NEW RESEARCH IN
SUSTAINABLE DEVELOPMENT

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Published by

Nirwan University Jaipur
Near Bassi-Rajadhok Toll, Village- Jhar
Agra Road, Jaipur – 303305 Rajasthan

Edition: 2024

ISBN: 978-81-975412-4-7

Price: 1395/-

Published by:
Nirwan University Jaipur
Rajasthan-303305

Printed by:
Inspira
Jaipur-302018

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Preface

Sustainable Development Requires Human Ingenuity. People are the Most Important Resource.

Dan Shecht man

In recent years, the urgent call for sustainable development has intensified, driven by the undeniable impacts of climate change, resource depletion, and social inequality. This collection, "New Research in Sustainable Development," aims to explore innovative approaches and solutions that address these pressing challenges. Our understanding of sustainability has evolved significantly, incorporating interdisciplinary perspectives that span environmental science, economics, social justice, and technology. The contributions in this book reflect the latest research and emerging trends, offering insights into how we can create resilient systems that benefit both people and the planet. Each chapter presents valuable findings that indicate sustainable development. Chapter 1 describes the challenges and opportunities that come in the way of sustainability in the form of water resource management. Further, explore the advancement in water quality management. Chapter 2 discussed how bioadsorbent could be a better source of water purification over carbon nanotubes.

Chapter 3 focuses on renewable energy technologies to conserve natural resources, from deterioration. Chapter 4 explains how ammonia can boost the hydrogen sector resulting in the greenhouse sector. Also indicates that by 2050, the transportation industry could potentially utilize an astounding 100 million metric tons of NH_3 yearly.

Chapter 5 discussed green banking practices to achieve sustainable goals. Chapter 6 elaborated on the implication of E-Commerce can develop a holistic approach in marketing which aims at delivery of environmental sustainability, social responsibility, and future valuation. In Chapter 7 the photogalvanic cells represent a promising technology with significant potential to drive sustainable development and address pressing energy and environmental challenges. We hope this book serves as a resource for researchers, policymakers, educators, and anyone committed to making a positive impact on our planet.

Sapna Nehra

Ravi Kant Modi

About the Editors

Dr. Sapna Nehra earned her M.Sc., Ph.D. From Banasthali Vidyapith and she has taught at various Universities. Currently, she has been working as Associate Professor, at Nirwan University Jaipur. She is guiding five Ph.D. scholars. Dr. Nehra has contributed twelve research papers with SCI and Scopus indexing and thirty-six book chapters. She has reviewed several manuscripts of ACS, Elsevier, and Springer. Dr. Nehra is also the editor of the CRC Press book and presented her work at numerous national and international conferences.

She was awarded with Excellence award for promoting research and innovation at an international conference (2023) by NMIET Bhubaneswar, Odisha. She has delivered many invited lectures and radio talks. She has served as an organizing secretary for many conferences, workshops, and FDPs.

Dr. Ravi Kant Modi is currently working as an Professor & Dean in the Department of Commerce and Management, Nirwan University Jaipur, Rajasthan, India. He is a distinguished faculty member bringing with him an extensive 13 years of teaching experience. His dedication to research has been recognized through the prestigious Young Researcher Award, bestowed upon him on September 5, 2021. As an author, He has contributed to the academic community through his textbooks and edited books. Moreover, he has published over 40 papers in renowned National and International journals, including notable Scopus journals. His expertise in research is further exemplified by his position as an editorial board member for reputable journals. Recently he has awarded best paper presentation award (Silver Medal) in the 75th All India Commerce Conference at Udaipur.

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Water Resource Management: Challenges and Opportunities for Sustainable Development

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1.1. Introduction

Water, the essence of life, is an invaluable resource that sustains ecosystems, nourishes societies, and fuels economies. From quenching thirst to irrigating fields, from powering industries to supporting biodiversity, water is vital for the prosperity and well-being of humanity and the planet. Water reserves are essential to human subsistence and a wide range of economic activities, making them important to sustainable socioeconomic development. The abundance and well-being of society are frequently determined by the availability and management of these resources [1]. However, the planet's lifeblood encounters enormous tensions from increasing need, environmental challenges, and pollution [2-4]. Weather shifts are changing precipitation patterns, leading to further repeated and severe droughts and floods [5-7]. Growing population pressures and rapid urbanization strain water supplies and sanitation systems. Pollution from industrial, agricultural, and urban sources contaminates rivers, lakes, and aquifers, jeopardizing human health and ecological integrity [8].

In the face of these hurdles, the priority for sustainable water resource management has never been more urgent. Sustainable development, as articulated in the United Nation's Sustainable Development Goals (SDGs), seeks to balance economic prosperity, social equity, and environmental stewardship [9-11]. At its core, sustainable water management embodies this ethos by ensuring the equitable distribution, efficient use, and responsible stewardship of water resources for current and future generations. This journey toward sustainable water management is fraught with complexities, yet it is also replete with opportunities for innovation, collaboration, and transformation. By harnessing the power of technology, policy, governance, and community engagement, it is possible to chart a course towards water security, resilience, and prosperity [12-14].

It also examines the interplay between climate change and water resources, the imperatives of water quality management, the intricacies of policy and governance frameworks, and the critical role of community engagement and participation. The chapter will explore the promise of technological innovations from smart water meters to remote sensing technologies and their potential to revolutionize water management practices.

The chapter provides an overview of the latest advancements in the research on water resource management, emphasizing contemporary challenges and advancements in water quality management. It delves into the understanding of water resources, highlighting the complexities surrounding their management. The narrative navigates through the challenges faced in water resource management, underscoring the critical need for effective strategies. Current advancements in water quality management, dissecting analytical techniques such as sensor technologies, remote sensing, bioanalytical methods, and integrated water quality checking systems are essential for sustainable development. Furthermore, the chapter elucidates the applications of nanotechnology, particularly in water treatment, desalination, and environmental risk assessment. Membrane filtration technologies, including nanofiltration, reverse osmosis, and photocatalytic membranes, are also examined. Look after the future directions and recommendations for improved water resource management, emphasizing the urgency of proactive measures in addressing water-related issues.

1.2. Understanding Water Resources

Water, the essence of life, plays a fundamental role in sustaining ecosystems, supporting human activities, and driving economic development worldwide. Understanding water resources entails a holistic exploration of the various forms, distribution patterns, dynamics, and importance of water on earth.

Water exists in different forms, primarily as surface water, groundwater, and rainwater. The water cycle, or hydrological cycle, illustrates the nonstop flow of water through various processes such as evaporation, condensation, precipitations, infiltration, and transpiration [15,16]. This natural cycle governs the distribution and availability of water resources, influencing weather patterns, ecosystem dynamics, and human activities.

Water distribution across the globe is characterized by significant spatial and temporal variations, shaped by factors including climate, geography, topography, and human interventions [17-19]. While some regions enjoy abundant water resources due to high rainfall and mountainous terrain, others face water scarcity challenges, particularly in arid and semi-arid areas. Managing transboundary water resources presents additional complexities, as rivers, lakes, and aquifers often traverse political boundaries, necessitating cooperation, and equitable sharing among neighbouring countries [20-23]. Water resources are dynamic and subject to change over time, influenced by natural processes and human activities. Weather changes, terrestrial usage variations, population growth, urbanization, and industrialization exert profound impacts on water availability, quality, and ecosystem health. Understanding water dynamics requires continuous monitoring, modelling, and assessment of hydrological processes, water quality parameters, and anthropogenic impacts [24-26].

The importance of water resources cannot be overstated. Water is indispensable for sustaining life, supporting ecosystems, ensuring food security, generating energy, facilitating transportation, and fostering economic prosperity. Access to clean and reliable water resources is recognized as a fundamental human right and a prerequisite for achieving the UN SDG 6 [27].

1.3. Challenges in the Management of Water Resources

Water resource management faces multifaceted challenges across the globe, demanding concerted efforts for sustainable solutions [28,29]. Foremost among these challenges is water scarcity exacerbated by population growth and climate change. Contaminations from numerous sources, comprising industrial discharge and agricultural runoff, threaten water quality, necessitating costly treatment measures. Climate change intensifies water-related risks and ends with increasing the frequency of extreme weather events [30,31].

Agriculture, a major water consumer, requires more efficient irrigation practices to mitigate water wastage, especially in rural areas and unorganized farming sectors [32]. Urbanization strains water supply systems, necessitating improved infrastructure and conservation measures. Ecosystem degradation due to human interventions disrupts natural watercourses and threatens biodiversity. Inadequate infrastructure impedes access to clean water and sanitation, particularly in rural and marginalized communities [33,34]. Governance and policy challenges, including fragmented regulations and insufficient political will, hinder effective water management. Socioeconomic disparities exacerbate water scarcity, underscoring the reputation of equitable resource allocation [35-37].

Addressing these obstacles requires integrated approaches that balance human needs with environmental sustainability. Strengthening institutional capacity, fostering stakeholder participation, and enforcing water laws are essential for promoting sustainable water governance. By prioritizing social equity and investing in innovative solutions, societies can safeguard water resources for present and future generations.

1.4. Water Quality Management: Current Advancements

Water quality management is a cornerstone of sustainable development and helps as a critical framework to safeguard the preservation and equitable distribution of clean water sources for present-day and forthcoming generations. The evolving challenges posed by pollution, climate change, population growth, and ongoing advancements in water quality management procedures are crucial for addressing complex environmental issues while fostering social, economic, and ecological resilience. Current years have observed outstanding growth in the arena of water quality management, driven by technological innovation, interdisciplinary collaboration, and a growing recognition of the interconnectedness between human activities and the health of aquatic ecosystems. These advancements are reshaping traditional approaches to monitoring, assessment, and remediation, offering novel solutions to safeguard water resources and promote sustainable development outcomes. Scientific advancements significantly contributed to the effective management of water quality by providing innovative methods for the detection, treatment, and prevention of water pollution.

1.4.1. Analytical Techniques

Analytical techniques play a central role in water quality management, providing the means to monitor, assess, and mitigate contaminants that impact water quality. These methods enable the identification of sources of contamination, assessment of risks to human health and ecosystems, and formulation of targeted interventions to safeguard water quality. Overall, ongoing research in analytical techniques for water quality management is focused on improving detection sensitivity, expanding analytical capabilities, enhancing data interpretation, and promoting interdisciplinary collaborations to address emerging water quality challenges and achieve sustainable development goals.

1.4.1.1. Sensor Technologies

Sensor technologies perform a critical role in water quality management for sustainable development by providing real-time or near real-time data on various parameters of water quality. These parameters include physical, chemical, and biological characteristics that affect the health of aquatic ecosystems and the safety of water for human consumption. Analytical techniques leverage sensor technologies to monitor, assess, and manage water resources efficiently. These sensors are becoming more affordable, portable, and capable of detecting a wide range of contaminants, including heavy metals, organic pollutants, and microbial pathogens. Advances in sensor design, miniaturization, and data processing algorithms are improving the accuracy and reliability of water quality measurements.

pH is a critical parameter that indicates the acidity or alkalinity of water. pH sensors help monitor variations in pH levels, which can impact aquatic life and the effectiveness of water treatment processes. Scientists could successfully develop a smart water quality monitoring system by measuring pH and other parameters to find out the water pollution in Fiji Islands and other rural areas respectively [38,39]. Dissolved oxygen (DO) sensors measure the amount of oxygen dissolved in water, which is essential for the survival of aquatic organisms. Monitoring DO levels helps assess water quality and the health of ecosystems, especially in bodies of water where oxygen depletion can occur. The use of multivariate adaptive regression splines to illustrate DO dynamic forces innate nonlinear and multidisciplinary correlations and observed that the hybrid algorithms showed higher accuracy on the predictions of DO contents were also explored efficiently [40].

Turbidity sensors measure the cloudiness or haziness of water caused by suspended particles. High turbidity levels can indicate sediment runoff, pollution, or the presence of harmful microorganisms, affecting water quality and clarity. A novel model for the effective identification of even low levels of turbidity with a system that consists of a multi-lighting source design and varied processing algorithm was developed to meet the social necessity [41]. European Parliament enforces dynamically to revise the toxic heavy metal limits in the drinking water by amending their drinking water directives (DWD) constantly. The historical limit of lead 40 µg/L in the 1970s was reduced to 25 µg/L in 2003, to 10 µg/L in 2013, and was again cut down to 5 µg/L with the new drinking water directive [42,43]. To deal with these dynamic regulatory changes there was always constant research back up in the analytical field. Heavy metal sensors detect the presence of heavy metals such as lead, mercury, and cadmium in water, which are harmful to human health and aquatic life even at low concentrations. Rapid detection of heavy metals enables timely intervention to prevent contamination [44,45].

Integration of sensor technologies with advanced analytical techniques such as remote sensing, data analytics, and machine learning enhances the efficiency and accuracy of water quality monitoring and management efforts. Real-time data provided by sensors enable prompt decision-making, early detection of pollution incidents, and proactive measures to safeguard water resources for sustainable development. Additionally, the development of portable and affordable sensor technologies facilitates their deployment in resource-limited settings, extending the reach of water quality monitoring initiatives across diverse geographic regions.

1.4.1.2. Remote Sensing

Remote sensing plays a crucial role in analytical techniques for water quality management, contributing to sustainable development efforts.

Remote sensing technologies, including satellite imagery and aerial photography, enable the monitoring of water bodies on a large scale. Procedures were developed effectively to identify surface water bodies by using spatial resolution pictures from satellites to eliminate the issues with the interpretations of such images [46]. Remote sensing provides valuable information about the spatial extent, distribution, and dynamics of water quality parameters such as chlorophyll concentration, turbidity, and algal blooms.

Remote sensing allows for the rapid detection of pollution events and environmental hazards in water bodies. Changes in water colour, temperature, and other indicators can signal the presence of pollutants or contaminants, helping authorities respond promptly to mitigate risks to public health and ecosystems. By analysing historical remote sensing data, researchers can assess long-term trends in water quality parameters. The whole information is essential for understanding the impact of human activities, climate change, and natural phenomena on water resources over time. Remote sensing data can be used to estimate water quantity and quality parameters, such as surface water extent, evapotranspiration rates, and water temperature. These estimates are valuable for water resource management, agricultural planning, and hydrological modelling.

Remote sensing information serves as a valuable tool for policymakers, resource managers, and stakeholders involved in water quality management. It provides spatially explicit data and insights that support evidence-based decision-making, helping to prioritize actions and allocate resources effectively [47-49].

1.4.1.3. Bioanalytical Methods

Bioanalytical methods are valuable tools in water quality management for sustainable development as they offer rapid, sensitive, and cost-effective means of detecting contaminants and assessing overall water quality. New research in this field could develop hydrogel-based biosensors to perceive glucose even at large limits of temperatures. Similarly, the accuracy and usefulness of a fluoride biosensor were measured in Kenya and observed that the sensor provides accurate data and is very much useful for the common man [50,51].

Biosensors are analytical devices that integrate biological sensing elements (e.g., enzymes, antibodies, microorganisms) with transducers to detect specific compounds or classes of compounds in water. They offer high sensitivity, specificity, and rapid response times, making them ideal for on-site monitoring of contaminants such as pesticides, heavy metals, and microbial pathogens. Enzyme-linked Immunosorbent Assay (ELISA) is a widely used bioanalytical method that utilizes antibodies to detect and quantify specific substances in water samples. ELISA assays are available for a variety of contaminants, including pesticides, hormones, and toxins, and they provide accurate measurements at low concentrations.

Microbial assays involve the use of microorganisms (e.g., bacteria, algae) to assess water quality based on indicators such as toxicity, biochemical oxygen demand (BOD), and microbial contamination. These assays can provide insights into the overall health of aquatic ecosystems and the presence of pollutants. Bioluminescent assays utilize the light-emitting properties of certain organisms (e.g., luminescent bacteria) to detect the presence of toxic compounds in water. A comparison of the bioluminescent assay and coliform paper assay showed that the bioluminescent assay was advantageous for quick on-site detection [52]. Changes in bioluminescence intensity or patterns indicate the presence and toxicity of contaminants, allowing for rapid screening of water samples. Phytochemical assays involve the use of plant-based bioassays to detect the presence of contaminants in water. Plants can accumulate pollutants from water and show visible signs of stress or toxicity, indicating water quality.

Pure physicochemical analysis may excuse a huge amount of possibly dangerous chemical molecules and ecological variables that jointly may have harmful biological impacts. Also sometimes, concentrations lower than the established governing controls, specific contaminants may have key interactive consequences. Ecotoxicological assessments integrate bioanalytical methods with ecological endpoints to evaluate the effects of contaminants on aquatic ecosystems. These assessments consider interactions between organisms, habitats, and contaminants to understand ecosystem-level impacts and guide management decisions. Studies with the consistency of ecotoxicological assessments in wastewater analysis in Korea showed that the integration of multiple methods to develop toxicity is very much essential [53].

1.4.1.4. Integrated Water Quality Monitoring Networks

Integrated water quality monitoring networks are comprehensive systems designed to assess and track the quality of water resources in a particular region or watershed. These networks typically involve the deployment of various monitoring stations strategically located across water bodies such as rivers, lakes, reservoirs, and groundwater sources. The research in this area continues to be a focus of advancement for sustainable water quality management.

Research is ongoing to develop and deploy advanced sensor technologies capable of measuring a broader range of water quality parameters with higher precision and sensitivity. These sensors may include miniaturized, low-cost devices, and emerging technologies such as nano-sensors and remote sensing techniques, which can enhance the spatial coverage and temporal resolution of monitoring networks.

Efforts are being made to integrate data from various sources, including satellite imagery, unmanned aerial vehicles (UAVs), citizen science initiatives, and traditional field monitoring stations. Because of the Industrial Revolution, waste generation increased exponentially, and its disposal management calls for consistent research and development.

As per the data from the US Federal Aviation Administration, there were 150 lakh UAVs and 1.6 lakh remote pilots by 2020 [54]. Real-time analysis of water quality at waste disposal sites using unmanned aerial vehicles helps to reach the industrial disposal site easily and safely. A wireless sensor network system could communicate the water quality wirelessly and such developments ensure the real-time quality measurements [55]. Integrating multiple data sources can provide a more comprehensive understanding of water quality dynamics, improve predictive modelling capabilities, and facilitate timely decision-making.

In the United States itself there were approximately 90 million waterborne ailments reported per year and the treatment cost for the same crosses $2 billion [56]. Research is focused on the development of real-time monitoring systems and early warning systems that can rapidly detect and respond to water quality issues such as contamination events, algal blooms, and changes in water chemistry. Early detection and classification of microbes such as E. coli, K. aerogenes, and K. pneumoniae is another area of interest and the development of a computational live bacteria detection system that regularly measures the microscopic image of bacterial growths suffice that requirement. Simultaneously that system will examine the time-laps hologram using a deep neural network for the quick recognition of bacteria development [57]. These systems provide stakeholders with timely information to implement appropriate mitigation measures and protect public health and the environment.

Integrated water quality monitoring networks require sensors capable of simultaneously measuring multiple parameters to provide a comprehensive understanding of water quality dynamics. Researchers are exploring multiparameter sensor platforms that can detect pH, dissolved oxygen, conductivity, turbidity, organic pollutants, and microbial contaminants in real time, enabling holistic assessments of water quality. The establishment of a submergible sensor probe, which constitutes Ultraviolet-Visible and fluorescence spectroscopy along with a customer-friendly data processing system meets those dynamic requirements [58].

Integrating data from multiple chemical sensors and analytical techniques requires sophisticated data fusion algorithms and chemometric approaches. Researchers are developing computational methods, including multivariate statistical analysis, pattern recognition, and machine learning algorithms, to process, interpret, and extract meaningful insights from large-scale water quality datasets. These techniques facilitate data integration, trend analysis, anomaly detection, and predictive modelling for effective water quality management [59.60].

1.4.2. Nano Technology Applications

Nanotechnology has emerged as a transformative tool in the realm of water quality management, offering innovative solutions for addressing the complex challenges of pollution, scarcity, and sustainability. At the intersection of science, engineering, and environmental stewardship, nanotechnology harnesses the unique properties and behaviours of materials at the nanoscale to revolutionize the way we treat, monitor, and safeguard water resources. By leveraging nanomaterials, nanoscale processes, and nanotechnology-enabled devices, researchers and practitioners are advancing the frontiers of water treatment, purification, and remediation while paving the way for more efficient, cost-effective, and environmentally sustainable approaches to water quality management. In this era of accelerating urbanization, industrialization, and climate change, the integration of nanotechnology into water management practices holds tremendous promise for ensuring access to clean, safe water for communities worldwide, fostering resilience, and promoting the long-term health and sustainability of our planet's most precious resource.

1.4.2.1. Water Treatment and Purification

Nanotechnology-based materials such as nanoparticles, nanofibers, and nanocomposites exhibit unique properties that enhance water treatment processes. These materials offer higher surface area-to-volume ratios and increased reactivity, enabling efficient removal of heavy metals, organic pollutants, and pathogens from water sources. Advancements in nanotechnology-based materials have revolutionized water treatment and purification methods, offering more efficient and sustainable solutions for addressing water quality challenges.

Nanoparticles for fluoride removal: Surplus amounts of fluoride ions in water produce fluorosis in teeth and bones, and it also causes muscle breakage, etc. Immense research is conducted to find novel solutions to overcome this problem. Advanced research in this field could create sustainable solutions by developing novel adsorbents with graphene and TiO_2 [61]. The incorporation of natural active biomolecules from *L. cylindrical* with nano forms of cerium oxide provides novel adsorbents for effective fluoride removals [62]. Research with multifunctional adsorbents such as fluoride adsorbers with antimicrobial activity gave very good results in the development of humic acid with aluminium zirconium bimetallic oxide [63]. Advanced research focusing on the production of adsorbents using chitin or cellulose beads showed high efficiency in fluoride removals [64,65].

Carbon-based nanomaterials: This includes carbon nanotubes, graphene, and activated carbon nanoparticles, which are widely used in water treatment applications due to their large surface area, high adsorption capacity, and chemical stability. These nanomaterials are effective in removing heavy metals, organic pollutants, and emerging contaminants from water through adsorption, catalysis, and filtration mechanisms. Advanced research focuses on developing carbon nanotubes to eliminate the toxins from water and could succeed with both single-walled and multi-walled carbon nanotubes [66-68]

Antimicrobial Nanomaterials: Silver nanoparticles and other antimicrobial nanomaterials are being incorporated into water treatment systems to disinfect and sterilize water by inactivating bacteria, viruses, and other pathogens. These nanomaterials release antimicrobial agents gradually, providing long-lasting protection against microbial contamination without the need for harsh chemicals. Recent studies concerning the effects of shapes and size of silver nanoparticles revealed that both the size and shapes have a major role in antimicrobial functioning [69].

1.4.2.2. Desalination and Water Cycling

Advancements in nanotechnology-based materials have significantly improved desalination and water recycling technologies, enabling more efficient and sustainable water management practices.

Forward osmosis process (FO), coupled with nanoparticles as draw solutes, offers an energy-efficient alternative for water desalination and concentration. Nanoparticles such as carbon nanotubes and magnetic nanoparticles enhance the osmotic pressure gradient across the membrane, enabling higher water flux rates and lower fouling propensity compared to traditional FO systems. Nanoparticle-enhanced FO has potential applications in seawater desalination and wastewater treatment. Challenges like, internal concentration polarisation, can be avoided by developing advanced ‘membranes by incorporating ZnO and ZnO- SiO_2-based core-shell nano compounds [70]. The development of sustainable solutions for forward osmosis must consider the efficient management of high osmotic pressure and also the simple and effective renewal of the force by the magnetic field [71].

Research in sustainable development in the refinement of brackish water using locally available materials like carbon, kaolin, sand, etc showed better efficiency [72]. Nanofiltration membranes with precise pore sizes and surface properties are well-suited for treating brackish water sources with moderate salt concentrations. These membranes selectively remove divalent ions, organic matter, and micropollutants while allowing monovalent ions and water molecules to pass through, resulting in high-quality permeate suitable for various applications, including agricultural irrigation and industrial processes. Another area of advanced research is in the field of direct dispersion of multiwalled carbon nanotubes along with the brackish water instead of using it as a membrane and this technique also showed better results [73].

Nanomaterial-based absorbents, such as graphene aerogels, metal-organic frameworks (MOFs), and nanoscale polymers, are utilized for water recycling and pollutant removal applications. These absorbents exhibit high surface area, porosity, and adsorption capacity, enabling efficient removal of contaminants, including heavy metals, organic pollutants, and microplastics, from wastewater streams. MOFs are used as multifunctional components to achieve maximum sustainability. The latest research showed that copper-based MOF can be used for simultaneous electricity production and water purification [74]. Nanomaterial-based absorbents can be regenerated and reused multiple times, making them economically viable for decentralized water treatment systems.

1.4.2.3. Smart Nano Material for Water Management

In the quest for sustainable water management solutions, the integration of smart nanomaterials emerges with a quiet number of innovations and promises. With their remarkable properties and responsive behaviours, smart nanomaterials are revolutionizing the landscape of water treatment, monitoring, and resource utilization. These materials, meticulously engineered at the nanoscale, possess the ability to sense, target, and respond to specific water quality parameters and contaminants in real time. From selective adsorption to controllable release systems, and self-cleaning surfaces to advanced monitoring devices, smart nanomaterials offer a versatile toolkit for addressing the complex challenges of water management in the modern era. Smart nanomaterials hold significant promise for revolutionizing water management practices by enabling real-time monitoring, targeted treatment, and efficient resource utilization.

Nanomaterials with responsive properties, such as pH-sensitive hydrogels and stimuli-responsive nanoparticles, are being developed for controlled release and targeted delivery of water treatment agents. These materials release treatment chemicals or nanoparticles in response to changes in environmental conditions, optimizing treatment efficiency and minimizing environmental impacts. Water purification using stimuli-responsive nanomaterials calls for further advanced research as it is proven to be a multidimensional sustainable solution. These materials could change their physical and chemical characteristics concerning the differences in their circumstances by changing their size, and optical as well as electrical functionalities. It was observed that changing the end functional moiety for the creation of stimuli-responsive cellulose-derived polymeric nanomaterials is an easy process methodology [75].

MXene-based smart materials showed high efficiency in the removal of pollutants like polyaromatic hydrocarbons, heavy metals, organic contaminants, etc from aquatic environments. It also provides the way forward to future inventions in the field of smart materials for water purification [76]. Nanotechnology enables the design of controllable release systems for water treatment agents and functional additives. Smart nanomaterials with stimuli-responsive properties, such as hydrogels, liposomes, and nano capsules, release treatment chemicals, disinfectants, or nanoparticles in response to changes in environmental conditions or target concentrations, optimizing treatment efficiency and minimizing chemical consumption.

