste, Sustainable, Volatility.

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INTRODUCTION

Rapid urbanization, population growth, and changing consumption patterns have led to an exponential increase in waste generation. India, with its burgeoning population and expanding cities, experiences significant fluctuations, or "volatility," in the production of MSW, which poses complex environmental, social, and economic challenges. The concept of waste volatility refers to the unpredictability and variability in waste generation, composition, and disposal. In India's dynamic society, socioeconomic shifts, including urbanization, migration, industrialization, and population pressure, have contributed to a notable rise in municipal solid waste. Only about 28% of the 80% of Municipal Solid Waste (MSW) that is collected is currently utilized. India generates approximately 70 million tonnes of MSW annually, and if current trends persist, this figure is projected to rise to 165 million tonnes by 2030 and 436 million tonnes by 2050 (Planning Commission Report, 2014). The ongoing and indiscriminate disposal of Municipal Solid Waste (MSW) is closely linked to unscientific practices, rapid urbanization, population growth, changing lifestyles, and a lack of ecological awareness. Open disposal of Municipal Solid Waste (MSW) has harmful effects on both human health and the environment [1]. Globally, the primary causes of MSW accumulation are unscientific waste collection practices and inadequate transportation infrastructure. This remains one of the primary environmental challenges facing Indian megacities and is crucial to the effective management of Municipal Solid Waste (MSW). It also includes tasks related to solid waste generation, storage, collection, transportation, processing, and disposal. Approximately 48–50% of MSW is organic, posing a significant problem for the nation [1]. Its inappropriate disposal is mainly caused by environmental contamination, hazards to human health, and a lack of disposal space. A tiny portion of MSW (6–7%) is intended for composting; however, the majority of MSW in Indian megacities is already disposed of in landfills [2]. Because of the increased creation of MSW per capita brought about by urbanisation, industrialisation, and economic growth, managing MSW is a severe problem for ULBs in Indian megacities. Thus, efficient solid waste management is a key concern for densely populated cities. Despite notable advancements in the social, economic, and environmental spheres, the state of MSW treatment in the nation stayed unchanged. Approximately 90% of residual waste was disposed of in the informal sector rather than in a proper landfill, contributing significantly to the extraction of value from MSW [2]. This review focuses on using MSW as an organic amendment for the reclamation of salt-affected soils. This article provides a comprehensive examination of Solid Waste Management (SWM) practices and regulations, with a focus on their application as organic amendments and fertilizers for sustainable crop production in India. There is an urgent need for scientifically grounded MSW management, supported by advanced systems and infrastructure [2]. Current technologies for managing solid waste are inadequate and have a negative impact on human health, environmental pollution, and the nation's economy [3].

Future research on these issues should focus on a global scale to minimize ecological disturbances, establish environmental standards, and assess the effectiveness of policies in different countries and their impact on the socioeconomic conditions of local populations.

Model Specification and Justification

To examine the volatility patterns in Municipal Solid Waste (MSW) generation across India, this study employs a GARCH (Generalized Autoregressive Conditional Heteroskedasticity) modeling approach. The GARCH model is well-suited for analyzing time-series data with volatility clustering, where periods of high and low variability alternate over time. Since MSW generation is influenced by seasonal trends, consumption patterns, and infrastructural changes, it demonstrates characteristics of time-dependent variability. The GARCH framework allows us to capture such heteroskedastic behavior, offering insights into both the persistence and magnitude of fluctuations in MSW data. This approach is particularly valuable for municipal planning and policy design, as it helps identify whether short-term shocks or long-term structural shifts drive fluctuations in waste generation.

Data Overview

The data represent Municipal Solid Waste (MSW) in India, measured in tons per day over 10 years from 2013-14 to 2023-24 (Table **1**). The data points reveal some significant fluctuations in waste generation trends:

Table 1. Municipal Solid Waste (MSW) data.

Municipal Solid Waste (Tons per day)	India (proxy Variable)
2013-14	142566
2014-15	141064
2015-16	135198.27
2016-17	119140.9
2017-18	43298.385
2018-19	43597.353
2019-20	43902.53447
2020-21	44209.85221

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