Nanostructured coatings and surfaces with self-cleaning properties repel contaminants and prevent fouling, scaling, and biofilm formation on water treatment membranes, pipes, and surfaces. Smart nanomaterials, such as superhydrophobic coatings and photocatalytic nanoparticles, promote the spontaneous removal of dirt, algae, and organic matter from water contact surfaces, reducing maintenance costs and extending the lifespan of water infrastructure. Advanced research focuses on self-cleaning materials based on metal nanostructures. Aluminium-based nanomaterials with extra hydrophobicity showed effectiveness in the self-cleaning properties [77].

1.4.2.4. Environmental Nano-safety and Risk Assessment

As nanotechnology applications in water quality management continue to expand, there is a growing need to evaluate the environmental fate, toxicity, and potential risks associated with nanomaterials released into aquatic ecosystems. Research efforts focus on understanding the behaviour, bioavailability, and ecotoxicological effects of engineered nanoparticles on aquatic organisms, food webs, and ecosystem health. Sustainable nanomaterial design, lifecycle assessment, and regulatory frameworks are essential for ensuring responsible development and deployment of nanotechnology-based solutions in water management. Therefore, integrating nano-safety and risk assessment into water quality management strategies is essential for ensuring the long-term sustainability of our water resources.

Understanding the physicochemical properties of nanomaterials is crucial for assessing their environmental fate, transport, and toxicity. Characterization techniques such as electron microscopy, dynamic light scattering, and spectroscopy help determine the size, shape, surface charge, and composition of nanoparticles. Nanotubular structures of carbon showed higher pulmonary toxicity in mice in comparison with its graphite form [78].

Assessing the routes and levels of exposure to nanomaterials in aquatic environments is essential for evaluating their potential risks. Factors such as nanoparticle stability, mobility, and bioavailability influence their exposure pathways to aquatic organisms and ecosystems. The greatest risk in this area is the fact that the factual intensities of nanomaterials in aquatic environments are yet to be established. The quantification of the number of nanomaterials that are released into the aquatic environment is not yet established. Advanced research is required to reduce the technical difficulties in measuring the concentrations of nanomaterials in aquatic environments [79,80]. Developing predictive models and frameworks for assessing the environmental risks posed by nanomaterials facilitates decision-making in water quality management. These models integrate data on nanomaterial properties, exposure scenarios, and toxicity endpoints to estimate the likelihood and magnitude of adverse effects on aquatic ecosystems [81].

Life cycle assessment (LCA): Conducting life cycle assessments helps evaluate the environmental impacts associated with the entire life cycle of nanomaterials, from production and use to disposal or recycling. LCA considers factors such as energy consumption, resource utilization, emissions, and waste generation to identify opportunities for improving the sustainability of nanotechnology-based water treatment processes. Comparison of regular chemicals with nanomaterials on the LCA and risk assessment pointed out the fact that the dose matrices of nanomaterial should be established at the initial stage itself [82,83].

1.4.3. Membrane Filtration Technologies

Membrane filtration technologies, coupled with advancements in nanotechnology, are revolutionizing water quality management for sustainable development. These technologies offer efficient and cost-effective solutions for removing contaminants, pathogens, and pollutants from water sources. Nanomaterial-based membrane filtration technologies are advancing rapidly, offering innovative solutions for various applications including water purification, desalination, wastewater treatment, and resource recovery. These rapid advancements offer promising opportunities to address key challenges in water treatment, resource recovery, and environmental sustainability, paving the way for the development of advanced membrane solutions tailored to specific application requirements and operational conditions.

1.4.3.1. Nanofiltration and Reverse Osmosis Membranes

Research in nanofiltration (NF) and reverse osmosis (RO) membranes is constantly evolving, driven by the need for more efficient, sustainable, and cost-effective water treatment solutions. ongoing research in NF and RO membrane technologies aims to address key challenges in water treatment, such as fouling mitigation, energy efficiency, and environmental sustainability while advancing the development of advanced membrane solutions for diverse applications. Recent studies explore the integration of nanomaterials into NF and RO membranes to enhance their performance and functionality. Research focuses on developing novel nanocomposite membranes with improved selectivity, permeability, and fouling resistance through the incorporation of nanomaterials such as graphene oxide, carbon nanotubes, metal nanoparticles, and nanofibers.

Energy consumption is a critical consideration in NF and RO membrane processes, particularly for desalination and water reuse applications. Research efforts aim to develop energy-efficient membrane processes through the optimization of system design, operating parameters, and membrane materials. Advances in energy recovery devices, membrane modules, and process integration schemes contribute to reducing the energy footprint of NF and RO water treatment systems [84].

Research continues to explore the development of novel membrane materials with improved selectivity, durability, and sustainability. Studies investigate the use of renewable and biodegradable polymers, environmentally friendly solvents, and biomimetic materials for membrane fabrication. Innovations in membrane synthesis techniques, such as electrospinning, layer-by-layer assembly, and template-assisted methods, enable the design of membranes with tailored properties for specific water treatment applications. Material consisting of graphene in the form of layers showed good results in the seawater purification processes [85].

Research initiatives explore sustainable membrane manufacturing processes that minimize environmental impact and resource consumption. Studies investigate green synthesis routes, waste utilization strategies, and life cycle assessment methodologies to evaluate the environmental footprint of membrane production and deployment. Sustainable membrane manufacturing practices promote circular economy principles and contribute to the development of environmentally responsible water treatment technologies [86,87].

1.4.3.2. Membrane Distillations

Membrane distillation (MD) emerges as a promising thermal separation process, particularly for applications demanding the removal of volatile compounds or the concentration of solutions. Unlike conventional distillation methods that rely on boiling points, MD capitalizes on the vapor pressure difference across a hydrophobic porous membrane to facilitate mass transfer. This technique is especially advantageous for processing sensitive or concentrated solutions, as it operates at low temperatures and pressures, minimizing thermal degradation and energy consumption. By harnessing the principles of phase change and selective permeation, membrane distillation holds immense potential across diverse industries including desalination, wastewater treatment, food and beverage, pharmaceuticals, and beyond. Its scalability, efficiency, and versatility position membrane distillation as a compelling solution to address contemporary challenges in separation processes. Recent advancements in nanomaterials for MD have significantly contributed to the sustainable development of water quality management. Nanomaterials, with their unique properties and functionalities, enhance the performance and efficiency of MD membranes, making them more effective for various water treatment applications.

Surface functionalization of nanomaterials with hydrophilic or hydrophobic groups allows for precise control over membrane surface properties, facilitating tailored wetting behavior and enhanced water vapor transport. Functionalized nanomaterials offer improved control over membrane pore size distribution and surface chemistry, thereby enhancing membrane selectivity and permeability. Advanced research in this field consists of the creation of membranes with specific material characteristics. Modifications of carbon nanotubes by covalently or changing the functional groups improve their dispersibility and contact with other polymeric membranes [88].

Researchers have explored the integration of nanostructured surfaces on MD membranes to improve wetting resistance, increase surface area, and enhance mass transfer efficiency. Nano-coatings or nanostructures composed of materials like graphene, carbon nanotubes, and nano-porous polymers exhibit promising anti-fouling properties and enhance the durability of MD membranes. As industrial wastewater contains high levels of oils, MD units require omniphobic membranes that ensure the resistance to wetness on the membrane surfaces by both the oil and water mediums. Nanostructures consists of cylindrical glass fibre and nano-silica on those fibres ensures an omni-phobic nature [89].

1.4.3.3. Photocatalytic Membranes

Photocatalytic membranes represent an innovative approach at the intersection of membrane technology and photocatalysis, offering a multifunctional platform for advanced water treatment and environmental remediation. By integrating photocatalytic materials onto membrane surfaces, these membranes harness the power of light-driven chemical reactions to degrade organic pollutants, disinfect water, and even generate clean energy. As research and development efforts continue to evolve, the design and optimization of photocatalytic membranes are poised to revolutionize the landscape of water and environmental management, offering efficient, cost-effective, and eco-friendly solutions to address pressing global challenges.

Engineering research in the field of reactors with ceramic photo-catalytic membranes brings novel solutions for water purification systems [90]. Cleavage of water to produce hydrogen by photo-catalysis is the most advanced and sustainable solution for the energy creation. Nanostructures such as titanium dioxide (TiO_2), zinc oxide (ZnO), and graphene oxide (GO) exhibit exceptional photocatalytic properties due to their high surface area-to-volume ratio and unique electronic structure. Recent research focuses on engineering nanomaterials with enhanced light absorption and charge separation properties to boost photocatalytic activity, leading to more efficient pollutant degradation and water disinfection. Materials such as pristine and Sr-doped TiO_2 nano catalysts showed very good results in the energy creation [91].

As the requirements of water purification diverge, the requirement for effective membrane technologies also should suffice that requirement and current research focused on tailored nanomaterial design for the same [92]. Advances in nanotechnology enable the precise design and synthesis of nanomaterials with tailored properties for specific water treatment applications. Researchers explore novel nanostructures, such as quantum dots, and carbon-based nanomaterials, to address challenges such as emerging contaminants, heavy metal removal, and antibiotic resistance in water.

1.5. Future Directions and Recommendations

Future directions for addressing water resource management challenges and opportunities for sustainable development require a comprehensive and collaborative approach across multiple sectors and stakeholders. Investment in modern water infrastructure, including efficient treatment plants and distribution networks, is imperative to ensure reliable access to clean water. Additionally, promoting water conservation practices and implementing innovative technologies such as drip irrigation and rainwater harvesting can help minimize wastage and preserve freshwater resources. Embracing nature-based solutions like wetland restoration and green infrastructure can enhance water quality, recharge aquifers, and mitigate the impacts of climate change on water availability. Moreover, advancing water governance frameworks and fostering international cooperation are essential for addressing transboundary water issues and promoting equitable access to water resources while safeguarding the rights of marginalized communities.

To achieve sustainable water management, it is crucial to integrate social, economic, and environmental considerations into water resource planning and decision-making processes. This involves adopting integrated water resource management approaches that prioritize stakeholder engagement, adaptive governance structures, and capacity-building initiatives. Strengthening regulatory frameworks and enforcing laws to protect water quality and ensure equitable distribution is paramount. Moreover, investing in research and development of innovative water treatment technologies can address emerging contaminants and expand access to safe drinking water, especially in regions facing water scarcity and pollution challenges. By embracing these future directions and recommendations, communities, governments, and organizations can work together to build resilience, promote inclusive water governance, and secure water resources for sustainable development and the well-being of present and future generations.

1.6. Conclusion

Water resource management presents multifaceted challenges and opportunities for sustainable development, as discussed in this chapter. Understanding the complexities of water resources is essential for effective management strategies. Challenges such as water scarcity, pollution, and inadequate infrastructure underscore the urgent need for innovative solutions and collaborative efforts. Current advancements in water quality management, particularly in analytical techniques, nanotechnology applications, and membrane filtration technologies, offer promising avenues for addressing water quality issues and enhancing access to clean water. Analytical techniques, including sensor technologies and remote sensing, enable real-time monitoring and assessment of water quality parameters, facilitating timely interventions and informed decision-making.

Nanotechnology applications have revolutionized water treatment and purification processes, offering efficient and sustainable solutions for desalination, water recycling, and environmental remediation. The development of smart nanomaterials further enhances the effectiveness and environmental safety of water management practices.

Looking ahead, future directions and recommendations for water resource management emphasize the integration of nature-based solutions, promotion of water conservation practices, enhancement of water governance frameworks, and fostering international cooperation. By embracing holistic approaches and leveraging technological innovations, stakeholders can work towards achieving water security, equitable access to clean water, and sustainable development goals for present and future generations.

References

1. Farid Ahmed, Minhaz, Mazlin Bin Mokhtar, Chen Kim Lim, Izzati Afiqah Binti Che Suza, Ku Adriani Ku Ayob, Rd Puteri Khairani Khirotdin, and Nuriah Abd Majid. "Integrated River Basin Management for Sustainable Development: Time for Stronger Action." *Water* 15, 13 (2023), 2497. https://doi.org/10.3390/w15132497.
2. Pastukhov, Mikhail V., Vera I. Poletaeva, and Guvanchgeldi B. Hommatlyyev. "Hydrochemical Characteristics and Water Quality Assessment of Irkutsk Reservoir (Baikal Region, Russia)." *Water* 15, 23 (2023), 4142. https://doi.org/10.3390/w15234142.
3. Mishra, Rakesh Kumar. "Fresh water availability and its global challenge." *British Journal of Multidisciplinary and Advanced Studies* 4, 3 (2023), 1-78. https://doi.org/10.37745/bjmas.2022.0208.

4. Papa, Fabrice, Jean-François Crétaux, Manuela Grippa, Elodie Robert, Mark Trigg, Raphael M. Tshimanga, Benjamin Kitambo. "Water resources in Africa under global change: monitoring surface waters from space." *Surveys in Geophysics* 44, 1 (2023), 43-93. https://doi.org/10.1007/s10712-022-09700-9.

5. Asif, Zunaira, Zhi Chen, Rehan Sadiq, and Yinying Zhu. "Climate change impacts on water resources and sustainable water management strategies in North America." *Water Resources Management* 37, 6 (2023), 2771-2786. https://doi.org/10.1007/s11269-023-03474-4.

6. Rahmani, Farhang, and Mohammad Hadi Fattahi. "Investigation of alterations in droughts and floods patterns induced by climate change." *Acta Geophysica* 72, 1 (2024), 405-418. https://doi.org/10.1007/s11600-023-01043-2.

7. Wang, Rong, Xianghu Li, Qi Zhang, Junxiang Cheng, Jianfeng Li, Dan Zhang, and Yuanbo Liu. "Projection of drought-flood abrupt alternation in a humid subtropical region under changing climate." *Journal of Hydrology* 624 (2023), 129875. https://doi.org/10.1016/j.jhydrol.2023.129875.

8. Chakraborty, Susanta Kumar, Poulomi Sanyal, and Ratnadeep Ray. "Pollution, Environmental Perturbation and Consequent Loss of Wetlands." In *Wetlands Ecology: Eco-biological uniqueness of a Ramsar site (East Kolkata Wetlands, India)* (2023), 521-582. https://doi.org/10.1007/978-3-031-09253-4_8.

9. Sugiawan, Yogi, Robi Kurniawan, and Shunsuke Managi. "Assessing the United Nations sustainable development goals from the inclusive wealth perspective." *Scientific reports* 13, 1 (2023), 1601. https://doi.org/10.1038/s41598-023-28540-0.

10. Whittingham, Keith L., Andrew G. Earle, Dante I. Leyva-de la Hiz, and Alessia Argiolas. "The impact of the United Nations Sustainable Development Goals on corporate sustainability reporting." *BRQ Business Research Quarterly* 26, 1 (2023), 45-61. https://doi.org/10.1177/23409444221085585.

11. Sommer, Chelsea L., Catherine J. Crowley, Gemma Moya-Galé, Edouardo Adjassin, Evelyn Caceres, Veronica Yu, Kimmy Coseteng-Flaviano. "Global partnerships to create communication resources addressing Sustainable Development Goals 3, 4, 8, 10, and 17." *International Journal of Speech-Language Pathology* 25, 1 (2023), 167-171. https://doi.org/10.1080/17549507.2022.2130430.

12. Mujtaba, Ghulam, Mansoor Ul Hassan Shah, Abdul Hai, Muhammad Daud, and Mazhar Hayat. "A holistic approach to embracing the United Nation's Sustainable Development Goal (SDG-6) towards water security in Pakistan." *Journal of Water Process Engineering* 57 (2024), 104691. https://doi.org/10.1016/j.jwpe.2023.104691.

13. Nwokolo, Samuel Chukwujindu, Eyime Echeng Eyime, Anthony Umunnakwe Obiwulu, and Julie C. Ogbulezie. "Africa's Path to Sustainability: Harnessing Technology, Policy, and Collaboration." *Trends in Renewable Energy* 10, 1 (2023), 98-131. https://doi.org/10.17737/tre.2024.10.1.00166.

14. Nguyen, Hanh. "How to harness the digital transformation towards sustainability: Fostering a resilient and inclusive digitalization in Finland." Master's thesis, (2023). https://urn.fi/URN:NBN:fi:aalto-202304162739.

15. Meran, Georg, Markus Siehlow, Christian von Hirschhausen, Georg Meran, Markus Siehlow, and Christian von Hirschhausen. "Water availability: A hydrological view." *The Economics of Water: Rules and Institutions* (2021), 9-21. https://doi.org/10.1007/978-3-030-48485-9_2.

16. Wang, Y., N. Meili, and S. Fatichi. "Evidence and controls of the acceleration of the hydrological cycle over land." *Water Resources Research* 59, 8 (2023), e2022WR033970. https://doi.org/10.1029/2022WR033970.

17. Shibata, Hideaki, Ryosuke Ban, Nanae Hirano, Sadao Eguchi, Shin-Ichiro Mishima, Masaaki Chiwa, and Naoyuki Yamashita. "Comparison of spatial and temporal changes in riverine nitrate

concentration from terrestrial basins to the sea between the 1980s and the 2000s in Japan: Impact of recent demographic shifts." *Environmental Pollution* 288 (2021), 117695. https://doi.org/10.1016/j.envpol.2021.117695.

18. Saleem, Ashty, Ashraf Dewan, Md Masudur Rahman, Shahrin M. Nawfee, Rajimul Karim, and Xi Xi Lu. "Spatial and temporal variations of erosion and accretion: a case of a large tropical river." *Earth Systems and Environment* 4 (2020), 167-181. https://doi.org/10.1007/s41748-019-00143-8.

19. Yin, Shihua, Guangyao Gao, Lishan Ran, Xixi Lu, and Bojie Fu. "Spatiotemporal variations of sediment discharge and in-reach sediment budget in the Yellow River from the headwater to the delta." *Water Resources Research* 57, 11 (2021), e2021WR030130. https://doi.org/10.1029/2021WR030130.

20. Wang, Xuanxuan, Yaning Chen, Zhi Li, Gonghuan Fang, Fei Wang, and Haichao Hao. "Water resources management and dynamic changes in water politics in the transboundary river basins of Central Asia." *Hydrology and Earth System Sciences* 25, 6 (2021), 3281-3299. https://doi.org/10.5194/hess-25-3281-2021.

21. Gupta, Nishikant, Santosh Dahal, Anil Kumar, Chandan Kumar, Mukul Kumar, Anil Maharjan, Dinesh Mishra. "Rich water, poor people: Potential for transboundary flood management between Nepal and India." *Current Research in Environmental Sustainability* 3 (2021), 100031. https://doi.org/10.1016/j.crsust.2021.100031.

22. Baranyai, Gábor, and Gábor Baranyai. "Emerging challenges to transboundary water governance." *European Water Law and Hydropolitics: An Inquiry into the Resilience of Transboundary Water Governance in the European Union* (2020), 53-68. https://doi.org/10.1007/978-3-030-22541-4_6.

23. Acharya, Vijeth, Bhavana Halanaik, Arkalgud Ramaprasad, TR Kumara Swamy, Chetan B. Singai, and Thant Syn. "Transboundary sharing of river water: Informating the

policies." *River research and applications* 36, 1 (2020), 161-170. https://doi.org/10.1002/rra.3564.

24. Rickards, Nathan, Thomas Thomas, Alexandra Kaelin, Helen Houghton-Carr, Sharad K. Jain, Prabhash K. Mishra, Manish K. Nema. "Understanding future water challenges in a highly regulated Indian river basin—modelling the impact of climate change on the hydrology of the Upper Narmada." *Water* 12, 6 (2020), 1762. https://doi.org/10.3390/w12061762.
25. Richards, Laura A., Bethany G. Fox, Michael J. Bowes, Kieran Khamis, Arun Kumar, Rupa Kumari, Sumant Kumar. "A systematic approach to understand hydrogeochemical dynamics in large river systems: Development and application to the River Ganges (Ganga) in India." *Water Research* 211 (2022), 118054. https://doi.org/10.1016/j.watres.2022.118054.
26. Ramachandra, T. V., S. Vinay, S. Bharath, MD Subash Chandran, and Bharath H. Aithal. "Insights into riverscape dynamics with the hydrological, ecological and social dimensions for water sustenance." *Current Science* 118, 9 (2020), 1379-1393. https://doi.org/10.18520/cs/v118/i9/1379-1393.
27. Spijkers, Otto. "The sustainable human right to water as reflected in the sustainable development goals." *Utrecht Law Review* 16, 2 (2020), 18-32. https://doi.org/10.36633/ulr.560.
28. Tarhule, A. "The future of water: Prospects and challenges for water management in the 21st century." *Competition for Water Resources* (2017), 442-454. https://doi.org/10.1016/B978-0-12-803237-4.00025-2.
29. Sultana, Farhana. "Water justice: why it matters and how to achieve it." *Water International* 43, 4 (2018), 483-493. https://doi.org/10.1080/02508060.2018.1458272.
30. Bolan, Shiv, Lokesh P. Padhye, Tahereh Jasemizad, Muthusamy Govarthanan, N. Karmegam, Hasintha Wijesekara, Dhulmy Amarasiri. "Impacts of climate change on the fate of contaminants through extreme weather events." *Science of The*

Total Environment (2023), 168388. https://doi.org/10.1016/j.scitotenv.2023.168388.

31. Rachid, ECH-CHOUDANY, and Hicham Hafid. "Climate change and water resources: A comparative study in the MAGHREB." *International Journal of Accounting, Finance, Auditing, Management and Economics* 5, 3 (2024), 339-351. https://doi.org/10.5281/zenodo.10864642.
32. Bajaj, Akshi, S. P. Singh, and Diptimayee Nayak. "Impact of water markets on equity and efficiency in irrigation water use: a systematic review and meta-analysis." *Agricultural Water Management* 259 (2022), 107182. https://doi.org/10.1016/j.agwat.2021.107182.
33. Unicef, and Unicef. "Strategy for water, sanitation and hygiene 2016-2030." (2016).
34. Murei, Arinao, Barbara Mogane, Dikeledi Prudence Mothiba, Opelo Tlotlo Wryl Mochware, Jeridah Matlhokha Sekgobela, Mulalo Mudau, Ndamulelo Musumuvhi, Colette Mmapenya Khabo-Mmekoa, Resoketswe Charlotte Moropeng, and Maggie Ndombo Benkete Momba. "Barriers to water and sanitation safety plans in rural areas of South Africa—A case study in the Vhembe District, Limpopo Province." *Water* 14, 8 (2022), 1244. https://doi.org/10.3390/w14081244.
35. Santos, Eleonora, Milena Carvalho, and Susana Martins. "Sustainable Water Management: Understanding the Socioeconomic and Cultural Dimensions." *Sustainability* 15, 17 (2023), 13074. https://doi.org/10.3390/su151713074.
36. Shi, Linda, Sonia Ahmad, Prakriti Shukla, and Sauvanithi Yupho. "Shared injustice, splintered solidarity: Water governance across urban-rural divides." *Global Environmental Change* 70 (2021), 102354. https://doi.org/10.1016/j.gloenvcha.2021.102354.
37. Chaudhuri, Sriroop, Mimi Roy, Louis M. McDonald, and Yves Emendack. "Water for All (Har Ghar Jal): rural water supply services (RWSS) in India (2013–2018), challenges and

opportunities." *International Journal of Rural Management* 16, 2 (2020), 254-284. https://doi.org/10.1177/09730052209466.

38. Prasad, A. N., K. Al Mamun, F. R. Islam, and Haq Haqva. "Smart water quality monitoring system." In *2015 2nd Asia-Pacific World Congress on Computer Science and Engineering* (2015), 1-6. https://doi.org/10.1109/APWCCSE.2015.7476234.

39. Bogdan, Razvan, Camelia Paliuc, Mihaela Crisan-Vida, Sergiu Nimara, and Darius Barmayoun. "Low-cost internet-of-things water-quality monitoring system for rural areas." *Sensors* 23, 8 (2023), 3919. https://doi.org/10.3390/s23083919.

40. Ahmed, Abul Abrar Masrur, S. Janifer Jabin Jui, Mohammad Aktarul Islam Chowdhury, Oli Ahmed, and Ambica Sutradha. "The development of dissolved oxygen forecast model using hybrid machine learning algorithm with hydro-meteorological variables." *Environmental Science and Pollution Research* 30, 3 (2023), 7851-7873. https://doi.org/10.21203/rs.3.rs-1100147/v1.

41. Chu, Chen-Hua, Yu-Xuan Lin, Chun-Kuo Liu, and Mei-Chun Lai. "Development of innovative online modularized device for turbidity monitoring." *Sensors* 23, 6 (2023), 3073. https://doi.org/10.3390/s23063073.

42. Sadia, Mohammad, Ingeborg Nollen, Rick Helmus, Thomas L. Ter Laak, Frederic Béen, Antonia Praetorius, and Annemarie P. van Wezel. "Occurrence, fate, and related health risks of PFAS in raw and produced drinking water." *Environmental Science & Technology* 57, 8 (2023), 3062-3074. https://doi.org/10.1021/acs.est.2c06015.

43. Valbonesi, Paola, Marilin Profita, Ivo Vasumini, and Elena Fabbri. "Contaminants of emerging concern in drinking water: Quality assessment by combining chemical and biological analysis." *Science of the Total Environment* 758 (2021), 143624. https://doi.org/10.1016/j.scitotenv.2020.143624.

44. Sudarman, F., M. Shiddiq, B. Armynah, and D. Tahir. "Silver nanoparticles (AgNPs) synthesis methods as heavy-metal

sensors: a review." *International Journal of Environmental Science and Technology* 20, 8 (2023), 9351-9368. https://doi.org/10.1007/s13762-022-04745-0.

45. Vonnie, J. M., K. Rovina, A. M. A. Mariah, K. H. Erna, W. X. L. Felicia, and Md NN ‘Aqilah. "Trends in nanotechnology techniques for detecting heavy metals in food and contaminated water: a review." *International Journal of Environmental Science and Technology* 20, 7 (2023), 8041-8072. https://doi.org/10.1007/s13762-022-04487-z.

46. Tomar, Pallavi, Suraj Kumar Singh, Shruti Kanga, and Amitanshu Pattanaik. "Water Bodies mapping and monitoring using high-resolution satellite images." *Sustainability, Agri, Food and Environmental Research* 11 (2023). https://doi.org/10.7770/safer-V11N1-art2673.

47. Quinn, Nigel WT, Vamsi Sridharan, John Ramirez-Avila, Sanaz Imen, Huilin Gao, Rocky Talchabhadel, Saurav Kumar, and Walter McDonald. "Applications of GIS and remote sensing in public participation and stakeholder engagement for watershed management." (2023), 1-27. https://doi.org/10.18174/sesmo.18149.

48. Adjovu, Godson Ebenezer, Haroon Stephen, David James, and Sajjad Ahmad. "Overview of the application of remote sensing in effective monitoring of water quality parameters." *Remote Sensing* 15, 7 (2023), 1938. https://doi.org/10.3390/rs15071938.

49. Agnoli, Lara, Erin Urquhart, Nikolaos Georgantzis, Blake Schaeffer, Richard Simmons, Bilqis Hoque, Merrie Beth Neely, Claire Neil, Jacques Oliver, and Andrew Tyler. "Perspectives on user engagement of satellite Earth observation for water quality management." *Technological Forecasting and Social Change* 189 (2023), 122357. https://doi.org/10.1016/j.techfore.2023.122357.

50. Wang, Qian, Caicai Jiao, Xinpeng Wang, Yang Wang, Kang Sun, Liangtao Li, Yubo Fan, and Liang Hu. "A hydrogel-based biosensor for stable detection of glucose." *Biosensors and*

Bioelectronics 221 (2023), 114908. https://doi.org/10.1016/j.bios.2022.114908.

51. Thavarajah, Walter, Patrick Mbullo Owuor, Diana Ross Awuor, Karlmax Kiprotich, Rahul Aggarwal, Julius B. Lucks, and Sera L. Young. "The accuracy and usability of point-of-use fluoride biosensors in rural Kenya." *NPJ Clean Water* 6, 1 (2023), 5. https://doi.org/10.1038/s41545-023-00221-5.

52. Tang, Yue, Jie Sun, Derong Dong, Xiushan Zhang, Ruizhong Jia, Yong Wang, Yong Chen, Jinpeng Guo, and Lianqun Jin. "Comparison of coliform paper test and ATP bioluminescence assay for monitoring the disinfection of kitchen utensils in canteens of hebei, China." *Heliyon* 9, 4 (2023), 1-8. https://doi.org/10.1016/j.heliyon.2023.e14839.

53. Park, Jihae, Kisik Shin, Hojun Lee, Soyeon Choi, Geonhee Kim, Stephen Depuydt, Jonas De Saeger et al. "Evaluating ecotoxicological assays for comprehensive risk assessment of toxic metals present in industrial wastewaters in the Republic of Korea." *Science of the Total Environment* 867 (2023), 161536. https://doi.org/10.1016/j.scitotenv.2023.161536.

54. Acharya, Bharat Sharma, Mahendra Bhandari, Filippo Bandini, Alonso Pizarro, Matthew Perks, Deepak Raj Joshi, Sheng Wang et al. "Unmanned aerial vehicles in hydrology and water management: Applications, challenges, and perspectives." *Water Resources Research* 57, 11 (2021), e2021WR029925. https://doi.org/10.1029/2021WR029925.

55. Etikasari, Bety, S. Kautsar, H. Y. Riskiawan, and D. P. S. Setyohadi. "Wireless sensor network development in unmanned aerial vehicle (uav) for water quality monitoring system." In *IOP Conference Series: Earth and Environmental Science*, 411, 1, (2020), 012061. https://doi.org/10.1088/1755-1315/411/1/012061.

56. DeFlorio-Barker, Stephanie, Coady Wing, Rachael M. Jones, and Samuel Dorevitch. "Estimate of incidence and cost of recreational waterborne illness on United States surface

waters." *Environmental Health* 17 (2018), 1-10. https://doi.org/10.1186/s12940-017-0347-9.

57. Wang, Hongda, Hatice Ceylan Koydemir, Yunzhe Qiu, Bijie Bai, Yibo Zhang, Yiyin Jin, Sabiha Tok et al. "Early detection and classification of live bacteria using time-lapse coherent imaging and deep learning." *Light: Science & Applications* 9, 1 (2020), 118. https://doi.org/10.1038/s41377-020-00358-9.

58. Goblirsch, Tobias, Thomas Mayer, Stefanie Penzel, Mathias Rudolph, and Helko Borsdorf. "In Situ Water Quality Monitoring Using an Optical Multiparameter Sensor Probe." *Sensors* 23, 23 (2023), 9545. https://doi.org/10.3390/s23239545.

59. Azcarate, Silvana M., Rocío Ríos-Reina, José M. Amigo, and Héctor C. Goicoechea. "Data handling in data fusion: Methodologies and applications." *TrAC Trends in Analytical Chemistry* 143 (2021), 116355. https://doi.org/10.1016/j.trac.2021.116355.

60. Chapman, James, Vi Khanh Truong, Aaron Elbourne, Sheeana Gangadoo, Samuel Cheeseman, Piumie Rajapaksha, Kay Latham, Russell J. Crawford, and Daniel Cozzolino. "Combining chemometrics and sensors: Toward new applications in monitoring and environmental analysis." *Chemical Reviews* 120, 13 (2020), 6048-6069. https://doi.org/10.1021/acs.chemrev.9b00616.

61. Nehra, Sapna, Manjula Nair, and Dinesh Kumar. "Hydrothermally shape-controlled synthesis of TiO_2/Graphene for fluoride adsorption studies." *Journal of Chemical & Engineering Data* 64, 12 (2019), 5373-5384. https://doi.org/10.1021/acs.jced.9b00591.

62. Nehra, Sapna, Sapna Raghav, and Dinesh Kumar. "Biomaterial functionalized cerium nanocomposite for removal of fluoride using central composite design optimization study." *Environmental pollution* 258 (2020), 113773. https://doi.org/10.1016/j.envpol.2019.113773.

63. Nehra, Sapna, Ankita Dhillon, and Dinesh Kumar. "Freeze–dried synthesized bifunctional biopolymer nanocomposite for efficient fluoride removal and antibacterial activity." *Journal of Environmental Sciences* 94 (2020), 52-63. https://doi.org/10.1016/j.jes.2020.03.047.
64. Nehra, Sapna, Sapna Raghav, and Dinesh Kumar. "Rod–shaped Ca–Zn@ Chitin composite for fluoride removal studies by adsorption and statistical experiments." *Environmental nanotechnology, monitoring & management* 12 (2019), 100264. https://doi.org/10.1016/j.enmm.2019.100264.
65. Nehra, Sapna, Ankita Dhillon, Rekha Sharma, Manjula Nair, and Dinesh Kumar. "Water–dispersible magnetite montmorillonite encapsulated cellulose beads for fluoride removal and their kinetics and mechanism." *Environmental Nanotechnology, Monitoring & Management* 18 (2022), 100690. https://doi.org/10.1016/j.enmm.2022.100690.
66. Cho, Hyun-Hee, Kevin Wepasnick, Billy A. Smith, Fazlullah K. Bangash, D. Howard Fairbrother, and William P. Ball. "Sorption of aqueous Zn [II] and Cd [II] by multiwall carbon nanotubes: the relative roles of oxygen-containing functional groups and graphenic carbon." *Langmuir* 26, 2 (2010), 967-981. https://doi.org/10.1021/la902440u.
67. Madrakian, Tayyebeh, Abbas Afkhami, Mazaher Ahmadi, and Hasan Bagheri. "Removal of some cationic dyes from aqueous solutions using magnetic-modified multi-walled carbon nanotubes." *Journal of hazardous materials* 196 (2011), 109-114. https://doi.org/10.1016/j.jhazmat.2011.08.078.
68. Yang, Cheol-Min, Jin Sung Park, Kay Hyeok An, Seong Chu Lim, Kwanyong Seo, Bongsoo Kim, Kyung Ah Park, Seungwu Han, Chong Yun Park, and Young Hee Lee. "Selective removal of metallic single-walled carbon nanotubes with small diameters by using nitric and sulfuric acids." *The Journal of Physical Chemistry B* 109, 41 (2005), 19242-19248. https://doi.org/10.1021/jp053245c.

69. Moon, Jongmin, Jin Il Kwak, and Youn-Joo An. "The effects of silver nanomaterial shape and size on toxicity to Caenorhabditis elegans in soil media." *Chemosphere* 215 (2019), 50-56. https://doi.org/10.1016/j.chemosphere.2018.09.177.

70. Rastgar, Masoud, Alireza Shakeri, Ali Bozorg, Hasan Salehi, and Vahid Saadattalab. "Impact of nanoparticles surface characteristics on pore structure and performance of forward osmosis membranes." *Desalination* 421 (2017), 179-189. https://doi.org/10.1016/j.desal.2017.01.040.

71. Hafiz, MhdAmmar, Amani Hassanein, Mohammed Talhami, AL-Ejji Maryam, Mohammad K. Hassan, and Alaa H. Hawari. "Magnetic nanoparticles draw solution for forward osmosis: Current status and future challenges in wastewater treatment." *Journal of Environmental Chemical Engineering* 10, 6 (2022), 108955. https://doi.org/10.1016/j.jece.2022.108955.

72. Hermawan, S., P. Tiewanto, A. J. T. Tjahyana, K. P. Utomo, and N. Wahyuni. "Brackish water treatment with sustainable local materials." In *AIP Conference Proceedings*, 2680, 1 (2023), 020146. https://doi.org/10.1063/5.0126551.

73. Foglia, P., D. Vuono, C. Siciliano, A. Napoli, J. B. Nagy, and P. De Luca. "Brackish water treatment with carbon nanotubes." In *IOP Conference Series: Materials Science and Engineering*, 572, 1, (2019), 012047. https://doi.org/10.1088/1757-899X/572/1/012047.

74. Zhu, Xiuying, Mengjie Li, Lian Song, Xiong-Fei Zhang, and Jianfeng Yao. "Metal organic framework enabled wood evaporator for solar-driven water purification." *Separation and Purification Technology* 281 (2022), 119912. https://doi.org/10.1016/j.seppur.2021.119912.

75. Wang, Yonggui, Thomas Heinze, and Kai Zhang. "Stimuli-responsive nanoparticles from ionic cellulose derivatives." *Nanoscale* 8, 1 (2016), 648-657. https://doi.org/10.1039/C5NR05862G.

76. Nehra, Sapna, Rekha Sharma, and Dinesh Kumar. "Remediation of Hazardous Pollutants via MXenes-Based Smart Materials." In *Age of MXenes, Volume 2. Applications in Diagnostics, Therapeutics, and Environmental Remediation*, (2023), 169-191. https://doi.org/10.1021/bk-2023-1443.ch009.

77. Mandal, Priya, Gopinath Perumal, Harpreet S. Arora, Sajal K. Ghosh, and Harpreet S. Grewal. "Green manufacturing of nanostructured Al-Based sustainable self-cleaning metallic surfaces." *Journal of cleaner production* 278 (2021), 123373. https://doi.org/10.1016/j.jclepro.2020.123373.

78. Tsuji, Joyce S., Andrew D. Maynard, Paul C. Howard, John T. James, Chiu-wing Lam, David B. Warheit, and Annette B. Santamaria. "Research strategies for safety evaluation of nanomaterials, part IV: risk assessment of nanoparticles." *Toxicological sciences* 89, 1 (2006), 42-50. https://doi.org/10.1093/toxsci/kfi339.

79. Abbott, Linda C., and Andrew D. Maynard. "Exposure assessment approaches for engineered nanomaterials." *Risk Analysis: An International Journal* 30, 11 (2010), 1634-1644. https://doi.org/10.1111/j.1539-6924.2010.01446.x.

80. Keller, Arturo A., Yuanfang Zheng, Antonia Praetorius, Joris TK Quik, and Bernd Nowack. "Predicting environmental concentrations of nanomaterials for exposure assessment-a review." *NanoImpact* (2024), 100496. http://dx.doi.org/10.1016/j.impact.2024.100496.

81. Linkov, Igor, F. Kyle Satterstrom, Jeffery Steevens, Elizabeth Ferguson, and Richard C. Pleus. "Multi-criteria decision analysis and environmental risk assessment for nanomaterials." *Journal of Nanoparticle Research* 9 (2007), 543-554. https://doi.org/10.1007/s11051-007-9211-0.

82. Hischier, Roland, and Tobias Walser. "Life cycle assessment of engineered nanomaterials: State of the art and strategies to overcome existing gaps." *Science of the Total Environment* 425 (2012), 271-282. https://doi.org/10.1016/j.scitotenv.2012.03.001.

83. Grieger, Khara D., Alexis Laurent, Mirko Miseljic, Frans Christensen, Anders Baun, and Stig I. Olsen. "Analysis of current research addressing complementary use of life-cycle assessment and risk assessment for engineered nanomaterials: have lessons been learned from previous experience with chemicals?." *Journal of Nanoparticle Research* 14 (2012), 1-23. https://doi.org/10.1007/s11051-012-0958-6.

84. Grzegorzek, Martyna, Katarzyna Wartalska, and Bartosz Kaźmierczak. "Review of water treatment methods with a focus on energy consumption." *International Communications in Heat and Mass Transfer* 143 (2023), 106674. https://doi.org/10.1016/j.icheatmasstransfer.2023.106674.

85. Rehman, Faisal, Fida Hussain Memon, Akbar Ali, Shah Masaud Khan, Faheeda Soomro, Muzaffar Iqbal, and Khalid Hussain Thebo. "Recent progress on fabrication methods of graphene-based membranes for water purification, gas separation, and energy sustainability." *Reviews in Inorganic Chemistry* 43, 1 (2023), 13-31. https://doi.org/10.1515/revic-2022-0001.

86. Buonomenna, Maria Giovanna. "Membrane processes for a sustainable industrial growth." *RSC advances* 3, 17 (2013), 5694-5740. https://doi.org/10.1039/C2RA22580H.

87. Pasichnyk, Mariia, Petr Stanovsky, Petr Polezhaev, Boleslav Zach, Michal Šyc, Marek Bobák, Johannes C. Jansen et al. "Membrane technology for challenging separations: Removal of CO_2, SO_2 and NOX from flue and waste gases." *Separation and Purification Technology* (2023), 124436. https://doi.org/10.1016/j.seppur.2023.124436.

88. Kyoungjin An, Alicia, Eui-Jong Lee, Jiaxin Guo, Sanghyun Jeong, Jung-Gil Lee, and Noreddine Ghaffour. "Enhanced vapor transport in membrane distillation via functionalized carbon nanotubes anchored into electrospun nanofibres." *Scientific reports* 7, 1 (2017), 41562. https://doi.org/10.1038/srep41562.

89. Boo, Chanhee, Jongho Lee, and Menachem Elimelech. "Engineering surface energy and nanostructure of microporous

films for expanded membrane distillation applications." *Environmental science & technology* 50, 15 (2016), 8112-8119. https://doi.org/10.1021/acs.est.6b02316.

90. Horovitz, Inna, Vitaly Gitis, Dror Avisar, and Hadas Mamane. "Ceramic-based photocatalytic membrane reactors for water treatment–where to next?." *Reviews in Chemical Engineering* 36, 5 (2020), 593-622. https://doi.org/10.1515/revce-2018-0036.

91. Fazil, Mohd, and Tokeer Ahmad. "Pristine TiO_2 and Sr-doped TiO_2 nanostructures for enhanced photocatalytic and electrocatalytic water splitting applications." *Catalysts* 13, 1 (2023), 93. https://doi.org/10.3390/catal13010093.

92. Wang, Kunpeng, Xiaomao Wang, Brielle Januszewski, Yanling Liu, Danyang Li, Ruoyu Fu, Menachem Elimelech, and Xia Huang. "Tailored design of nanofiltration membranes for water treatment based on synthesis–property–performance relationships." *Chemical Society Reviews* 51, 2 (2022), 672-719. https://doi.org/10.1039/D0CS01599G.

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 ISBN: 978-81-975412-4-7

2

Potential of Nanocellulose as A Sustainable Replacement of CNTs in Water Purification Methods

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Contents

2.1 Introduction

Clean and accessible water is essential for sustaining life and ensuring public health, yet millions of people worldwide lack access to safe drinking water [1]. The increasing global population, urbanization, industrialization, and environmental pollution have exacerbated the challenges associated with water scarcity and contamination. Consequently, there is a pressing need for innovative and sustainable water purification technologies to address these complex issues [2]. Carbon nanotubes (CNTs) have emerged as promising materials for water purification due to their unique physical, chemical, and mechanical properties. Their high aspect ratio, large surface area, and exceptional adsorption capacity make them effective in removing contaminants such as heavy metals, organic pollutants, and pathogens from water. However, despite their remarkable properties, the widespread use of CNTs in water purification is hindered by concerns over their high cost, limited scalability, and potential environmental impact [3-5].

In recent years, nanocellulose has garnered increasing attention as a sustainable alternative to CNTs in various applications, including water purification. Nanocellulose, derived from renewable sources such as wood pulp, agricultural residues, and bacteria, exhibits remarkable mechanical strength, biocompatibility, and environmentally benign properties. These inherent characteristics make nanocellulose an attractive candidate for addressing the limitations of CNTs and advancing the development of sustainable water purification methods [6-8].

This chapter aims to explore the potential of nanocellulose as a sustainable replacement for CNTs in water purification methods. We will begin by providing an overview of the properties and applications of CNTs in water purification, highlighting their strengths and limitations. Subsequently, we will delve into the properties of nanocellulose, its sources, and its advantages over CNTs in the context of water purification. We will then discuss various nanocellulose-based water purification methods, including membrane filtration, surface modification for enhanced adsorption, and composite materials synthesis.

Additionally, we will conduct a comparative analysis of the performance and efficiency of nanocellulose and CNTs in water purification, considering factors such as cost-effectiveness, scalability, and environmental impact.

By elucidating the potential of nanocellulose as a sustainable alternative to CNTs in water purification, this chapter aims to contribute to the advancement of environmentally responsible and cost-effective solutions for addressing water quality challenges. Furthermore, we will identify remaining challenges and opportunities for future research and development in the field of nanocellulose-based water purification, ultimately advocating for the adoption of sustainable technologies to ensure access to clean water for all.

2.2 Properties of CNTs and Nanocellulose

Carbon nanotubes (CNTs) and nanocellulose are two nanomaterials with distinct properties that make them promising candidates for various applications, including water purification. Understanding their properties is crucial for harnessing their potential in addressing global challenges related to water scarcity and contamination [9-10]. Below, we discuss the key properties of CNTs and nanocellulose and their significance in water purification:

2.2.1 Properties of nanocellulose

Nanocellulose, comprised of cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs), exhibits a unique set of properties that render it highly versatile and suitable for a wide range of applications. Understanding these properties is essential for harnessing the full potential of nanocellulose in various fields, including water purification. Below are the key properties of nanocellulose:

- **High Surface Area:** Nanocellulose possesses an exceptionally high surface area per unit mass due to its nanostructured morphology. This property enhances its adsorption capacity, allowing for efficient removal of contaminants from water by providing numerous active sites for interaction.

- **Mechanical Strength:** Despite its nanoscale dimensions, nanocellulose exhibits impressive mechanical strength, comparable to or even exceeding that of traditional engineering materials like steel. This inherent strength ensures the durability and structural integrity of nanocellulose-based purification systems, making them suitable for demanding water treatment applications.
- **Biodegradability:** Derived from renewable biomass sources, nanocellulose is inherently biodegradable. This property makes nanocellulose environmentally friendly and sustainable, as it can decompose naturally at the end of its lifecycle without leaving harmful residues or contributing to pollution.
- **Biocompatibility:** Nanocellulose materials are biocompatible and non-toxic, making them safe for use in various applications, including water purification. This biocompatibility ensures that nanocellulose-based purification methods do not pose risks to human health or the environment.
- **Tunable Porosity:** Nanocellulose structures can be engineered to exhibit tunable porosity and pore size distribution. This tunability allows for precise control over filtration and adsorption processes, enabling selective removal of contaminants from water while maintaining high flow rates and minimizing energy consumption.
- **Chemical Functionalization:** Nanocellulose surfaces can be chemically modified to introduce desired functionalities such as surface charge, hydrophobicity, or specific binding sites. This versatility enables the customization of nanocellulose-based materials for enhanced water purification performance and selectivity tailored to specific contaminants and purification techniques.

Nanocellulose represents a sustainable and versatile nanomaterial with properties that make it highly attractive for water purification applications. Its high surface area, mechanical strength, biodegradability, and biocompatibility position it as a promising alternative to conventional purification materials. Moreover, its tunable porosity and chemical functionalization capabilities offer opportunities for tailored solutions to water treatment challenges. Harnessing the potential of nanocellulose requires a comprehensive understanding and innovative approaches to leverage its unique properties effectively. By capitalizing on these properties, nanocellulose-based purification methods can contribute to addressing global water challenges while promoting environmental sustainability and human health [11-15].

2.2.2 Properties of Carbon Nanotubes

Carbon nanotubes (CNTs) exhibit a plethora of remarkable properties that stem from their unique cylindrical nanostructure composed of rolled-up graphene sheets. These properties contribute to their widespread applications across various fields, including electronics, materials science, and biomedical engineering. Understanding the distinctive characteristics of CNTs is crucial for leveraging their potential in diverse applications. Below are the key properties of carbon nanotubes:

- **High Aspect Ratio:** CNTs typically have aspect ratios (length-to-diameter ratios) ranging from several hundred to several thousand. This high aspect ratio allows for an exceptionally large surface area per unit mass, facilitating interactions with molecules and surfaces in applications such as gas adsorption, catalysis, and reinforcement in composites.
- **Exceptional Mechanical Strength:** One of the most outstanding properties of CNTs is their extraordinary mechanical strength. They possess an intrinsic tensile strength several times greater than that of steel, combined with exceptional stiffness. These mechanical properties make CNTs ideal candidates for reinforcing materials in composites, leading to enhanced structural integrity and mechanical performance.
- **Electrical Conductivity:** Carbon nanotubes exhibit excellent electrical conductivity, comparable to or even surpassing that of copper. This property arises from the delocalized pi-electron system along the nanotube's length. It enables CNTs to conduct

electricity efficiently, making them valuable components in applications such as conductive films, field-effect transistors, and energy storage devices.

- **Thermal Conductivity:** CNTs demonstrate high thermal conductivity along their axial direction, surpassing that of most conventional materials. This property, coupled with their lightweight and mechanical strength, makes CNTs promising candidates for thermal management applications such as heat sinks, thermal interface materials, and thermal conductive composites.
- **Chemical Stability:** Carbon nanotubes exhibit remarkable chemical stability, making them resistant to degradation in harsh environments, including acidic or alkaline solutions, oxidation, and high temperatures. This stability ensures the long-term performance and reliability of CNT-based materials and devices in various applications.
- **Flexibility and Elasticity:** Despite their exceptional mechanical strength, CNTs also possess flexibility and elasticity, allowing them to undergo reversible deformation without structural damage. This property is advantageous in applications where flexibility and conformability are required, such as flexible electronics and sensors.
- **Optical Properties:** Depending on their structure, carbon nanotubes can exhibit unique optical properties, including absorption and emission in the visible and near-infrared regions of the electromagnetic spectrum. These properties have implications for applications such as photodetection, photovoltaics, and optical sensors.

In summary, carbon nanotubes possess a diverse range of properties that make them highly attractive for a wide array of applications [16-20]. Their exceptional mechanical strength, electrical and thermal conductivity, chemical stability, and optical properties contribute to their versatility and potential for innovation in fields ranging from electronics to materials science to biomedical engineering.

Understanding and harnessing these properties are essential for unlocking the full potential of carbon nanotubes in addressing current and future technological challenges.

2.3 Potential of Nano Cellulose Over CNTs In Water Purification

Nanocellulose presents a compelling alternative to carbon nanotubes (CNTs) in water purification applications, boasting several distinct advantages that address key concerns associated with CNT-based purification systems [21]. One of the primary advantages of nanocellulose lies in its sustainability, derived from renewable biomass sources such as wood pulp or agricultural residues, nanocellulose production aligns with principles of green chemistry and sustainable development. In contrast, the synthesis of CNTs often involves energy-intensive processes using carbonaceous precursors, raising environmental sustainability concerns [22]. Nanocellulose's renewable nature not only reduces dependence on finite resources but also minimizes environmental impact, making it an environmentally friendly choice for water purification technologies.

Moreover, nanocellulose offers inherent biodegradability, a feature absent in CNTs. While CNTs may persist in the environment for extended periods due to their chemical stability, nanocellulose materials can naturally decompose through enzymatic or microbial action at the end of their lifecycle. This biodegradability minimizes environmental pollution and waste accumulation, supporting circular economy principles and mitigating concerns about long-term environmental persistence associated with CNTs. Additionally, the biocompatibility of nanocellulose further enhances its appeal for water purification applications. Non-toxic and biocompatible, nanocellulose is safe for use in applications where contact with potable water or biological systems is inevitable, such as point-of-use water filters or medical devices. This property ensures that nanocellulose-based purification systems prioritize human health and safety [23-25].

Cost-effectiveness is another advantage of nanocellulose over CNTs. Nanocellulose production processes are generally simpler and more economical compared to the complex and energy-intensive synthesis methods employed for CNTs. With abundant cellulose feedstocks and advancements in production technologies, nanocellulose production costs continue to decline, making it an attractive option for large-scale water purification applications, particularly in resource-constrained settings [26]. Furthermore, the tunability of nanocellulose properties enhances its versatility and applicability in water purification. Nanocellulose materials can be tailored to exhibit specific surface chemistries, porosities, and mechanical strengths, allowing for customization to meet the requirements of diverse water treatment scenarios. This tunability enables the design of nanocellulose-based purification systems with enhanced efficiency, selectivity, and performance.

From a regulatory perspective, nanocellulose enjoys approvals for various applications, including food packaging, biomedical devices, and cosmetics. Its biocompatibility, renewable origin, and low environmental impact contribute to its regulatory acceptance, facilitating its adoption in water purification technologies [27]. In contrast, the regulatory status of CNTs remains subject to scrutiny due to concerns about potential health and environmental risks, posing challenges to their widespread commercialization and deployment in water treatment applications. Overall, nanocellulose's sustainability, biodegradability, biocompatibility, cost-effectiveness, tunable properties, and regulatory acceptance position it as a promising alternative to CNTs in water purification, offering solutions that prioritize environmental stewardship, human health, and sustainability.

2.4 Nanocellulose Water Purification Applications

Recent years have seen a notable increase in the interest in nanocellulose, an inventive natural and sustainable substance, made from cellulose fibers, due to its exceptional qualities and numerous industrial applications [28 - 30]. Nanocellulose offers a wide range of applications, but one that shows great promise is transforming water filtration technology. Worldwide, pollution and water scarcity are major concerns to environmental sustainability and public health [31,32]. Many communities find themselves unable to utilize tractional water purification technologies due to the complicated procedures and costly equipment involved, especially in distant or resource-poor places. Furthermore, traditional purifying methods can produce hazardous byproducts and use a lot of energy, which exacerbates environmental issues.

Within this framework, water filtration with nanocellulose presents an economical and environmentally friendly option [33]. Nanocellulose is an excellent option for a variety of filtration and adsorption applications because of its remarkable mechanical strength, large surface area, and biocompatibility. It is derived from abundant and renewable sources, such as wood pulp [34,35]. To improve its adsorptive qualities and customize its performance for pollutants, nanocellulose can also be chemically functionalized [36] or composite formed [37].

Using processes including adsorption, sieving, and electrostatic interactions, pollutants can be effectively removed from water thanks to the special structure of nanocellulose, which is made up of tiny fibrils with linked pores. Additionally, contaminants such as organic molecules, heavy metals, microbes, and nanoparticles can be selectively targeted by nanocellulose due to its programmable surface chemistry. Membranes, composite materials, adsorbents, and filter membranes based on nanocellulose have proven to be extremely effective in eliminating a variety of pollutants from water sources, such as municipal sewage, agricultural runoff, and industrial wastewater. Furthermore, nanocellulose is a feasible alternative for large-scale water treatment systems due to its low production cost and scalability, which might benefit both rural and urban communities [38].

Beyond its efficacy in water purification, nanocellulose exhibits biodegradability and compatibility with existing water treatment infrastructure, minimizing environmental impact and facilitating integration into existing systems [39-41]. Furthermore, ongoing research and development efforts continue to explore novel applications and advancements in nanocellulose-based water purification technologies, promising further improvements in efficiency, affordability, and sustainability. Nanocellulose holds immense promise for revolutionizing water purification technologies, offering sustainable solutions to address the pressing challenges of water scarcity and pollution. By harnessing the unique properties of nanocellulose, researchers and engineers are paving the way for accessible, cost-effective, and environmentally friendly approaches to ensure clean and safe water for communities worldwide.

2.4.1 Potential of Nanocellulose-Based Adsorbents for Heavy Metal Ions

Given its damaging effects on ecosystems and human health, heavy metal poisoning of water sources is a major global environmental concern. The high expense, poor performance, and production of secondary pollutants are common drawbacks of conventional heavy metal ion removal techniques [42]. An effective and long-lasting heavy metal ion remediation method is possible with nitrocellulose-based adsorbents in recent years [43].

Originating from cellulose, nanocellulose has special qualities that make it ideal for adsorption uses. Because of its high surface area-to-volume ratio and nanoscale size, it can interact with heavy metal ions more effectively [44]. Furthermore, nanocellulose has a large number of surface hydroxyl groups that are readily functionalized to improve selectivity and adsorption capability [45]. These characteristics make it possible for adsorbents based on nanocellulose to efficiently remove heavy metal ions from aqueous solutions. Heavy metal ions bind to nanocellulose-based adsorbents through a variety of mechanisms, such as surface precipitation [46], ion exchange [47], complexation [48], and electrostatic contact [49]. The precise process is contingent upon various elements, including the kind of heavy metal ions, the pH of the solution, nanocellulose surface chemistry, and the existence of competing ions. Comprehending these mechanisms is crucial to maximise adsorption efficiency and create specialized adsorbents for certain heavy metal pollutants.

Lead, cadmium, mercury, arsenic, and chromium are only a few of the heavy metal ions that can be effectively removed from aqueous solutions using adsorbents based on nitrocellulose, as shown by several research. Through modification techniques such as chemical functionalization, composite creation, and nanoparticle integration, these materials' adsorption capacity and efficiency can be further increased. Furthermore, nanocellulose-based adsorbents' regeneration and recyclability support their commercial feasibility in large-scale water treatment applications.

Although nitrocellulose-based adsorbents have great potential, there are several obstacles in the way of their practical application for the removal of heavy metal ions. Developing robust regeneration techniques, optimizing adsorbent performance under a range of environmental conditions, and cost-effective large-scale production are some of these problems [50]. Research projects combining materials science, chemistry, engineering, and environmental science must be multidisciplinary to tackle these problems.

Moving forward, future directions in the field of heavy metal ion removal using nanocellulose-based adsorbents involve exploring novel composite materials and hybrid systems for synergistic adsorption and catalytic degradation of heavy metal pollutants. By integrating advanced material design strategies with sustainable production processes, nanocellulose-based adsorbents hold great promise for mitigating heavy metal pollution and safeguarding both ecosystems and human health. It offers a sustainable and effective solution for the removal of heavy metal ions from contaminated water sources. Leveraging the unique properties of nanocellulose, ongoing research efforts aim to overcome existing challenges and advance the practical implementation of these materials in water treatment and environmental remediation applications.

2.4.2 Potential of Nanocellulose-Based Adsorbents for Dyes

Due to its common presence in industrial effluents, dye pollution presents a serious environmental risk to aquatic ecosystems as well as public health. Traditional colour removal techniques frequently have drawbacks, including high costs, insufficient removal, and the production of secondary pollutants. Recently, adsorbents based on nanocellulose have shown great promise as effective and long-lasting colour cleanup methods.

The special qualities of nanocellulose, which is made from cellulose, make it ideal for use in adsorption uses [51,52]. With a high surface area-to-volume ratio due to its nanoscale size, it can interact with dye molecules more effectively. It can also be easily functionalized to increase adsorption capacity and selectivity since nanocellulose has a large number of surface hydroxyl groups. These characteristics allow dyes in aqueous solutions to be efficiently absorbed by adsorbents based on nanocellulose. Physical adsorption, chemical interaction, electrostatic attraction, and π-π stacking are some of the mechanisms involved in the adsorption mechanism of dyes onto nanocellulose-based adsorbents. The precise mechanism is dependent on a number of variables, including temperature, pH of the solution, surface chemistry of the nanocellulose [53], and the chemical structure of the dye molecules. Comprehending these mechanisms is essential for enhancing adsorption effectiveness and creating customised adsorbents for certain dye pollutants.

Many studies have shown how well nanocellulose-based adsorbents work to remove a variety of dyes from aqueous solutions, including synthetic, reactive, acid, basic, and even dyes with complicated molecular structures. These materials' adsorption effectiveness and capacity can be further increased by modifying them using methods such chemical functionalization, composite creation, and nanoparticle integration [54]. Furthermore, the economic feasibility of nanocellulose-based adsorbents for extensive wastewater treatment applications is bolstered by their regeneration and recyclability. Although nanocellulose-based adsorbents have great potential, there are a number of obstacles in the way of their practical application for dye removal. Developing robust regeneration techniques, optimizing adsorbent performance under a range of dye kinds and concentrations, and cost-effective large-scale production are some of these problems. Multidisciplinary research projects combining materials science, chemistry, engineering, and environmental science are needed to address these issues.

Going forward, new composite materials and hybrid systems for synergistic adsorption and dye degradation will be explored in the field of dye removal employing nanocellulose-based adsorbents.

Nanocellulose-based adsorbents show significant promise for reducing dye pollution and advancing environmental sustainability through the integration of sophisticated material design methodologies with sustainable production processes. Adsorbents based on nanocellulose provide an efficient and long-lasting way to remove dyes from contaminated water sources. Ongoing research initiatives seek to address current obstacles and progress the useful utilization of these materials in wastewater treatment and environmental remediation applications by utilising the special qualities of nanocellulose.

2.4.3 Potential of Nanocellulose-Based Adsorbents for Other Pollutants

Numerous sources of water contamination are serious threats to human health and ecosystems. While heavy metals and dyes have garnered a lot of attention in remediation efforts, many additional contaminants need to be mitigated because of industrial, agricultural, and residential activities. Because of their special qualities and flexible functionalization abilities, adsorbents based on nanocellulose present a viable solution for a wide range of contaminants in water. This two-page article discusses the significance and prospective applications of nanocellulose in the removal of contaminants other than heavy metals and dyes.

- **Organic Pollutants:** Adsorbents based on nanocellulose have the potential to eliminate organic pollutants from water sources, including phenols, hydrocarbons, and volatile organic compounds (VOCs). The hydrophilic and porous properties of nanocellulose enable efficient organic molecule adsorption via hydrogen bonding and physical adsorption, enhancing the quality of water and the health of ecosystems [55].
- **Pharmaceuticals:** Because of their enduring nature and possible ecological effects, pharmaceutical residues in wastewater provide new environmental challenges. Adsorbents based on nanocellulose provide an effective way to remove pharmaceuticals from water by adsorption, complexation, or electrostatic interactions, reducing their harmful effects on

aquatic life and ecosystems [56]. **Pesticides:** Water contamination and ecological damage are caused by agricultural runoff that contains pesticide residues. Through physical adsorption, chemical interactions, and surface modification, nanocellulose-based adsorbents can efficiently adsorb pesticide molecules, lowering their concentration in water bodies and preserving water quality [57].

- **Emerging New Pollutants**: Per- and polyfluoroalkyl substances (PFAS), nanoparticles, and microplastics are examples of developing pollutants that could be effectively addressed by adsorbents based on nanocellulose. Because of the high selectivity and customizable surface chemistry of nanocellulose, customized adsorbents that can minimize the environmental impact of developing pollutants can be developed [58].

Although adsorbents based on nanocellulose have the ability to remove pollutants, there are a number of obstacles in the way of their practical application. These problems include guaranteeing cost-effectiveness for large-scale applications, scalability of production, and optimizing adsorbent performance under a variety of environmental conditions. In order to improve adsorbent efficiency and selectivity, future research areas include creating multifunctional composite materials, investigating novel material design strategies, and incorporating cutting-edge characterization methods.

Adsorbents based on nanocellulose provide adaptable and environmentally friendly ways to eliminate contaminants from water sources other than heavy metals and dyes. Nanocellulose-based adsorbents have the potential to improve water quality and ecosystem health by addressing a variety of environmental issues by using their special qualities and functionalization abilities. To fully realise the potential of nanocellulose-based adsorbents and expedite their practical application in water treatment and environmental remediation applications, multidisciplinary research endeavours must continue.

2.5 Conclusion

In summary, the application of nanocellulose in water treatment marks a substantial advancement in the effective and long-term removal of contaminants found in water. Nanocellulose is a viable substitute for traditional purification techniques due to its intrinsic qualities of large surface area, biocompatibility, and renewable supply. Its capacity to absorb dyes, heavy metal ions, and other impurities highlights how adaptable and efficient it is in addressing a range of problems related to water quality. Additionally, nanocellulose's affordability and environmentally favourable qualities increase its allure for large-scale water treatment applications, providing a workable answer to the urgent worldwide problem of water pollution.

In the future, more research and development work will be necessary to fully realise nanocellulose's promise for water filtration. Investigating new synthesis routes, functionalization strategies, and combining it with other nanomaterials could improve its adsorption effectiveness even more and modify its characteristics to remove particular pollutants. Furthermore, overcoming obstacles like scalability and recyclability will be essential to achieving broad acceptance of purifying systems based on nanocellulose. We can lead the way towards a more sustainable and clean future for our water resources by utilising the special qualities of nanocellulose and expanding its uses in water treatment.

References

1. Moe, C. L., & Rheingans, R. D. (2006). Global challenges in water, sanitation and health. *Journal of water and health*, *4*(S1), 41-57. https://doi.org/10.2166/wh.2006.0043.
2. Hutton, G., & Chase, C. (2016). The knowledge base for achieving the sustainable development goal targets on water supply, sanitation and hygiene. *International journal of environmental research and public health*, *13*(6), 536. https://doi.org/10.3390/ijerph13060536
3. Ali, S., Rehman, S. A. U., Luan, H. Y., Farid, M. U., & Huang, H. (2019). Challenges and opportunities in functional carbon nanotubes for membrane-based water treatment and desalination.

Science of the Total Environment, 646, 1126-1139. https://doi.org/10.1016/j.scitotenv.2018.07.348

4. Chai, W. S., Cheun, J. Y., Kumar, P. S., Mubashir, M., Majeed, Z., Banat, F., & Show, P. L. (2021). A review on conventional and novel materials towards heavy metal adsorption in wastewater treatment application. *Journal of Cleaner Production*, 296, 126589. https://doi.org/10.1016/j.jclepro.2021.126589
5. Mohmood, I., Lopes, C. B., Lopes, I., Ahmad, I., Duarte, A. C., & Pereira, E. (2013). Nanoscale materials and their use in water contaminants removal—a review. *Environmental Science and Pollution Research*, *20*, 1239-1260. https://doi.org/10.1007/s11356-012-1415-x
6. Thomas, B., Raj, M. C., Joy, J., Moores, A., Drisko, G. L., & Sanchez, C. (2018). Nanocellulose, a versatile green platform: from biosources to materials and their applications. *Chemical reviews*, 118(24), 11575-11625. https://doi.org/10.1021/acs.chemrev.7b00627
7. Reshmy, R., Philip, E., Paul, S. A., Madhavan, A., Sindhu, R., Binod, P., & Sirohi, R. (2020). Nanocellulose-based products for sustainable applications-recent trends and possibilities. *Reviews in Environmental Science and Bio/Technology*, 19, 779-806. https://doi.org/10.1007/s11157-020-09551-z
8. Yu, S., Sun, J., Shi, Y., Wang, Q., Wu, J., & Liu, J. (2021). Nanocellulose from various biomass wastes: Its preparation and potential usages towards the high value-added products. *Environmental Science and Ecotechnology*, *5*, 100077. https://doi.org/10.1016/j.ese.2020.100077
9. Bacakova, L., Pajorova, J., Tomkova, M., Matejka, R., Broz, A., Stepanovska, J., & Kallio, P. (2020). Applications of nanocellulose/nanocarbon composites: Focus on biotechnology and medicine. *Nanomaterials*, *10*(2), 196. https://doi.org/10.3390/nano10020196

10. Das, R., Lindstrom, T., Sharma, P. R., Chi, K., & Hsiao, B. S. (2022). Nanocellulose for sustainable water purification. *Chemical Reviews,* 122(9), 8936-9031. https://doi.org/10.1021/acs.chemrev.1c00683

11. Chu, Y., Sun, Y., Wu, W., & Xiao, H. (2020). Dispersion properties of nanocellulose: *a review. Carbohydrate polymers*, 250, 116892. https://doi.org/10.1002/app.48544

12. Randhawa, A., Dutta, S. D., Ganguly, K., Patil, T. V., Patel, D. K., & Lim, K. T. (2022). A review of properties of nanocellulose, its synthesis, and potential in biomedical applications. *Applied Sciences*, 12(14), 7090 https://doi.org/10.3390/app12147090.

13. Mautner, A. (2020). Nanocellulose water treatment membranes and filters: a review. *Polymer International*, 69(9), 741-751. https://doi.org/10.1002/pi.5993

14. Voisin, H., Bergström, L., Liu, P., & Mathew, A. P. (2017). Nanocellulose-based materials for water purification. *Nanomaterials*, 7(3), 57. https://doi.org/10.3390/nano7030057

15. Jing, S., Wu, L., Siciliano, A. P., Chen, C., Li, T., & Hu, L. (2023). The critical roles of water in the processing, structure, and properties of nanocellulose. *ACS nano*, 17(22), 22196-22226. https://doi.org/10.1021/acsnano.3c06773

16. Aslam, M. M. A., Kuo, H. W., Den, W., Usman, M., Sultan, M., & Ashraf, H. (2021). Functionalized carbon nanotubes (CNTs) for water and wastewater treatment: preparation to application. *Sustainability*, 13(10), 5717. https://doi.org/10.3390/su13105717

17. Das, R., Abd Hamid, S. B., Ali, M. E., Ismail, A. F., Annuar, M. S. M., & Ramakrishna, S. (2014). Multifunctional carbon nanotubes in water treatment: *the present, past and future. Desalination,* 354, 160-179. https://doi.org/10.1016/j.desal.2014.09.032

18. Jain, N., & Kanu, N. J. (2021). The potential application of carbon nanotubes in water treatment: A state-of-the-art-review.

Materials Today: Proceedings, 43, 2998-3005. https://doi.org/10.1016/j.matpr.2021.01.331

19. Shi, W., & Plata, D. L. (2018). Vertically aligned carbon nanotubes: Production and applications for environmental sustainability. *Green chemistry*, 20(23), 5245-5260. https://doi.org/10.1039/C8GC02195C

20. Das, R., Leo, B. F., & Murphy, F. (2018). The toxic truth about carbon nanotubes in water purification: a perspective view. *Nanoscale research letters*, 13, 1-10. https://doi.org/10.1186/s11671-018-2589-z

21. Emenike, E. C., Iwuozor, K. O., Saliu, O. D., Ramontja, J., & Adeniyi, A. G. (2023). Advances in the extraction, classification, modification, emerging and advanced applications of crystalline cellulose: a review. *Carbohydrate Polymer Technologies and Applications*, 100337. https://doi.org/10.1016/j.carpta.2023.100337

22. Peter, S., Lyczko, N., Gopakumar, D., Maria, H. J., Nzihou, A., & Thomas, S. (2022). Nanocellulose and its derivative materials for energy and environmental applications. *Journal of Materials Science*, 57(13), 6835-6880. https://doi.org/10.1007/s10853-022-07070-6

23. Sheldon, R. A., & Norton, M. (2020). Green chemistry and the plastic pollution challenge: towards a circular economy. *Green Chemistry*, 22(19), 6310-6322. DOI https://doi.org/10.1039/D0GC02630A

24. Olugbenga, O. S., Adeleye, P. G., Oladipupo, S. B., Adeleye, A. T., & John, K. I. (2023). Biomass-derived biochar in wastewater treatment-a circular economy approach. *Waste Management Bulletin*. https://doi.org/10.1016/j.wmb.2023.07.007

25. Sjahro, N., Yunus, R., Abdullah, L. C., Rashid, S. A., Asis, A. J., & Akhlisah, Z. N. (2021). Recent advances in the application of cellulose derivatives for removal of contaminants from aquatic environments. *Cellulose, 28(12)*, 7521-7557. https://doi.org/10.1007/s10570-021-03985-6

26. Kehrein, P. A. (2021). Towards water resource factories: Designing and planning sustainable circular wastewater treatment processes. https://doi.org/10.4233/uuid:227a498c-52ee-4848-9e98-74fe0e7d2453

27. Li, T., Chen, C., Brozena, A. H., Zhu, J. Y., Xu, L., Driemeier, C., ... & Hu, L. (2021). Developing fibrillated cellulose as a sustainable technological material. *Nature*, 590(7844), 47-56. https://doi.org/10.1038/s41586-020-03167-7

28. Khalid, M. Y., Al Rashid, A., Arif, Z. U., Ahmed, W., & Arshad, H. (2021). Recent advances in nanocellulose-based different biomaterials: types, properties, and emerging applications. *Journal of Materials Research and Technology, 14,* 2601-2623. https://doi.org/10.1016/j.jmrt.2021.07.128

29. Thomas, B., Raj, M. C., Joy, J., Moores, A., Drisko, G. L., & Sanchez, C. (2018). Nanocellulose, a versatile green platform: from biosources to materials and their applications. *Chemical reviews, 118(24),* 11575-11625. https://doi.org/ 10.1021/acs.chemrev.7b00627

30. Klemm, D., Cranston, E. D., Fischer, D., Gama, M., Kedzior, S. A., Kralisch, D., & Rauchfuß, F. (2018). Nanocellulose as a natural source for groundbreaking applications in materials science: Today’s state. Materials Today, 21(7), 720-748. https://doi.org/ 10.1016/j.mattod.2018.02.001

31. Padder, F. A., & Bashir, A. (2023). Scarcity of water in the twenty-first century: problems and potential remedies. *Medalion journal: Medical Research, Nursing, Health and Midwife Participation, 4(1),* 1-5. https://doi.org/ 10.1080/07900629948916

32. Shemer, H., Wald, S., & Semiat, R. (2023). Challenges and solutions for global water scarcity. *Membranes, 13(6),* 612. https://doi.org/ 10.3390/membranes13060612

33. Liu, Y., Liu, H., & Shen, Z. (2021). Nanocellulose based filtration membrane in industrial waste water treatment: A

review. *Materials, 14(18),* 5398. https://doi.org/ 10.3390/ma14185398

34. Winter, A., Arminger, B., Veigel, S., Gusenbauer, C., Fischer, W., Mayr, M., & Gindl-Altmutter, W. (2020). Nanocellulose from fractionated sulfite wood pulp. *Cellulose, 27,* 9325-9336. https://doi.org/ 0.1163/016942410X525975

35. Barbash, V. A., Yaschenko, O. V., & Shniruk, O. M. (2017). Preparation and properties of nanocellulose from organosolv straw pulp. Nanoscale Research Letters, 12, 1-8. https://doi.org/ 10.1186/s11671-017-2001-4

36. Mondal, S. (2021). Chemical modification of nanocellulose for water purification. In Nanocellulose and Its Composites for Water Treatment Applications 51-61. CRC Press.

37. Voisin, H., Bergström, L., Liu, P., & Mathew, A. P. (2017). Nanocellulose-based materials for water purification. *Nanomaterials, 7(3),* 57. htttps://doi.org/10.3390/nano7030057

38. Martínez, E., Posada, L., Botero, J. C., Rios-Arango, J. A., Zapata-Benabithe, Z., López, S., & Castro, C. I. (2023). Nata de fique: A cost-effective alternative for the large-scale production of bacterial nanocellulose. Industrial Crops and Products, 192, 116015. https://doi.org/10.1016/j.indcrop.2022.116015

39. Zinge, C., & Kandasubramanian, B. (2020). Nanocellulose based biodegradable polymers. *European Polymer Journal, 133*, 109758. https://doi.org/10.1016/j.eurpolymj.2020.109758

40. Kargarzadeh, H., Huang, J., Lin, N., Ahmad, I., Mariano, M., Dufresne, A., & Gałęski, A. (2018). Recent developments in nanocellulose-based biodegradable polymers, thermoplastic polymers, and porous nanocomposites. *Progress in Polymer Science, 87,* 197-227. https://doi.org/10.1016/j.progpolymsci.2018.07.008

41. Khan, R. A., Salmieri, S., Dussault, D., Uribe-Calderon, J., Kamal, M. R., Safrany, A., & Lacroix, M. (2010). Production

and properties of nanocellulose-reinforced methylcellulose-based biodegradable films. *Journal of agricultural and food chemistry, 58(13),* 7878-7885. https://doi.org/10.1021/jf1006853

42. Chai, W. S., Cheun, J. Y., Kumar, P. S., Mubashir, M., Majeed, Z., Banat, F., & Show, P. L. (2021). A review on conventional and novel materials towards heavy metal adsorption in wastewater treatment application. *Journal of Cleaner Production, 296,* 126589. https://doi.org/10.1016/j.jclepro.2021.126589

43. Pandey, A., Kalamdhad, A., & Sharma, Y. C. (2023). Recent advances of nanocellulose as biobased adsorbent for heavy metal ions removal: A sustainable approach integrating with waste management. *Environmental Nanotechnology, Monitoring & Management, 20,* 100791. https://doi.org/0.1016/j.enmm.2023.100791

44. Sarma, G. K., Sen Gupta, S., & Bhattacharyya, K. G. (2019). Nanomaterials as versatile adsorbents for heavy metal ions in water: a review. *Environmental Science and Pollution Research, 26,* 6245-6278. https://doi.org/10.1007/s11356-018-04093-y

45. Chu, Y., Sun, Y., Wu, W., & Xiao, H. (2020). Dispersion properties of nanocellulose: a review. *Carbohydrate polymers, 250,* 116892. https://doi.org/0.1016/j.carbpol.2020.116892

46. Ibrahim, H., Sazali, N., Salleh, W. N. W., & Ismail, A. F. (2021). Nanocellulose-based materials and recent application for heavy metal removal. *Water, Air, & Soil Pollution, 232(7),* 305. https://doi.org/10.1007/s11270-021-05245-6

47. Si, R., Pu, J., Luo, H., Wu, C., & Duan, G. (2022). Nanocellulose-based adsorbents for heavy metal ion. *Polymers, 14(24),* 5479. https://doi.org/10.21203/rs.3.rs-594942/v1

48. Abou-Zeid, R. E., Ali, K. A., Gawad, R., Kamal, K. H., Kamel, S., & Khiari, R. (2021). Removal of Cu (II), Pb (II), Mg (II), and

Fe (II) by adsorption onto alginate/nanocellulose beads as bio-sorbent. *Journal of Renewable Materials, 9(4),* 601-613. https://doi.org/10.32604/jrm.2021.014005

49. Omoregie, A., Bakri, M., & Rahman, M. (2021). Elimination of heavy metal ion using nanocellulose based membranes. *Academia Lett, 3130(8)* 1-7. https://doi.org/10.20935/AL3130

50. Thomas, P., Duolikun, T., Rumjit, N. P., Moosavi, S., Lai, C. W., Johan, M. R. B., & Fen, L. B. (2020). Comprehensive review on nanocellulose: Recent developments, challenges and future prospects. *Journal of the mechanical behavior of biomedical materials, 110,* 103884. https://doi.org/10.1016/j.jmbbm.2020.103884

51. Amiralian, N., Mustapic, M., Hossain, M. S. A., Wang, C., Konarova, M., Tang, J., & Rowan, A. (2020). Magnetic nanocellulose: A potential material for removal of dye from water. *Journal of hazardous materials, 394,* 122571. https://doi.org/10.1016/j.jhazmat.2020.122571

52. Tavakolian, M., Wiebe, H., Sadeghi, M. A., & van de Ven, T. G. (2019). Dye removal using hairy nanocellulose: experimental and theoretical investigations. *ACS applied materials & interfaces, 12(4),* 5040-5049. https://doi.org/10.1021/acsami.9b18679

53. Heise, K., Koso, T., King, A. W., Nypelö, T., Penttilä, P., Tardy, B. L., & Beaumont, M. (2022). Spatioselective surface chemistry for the production of functional and chemically anisotropic nanocellulose colloids. *Journal of Materials Chemistry A, 10(44),* 23413-23432. https://doi.org/10.1039/d2ta05277f

54. Thakur, V., Guleria, A., Kumar, S., Sharma, S., & Singh, K. (2021). Recent advances in nanocellulose processing, functionalization and applications: A review. *Materials Advances, 2(6),* 1872-1895. https://doi.org/10.1039/D1MA00049G

55. Herrera-Morales, J., Turley, T. A., Betancourt-Ponce, M., & Nicolau, E. (2019). Nanocellulose-block copolymer films for the removal of emerging organic contaminants from aqueous solutions. *Materials, 12(2),* 230. https://doi.org/10.3390/ma12020230

56. Pradeep, H. K., Patel, D. H., Onkarappa, H. S., Pratiksha, C. C., & Prasanna, G. D. (2022). Role of nanocellulose in industrial and pharmaceutical sectors-A review. International *Journal of Biological Macromolecules, 207,* 1038-1047. https://doi.org/10.1016/j.ijbiomac.2022.03.171

57. Rana, A. K., Mishra, Y. K., Gupta, V. K., & Thakur, V. K. (2021). Sustainable materials in the removal of pesticides from contaminated water: Perspective on macro to nanoscale cellulose. *Science of The Total Environment, 797*, 149129. https://doi.org/10.1016/j.scitotenv.2021.149129

58. Li, D., Lee, C. S., Zhang, Y., Das, R., Akter, F., Venkatesan, A. K., & Hsiao, B. S. (2023). Efficient removal of short-chain and long-chain PFAS by cationic nanocellulose. *Journal of Materials Chemistry A, 11(18),* 9868-9883. https://doi.org/10.1039/D3TA01851B.

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ISBN: 978-81-975412-4-7

3

Renewable Energy Technologies for Sustainable Development

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Contents

1. Introduction

It is now essential to switch to renewable energy sources as the globe grapples with urgent issues including climate change, unequal access to energy, and environmental damage. The COP26 Climate Change Conference took place in Glasgow, UK, in 2021, following guidance from the UN. Delegates from 197 nations committed to reducing dependency on coal and fossil fuels, stressing the need to prioritize health and equity in the worldwide climate action and sustainable development agendas, highlighting the necessity for energy systems that protect and improve both climate and public health[1]. In this context, the significance of renewable energy technologies cannot be overstated, as they offer multifaceted solutions that align with the principles of sustainable development. At the heart of the matter lies the urgent need to mitigate climate change by reducing greenhouse gas emissions, transitioning away from fossil fuels, and embracing clean and renewable energy sources. Renewable energy technologies, encompassing solar, wind, hydro, biomass, geothermal, and others, provide viable alternatives to conventional energy sources that are finite, polluting, and increasingly unsustainable. By harnessing natural resources such as sunlight, wind, water, and heat from the Earth, these technologies offer pathways towards low-carbon energy systems that are critical for achieving global climate targets and safeguarding the planet for future generations. Moreover, renewable energy technologies play a pivotal role in addressing energy poverty and promoting social equity by expanding access to clean and affordable electricity in underserved communities. Off-grid renewable energy solutions empower rural areas and marginalized populations with energy independence, economic opportunities, and improved living standards. Furthermore, the decentralized nature of renewable energy systems fosters local ownership, community resilience, and inclusive development, aligning with the principles of social justice and equity embedded within the SDGs [2,3].Transitioning to renewable energy helps mitigate health risks associated with air pollution and fossil fuel combustion, thereby reducing respiratory diseases, premature mortality, and healthcare costs. Cleaner energy sources improve indoor and outdoor air quality, enhance living conditions, and promote overall well-being and quality of life, particularly in urban areas [4,5].

From an economic perspective, switching to renewable energy offers a lot of potential for industry innovation, job development, and economic expansion. Investments in renewable energy projects drive technological advancements, enhance energy security, and stimulate green economies, thereby contributing to sustainable development objectives while fostering competitiveness and prosperity on a global scale [6-8].

Renewable energy technologies are indispensable tools for advancing sustainable development goals by promoting environmental stewardship, economic prosperity, social equity, and climate resilience on a global scale.

2. Different Types of renewable Energy technologies

Renewable energy technologies offer a promising pathway towards achieving sustainability by providing clean, abundant, and accessible energy sources. A wide range of green energy technologies are propelling the world's shift to a reduced-carbon future, while fostering economic growth, environmental stewardship, and social equity. An overview of different types of renewable energy technologies that are leading the charge towards sustainable development is given in this chapter

2.1. Solar Energy

Many industrialized economies are expected to reach net-zero emissions by 2050, aligning with sustainable development objectives. The International Energy Agency (IEA) has outlined the necessary strategies over the next decade to achieve global net-zero carbon emissions by 2050, with notable reductions, driven by factors including declining coal-fired energy generation and the rise of renewables [9]. Solar energy stands as a cornerstone of sustainable development, offering multifaceted solutions to pressing environmental, social, and economic challenges. Its pivotal role is evident across various dimensions [10]. By displacing fossil fuels, solar power mitigates air and water pollution, reduces carbon emissions, and contributes to combating climate change. The harnessing of solar energy minimizes environmental degradation associated with resource extraction, land disturbance, and habitat destruction, thereby preserving ecosystems and biodiversity [11,12]. Solar energy plays a transformative role in expanding energy access and alleviating energy poverty, particularly in remote and underserved areas lacking grid infrastructure. Off-grid solar solutions like solar lanterns, home systems, and microgrids give reliable electric energy for lighting, heating, cooking, and powering essential appliances, improving livelihoods, education, healthcare, and socioeconomic opportunities [13,14].

2.1.1. Solar Photovoltaic technology

Using solar photovoltaic technology, power may be produced sustainably by capturing sunlight. Photovoltaic systems contain solar panels which convert sunlight to electricity through the photovoltaic effect. These cells are typically made of semiconductor materials such as silicon. The operation of PV technology is based on the interaction between photons (light particles) from the sun and electrons in the semiconductor material. When photons strike the surface of the solar cell, they transfer their energy to electrons, causing them to become excited and create an electric current. For usage in residences, companies, and the power grid, inverters can transform this flow of electrons from direct current to alternating current. [15-16]. Solar energy is abundant and inexhaustible, providing a virtually limitless source of clean power without producing greenhouse gas emissions or air pollutants during operation. Once installed, solar PV systems have minimal operating costs and require little maintenance, making them cost-effective over their long lifespan. By generating electricity on-site, solar PV systems reduce reliance on centralized power grids and fossil fuels, enhancing energy security and resilience. PV systems can be easily expanded or modified to accommodate changing energy needs, making them flexible and adaptable to evolving requirements [17,18]. In 2022, solar PV generation surged by 270 TWh (up 26%) to nearly 1 300 TWh, exhibiting the largest absolute growth among renewable technologies and exceeding wind power for the first time. This growth aligns with projections from 2023 to 2030 in the Net Zero Emissions by 2050 Scenario, with expectations of further acceleration driven by increased economic attractiveness, supply chain development, and policy support, leading to an upgraded tracking status for solar PV in 2023 [19]. Even though solar PV systems are environment friendly there are some challenges associated with it. It depends on the availability of sunlight; it has high initial investment cost and requires large area. Continued research, innovation, and policy support are essential to further improve efficiency, reduce costs, and address challenges to widespread adoption.

Greater conversion capacities have resulted from advancements in cell design, materials, and manufacturing methods, enabling PV modules to produce more power from the same quantity of sunshine. Thin-film solar cells, made from alternative components like cadmium telluride or copper indium gallium selenide offer lower production costs and can be manufactured using less energy compared to traditional crystalline silicon cells [20-22]. Perovskite solar cells, a relatively new technology, have shown great promise for achieving high efficiencies at lower costs, although commercialization is still in progress [23-25]. Bifacial solar modules capture sunlight from both the front and rear sides, increasing energy yield by utilizing reflected sunlight from the ground or surrounding surfaces. This design optimization improves overall system efficiency and enhances energy generation in various environments [26,27]. Solar tracking systems, h as single-axis and dual-axis trackers, improve system efficiency by optimizing the angle of incidence between sunlight and PV modules, especially in locations with high solar variability [28]. Advances in manufacturing technologies, such as automated production lines, precision printing techniques, and inline quality control measures, have led to cost reductions and yield improvements in PV module production. Streamlined manufacturing processes enable higher throughput, lower labor costs, and tighter quality control, contributing to overall cost reductions [29,30]. The scaling up of PV manufacturing facilities and increased production volumes have resulted in economies of scale, driving down production costs through bulk purchasing of materials, optimization of supply chains, and improvements in production efficiency. Innovations in balance of system components, including inverters, racking systems, and mounting hardware, have led to cost reductions and improved system performance. Integration of advanced power electronics, such as maximum power point tracking (MPPT) algorithms and grid-responsive inverters, enhances system efficiency and grid stability [31,32].

2.1.2. Concentrated solar power

Another renewable energy method called concentrated solar power (CSP) also uses sunlight to create electricity. CSP systems employ mirrors or lenses to focus sunlight onto a tiny area, usually a receiver, in order to produce heat, as opposed to photovoltaic (PV) solar panels, which directly transform sunlight into electricity. Steam is generated from this heat and utilized to power a generator through a turbine [33]. By incorporating thermal energy storage, CSP systems may harness the sun's rays during the day and use them to generate electricity at night, when sunlight is scarce, delivering controllable, dispatchable power When coupled with thermal storage and used in hybrid configurations, CSP systems may convert sunlight into energy quite efficiently. CSP plants can contribute to grid stability and reliability by providing controllable power generation that can be ramped up or down to meet changing demand, helping to balance supply and demand on the electricity grid. Parabolic trough systems, solar power towers and dish engine systems are some of the types concentrated solar power systems. Parabolic trough systems are well-suited for large-scale commercial power plants and have been widely deployed in desert regions with high solar irradiance. Solar power towers offer higher operating temperatures and efficiency compared to parabolic trough systems, that they can be used to generate power on a grand scale. They can achieve higher energy concentration and thermal storage capacity, enabling them to provide dispatchable power and operate during periods of low solar irradiance. Dish/engine systems are highly efficient and can achieve high temperatures and energy concentration ratios, making them suitable for both small-scale distributed generation and utility-scale power plants. They are modular and can be deployed in remote or off-grid locations, providing decentralized power generation and energy access. CSP technology can be integrated with fossil fuel power plants to enable hybrid operation, reducing greenhouse gas emissions and increasing overall efficiency. For reliable power production, CSP systems can be simply combined with other energy sources like biomass or natural gas. The efficiency and dependability of large-scale power plants can be enhanced by this combined method [34]. CSP technology also faces challenges, including high upfront costs, water usage for steam generation in dry-cooled systems, and land requirements for large-scale installations.

Solar energy offers community members without access to centralized power networks dependable and affordable electricity through off-grid alternatives, including solar lights, residential systems, and microgrids. These off-grid solar options give people and families more power by giving them access to basic services like cooking, heating, lighting, and charging their phones. This makes life better and increases productivity.

2.1.3. Solar Thermal Heating

Solar thermal energy technologies harness the sun's heat to generate electricity or provide heat for various applications. Solar water heating systems use solar collectors, typically flat-plate or evacuated tube collectors, to absorb sunlight and heat water for domestic, commercial, or industrial use. The heated water is stored in insulated tanks for later use, providing hot water for bathing, cleaning, and space heating [35]. Solar desalination systems use solar energy to evaporate and condense water, producing freshwater from saline or brackish water sources.

Solar stills, solar distillation systems, and solar-powered reverse osmosis systems are examples of solar desalination technologies used to provide clean drinking water in water-scarce regions [36,37]. Solar cookers and ovens use sunlight to cook food without the need for traditional fuel sources such as wood, charcoal, or gas. These devices concentrate sunlight onto a cooking area, heating pots and pans to cook food through direct or indirect solar radiation. [38,39]. Solar thermal air conditioning systems use solar energy to power absorption chillers or adsorption chillers, which provide cooling by using heat to drive refrigeration cycles. Building integration or district cooling with these systems reduces the need for energy-intensive and environmentally harmful conventional air conditioning [40-41]. Solar thermal technologies can provide heat for various industrial processes, such as drying, heating, sterilization, and chemical processing. Solar thermal collectors or concentrators are used to generate high-temperature heat, replacing or supplementing fossil fuel-based heating systems [42-44].

2.2. Wind Energy

Wind energy stands as a pivotal component offering a sustainable solution to global energy needs. This energy source, which uses wind to generate electricity, has grown and improved at a remarkable rate in recent years, and it is now a major participant in the movement towards a greener, more sustainable energy future.

2.2.1. Wind Turbines

Wind turbines harness the kinetic energy of the wind and turn it into electricity, a source of renewable energy. When the wind blows across a wind turbine, it causes the rotor blades connected to the hub to spin. A generator, driven by the rotational motion, transforms mechanical energy into electrical energy. Thanks to technological advancements, wind turbines have grown in size, efficiency, and reliability, allowing them to harness more wind energy. Turbine performance, cost, and energy production have all been enhanced by advancements in materials, aerodynamics, and control systems. With an abundance of onshore and offshore wind resources available around the world, wind energy has a lot of room to grow [45-47].

2.2.2. Wind farms

Wind farms can be deployed in various geographic locations, from windy plains and coastal regions to high-altitude sites, maximizing energy generation opportunities. Onshore wind farms are large-scale installations of wind turbines on land, providing a significant source of renewable electricity. Wind turbines installed offshore in bodies of water, offering higher wind speeds and reduced visual impact compared to onshore installations [48-51]. Wind power, which harnesses the kinetic energy of the wind, is an eco-friendly alternative to fossil fuels that can help slow global warming and other climate crises. Wind farms provide stable, long-term revenue streams for landowners and communities hosting wind turbines, contributing to local economies and rural development.

One way to ensure that electricity demand is met reliably is by incorporating wind energy into existing electricity systems. By capturing energy during bursts of strong wind and releasing it when needed, energy storage technologies like batteries and pumped hydro storage can work in tandem with wind power to improve the stability and reliability of the grid [52-54]. Despite its many advantages, wind energy faces challenges such as intermittency, visual impact, and potential conflicts with wildlife and ecosystems. Continued research, innovation, and policy support are essential to mitigate these challenges and develop wind energy as a sustainable and reliable source of electricity.

2.3. Hydropower

One of the first and most popular renewable energy sources, hydropower harnesses the force of moving water. Hydropower has been around for a long time and is used all around the world, thus it helps meet energy needs while reducing pollution from burning fossil fuels.

The process of hydropower involves harnessing the mechanical energy of flowing water, usually from dams, streams, or rivers, in order to produce electrical energy. Water is directed through turbines, causing them to spin and drive generators, which convert mechanical energy into electrical energy [58-60]. Despite environmental considerations, hydropower offers significant advantages in terms of reliability, flexibility and cost-effectiveness [55,56]. Conventional hydropower plants, run-of-river installations, and pumped storage facilities contribute to electricity generation, water management, and grid stability [57].

2.3.1. Conventional Hydropower

Conventional hydropower refers to the longstanding practice of generating electricity from flowing water using dams and reservoirs. Water stored in reservoirs is released through turbines, that drives generators, producing electricity. This form of renewable energy provides reliable and scalable electricity generation, contributing to grid stability and meeting base-load energy demand. Conventional hydropower projects have their advantages, but they also have the potential to disrupt habitats, reduce biodiversity, and force communities to relocate. Therefore, it is crucial to carefully plan and manage these projects so that they produce energy while also preserving the environment and promoting social equity. [58].

2.3.2. Run-of-River Hydropower

One form of hydroelectric generating, known as run-of-river hydropower, doesn't involve building massive reservoirs or dams; instead, it harnesses the energy already present in rivers and streams. Unlike conventional hydropower, run-of-river projects divert a portion of the river's flow through a canal or penstock to drive turbines, generating electricity as water passes through the system. This approach minimizes environmental impacts such as habitat disruption and avoids the need for large-scale reservoirs, preserving river ecosystems and maintaining natural water flow patterns. Run-of-river hydropower offers a sustainable and renewable energy solution that provides clean electricity while minimizing environmental and social impacts, making it an attractive option for regions with suitable water resources and a focus on sustainable development [59].

2.3.3. Pumped Storage Hydropower

During times of low demand, it stores energy by pumping water uphill; during times of high demand, it releases this stored energy through turbines to generate power. When it comes to maintaining grid stability and balancing supply and demand, pumped storage hydropower—a form of hydroelectric energy storage—is indispensable. During periods of low electricity demand and excess generation, it pumps water from a lower reservoir to a higher reservoir, storing energy in the form of gravitational potential energy. Water is discharged from the upper reservoir to the lower reservoir through turbines, which generate power as it flows back down in response to an increase in electrical demand. To provide a steady flow of electricity even when renewable power sources, such as wind and solar, are intermittent, pumped storage hydroelectric facilities offer grid services that are both quick to act and highly adaptable. In addition, these systems have a lot of room to store energy, so they can help keep the grid stable and cut down on the use of peaking power plants that rely on fossil fuels. This way, they can keep excess energy from times of low demand and release it during times of high demand. [60].

Hydropower plays a significant role in global electricity generation, accounting for a substantial share of renewable energy capacity worldwide. As countries strive to transition to low-carbon energy systems and achieve climate target, hydropower remains an inevitable technology, providing reliable, affordable, and sustainable electricity for generations to come. Sustainable hydropower development requires careful planning, environmental assessment, and stakeholder engagement to minimize adverse impacts and maximize benefits.

2.4. Biomass Energy

Combustion, gasification, or biochemical processes can transform organic resources like wood, agricultural wastes, or organic waste into heat, power, or biofuels. This category of materials is known as biomass. Biomass energy systems facilitate waste management, generate renewable energy alternatives to fossil fuels, and boost agricultural employment and rural development. [61,62].

2.4.1. Biomass Combustion

Wood, crop residues, and agricultural waste are all examples of organic materials that can be burned to produce heat or power through biomass combustion, a renewable energy technique. Combustion releases carbon dioxide into the atmosphere, which plants can then absorb and utilize to offset their own emissions. This makes this energy source renewable. Biomass combustion offers a sustainable alternative to fossil fuels, providing a reliable source of energy for heating, power generation, and industrial processes. However, careful management of biomass resources is essential to ensure sustainability, minimize environmental impacts, and maximize the efficiency of biomass energy systems [63,64]

2.4.2. Biogas Production

A sustainable energy technique known as biogas production uses anaerobic digestion to create a flammable gas mainly made of carbon dioxide and methane from organic materials like sewage, food scraps, animal manure, and agricultural waste. As a renewable fuel, this gas can be utilized for heating, cooking, and power generation; it is called biogas [65]. By removing methane, a powerful greenhouse gas, from the atmosphere during biogas generation, one of the many environmental advantages is a decrease in emissions of this gas. Managing organic waste, reducing odors, and producing valuable by-products like nutrient-rich digestate—which may be used as fertilizer—are all benefits of biogas generation. Decentralized and environmentally friendly energy solutions are available to communities all over the globe through the usage of biogas systems, which can range in size from small-scale home digesters to large-scale industrial biogas plants [66].

2.5. Geothermal Energy

Geothermal energy is a renewable resource that can be used to power homes, businesses, and other infrastructure by tapping into the Earth's natural heat reserves. Radioactive decay of minerals and the

Earth's internal heat flux produce this naturally occurring heat, which is a continuous and almost endless source of energy [67]. Compared to fossil fuels, geothermal energy is more sustainable and less harmful to the environment since it produces very little waste and produces very little greenhouse gas emissions. By tapping into geothermal reservoirs through wells or boreholes, heat is extracted and converted into usable energy through geothermal power plants or direct-use systems. Geothermal energy holds significant potential for meeting energy demand, reducing carbon emissions, and promoting energy security [68]. Geothermal power plants and heat pumps offer reliable, baseload power and heating solutions with minimal environmental impact, particularly in regions with high geothermal potential.

2.5.1. Geothermal Power Plants

One sustainable and eco-friendly way to create electricity is through geothermal power plants, which use the Earth's natural heat. By connecting turbines to generators, these plants transform thermal energy into electrical power by drawing on the heat stored under the Earth's surface, usually in the form of steam or hot water. There are various types of geothermal power plants. One type uses dry steam, which draws steam directly from underground reservoirs. Another type uses flash steam, which draws hot water from underground reservoirs and reduces its pressure to produce steam. Finally, there is the binary cycle, which uses heat exchangers to vaporize a secondary fluid that has a lower boiling point than water. The goal is to power turbines [69,70].

2.5.2. Geothermal Heat pumps

The extremely efficient heating and cooling systems that draw on the relatively constant subsurface temperature of the Earth to regulate indoor environment are called geothermal heat pumps (GHPs) or ground-source heat pumps. A fluid, typically water or a combination of water and antifreeze, is circulated through a network of pipes buried underground, where the temperature remains mild all year round. This is how these systems function. During the winter, the fluid acts as a heat exchanger by drawing heat from the earth and transferring it to the inside of the structure. During summer, the process is turned around, as heat is transmitted from the building to the colder ground, resulting in cooling. When compared to more conventional heating and cooling systems, GHPs have a number of benefits, such as lower running costs, less greenhouse gas emissions, and high energy efficiency. You may install them in a variety of designs, including vertical, horizontal, or pond/lake loop systems, and they are ideal for a wide range of applications, from private residences to commercial buildings. Although geothermal heat pumps have a larger initial investment, they are a sustainable and appealing heating and cooling option due to their low environmental impact and high energy savings over time. [71-73].

Geothermal energy can be used to heat water directly for domestic, commercial, and industrial purposes, eliminating the need for fossil fuel-based water heating systems and reducing energy costs and emissions. Geothermal energy can be used for greenhouse heating, soil warming, and aquaculture pond heating, extending growing seasons, increasing crop yields, and supporting fish farming operations in colder climates [74]. Geothermal energy can provide heat for various industrial processes, such as food processing, paper and pulp production, and mineral extraction, reducing energy costs and improving process efficiency. Geothermal hot springs and geothermal wells can be developed into spa and recreational facilities, offering therapeutic benefits and attracting tourists to geothermal-rich areas [75].

Geothermal technologies offer numerous advantages, including minimal greenhouse gas emissions, high reliability, and low operating costs over their long operational lifespans. They provide a stable and renewable source of electricity, contributing to energy security and reducing dependence on fossil fuels. Despite their benefits, geothermal power plants require careful site selection and resource assessment to ensure sustainable development and minimize environmental impacts [76]. As renewable energy sources are more widely acknowledged and technology continues to improve, geothermal power plants are becoming more important in helping the world move towards a greener, more sustainable energy future.

2.6. Tidal and Wave Energy

Ocean currents can be used for sustainable energy purposes through tidal and wave power. By capturing the gravitational force of the sun and moon on Earth's seas, which causes tidal currents to flow into and out of coastal regions, tidal energy can be produced. Separately, wave energy is generated by harnessing the kinetic energy of ocean waves as they travel across the water's surface. Clean, sustainable power generation from tidal and wave energy has the ability to lessen the impact of climate change by reducing emissions of greenhouse gases. Though they are in their infancy, these technologies show great potential to add to the world's energy mix down the road.

2.6.1. Tidal Energy

A renewable and reliable source of power, tidal energy systems convert the kinetic energy of the ocean's tides into electricity. Most tidal energy systems fall into one of two categories: tidal stream systems or tidal barrage systems. Systems of tidal streams harness the power of the water currents produced by the tides.

These systems typically consist of underwater turbines or rotors installed on the seabed, similar to underwater wind turbines. As tidal currents flow past the turbines, they spin, generating electricity that is transmitted to the shore via underwater cables. Tidal barrage systems utilize the potential energy of tidal height differences between high and low tides. Barrages are built across estuaries or coastal bays, creating a reservoir on one side that fills and empties with the rise and fall of the tides. Turbines, similar to those used in conventional hydroelectric dams, are installed within the barrage structure to capture the energy of water flowing in and out of the reservoir, generating electricity [77-79].

The global production of tidal energy is still modest when contrasted with other renewable energy sources like solar and wind. A number of nations have set up tidal power plants, mostly for demonstration and research but with varied degrees of commercial operation. With a capacity of 254 MW and starting commercial operation in 2011, the Sihwa Lake Tidal Power Station in South Korea is the biggest operational tidal energy facility [80]. In order to harness the power of the tides, this idea builds a tidal basin using a seawall. Two other tidal energy projects that deserve mention are the 240 MW Rance Tidal Power Station in France and the 6 MW MeyGen project in Scotland. The former has been active since 1966 and is one of the biggest tidal energy arrays in the world [81]. While tidal energy has significant potential for clean and predictable power generation, technical and economic challenges, including high upfront costs, environmental impacts, and grid integration issues, have hindered its widespread deployment.

2.6.2. Wave Energy

The renewable power that the ocean's natural wave motion can produce is known as wave energy. This renewable energy source has great promise for long-term, environmentally friendly power generation because it is plentiful, reliable, and accessible along coastlines around the globe [82]. The kinetic energy of waves can be converted into electricity utilizing a variety of technologies that are often used to harvest wave energy. Water columns that oscillate, point absorbers, attenuators, and overtopping devices are all examples of such technology. Columns of oscillating water include air and are partially submerged beneath the water's surface, with a vent facing the direction of the waves. Waves penetrating the chamber cause the water level to rise and fall, which in turn causes the air within to oscillate. The air's oscillations power a generator or turbine, which in turn generates electricity [83]. Point absorbers are buoyant objects that bob on the water's surface, rising and falling with the waves. The device's oscillations transform mechanical energy from the waves into electrical energy by driving a hydraulic pump or generator [84]. Attenuators are lengthy, free-floating structures with an orientation opposite to the wave's propagation direction. The attenuator converts mechanical energy by bending and flexing as waves go across it [85]. Overtopping devices consist of a reservoir or basin that is partially filled with water. Waves flow over the top of the device and fill the reservoir, creating a head of water. The water is then released through turbines or generators, generating electricity as it flows back to the sea [86]. These wave energy systems vary in design, scale, and efficiency, and each has its own advantages and limitations.

Wave energy projects are still in the demonstration and pilot phases, with few commercial-scale installations in operation. Several countries have invested in wave energy research and development, with notable projects and initiatives in regions with strong wave energy potential. Wave energy production worldwide is facing challenges such as high upfront costs, technical complexity, and environmental considerations [87]. Although wave energy technology is in its infancy, studies and innovations are constantly working to make these systems better and more affordable. This bodes well for the future of wave energy as a sustainable energy source.

2.7. Hydrogen Energy

T When combined with other renewable energy sources, such as solar, wind, or hydropower, hydrogen has the ability to generate clean and sustainable power, making it an attractive renewable energy option. A number of processes can be employed to generate hydrogen, such as electrolysis, biomass gasification, and steam methane reforming (SMR) [88]. Green hydrogen is hydrogen that does not contribute to greenhouse gas emissions when it is produced by electrolysis utilizing renewable energy sources like solar or wind power [89]. Liquid hydrogen, compressed gas, and chemical compounds like ammonia and metal hydrides are some of the ways hydrogen can be stored and delivered. This versatility makes hydrogen suitable for applications where direct electrification or grid integration may be challenging, such as long-distance transportation, industrial processes, and energy storage. Compressed gas, liquid hydrogen, and chemical compounds like ammonia or metal hydrides are some of the ways hydrogen can be kept and delivered. This versatility makes hydrogen suitable for applications where direct electrification or grid integration may be challenging, such as long-distance transportation, industrial processes, and energy storage. Electrolysis and Hydrogen fuel cells are the integral parts of hydrogen energy.

2.7.1. Electrolysis

By dividing water molecules into hydrogen (H2) and oxygen (O2), electrolysis can be used to generate hydrogen energy from water

[90]. There are a number of variables that affect the efficiency and purity of electrolyzed hydrogen, such as the electrolyzer type, the amount of electrical energy input, and the water source quality. Advanced electrolysis technologies, such as proton exchange membrane (PEM) electrolysis and alkaline electrolysis, offer high efficiency and purity levels, making them suitable for large-scale hydrogen production [91]. Producing green hydrogen through electrolysis using renewable energy sources like solar or wind power means no emissions of greenhouse gases. Hydrogen production, which combines electrolysis with renewable energy output, has the potential to decarbonize transportation, industry, and electricity generation while also balancing grid fluctuations and storing extra renewable energy [92,93].

2.7.2. Hydrogen Fuel Cells

Electrochemical machines known as hydrogen fuel cells transform the chemical energy of hydrogen and oxygen into electricity, with the sole byproduct being water vapor. Redox reactions involving hydrogen and oxygen are the building blocks of hydrogen fuel cells. Hydrogen fuel cells transform the chemical energy of hydrogen into electricity with a high efficiency, usually between 40% and 60%. They are more efficient than internal combustion engines and batteries, especially in applications requiring continuous power generation and long-range transportation. Hydrogen fuel cells have diverse applications across sectors, including transportation (fuel cell vehicles, buses, trucks, and trains), stationary power generation (backup power, off-grid power, and combined heat and power systems), and portable power (consumer electronics, military applications, and remote sensing devices) [94-96].

Compressed gas, liquid hydrogen, and chemical compounds like ammonia or metal hydrides are some of the ways hydrogen can be kept and delivered. This versatility makes hydrogen suitable for applications where direct electrification or grid integration may be challenging, such as long-distance transportation, industrial processes, and energy storage [97,98]. Despite its potential, hydrogen energy faces several challenges, including high production costs, limited infrastructure for storage and distribution, and efficiency losses during production, storage, and conversion processes. Addressing these challenges will require continued research, technological innovation, policy support, and investment in hydrogen infrastructure.

Conclusion

To combat climate change, ensure reliable energy supply, and preserve our planet for future generations, renewable energies are essential. These renewable energy sources provide limitless, abundant, and environmentally friendly alternatives to fossil fuels, including solar, wind, hydroelectricity, geothermal, and biomass power. Renewable energies help conserve natural resources, lessen air and water pollution, and cut down on emissions of greenhouse gases by utilizing the energy already present in the environment. Their decentralized design also promotes energy independence, opens up new business opportunities, and gives communities more authority. Fast renewable energy technology advancements, along with supportive policies and rising public awareness, are propelling a cleaner, greener, and more sustainable energy future on a global scale, despite obstacles like intermittency, technical limitations, and initial investment costs. Renewable energy is the way of the future, and its adoption is not a luxury but a must if we want to leave our planet habitable and rich for years to come.

References

3. Hunter, David B., James E. Salzman, and Durwood Zaelke. "Glasgow climate summit: Cop26." *UCLA School of Law, Public Law Research Paper,* 22-02 (2021). http://dx.doi.org/10.2139/ssrn.4005648

4. Hussain, Akhtar, Syed Muhammad Arif, and Muhammad Aslam. "Emerging renewable and sustainable energy technologies: State of the art." *Renewable and sustainable energy reviews,* 71 (2017), 12-28. https://doi.org/10.1016/j.rser.2016.12.033

5. Østergaard, Poul Alberg, Neven Duic, Younes Noorollahi, Hrvoje Mikulcic, and Soteris Kalogirou. "Sustainable development using renewable energy technology." *Renewable energy,* 146 (2020), 2430-2437. https://doi.org/10.1016/j.renene.2019.08.094

6. Evans, Annette, Vladimir Strezov, and Tim J. Evans. "Assessment of sustainability indicators for renewable energy technologies." *Renewable and sustainable energy reviews*,13(2009), 1082-1088. https://doi.org/10.1016/j.rser.2008.03.008

7. Demirtas, Ozgur. "Evaluating the best renewable energy technology for sustainable energy planning." *International Journal of Energy Economics and Policy*, 3(2013), 23-33. https://www.econjournals.com/index.php/ijeep/article/view/571

8. Altıntas, Koray, Tuğba Turk, and Özalp Vayvay. "Renewable energy for a sustainable future." *Marmara Fen Bilimleri Dergisi*, 28 (2016), 7-13. https://doi.org/10.7240/mufbed.97723

9. Evans, Annette, Vladimir Strezov, and Tim J. Evans. "Assessment of sustainability indicators for renewable energy technologies." *Renewable and sustainable energy reviews*, 13 (2009), 1082-1088. https://doi.org/10.1016/j.rser.2008.03.008

10. Chel, Arvind, and Geetanjali Kaushik. "Renewable energy technologies for sustainable development of energy efficient building." *Alexandria engineering journal*, 57(2018), 655-669. https://doi.org/10.1016/j.aej.2017.02.027

11. Cozzi, Laura, Tim Gould, Stéphanie Bouckart, Daniel Crow, Tae-Yoon Kim, Christophe McGlade, Pawet Olejarnik, Brent Wanner, and Daniel Wetzel. "World energy outlook 2020." *International Energy Agency: Paris, France*,2050 (2020). https://doi.org/10.1787/20725302

12. Maka, Ali OM, and Jamal M. Alabid. "Solar energy technology and its roles in sustainable development." *Clean Energy*, 6(2022), 476-483. https://doi.org/10.1093/ce/zkac023

13. Kuşkaya, Sevda, Faik Bilgili, Erhan Muğaloğlu, Kamran Khan, Mohammad Enamul Hoque, and Nurhan Toguç. "The role of solar energy usage in environmental sustainability: Fresh evidence through time-frequency analyses." *Renewable Energy*, 206 (2023), 858-871. https://doi.org/10.1016/j.renene.2023.02.063

14. Vadiyala, Vishal Reddy. "Sunlight to Sustainability: A Comprehensive Analysis of Solar Energy's Environmental Impact and Potential." *Asia Pacific Journal of Energy and Environment,* 7(2020), 103-110. https://doi.org/10.18034/apjee.v7i2.711

15. Liu, Jing, Fubin Huang, Zihan Wang, and Chuanmin Shuai. "What is the anti-poverty effect of solar PV poverty alleviation projects? Evidence from rural China." *Energy,* 218 (2021), 119498. https://doi.org/10.1016/j.energy.2020.119498

16. Zhao, Jun, Kangyin Dong, Xiucheng Dong, and Muhammad Shahbaz. "How renewable energy alleviate energy poverty? A global analysis." *Renewable Energy,* 186 (2022), 299-311. https://doi.org/10.1016/j.renene.2022.01.005

17. Kumar, Raj, and S. K. Singh. "Solar photovoltaic modeling and simulation: As a renewable energy solution." *Energy Reports,* 4 (2018), 701-712. https://doi.org/10.1016/j.egyr.2018.09.008

18. Parida, Bhubaneswari, Selvarasan Iniyan, and Ranko Goic. "A review of solar photovoltaic technologies." *Renewable and sustainable energy reviews,* 15(2011): 1625-1636. https://doi.org/10.1016/j.rser.2010.11.032

19. Zahedi, Ahmad. "Solar photovoltaic (PV) energy; latest developments in the building integrated and hybrid PV systems." *Renewable energy,* 31(2006), 711-718. https://doi.org/10.1016/j.renene.2005.08.007

20. Sahoo, Sarat Kumar. "Renewable and sustainable energy reviews solar photovoltaic energy progress in India: A review." *Renewable and Sustainable Energy Reviews,* 59 (2016), 927-939. https://doi.org/10.1016/j.rser.2016.01.049

21. Hassan, Qusay, Patrik Viktor, Tariq J. Al-Musawi, Bashar Mahmood Ali, Sameer Algburi, Haitham M. Alzoubi, Ali Khudhair Al-Jiboory, Aws Zuhair Sameen, Hayder M. Salman, and Marek Jaszczur. "The renewable energy role in the global energy Transformations." *Renewable Energy Focus*, 48 (2024), 100545. https://doi.org/10.1016/j.ref.2024.100545

22. Lee, Taesoo D., and Abasifreke U. Ebong. "A review of thin film solar cell technologies and challenges." *Renewable and Sustainable Energy Reviews,* 70 (2017), 1286-1297. https://doi.org/10.1016/j.rser.2016.12.028

23. Ramanujam, Jeyakumar, Douglas M. Bishop, Teodor K. Todorov, Oki Gunawan, Jatin Rath, Reza Nekovei, Elisa Artegiani, and Alessandro Romeo. "Flexible CIGS, CdTe and a-Si: H based thin film solar cells: A review." *Progress in Materials Science*,110 (2020), 100619. https://doi.org/10.1016/j.pmatsci.2019.100619

24. Fthenakis, Vasilis. "Sustainability of photovoltaics: The case for thin-film solar cells." *Renewable and Sustainable Energy Reviews*, 13(2009), 2746-2750. https://doi.org/10.1016/j.rser.2009.05.001

25. Snaith, Henry J. "Perovskites: the emergence of a new era for low-cost, high-efficiency solar cells." *The journal of physical chemistry letters*, 4(2013),3623-3630. https://doi.org/10.1021/jz4020162

26. Zhang, Pengyu, Menglin Li, and Wen-Cheng Chen. "A perspective on perovskite solar cells: Emergence, progress, and commercialization." *Frontiers in Chemistry*, 10(2022), 802890. https://doi.org/10.3389/fchem.2022.802890

27. Holzhey, Philippe, Michael Prettl, Silvia Collavini, Nathan L. Chang, and Michael Saliba. "Toward commercialization with lightweight, flexible perovskite solar cells for residential photovoltaics." *Joule*,7(2023), 257-271. https://doi:10.1016/j.joule.2022.12.012

28. Ernst, M., X. Liu, C-A. Asselineau, D. Chen, C. Huang, and A. Lennon. "Accurate modelling of the bifacial gain potential of rooftop solar photovoltaic systems." Energy Conversion and Management, 300 (2024), 117947. https://doi.org/10.1016/j.enconman.2023.117947

29. Yakubu, Rahimat O., Lena D. Mensah, David A. Quansah, and Muyiwa S. Adaramola. "Improving solar photovoltaic

installation energy yield using bifacial modules and tracking systems: An analytical approach." *Advances in Mechanical Engineering*, 14(2022), 16878132221139714. https://doi.org/10.1177/16878132221139714

30. de Melo, Karen Barbosa, Michelle Kitayama da Silva, João Lucas de Souza Silva, Tatiane Silva Costa, and Marcelo Gradella Villalva. "Study of energy improvement with the insertion of bifacial modules and solar trackers in photovoltaic installations in Brazil." *Renewable Energy Focus,* 41 (2022), 179-187. https://doi.org/10.1016/j.ref.2022.02.005

31. Smith, Brittany L., Michael Woodhouse, Kelsey AW Horowitz, Timothy J. Silverman, Jarett Zuboy, and Robert M. Margolis. Photovoltaic (PV) module technologies: 2020 benchmark costs and technology evolution framework results. No. NREL/TP-7A40-78173. "*National Renewable Energy Lab.(NREL)",* Golden, CO (United States), 2021. https://doi.org/10.2172/1829459·

32. Borja Block, Alejandro. *Advanced Manufacturing and Characterization of Building-Integrated Photovoltaic Modules*, No. 10575. EPFL, 2024. https://doi.org/10.5075/epfl-thesis-10575

33. Onu, Peter, and Charles Mbohwa. "Industry 4.0 opportunities in manufacturing SMEs: Sustainability outlook." *Materials Today: Proceedings,* 44 (2021), 1925-1930. https://doi.org/10.1016/j.matpr.2020.12.095

34. Allouhi, Amine, Shafiqur Rehman, Mahmut Sami Buker, and Zafar Said. "Up-to-date literature review on Solar PV systems: Technology progress, market status and R&D." *Journal of Cleaner Production*, 362 (2022), 132339. https://doi.org/10.1016/j.jclepro.2022.132339

35. Palacios, A., C. Barreneche, M. E. Navarro, and Y. Ding. "Thermal energy storage technologies for concentrated solar power–A review from a materials perspective." *Renewable*

Energy,156 (2020), 1244-1265. https://doi.org/10.1016/j.renene.2019.10.127

36. Pitz-Paal, Robert. "Concentrating solar power." In *Future energy*, (2020) Elsevier, 413-430. https://doi.org/10.1016/B978-0-08-102886-5.00019-0

37. Patel, Kishan, Pragna Patel, and Jatin Patel. "Review of solar water heating systems." *International Journal of Advanced Engineering Technology*, 3(2012), 146-149. https://doi.org/10.13140/2.1.1910.5281

38. Abdelaziz, Gamal B., Emad MS El-Said, Mohamed A. Dahab, M. A. Omara, and Swellam W. Sharshir. "Hybrid solar desalination systems review." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, (2021),1-31. https://doi.org/10.1080/15567036.2021.2005721

39. Reif, John H., and Wadee Alhalabi. "Solar-thermal powered desalination: Its significant challenges and potential." *Renewable and Sustainable Energy Reviews*, 48 (2015), 152-165. https://doi.org/10.1016/j.rser.2015.03.065

40. Schwarzer, Klemens, and Maria Eugenia Vieira Da Silva. "Solar cooking system with or without heat storage for families and institutions." *Solar Energy*, 75 (2003), 35-41. https://doi.org/10.1016/S0038-092X(03)00197-X

41. Aramesh, Mohamad, Mehdi Ghalebani, Alibakhsh Kasaeian, Hosein Zamani, Giulio Lorenzini, Omid Mahian, and Somchai Wongwises. "A review of recent advances in solar cooking technology." *Renewable Energy*, 140 (2019), 419-435. https://doi.org/10.1016/j.renene.2019.03.021

42. Al-Alili, Ali, Yunho Hwang, and Reinhard Radermacher. "Review of solar thermal air conditioning technologies." *International Journal of Refrigeration*, 39 (2014), 4-22. https://doi.org/10.1016/j.ijrefrig.2013.11.028

43. Nkwetta, Dan Nchelatebe, and Jim Sandercock. "A state-of-the-art review of solar air-conditioning systems." *Renewable and*

sustainable energy reviews, 60 (2016), 1351-1366. https://doi.org/10.1016/j.rser.2016.03.010

44. Farjana, Shahjadi Hisan, Nazmul Huda, MA Parvez Mahmud, and Rahman Saidur. "Solar process heat in industrial systems–A global review." *Renewable and Sustainable Energy Reviews*,82 (2018), 2270-2286. https://doi.org/10.1016/j.rser.2017.08.065
45. Kalogirou, Soteris. "The potential of solar industrial process heat applications." *Applied Energy,* 76 (2003), 337-361. https://doi.org/10.1016/S0306-2619(02)00176-9
46. Franco, Alessandro. "Methods for the sustainable design of solar energy systems for industrial process heat." *Sustainability*,12 (2020), 5127. https://doi.org/10.3390/su12125127
47. Blaabjerg, Frede, and Ke Ma. "Wind energy systems." *Proceedings of the IEEE*, 105 (2017), 2116-2131. https://doi.org/10.1109/JPROC.2017.2695485
48. Herbert, GM Joselin, Selvaraj Iniyan, Emer Sreevalsan, and Svony Rajapandian. "A review of wind energy technologies." *Renewable and sustainable energy Reviews*,11 (2007), 1117-1145. https://doi.org/10.1016/j.rser.2005.08.004
49. Kwok, K. C. S., and Gang Hu. "Wind energy system for buildings in an urban environment." *Journal of Wind Engineering and Industrial Aerodynamics,* 234 (2023), 105349. https://doi.org/10.1016/j.jweia.2023.105349
50. Li, Jinjiang, Guandao Wang, Zhiheng Li, Shaolong Yang, Wen Tong Chong, and Xianbo Xiang. "A review on development of offshore wind energy conversion system." *International Journal of Energy Research,* 44 (2020), 9283-9297. https://doi.org/10.1002/er.5751
51. Njiri, Jackson G., and Dirk Söffker. "State-of-the-art in wind turbine control: Trends and challenges." *Renewable and Sustainable Energy Reviews,* 60 (2016), 377-393. https://doi.org/10.1016/j.rser.2016.01.110

52. Wang, Xuefei, Xiangwu Zeng, Jiale Li, Xu Yang, and Haijun Wang. "A review on recent advancements of substructures for offshore wind turbines." *Energy conversion and management*, 158 (2018), 103-119. https://doi.org/10.1016/j.enconman.2017.12.061

53. Yaramasu, Venkata, Bin Wu, Paresh C. Sen, Samir Kouro, and Mehdi Narimani. "High-power wind energy conversion systems: State-of-the-art and emerging technologies." *Proceedings of the IEEE*, 103 (2015), 740-788. https://doi.org/10.1109/JPROC.2014.2378692

54. Mahela, Om Prakash, and Abdul Gafoor Shaik. "Comprehensive overview of grid interfaced wind energy generation systems." *Renewable and Sustainable Energy Reviews*, 57 (2016), 260-281. https://doi.org/10.1016/j.rser.2015.12.048

55. Javed, Muhammad Shahzad, Tao Ma, Jakub Jurasz, and Muhammad Yasir Amin. "Solar and wind power generation systems with pumped hydro storage: Review and future perspectives." *Renewable Energy*, 148 (2020), 176-192. https://doi.org/10.1016/j.renene.2019.11.157

56. Al-Masri, Hussein MK, Ayman Al-Quraan, Ahmad AbuElrub, and Mehrdad Ehsani. "Optimal coordination of wind power and pumped hydro energy storage." *Energies*, 12 (2019), 4387. https://doi.org/10.3390/en12224387

57. Hirth, Lion. "The benefits of flexibility: The value of wind energy with hydropower." Applied Energy, 181 (2016), 210-223. https://doi.org/10.1016/j.apenergy.2016.07.039

58. Moran, Emilio F., Maria Claudia Lopez, Nathan Moore, Norbert Müller, and David W. Hyndman. "Sustainable hydropower in the 21st century." *Proceedings of the National Academy of Sciences*, 115 (2018), 11891-11898. https://doi.org/10.1073/pnas.1809426115

59. Kougias, Ioannis, George Aggidis, François Avellan, Sabri Deniz, Urban Lundin, Alberto Moro, Sebastian Muntean et al. "Analysis of emerging technologies in the hydropower

sector." *Renewable and Sustainable Energy Reviews,* 113 (2019), 109257. https://doi.org/10.1016/j.rser.2019.109257

60. Liszka, Damian, Zbigniew Krzemianowski, Tomasz Węgiel, Dariusz Borkowski, Andrzej Polniak, Konrad Wawrzykowski, and Artur Cebula. "Alternative Solutions for Small Hydropower Plants." *Energies*, 15 (2022), 1275. https://doi.org/10.3390/en15041275

61. Gallagher, John, David Styles, Aonghus McNabola, and A. Prysor Williams. "Current and future environmental balance of small-scale run-of-river hydropower." *Environmental science & technology,* 49 (2015), 6344-6351. https://doi.org/10.1021/acs.est.5b00716

62. Canales, Fausto A., Alexandre Beluco, and Carlos André B. Mendes. "A comparative study of a wind hydro hybrid system with water storage capacity: Conventional reservoir or pumped storage plant?." *Journal of Energy Storage,* 4 (2015), 96-105. https://doi.org/10.1016/j.est.2015.09.007

63. Perea-Moreno, Miguel-Angel, Esther Samerón-Manzano, and Alberto-Jesus Perea-Moreno. "Biomass as renewable energy: Worldwide research trends." *Sustainability,* 11 (2019), 863. https://doi.org/10.3390/su11030863

64. Demirbas, M. Fatih, Mustafa Balat, and Havva Balat. "Potential contribution of biomass to the sustainable energy development." *Energy Conversion and Management,* 50 (2009), 1746-1760. https://doi.org/10.1016/j.enconman.2009.03.013

65. Lu, Hong, and Larry L. Baxter. "Biomass combustion characteristics and implications for renewable energy." In *Solid Biofuels for Energy: A Lower Greenhouse Gas Alternative*, (2011), 95-121. https://doi.org/10.1007/978-1-84996-393-0_5

66. Van den Broek, Richard, André Faaij, and Ad van Wijk. "Biomass combustion for power generation." *Biomass and bioenergy,* 11 (1996), 271-281. https://doi.org/10.1016/0961-9534(96)00033-5

67. Czekała, Wojciech. "Biogas as a sustainable and renewable energy source." In *Clean Fuels for Mobility*, (2022), 201-214. https://doi.org/10.1007/978-981-16-8747-1_10

68. Ošlaj, Matjaž, and Bogomir Muršec. "Biogas as a renewable energy source." *Tehnički vjesnik,* 17 (2010) 109-114. https://hrcak.srce.hr/50629

69. Dickson, Mary H., and Mario Fanelli. "What is geothermal energy?." In *Renewable Energy*, (2018), 302-328.

70. Shortall, Ruth, Brynhildur Davidsdottir, and Guðni Axelsson. "Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks." *Renewable and sustainable energy reviews,* 44 (2015), 391-406. https://doi.org/10.1016/j.rser.2014.12.020

71. Moya, Diego, Clay Aldás, and Prasad Kaparaju. "Geothermal energy: Power plant technology and direct heat applications." *Renewable and Sustainable Energy Reviews,* 94 (2018), 889-901. https://doi.org/10.1016/j.rser.2018.06.047

72. Yari, Mortaza. "Exergetic analysis of various types of geothermal power plants." *Renewable energy,* 35 (2010), 112-121. https://doi.org/10.1016/j.renene.2009.07.023

73. Omer, Abdeen Mustafa. "Ground-source heat pumps systems and applications." *Renewable and sustainable energy reviews*, 12 (2008), 344-371. https://doi.org/10.1016/j.rser.2006.10.003

74. Arghand, Taha, Saqib Javed, and Jan-Olof Dalenbäck. "Combining direct ground cooling with ground-source heat pumps and district heating: Energy and economic analysis." *Energy*, 270 (2023), 126944. https://doi.org/10.1016/j.energy.2023.126944

75. Sarbu, Ioan, and Calin Sebarchievici. "General review of ground-source heat pump systems for heating and cooling of buildings." *Energy and buildings*, 70 (2014), 441-454. https://doi.org/10.1016/j.enbuild.2013.11.068

76. Bertani, Ruggero. "Deep geothermal energy for heating and cooling." In *Renewable Heating and Cooling*, (2016), 67-88. https://doi.org/10.1016/B978-1-78242-213-6.00004-7

77. Soltani, M., Farshad M. Kashkooli, A. R. Dehghani-Sanij, A. R. Kazemi, N. Bordbar, M. J. Farshchi, M. Elmi, K. Gharali, and Maurice B. Dusseault. "A comprehensive study of geothermal heating and cooling systems." *Sustainable Cities and Society*, 44 (2019), 793-818. https://doi.org/10.1016/j.scs.2018.09.036

78. Anifantis, Alexandros Sotirios, Simone Pascuzzi, and Giacomo Scarascia-Mugnozza. "Geothermal source heat pump performance for a greenhouse heating system: An experimental study." *Journal of Agricultural Engineering*, 47 (2016), 164-170. https://doi.org/10.4081/jae.2016.544

79. Shetty, Chirag, and Abhishek Priyam. "A review on tidal energy technologies." *Materials Today: Proceedings*, 56 (2022), 2774-2779. https://doi.org/10.1016/j.matpr.2021.10.020

80. Segura, E., R. Morales, J. A. Somolinos, and A. López. "Techno-economic challenges of tidal energy conversion systems: Current status and trends." *Renewable and Sustainable Energy Reviews*, 77 (2017), 536-550. https://doi.org/10.1016/j.rser.2017.04.054

81. Greaves, Deborah. "Wave Energy Technology." *Wave and tidal energy* (2018): 52-104. https://doi.org/10.1002/9781119014492.ch3

82. Vigars, Paul, Kwangsoo Lee, Sungwon Shin, Boel Ekergard, Mats Leijon, Yago Torre-Enciso, Dorleta Marina, and Deborah Greaves. "Project Development." *Wave and Tidal Energy*, (2018), 533-586. https://doi.org/10.1002/9781119014492.ch12

83. Boretti, Alberto. "Trends in tidal power development." In *E3S web of conferences*, 173 (2020), 01003. https://doi.org/10.1051/e3sconf/202017301003

84. Folley, Matt. "The wave energy resource." *Handbook of ocean wave energy,* 7 (2017), 43-80. https://doi.org/10.1007/978-3-319-39889-1

85. Doyle, Simeon, and George A. Aggidis. "Development of multi-oscillating water columns as wave energy converters." *Renewable and sustainable energy reviews,* 107 (2019), 75-86. https://doi.org/10.1016/j.rser.2019.02.021

86. Al Shami, Elie, Ran Zhang, and Xu Wang. "Point absorber wave energy harvesters: A review of recent developments." *Energies,* 12 (2018), 47. https://doi.org/10.3390/en12010047

87. Mahmoud, Montaser, Mohammad Ali Abdelkareem, and Abdul Ghani Olabi. "Wave energy extraction technologies." *In Renewable Energy-Volume 2: Wave, Geothermal, and Bioenergy*, pp. 37-51. Academic Press, 2024. https://doi.org/10.1016/B978-0-323-95211-8.00013-0

88. Contestabile, Pasquale, Gaetano Crispino, Enrico Di Lauro, Vincenzo Ferrante, Corrado Gisonni, and Diego Vicinanza. "Overtopping breakwater for wave Energy Conversion: Review of state of art, recent advancements and what lies ahead." *Renewable Energy,* 147 (2020), 705-718. https://doi.org/10.1016/j.renene.2019.08.115

89. Chang, Grace, Craig A. Jones, Jesse D. Roberts, and Vincent S. Neary. "A comprehensive evaluation of factors affecting the levelized cost of wave energy conversion projects." *Renewable energy,* 127 (2018), 344-354. https://doi.org/10.1016/j.renene.2018.04.071

90. Hosseini, Seyed Ehsan, and Mazlan Abdul Wahid. "Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development." *Renewable and Sustainable Energy Reviews,* 57 (2016), 850-866. https://doi.org/10.1016/j.rser.2015.12.112

91. Chakraborty, Suprava, Santanu Kumar Dash, Rajvikram Madurai Elavarasan, Arshdeep Kaur, Devaraj Elangovan, Sheikh

Tanzim Meraj, Padmanathan Kasinathan, and Zafar Said. "Hydrogen energy as future of sustainable mobility." *Frontiers in energy research,* 10 (2022), 893475. https://doi.org/10.3389/fenrg.2022.893475

92. Koponen, Joonas. "Energy efficient hydrogen production by water electrolysis." (2020).https://urn.fi/URN:ISBN:978-952-335-491-3

93. Li, Changqing, and Jong-Beom Baek. "The promise of hydrogen production from alkaline anion exchange membrane electrolyzers." *Nano Energy,* 87 (2021), 106162. https://doi.org/10.1016/j.nanoen.2021.106162

94. Hassan, Qusay, Aws Zuhair Sameen, Hayder M. Salman, and Marek Jaszczur. "Large-scale green hydrogen production via alkaline water electrolysis using solar and wind energy." *International Journal of Hydrogen Energy,* 48 (2023), 34299-34315. https://doi.org/10.1016/j.ijhydene.2023.05.126

95. Benghanem, Mohamed, Adel Mellit, Hamad Almohamadi, Sofiane Haddad, Nedjwa Chettibi, Abdulaziz M. Alanazi, Drigos Dasalla, and Ahmed Alzahrani. "Hydrogen production methods based on solar and wind energy: a review." *Energies,* 16 (2023), 757. https://doi.org/10.3390/en16020757

96. Edwards, Peter P., Vladimir L. Kuznetsov, William IF David, and Nigel P. Brandon. "Hydrogen and fuel cells: Towards a sustainable energy future." *Energy policy,* 36 (2008): 4356-4362. https://doi.org/10.1016/j.enpol.2008.09.036

97. Rajalakshmi, Natarajan, Rengarajan Balaji, and Sundararajan Ramakrishnan. "Recent developments in hydrogen fuel cells: Strengths and weaknesses." *Sustainable Fuel Technologies Handbook,* (2021), 431-456. https://doi.org/10.1016/B978-0-12-822989-7.00015-9

98. Staffell, Iain, Daniel Scamman, Anthony Velazquez Abad, Paul Balcombe, Paul E. Dodds, Paul Ekins, Nilay Shah, and Kate R. Ward. "The role of hydrogen and fuel cells in the global energy

system." *Energy & Environmental Science*, 12 (2019), 463-491. https://doi.org/ 10.1039/C8EE01157E

99. Yang, Miao, Ralf Hunger, Stefano Berrettoni, Bernd Sprecher, and Baodong Wang. "A review of hydrogen storage and transport technologies." *Clean Energy,* 7 (2023), 190-216. https://doi.org/10.1093/ce/zkad021

100. Stetson, Ned T., Robert C. Bowman Jr, and Gregory L. Olson. "Overview of hydrogen storage, transportation, handling and distribution." *Handbook of Hydrogen Energy, CRC Press, Boca Raton* (2015), 567-592. https://doi.org/10.1201/b17226

 ISBN: 978-81-975412-4-7

4

Greening the Energy Sector: The Role of Ammonia in the Hydrogen Economy

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Contents

1. Introduction

Numerous methodologies have been developed to address the issue of carbon dioxide releases in the context of the manufacture of ammonia via the Haber-Bosch process, widely recognized as the typical approach to ammonia biosynthesis. These devices are commonly acknowledged as “CO_2 capture equipment". The scientific term used to describe the process of ammonia synthesis with reduced carbon dioxide emissions is commonly known to be the “Blue ammonia production method". The process demonstrates differences in comparison to the Haber-Bosch procedure specifically with regard to the phase involving the reduction of carbon dioxide. Nevertheless, in certain procedures like the blue ammonia production method, it might be viable to employ the carbon dioxide obtained via the capture or sequestration of CO_2 emissions in diverse industries, such as urea synthesis [1].

2. Ammonia as Hydrogen energy carrier for the decarbonization process

2.1 Amine absorption

This technique is largely acknowledged as the predominant commercially available approach for carbon dioxide collection within the range of technological alternatives [2]. Amines are a category of organic compounds characterized by the presence of a functional group comprising a lone pair of electrons along with a nitrogen atom exhibiting basic characteristics [3]. The removal of CO_2 from a gas is facilitated by alkanolamines through an exothermic interaction that involves the amine function of the alkanolamine molecule. Another method employed in the capture of carbon dioxide entails the extraction of carbon dioxide from a gas mixture by means of condensation [4]. The cryogenic separation procedure facilitates the direct production of liq. carbon dioxide from gases and is particularly suitable for long-distance transport of this chemical. One of the limitations connected with the proposed approach is the substantial energy requirement for the cooling phase. Furthermore, it is important to include specific elements, such as H_2O, in the procedure to mitigate the cooling effect induced by the flow of gas onto the blocks.

2.2 Membranes and other adsorbents

However, the implementation of membranes in separation of gases for carbon dioxide collection operations is an emerging method that shows potential for purifying and cleaning purposes. Membranes serve as semi-permeable barriers that possess the ability to selectively assist the transportation of particular substances. These membranes exhibit specialized adaptations that cater to the unique requirements of each material. The membranes utilized for the process of carbon dioxide decomposition include membrane of palladium, polymer membranes, zeolites etc. Another approach employs a solid adsorption device called a rotating concentrator. The method of adsorption often involves the utilization of multiple solid materials. Activated carbons are a type of porous substance that has been subjected to a specific treatment in order to augment its surface area and improve its ability to adsorb substances. The inorganic substances that have been referenced encompass active clays, silicon dioxide gel, zeolites, aluminium oxide, etc. The focus of this study is on synthetic polymers, particularly negative ion exchange polymers comprising of styrene, +ve ion-exchange polymers incorporating acylamine groups, also acrylic ester polymers. During the pressured swing adsorption (PSA) procedure, the gas mix is pushed towards a packed bed of adsorbent material under increased pressure till the intended gas concentration is reached at equilibrium. The configuration of the bed is modified by decreasing the pressure. A supplementary methodology that has been developed to alleviate carbon dioxide in the production of ammonia through the Haber-Bosch process is commonly known as the CO_2 storage approach. The aforementioned system has witnessed notable technological progress, leading to its incorporation onto the carbon dioxide capture technique. The main objective of this system is to optimize the efficient use of preserved carbon dioxide in an environment that is in accordance with natural processes. There are several prospective methodologies for the sequestration of carbon dioxide. These systems are designed to allocate land for agriculture or forests that have the ability to use carbon dioxide for their metabolic needs while going through underground storage in geological formations, storage in oceans, mineralization, or by means of the process of photosynthesis [5]. The prevailing consensus suggests that geological formations exhibit a storage capability that spans from 300 - 3100 gigatons. In a similar vein, it is estimated that the Earth's oceans possess a storage capacity ranging from 1400 - twenty million gigatons, whereas forests are thought to have a storing capacity of approximately 100 gigatons.

2.3 Carbon capture with storage operations

In the framework of carbon capture and storage operations, the inclusion of supplementary sectors is necessary to facilitate the transport, the collection, and distribution of carbon dioxide to the facility for storage. In addition, apart from the leaching process, the captured carbon dioxide has an opportunity to be employed in many other uses, including oil cleanup, methane generation from coal mines, and the preservation of pressure in drained gas reservoirs [6]. Subterranean water bodies containing saline solution, referred to as deeply salt reservoirs, possess a substantial depth of ~800 m and exhibit the capability to sequester carbon dioxide in an extremely condensed and packed supercritical state. The geographical range of such watersheds is vast, and they often contain small gaps that have a limited ability to absorb carbon dioxide. However, numerous basins exhibit unique configurations that enhance their storage capacity, to be the phenomenon of carbon dioxide dissolving in water transpires at a notably gradual rate. The application of Enhanced Oil Recovery when a technique for carbon dioxide storage is regarded as a conventional augmentation. In spite of the existence of supplementary reserves of oil, the pressure inside the oil field decreases gradually over time, ultimately leading to the upward movement of the oil towards the earth's surface and complete exhaustion of the pressure. The utilization of carbon dioxide injection, acquired through the separation of hydrogen in the manufacturing procedure, can be employed to maintain gas or water pressure and improve the efficiency of oil extraction [7]. The Coal Bed gas methane extraction process entails the retrieval of methane from deposits of coal, which commonly possess a significant methane composition. If the captured carbon dioxide is released to a coal mine, this will lead to the liberation of methane as a result of the stronger chemical bonding among coal as well as carbon dioxide in comparison to methane. Following this, methane can be harnessed for the use of electricity production. The implementation of Deep Ocean Injection as a technique for carbon sequestration entails acknowledging the ocean as a unified reservoir for atmospheric carbon dioxide. Nevertheless, it is imperative to acknowledge that the successful deployment of this system necessitates a substantial temporal investment for its establishment [8]. Therefore, the ocean injection method is perceived as a facilitator of the natural phenomenon. The oceans possess a substantial capacity for carbon dioxide preservation. However, several obstacles impede this phenomenon, encompassing environmental implications, legal factors, and societal reception [9]. The carbon dioxide that is produced as a byproduct of the hydrogen production process has the capability to be transported to specific locations and then published in condensed gas, solid, or any supercritical states while being subjected to increased pressure. Supercritical CO_2 is frequently favoured for transportation applications in situations where a pipeline infrastructure is accessible.

2.4 Risk factors

Although this methodology is portrayed as a developing technology, it is expected that the quantity of carbon dioxide needing to be transported in the future will rise due to concerns about climate change. The construction of the pipeline would be challenging, especially in places with dense populations, and it might cause security concerns. Additionally, the risks of pipeline impairment brought on by excavations performed without adequate awareness and expertise may result in a variety of difficulties, complex insurance-related problems, and concerns about the reliability of the pipeline network. The challenge of finding a good location for carbon dioxide disposal raises still another issue. International shipping may be a financially and safely viable choice when warehouses are unable to cope with the disposal of considerable quantities of carbon dioxide. Additionally, this strategy necessitates the adoption of complex and extensive legislation. [10] Around 85 percent of the carbon dioxide emission from human-caused events are stored in the oceans. However, this process moves at a somewhat slow pace. The introduction of small amounts of carbon dioxide to the ocean's near-surface areas necessitates an additional injection into deeper levels, according to empirical data from studies [11], in order to lessen its return into the atmosphere. Spending goes up as a result of this. The alteration in pH balance brought on by the administration of large doses of injections is a further cause for worry. This problem can be successfully mitigated by administering microscopic amounts in various locations. However, it is important to recognize that this will result in higher costs. The potential impacts of storing carbon dioxide in geological structures raise concerns regarding the safety or environmental compatibility of the storage method as well as possible adverse impacts on the structural integrity of the formations. The possibility for leakage resulting from both natural deterioration and the degraded integrity of dormant wells is a key problem connected to the geologic decomposition of carbon dioxide observed in gas and oil reservoirs. By converting the gas into a solid by producing a carbonate stone, one may be able to address this issue and maybe allay worries. However, there are budgetary limitations to this operation. According to research conducted with the aid of currently available technologies, the cost of the carbon separation procedure to reduce unwanted carbon emissions varies between $100 /ton - $300 /ton. Evidently, the effectiveness of carbon dioxide collection or storage devices in the long run to reduce carbon dioxide emissions in the massive production of anhydrous ammonia utilizing the Haber-Bosch process is limited. It is essential to obtain hydrogen and the required energy from sources that are renewable in order to completely eliminate carbon emissions from the method of producing ammonia [12]. As a result, hydrogen may be created on a huge scale using a variety of techniques. The aforementioned things can be categorized as either water electrolysis, proton exchange membranes, or anion exchange membranes. The Haber-Bosch method is being compared to a number of other procedures. A number of plasma catalyst can be used to speed up the ammonia production process in conjunction with factors like temperature and pressure. However, plasma significantly slows down the rate of ammonia generation. The exact amount of energy used and the cost consequences that result from an inefficient plaza catalyst are still unknown. The electrolytic breakdown of water can be used to produce the phenomena of renewable hydrogen synthesis. The material can be added to the Haber-Bosch process after oxidation to get the necessary temperature and pressure conditions. In a low-pressure setting, diazole is reduced electrochemically when there is water present. A different method of producing hydrogen combines the creation of renewable hydrogen with the electrochemical production of ammonia [13]. A sustainable energy source is assumed to be used in the manufacturing of ammonia in the existing body of scientific research. For sustaining accurate pressure and temperature settings, the ammonia synthesis reaction necessitates an electrical power consumption range of 100–200 MW. The current energy production capacity required for the procedure of ammonia synthesis is estimated to be 200 MWatt/hour, despite keeping an average production consumption of 20 metric tons of ammonia, according to study findings. When compared to an ammonia factory that runs on renewable energy, the Haber-Bosch process outlay often shows a sizable economic benefit. It seems that this alternative is not economically viable for numerous producers, though. Owing to the absence of continuous operational benefits often seen in facilities like ammonia manufacturing plants, the restricted availability of resources for producing electricity from sources that are renewable poses a constraint that may be perceived as a disadvantage [14].

2.5 Membrane technology

When it comes to using renewable sources to produce ammonia, the absence of a good storage mechanism to deal with the unpredictable nature of wind and solar power can be viewed as a restriction. Alternative methods for producing hydrogen have also been developed, including solid-oxygen electrolysis with proton exchange membrane - PEM fuel cells. These innovations also make it easier to use ammonia as a renewable energy source. Utilizing a variety of membrane technologies, including PEM fuel batteries, transportable membranes, and absorption-based systems, hydrogen can be produced. Membrane technology have several uses in a variety of disciplines, including diverse industries like energy production. The use of membrane technology for hydrogen production has become a crucially significant field of research and development within the context of numerous applications. Technology for producing hydrogen at elevated temperatures is made possible by the use of solid-state oxide electrolysis cells, which eliminates the need for an air separating unit. Comparing this specific method's energy use to other, more traditional ammonia production techniques, it is more negligible. The possibility of ammonia and hydrogen as green energy sources has been tapped by a number of different alternative technologies. Fuel cells of all stripes, including PEM fuel cells, and Solid Oxide Fuel Cells (SOFC), and Alkali Fuel Cells (AFC) are covered under the previously mentioned technologies. Other energy conversion technologies are also mentioned, such as engines with internal combustion, boilers including furnaces, especially combined cycle gas turbines (CCGT). These innovations are typically regarded as very efficient fuel technologies. The life cycle assessment of ammonia synthesis, water splitting, and ammonia cracking for the hydrogen fuel is shown in the Fig. 1.

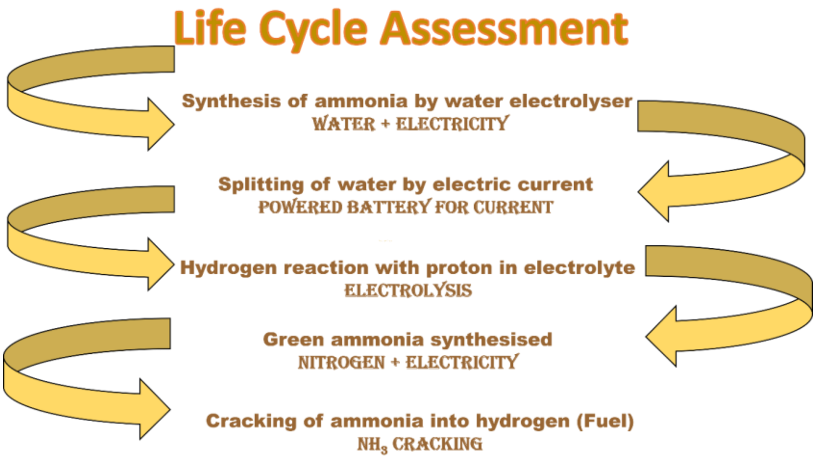

Fig. 1: Life cycle assessment of ammonia synthesis, water splitting, and ammonia cracking for the hydrogen fuel.

3. Ammonia-hydrogen blends and ammonia-methane blends

A great deal of study has been conducted on the utilization of methane as an alternative to improve the rate of burning and mitigate the release of nitrogen oxides (NO_x). The burning rate of hydrogen, or H_2, in atmosphere exhibits a higher magnitude compared to the rate of ammonia, or NH_3, in atmosphere. Research studies that have included chemical kinetic simulations as well as experimental investigations have provided evidence that flames consisting of NH_3/H_2/air display an exponential increase in burning velocity as the concentration of gas in the fuel mixture rises [15]. Several investigations have provided evidence that the enhanced influence of hydrogen gas on the combustion speed of an ammonia flame appears particularly significant when the hydrogen ratio surpasses 0.31 in the fuel mix. The utilization of the gas NH_3 in conjunction with hydrogen has been identified as a notably effective approach for augmenting the rate of combustion in fuel mixes that incorporate NH_3. The burning rate of flames composed of NH_3/H_2/air firstly demonstrates an ascending pattern as the equivalency ratio is augmented, culminating in a peak value at 1.1. The addition of H_2 to NH_3/air flames at various ratios of equivalence (0.7–1.5) results in a measured rise in the combustion velocity, as reported in previous studies [16]. When the proportion of ammonia is decreased, the combustion properties of the flames demonstrate resemblance to hydrogen-based flames instead of ammonia-based flames.

Moreover, the consistency of the change in burning speed for NH_3/H_2/air flames persists with respect to the hydrogen amount, irrespective of fluctuations in environmental pressures. However, it has been shown that the rate of combustion reduces as pressure increases [17]. This phenomenon may be attributed to the varying sensitivity of specific processes to the stoichiometric limits. Furthermore, it has been shown that an elevation in pressure results in a predominance of nitrogen-based elementary processes compared to hydrogen-based reactions, further contributing to the interactions $H+O_2=O+OH$ with $NH_3+M=NH_2+H+M$. Scientific experiments have continuously shown reliable conclusions about the fluctuations in NO_x emissions related to the hydrogen proportion in the blended fuel. Also, there is a rise in the level of NO_x once the mole fraction of H_2 approaches 0.81. The observed phenomena can be plausibly ascribed to the increased temperature, which leads to the generation of OH as well as O radicals. However, it has been observed that when the fraction of hydrogen gas exceeds 0.81, there's a noticeable decrease in the generation of oxides of nitrogen (NOx). The observed phenomenon can be ascribed to the reduction in the concentration of ammonia (NH_3) within the mixtures. The study conducted [18] demonstrates that there is a noticeable decrease in fuel NOx emissions once the mole fraction of H_2 exceeds 0.8 in NH_3/H_2 blends. A higher density of hydroxyl (OH) molecules can be attained by increasing the amount of hydrogen (H_2) in ammonia/hydrogen (NH_3/H_2) mixes. This concentration reaches its maximum level when the NH_3 fraction is 0%.

In an independent study, researchers detected a positive relationship between the release of nitrogen oxides and the percentage of hydrogen within NH_3/H_2 mixes, and also with the equivalency ratio. Nevertheless, the rise in NO_x emissions did not exhibit a substantial impact beyond an equivalency ratio of 1.1 [19]. When running in stoichiometric as well as fuel-rich conditions, NO_x emissions demonstrate low levels, while the generation of N_2O stays negligible under these particular conditions. The total amount of NO_x typically declines when the stoichiometric proportion (φ) increases, across different beginning NH_3 concentrations [50]. Furthermore, a supplementary investigation has shown evidence that the release of NO_x and N_2O emissions is notably diminished when hydrogen is used as a substitute during rich combustion, as opposed to inefficient combustion. The event under observation demonstrates a diminished magnitude when the starting level of NH_3 is at 50%. In the majority of cases, a stable level of NO_x is seen, commencing at the 10-minute interval. Increasing the molar fraction of ammonia and the equivalency ratio will lead to a decrease in the temperature of the flame. At an equivalent ratio of 1.24, the attainment of the lowest amount of nitrogen oxides as well as the flame temperature happens when the initial levels of ammonia (NH_3) are 45% and 50%, correspondingly [20]. Another study conducted found that a drop in oxygen content leads to a reduction in nitrogen oxide fabrication, suggesting that the equivalency ratio plays a crucial role in the creation of NO [21]. Nevertheless, a further captivating observation was noted with regards to the influence of pressure on the emissions of nitrogen oxides (NO_x) in flames consisting of ammonia

(NH_3), hydrogen (H_2), and air. According to previous research findings, it has been observed that when pressures are around 1 atmosphere, an elevation in pressure leads to a reduction in the release of NO.

In a similar manner, it has been reported that the released levels of nitrogen oxides demonstrate a significant decrease while operating at higher pressures in comparison to atmospheric pressure. According to reference [22], it has been shown that NO_x emissions exhibit a reduction to levels below 5ppm and 1ppm when the pressure surpasses 10 and 20 atm, accordingly. Moreover, the incorporation of vapor into NH_3/H_2 mixtures has been found to boost power output, while concurrently decreasing Zeldovich NOx emissions along with infusing O/H radicals to the reactive mixture. The enhancement of both nitrogen oxides (NO_x) reduction and the decrease in leftover ammonia (NH_3) can be achieved by running with a fuel-to-air ratio (φ) that is smaller, and the introduction of steam contributes to the latter effect [23]. The empirical data suggests that there is a direct relationship between the flame temperature and the proportion of hydrogen in the fuel blend. Moreover, it is possible to partition the flame temperature distribution into two separate linear sections. The rate of flame temperature escalation has a more pronounced trend when the proportion of H_2 surpasses 90%, indicating that H_2 plays a predominant role in the second phase. In contrast, Choi et al. conducted an experimental study aimed at investigating the potential of hydrogen-doped ammonia to serve as a carbon emission-free fuel source.

According to the results, it was observed that augmenting the ratio of hydrogen within the NH_3/H_2/air flame resulted in an elevated maximum temperature of the flame. An increase in the amount of heat transfer rate, when normalized, was seen with the inclusion of H_2 across all examined equivalency ratios. The maximum rate of heat release appears at the exact same temperature in the fuel-rich zone, but it is observed at less temperature in the stoichiometric as well as fuel-lean areas when the fraction of hydrogen is raised. It has been noted that places characterized by a fuel-to-air ratio that is either rich or stoichiometric exhibit an elevated heat release rate. The combustion velocity of flames consisting of NH_3/H_2/air is augmented by an elevated concentration of hydrogen along with an increased equivalence ratio (φ). Furthermore, the mitigation of NO_x emissions can be achieved by optimizing the parameters of φ, pressure, with NH_3 concentration. The generation of nitrogen oxides (NO_x) is predominantly affected by the pressure state, with emissions below 5 ppm being attained at an atmospheric pressure of 10atm. The optimal flame temperature and nitrogen oxides (NO_x) concentration were attained at an initial ammonia (NH_3) concentration of 41% and 45%, accordingly, with an equivalency ratio of 1.3. Therefore, it would be beneficial to conduct NH_3/H_2/air combustion in a fuel-rich and high-pressure setting in order to get the optimum burning velocity and reduce the emissions of NO_x. The phenomenon of combustion velocity- The speed of flame of NH_3/CH_4/air demonstrates a nearly gradual rise as the proportion of CH_4 is augmented. The observed improvement in performance occurs across a spectrum of less-fuel to fuel-rich conditions, primarily due to the increased stoichiometric limit as well as methane reactivity. [24] The stoichiometric proportion demonstrates an upward trend as the fuel-less condition shifts towards nearly stoichiometric conditions. Conversely, it shows a decline when fuel-rich circumstances are observed, irrespective of the quantity of methane. The researchers observed a stronger fluctuation in the stoichiometric proportion gradient when the system was near to laminar speed of flame, indicating an increased sensitivity to alterations in the CH_4 substitution ratio. The correlation between the alteration in the trajectory of the flame velocity of NH_3/CH_4/air alongside the ratio of CH_4 remains constant across different ambient pressures.

The literature indicates that there is a positive correlation between sound level and the temperature of not burned gas. Additionally, previous studies have shown a negative correlation between sound level and pressure. Both of the Okafor mechanism along with the San Diego mechanism offer adequate explanations for the process of NH_3/CH_4/air combustion process. The use of NH_3 to be a fuel presents a challenge due to the increased production of NO_x emissions associated with this fuel. The mitigation of emissions of greenhouse gases can be accomplished by the combustion of hydrocarbon-based fuel in conjunction with NH_3, leading to the decrease in CO_2 and NO_x generated throughout the combustion procedure. The reduction in carbon dioxide (CO_2) emissions is observed to be 50% in comparison to pristine methane whenever the amount of ammonia exceeds 60 mol%. In the same way, the release of the poisonous gas carbon monoxide is reduced when there is a greater proportion of ammonia substitute in NH_3/CH_4 mixtures. The levels of nitrogen oxide demonstrate a positive correlation with the concentration of ammonia, peaking at approximately 60 mol%. However, as the proportion of NH_3 continues to increase above this threshold, the emissions of NO_x subsequently decrease. The oxidation process of CH_4 is highly efficient, irrespective of the equivalency proportion. The process of fuel combustion, when the fuel-to-air ratio is high, has been observed to lead to elevated levels of emission of monoxide. On the contrary, the combustion of a fuel with a fuel-to-air ratio that is lessor stoichiometric is linked to increased emissions of nitrogen oxide [25]. On the contrary, the process of fuel combustion involving a combination that is simultaneously rich and stoichiometric leads to the production of a higher quantity of carbon dioxide.

In experiments conducted under fuel-rich conditions, it has been observed that the presence of CH_4 has a minimal effect. Previous studies have reported a decrease in total nitrogen oxide (NOx) emissions under fuel-rich circumstances. Furthermore, empirical evidence suggests that higher pressure environments have a mitigating effect on the production of carbon monoxide (CO) and nitrogen oxides (NO_x). The observed sensitivity of nitrogen oxide (NO_x) emissions to changes in pressure is higher compared to carbon monoxide (CO). Furthermore, the introduction of a fuel-rich main region has been shown to decrease these emissions. The levels of NO_x as well as CO emissions demonstrate a slight increase in instances of elevated levels of oxygen, while they remain unaltered under pressurized circumstances. Nevertheless, it is crucial to acknowledge that the latter circumstance greatly hampers the release of NO_x and CO, especially within an oxygen-enriched setting. Under conditions of increased pressure, irrespective of the oxygen levels, amounts of both nitrogen oxides (NOx) and carbon monoxide (CO) beneath 10 ppm are attained [26]. The emission pattern of a liquid NH_3

spray co-fired using CH_4 displays a similarity to that of the gaseous form and has an ideal equivalence proportion of 1.1. Previous research [26] has indicated that the release of N_2O can be mitigated by augmenting the flowrate. In comparison to NH_3/H_2 mixtures, the addition of steam increases the formation of NO while reducing the formation of CO in fuel-rich conditions. Tian system exhibits a commendable capability in forecasting NO_x emissions in a wide range of scenarios, while the Okafor system offers an adequate forecast for CO emissions specifically under fuel-less circumstances. The adiabatic temperature of the flame shows an escalation as the concentration of CH_4 is enhanced [27], and also in the presence of higher-pressure conditions. This observed pattern exhibits consistent persistence across a range of equivalence ratios. The observed difference in flame temperature, with respect to CH_4, is most prominent when the conditions are stoichiometric. While the presence of an enhanced flame temperature with respect to pressure is observed, the reduction in NO_x emissions implies that pressure has a greater influence on the generation of fuel NO when compared with heating NO. The empirical findings indicate that an increase in the mole percentage of CH_4 leads to a greater flame temperature alongside heat release rate, implying that CH_4 demonstrates a higher level of reactivity in comparison to NH_3 .

The increase in IDT exhibits a positive correlation with the equivalency ratio, whereas it demonstrates a negative correlation with pressure, temperature, as well as CH_4 concentration. Significantly, the influence of pressure and CH_4 concentration on the ignition delay time (IDT) is more prominent when compared with temperature. The introduction of NH_3 demonstrates a nonlinear impact on IDT, with a more noticeable annual change in IDT observed as the NH_3 concentration surpasses 50 mol%. The incorporation of methane (CH_4) into ammonia/methane (NH_3/CH_4) mixtures results in an expanded operational power spectrum, along with enhanced burning and thermal efficiency when compared to pure ammonia (NH_3). The observed phenomenon can be linked to the burning enhancement effect of methane (CH_4) when it is combined with ammonia (NH_3). The rise in the methane (CH_4) concentration and the higher equivalence ratio (φ) result in an elevated flame speed of ammonia/methane/air flames. However, the velocity of the flame reaches its peak at a condition where the fuel concentration is slightly higher than the stoichiometric ratio. Observations have revealed that an augmentation in an amount of φ and a rise in pressure levels lead to a decrease in the generation of NO_x. Under conditions of excess fuel, the influence of the methane (CH_4) proportion is insignificant. Therefore, it would be beneficial to conduct NH_3/H_2/air combustion under conditions of slight fuel excess and high pressure to maximize specific impulse along with minimize the generation of NO_x.

4. Green ammonia for Hydrogen 2.0

Ammonia, a vital chemical compound, retains a prominent place among the seven basic chemicals [28]. Ammonia is by far the most significant compound in terms of mass production, trailing only sulfuric acid. The ammonia industry is dominated by nitrogen fertilizers, specifically urea along with ammonium nitrate, which are responsible for around eighty percent of the sector collectively. The use of ammonia for pasture application is restricted to just 2%. Ammonia, a compound made up of both nitrogen and hydrogen, serves an essential function in maintaining the supply of food worldwide, supplying an essential commodity for around fifty percent of the world's populace. The remaining twenty percent of the worldwide ammonia market is credited to industrial applications, according to sources. The forecasted growth rate for existing ammonia markets is anticipated to reach 20% by 2030, according to current projections. Under the conditions associated with a temperature increase of 1.5 C, the anticipated demand growth for ammonia is projected to exceed the levels observed in 2020 by a number of 3- 4. The yearly need for ammonia is anticipated to reach between 560 to 665 million tonnes by the year 2050. This market's anticipated development is anticipated to be fuelled by the accessibility of low-carbon ammonia production.

In accordance with the scenario laid out by the International Renewable Energy Agency - IRENA, it is expected that by the year 2050, approximately 83% of the ammonia produced will be derived from renewable hydrogen. In the scenario described previously, it is anticipated that blue ammonia will be responsible for approximately 11% of the total market share. The remaining 6% is anticipated to be derived from fossil fuels in the absence of carbon capture technology. The implementation of a regulated, long-term storage mechanism for carbon dioxide in drained oil and gas fields and deep saline aquifers is a potential strategy for addressing emissions. Certain proponents view the production of blue hydrogen as an interim measure for the production of ammonia, permitting the use of present infrastructure until the widespread use of green ammonia grows commercially viable. A recent announcement disclosed the introduction of 5 million tonnes of new ammonia manufacturing capacity. This capacity will be distributed among ten ammonia facilities that utilize carbon capture and storage technology and are powered by fossil fuels. In accordance with the author [27], an aggregate of 05 operational units are presently available among the choices provided. In September of 2022, Qatar Energy Renewable Solutions as well as Qatar Fertiliser Company entered into a contract to construct a large-scale blue ammonia production complex. It is anticipated that this facility will begin operations in 2026. It is anticipated to have a yearly capacity for production of 1.2 million tons. Although the generation of green ammonia is presently limited, there is a notable upward trend. Using alkaline electrolysers powered by hydroelectricity facilitated the generation of ammonia in the early 1920s. Because of the development of natural gas as an increasingly cost-effective alternative in the 1960s, the market share of these facilities declined. Current early-stage initiatives centred on green ammonia exhibit a prevalent trend of restricted annual capacity for production, typically below 0.1 metric tons. The observed phenomenon can be primarily attributed to unidentified demand determinants. As of May 2022, more than sixty green ammonia plants have been disclosed publicly, based on recent data [28]. In the short term, it is expected that quite a few of these power plants will be constructed in just five years, utilizing both solar and wind power sources. The anticipated result of this combination is the achievement of a combined annual ammonia capacity of between 02 and 03 million metric tonnes. This study's findings will be implemented in a variety of ammonia markets, such as both established and emerging markets. In accordance with current projections, the amount of production of renewable ammonia plants is expected to increase significantly, reaching an estimated 34 million tonnes per year by 2030. The aforementioned projects are predominantly concentrated in regions with abundant and economically viable solar and wind power resources. Green ammonia production could reach 83 Mt by 2030, according to projections based on alternative sources. [28] The mechanism of green ammonia conversion to hydrogen is presented in (Fig. 2).

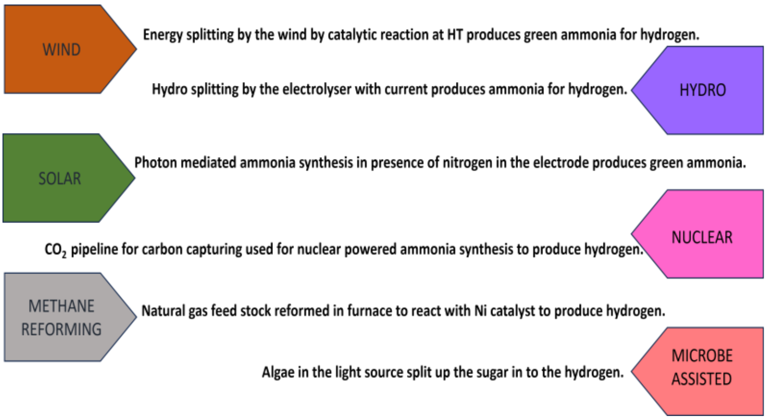

Fig. 2: Mechanism of green ammonia conversion to hydrogen

Numerous individuals and organizations have demonstrated an important interest in acquiring green ammonia facilities operated by publicly traded fertilizer companies in various regions, including Europe, Saudi Arabia, along with Australia, and the United States. In emergent and developing nations, particularly in the Middle East alongside Africa, there are currently a number of ongoing or planned initiatives for the construction of numerous vast ammonia facilities. According to numerous sources [29], these initiatives are anticipated to be completed within the next few years. The effective use of transcontinental hydrogen shipping is regarded as of the uttermost importance for maximizing the energy-carrying potential of hydrogen. Significant likelihood exists that hydrogen will be converted into alternative products to enhance its potential for transportation applications. Hydrogen storage is essential for hydrogen's use as an energy carrier. Understanding its advantages and disadvantages is essential for the successful implementation of hydrogen storage systems using these techniques. The insertion of extra conversion stages into the process of operation induces energy dissipation, leading to an increase in energy unit costs. Notably, however, ammonia has become known as a feasible and economically feasible option for transportation.

5. Future Aspects

Indeed, projections indicate that by 2050, the transportation industry could potentially utilize an astounding 100 million metric tons of NH_3 yearly. This demonstrates the immense potential of ammonia as an energy source in the very near future. The present state of circumstances reveals that a total of 65 ammonia-transporting vessels exist. The aforementioned tally excludes vessels that are designed to transport liquefied petroleum gas -LPG yet can also be converted for ammonia transport. Temperatures of liquefaction under atmospheric pressure distinguish ammonia and hydrogen in a substantial way. Ammonia can be liquefied at approximately -33°C, while hydrogen must be liquefied at substantially lower temperatures, precisely below -253°C [30]. It is well known that transporting ammonia has distinct advantages over transporting hydrogen, resulting in greater convenience and lower costs. The current state of hydrogen liquefaction is characterized by a significant energy demand that exceeds 1/3 of its lower value for heating. Current advancements in the hydrogenation and dehydrogenation of fluid organic hydrogen carriers are widely acknowledged to be in their infancy. A sizeable portion of the NH_3 which is being shipped has a possibility for direct use, particularly in the framework of the production of products that were originally intended for the production of green hydrogen. Notably, a portion of the ammonia will go through a chemical transformation known as "cracking" upon arriving its intended location, resulting in the transformation of ammonia into hydrogen. According to current research, it is anticipated that emerging ammonia marketplaces will become commercialized in 2024. Recent studies [32] demonstrate a growing interest in investigating ammonia as a viable alternative fuel for maritime transportation in recent years. According to the available literature, ships typically have operational lifespans extending from 20 to

25 years or even longer. Numerous studies alongside reports in the real world corroborate this observation. By 2030, ships should be able to utilize ammonia as an alternative fuel source, according to the aforementioned statement. This is essential in order to achieve their ambitious goal of reducing total greenhouse gas emissions through 50 percent by the year 2050, relative to the base year of 2008. Recent reports indicate that the initial quarter of 2022 observed the disclosure of over forty ship technology initiatives, with an emphasis on the use of ammonia as an essential element [33, 34]. The potential of retrofitting LPG containers in ammonia was suggested in a previous study. Ammonia has been recognized as a prospective significant part of the projected fuel mix for the shipping sector by 2050, based on various estimates. The estimates vary between 20% to 99%. In addition, it is important to note that ammonia possesses encouraging properties which render it a potential fuel choice for electricity production in plants. Ammonia has been proposed as an alternative to hydrogen in the Japanese power sector transition roadmap. The objective is to attain a co-firing rate ranging from 50-60% using ammonia as a source of energy by 2050. A 1-gigawatt coal-fired electricity facility is scheduled to host the suggested implementation and demonstration of this methodology by 2024. In this scenario, 20% of the available ammonia will be utilized. This document contains information gathered from an accredited source [35 - 37]. According to the findings of multiple sources [38], it was recently established that Japan's expected ammonia consumption by the year 2050 will be in excess of 30 million metric tons. Notable is the fact that this entire requirement would necessitate ammonia imports from outside sources. Similar to Japan, the Republic of Korea has launched a demonstration program in order to promote widespread adoption of ammonia co-combustion in a substantial portion of the nation's coal-fired power facilities by 2030. [39 – 41]

6. Conclusion

The chapter presents a comprehensive examination of the linked challenges associated with integrated synthesis, techno-economic analysis, the global emission profile of ammonia, and the source of the ammonia emission index in connection to its influence on living organisms. Ammonia-based fuel utilises dual fuel operations since ammonia has low efficiency and stability when used as a single fuel. The production of green ammonia using the Haber-Bosch process has demonstrated exceptional efficiency. Conducting a comprehensive evaluation of the whole cost of ammonia synthesis, which encompasses expenses related to equipment, labour, and other factors, prior to establishing the ammonia synthesis facility, can assist in preventing any additional fees, as recommended by the techno-economic study. European countries have embraced green hydrogen as a sustainable energy carrier for transportation, considering it a potential roadmap towards achieving a zero-carbon environment. This is due to the creation of green hydrogen from ammonia. The steam reforming process is a technique used to produce fuel-grade ethanol specifically for the purpose of generating hydrogen. In order to successfully bring ammonia production into the commercial market, it is essential to carefully analyse the key factors that impact the ratio between production and power charges. These factors include investment cost, operational cost, maintenance cost, and energy consumption.

References

[1] K. Bayramoglu, A. Bahlekeh, K. Masera, Numerical investigation of the hydrogen, ammonia and methane fuel blends on the combustion emissions and performance *Int. J. Hydrogen Energy* **48** (2023) 39586.

[2] M. U. Alzueta, M. Abián, I. Elvira, V.D. Mercader, L. Sieso, Unraveling the NO Reduction Mechanisms Occurring during the Combustion of NH_3/CH_4 Mixtures. Combust. Flame, **257** (2023) 112531.

[3] K. Uddeen, Q. Tang, H. Shi, G. Magnotti, J. Turner, A novel multiple spark ignition strategy to achieve pure ammonia combustion in an optical spark-ignition engine, *Fuel* **349** (2023) 128741.

[4] M. Lu, D. Dong, F. Wei, W. Long, Y. Wang, L. Cong, P. Dong, H. Tian, P. Wang, Chemical mechanism of ammonia-methanol

combustion and chemical reaction kinetics analysis for different methanol blends, *Fuel* **341** (2023) 127697.

[5] G. Thomas, N. Pidgeon, E. Roberts, Ambivalence, naturalness and normality in public perceptions of carbon capture and storage in biomass, fossil energy, and industrial applications in the United Kingdom, Energy *Res. Soc. Sci.* **46** (2018) 1.

[6] A. Dindi, D.V. Quang, L.F. Vega, E. Nashef, M.R. Abu-Zahra, Applications of fly ash for CO_2 capture, utilization, and storage. *J. CO_2 Util.*, 29 (2019), 82.

[7] S. Matkivskyi, O. Kondrat, O. Burachok, Investigation of the influence of the carbon dioxide (CO_2) injection rate on the activity of the water pressure system during gas condensate fields development. In E3S Web of Conferences, EDP *Sciences* 230 (2021) 1011.

[8] Z. Daia, Y. Zhangc, J. Bielickid, M.A. Amooief, M. Zhang C. Yangh, Y. Zoui, W. Ampomahk, T. Xiaob, W. Jial, R. Middleton, W. Zhang, Y. Sun, J. Moortgat, M.R. Soltanian, P. Stauffer, Heterogeneity-assisted carbon dioxide storage in marine sediments, *Appl. Energy* **225** (2018) 876.

[9] M.D. Aminu, S.A. Nabavi, C.A. Rochelle, V. Manovic, A review of developments in carbon dioxide storage, *Appl. Energy* **208** (2017) 1389.

[10] H. Al Baroudi, A. Awoyomi, K. Patchigolla, K. Jonnalagadda, E.J. Anthony, A review of large-scale CO_2 shipping and marine emissions management for carbon capture, utilization and storage, Appl. *Energy* **287** (2021) 116510

[11] E. J. Sala, D. Mayorga, R.B. Bradley, T.B. Cabral, A. Atwood, W. Auber, C. Cheung, F. Costello, A.M. Ferretti, S.D. Friedlander, C. Gaines, W. Garilao, B.S. Goodell, A. Halpern, K. Hinson, K. Kaschner, F. Kesner-Reyes, F. Leprieur, J. McGowan, L.E. Morgan, D. Mouillot, J. Palacios-Abrantes, H.P. Possingham, B. Rechberger, J. Worm, J. Lubchenco,

Protecting the global ocean for biodiversity, food and climate, Nature 592 (2021) 397.

[12] T. Ajayi, J.S. Gomes, A. Bera, A review of CO_2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches, Petrol. *Sci.* **16** (2019) 1028.

[13] C. Smith, A.K. Hill, L. Torrente-Murciano, Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape, *Energy Environ. Sci.* **13** (2020) 331.

[14] M.R. Shaner, H.A. Atwater, N.S. Lewis, E.W. McFarland, A comparative technoeconomic analysis of renewable hydrogen production using solar energy, *Energy Environ. Sci.* **9** (2016) 2354.

[15] R. C. Rocha, M. Costa, X. S. Bai, Chemical kinetic modelling of ammonia/hydrogen/ air ignition, premixed flame propagation and NO emission. *Fuel* **246** (2019) 24.

[16] A. Ichikawa, A. Hayakawa, Y. Kitagawa, K.D. Kunkuma Amila Somarathne, T. Kudo, H. Kobayashi, Laminar burning velocity and Markstein length of ammonia/ hydrogen/air premixed flames at elevated pressures. *Int J Hydrogen Energy* **40** (2015) 9570.

[17] J. H. Lee, S. I. Lee, O. C. Kwon, Effects of ammonia substitution on hydrogen/air flame propagation and emissions. *Int J Hydrogen Energy* **35** (2010) 11332.

[18] Y. Geng, R. Zhu, M. Maimaituerxun, Bibliometric review of carbon neutrality with CiteSpace: evolution, trends, and framework. *Environmental Science and Pollution Research* **29** (2022) 1.

[19] Li J, Huang H, Kobayashi N, He Z, Nagai Y. Study on using hydrogen and ammonia as fuels: combustion characteristics and NOx formation. *Int J Energy Res* **38** (2014) 1214.

[20] H. Xiao, A. Valera-Medina, P.J. Bowen, Modeling combustion of ammonia/ hydrogen fuel blends under gas turbine conditions. *Energy Fuel* **31** (2017) 8631.

[21] H. Nozari, A. Karabeyoglu, Numerical study of combustion characteristics of ammonia as a renewable fuel and establishment of reduced reaction mechanisms. *Fuel* **159** (2015) 223.

[22] L. Han, J. Li, D. Zhao, Y. Xi, X. Gu, N. Wang, Effect analysis on energy conversion enhancement and NOx emission reduction of ammonia/hydrogen fuelled wavy micro-combustor for micro-thermophotovoltaic application. *Fuel* **289 (**2021) 119755.

[23] Z. Li, S. Li, Kinetics modeling of NOx emissions characteristics of a NH_3/H_2 fueled gas turbine combustor. *Int J Hydrogen Energy* **46** (2021) 4526.

[24] A. Valera-Medina, D.G. Pugh, P. Marsh, G. Bulat, P. Bowen, Preliminary study on lean premixed combustion of ammonia-hydrogen for swirling gas turbine combustors. *Int J Hydrogen Energy* **42 (**2017) 24495.

[25] C. Jin, T. Sun, T. Xu, X. Jiang, M. Wang, Z. Zhang, Y. Wu, X. Zhang, H. Liu, Influence of Glycerol on Methanol Fuel Characteristics and Engine Combustion Performance. *Energies **15*** (2022) 6585.

[26] S. Choi, S. Lee, O. C. Kwon, Extinction limits and structure of counterflow non premixed hydrogen-doped ammonia/air flames at elevated temperatures. *Energy* **85** (2015) 503.

[27] H. Xiao, A. Valera-Medina, P.J. Bowen, Study on premixed combustion characteristics of co-firing ammonia/methane fuels. *Energy* **140** (2017) 125.

[28] T. Shu, Y. Xue, Z. Zhou, Z. Ren, An experimental study of laminar ammonia/ methane/air premixed flames using expanding spherical flames. *Fuel* **290** (2021) 120003.

[29] E. C. Okafor, Y. Naito, S. Colson, A. Ichikawa, T. Kudo, A. Hayakawa, Experimental and numerical study of the laminar burning velocity of CH_4–NH_3–air premixed flames. *Combust Flame* **187** (2018) 185.

[30] H. Xiao, S. Lai, A. Valera-MedinaA, J. Li, J. Liu, H. Fu, Study on counterflow premixed flames using high concentration ammonia mixed with methane. *Fuel* **275** (2020) 117902.

[31] C. Filipe Ramos, R.C. Rocha, PMR Oliveira, M. Costa, X. S. Bai, Experimental and kinetic modelling investigation on NO, CO and NH_3 emissions from NH3/CH4/ air premixed flames. *Fuel* **254** (2019) 115693.

[32] E.C. Okafor, H. Yamashita, A. Hayakawa, KDKA Somarathne, T. KUDO, T. Tsujimura, Flame stability and emissions characteristics of liquid ammonia spray co- fired with methane in a single stage swirl combustor. *Fuel* **287** (2021) 119433.

[33] H. Xiao, Z. Wang, A. Valera-Medina, P. J. Bowen, Study on characteristics of co-firing ammonia/methane fuels under oxygen enriched combustion conditions. *J Therm Sci* **27** (2018) 270.

[34] Y. Sun, T. Cai, D. Zhao, Thermal performance and NOx emission characteristics studies on a premixed methane-ammonia-fueled micro-planar combustor. *Fuel* **291** (2021) 120190.

[35] Y. He, C. Zou, Y. Song, W. Chen, H. Jia, C. Zheng, Experimental and numerical study of the effect of high steam concentration on the oxidation of methane and ammonia during oxy-steam combustion. *Energy Fuel* **30** (2016) 6799.

[36] Z. Jhang, M. Wen, Y. Ciu, Z. Ming, T. Wang, C. Jhang, J. D. Ampah, C. Jin, H. Huang, H. Liu, Effects of Methanol Application on Carbon Emissions and Pollutant Emissions Using a Passenger Vehicle. *Processes* **10** (2022) 525.

[37] H. Xiao, A. Medina, R. Marsh, P.J. Bowen, Numerical study assessing various ammonia/methane reaction models for use under gas turbine conditions. *Fuel* **196** (2017) 344.

[38] D. Saygin, D. Gielen, Zero-Emission Pathway for the Global Chemical and Petrochemical Sector. *Energies* 14 (2021) 3772.

[39] K.H. Rouwenhorst, A.S. Travis, L. Lefferts, 1921–2021: A Century of Renewable Ammonia Synthesis. *Sustain. Chem.* **2** (2022) 149.

[40] S. Ghavam, M. Vahdati, I.G. Wilson, P. Styring, Sustainable Ammonia Production Processes. *Front. Energy Res.* **9** (2021) 580808.

[41] G. Mallouppas, C. Ioannou, E.A. Yfantis, A Review of the Latest Trends in the Use of Green Ammonia as an Energy Carrier in Maritime Industry. *Energies* 15 (2022) 1453.

 ISBN: 978-81-975412-4-7

5

Dynamics Determinants of Green Banking Practices in Meeting Sustainable Development Goals: A Sem Analysis

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Contents

Introduction

Concerns about the environment are given a lot of attention in the marketing sector since they are considered crucial [1]. The concept of "green marketing" emerged as a result, which is predicated on the idea of creating marketing methods that cater to consumers' concerns about the environment [2]. Greening, which is related to social marketing but distinct from it, is essentially conventional marketing in that it seeks for environmentally conscious practices and beliefs in order to incorporate them into the creation of environmentally friendly goods and services [3]. Also, while offering values, greening promotes including variables that have social, environmental, and economic advantages [4].

The adoption of a socially responsible strategy is one approach for a company to demonstrate that it is serious about its corporate social responsibility (CSR) commitments and to boost its bottom line [5]. There are many who could claim that adopting a greener lifestyle is the best way to demonstrate social responsibility. A difficulty that is considered as a challenge for the majority of sectors throughout the world is the adoption and implementation of green strategies that are acceptable and successful [6]. These strategies are vital measures for modern-day businesses [7].

Investors are increasingly basing their assessments on a company's environmental commitment, so it's important to keep that in mind [8]. A large number of businesses have put their money into green inventions to increase their return on investment while simultaneously decreasing environmental deterioration [10], as investors judge businesses according to their eco-efficiency requirements [9]. A approach that has been utilized to enhance value creation and reduce risk in the financial industry in particular is investing in green developments [11]. For instance, to promote green finance, almost $30 billion has been invested in renewable energy sources [12].

The introduction of green banking techniques is considered extremely important due to the good impacts they have on the environment, companies, and society at large [13]. Furthermore, green banking may be used to get an edge in the market and keep customers

[14]. The reason for this is because clients are now more interested in the green banking strategy, as opposed to the traditional banking strategy, because the need for an ideal environment has increased [15].

This research looks at how customers feel about environmentally responsible banking practices and how it affects their loyalty to certain institutions. In addition to this, it investigates the extent to which a sustainable image and confidence in financial institutions operate as mediators between environmentally responsible banking operations and customer loyalty.

Through the process of filling in some of the gaps in the existing literature, our research makes a substantial contribution to the existing body of knowledge about green marketing and green banking. For example, a significant portion of the research that has been conducted on green practice has focused on its potential uses in enhancing the market for clean energy [16] or in achieving global sustainability [17,18]. There have been very few research that have investigated the connection between green practices, trust, and loyalty. Many of the studies that have investigated this connection [19] have concentrated on the impacts of green trust and loyalty, as well as how perceived green value may influence these three variables. Despite the growing importance of the green banking strategy, there is a lack of empirical data about how these practices affect customer trust and loyalty to banks. Furthermore, the concept of corporate image has received a great deal of attention from academics [20,21,22]. For instance, Dick and Basu looked at the relationship between customer loyalty and the effect of customers' impressions of a company's image [21]. The link between a bank's green image and customer loyalty has been the subject of a small number of empirical investigations. This is happening even if environmentally conscious policies and procedures greatly boost a company's public perception [22]. Studies have also used the concept of socially responsible investment (SRI) [18] to evaluate the eco-friendliness of the financial industry. Despite the existence of such findings, there is a dearth of research that has applied the SRI theory to the task of increasing bank loyalty via environmentally responsible banking practices.

Literature Review

Chen, J., Siddik, A. B., Zheng, G. W., Masukujjaman, M., & Bekhzod, S. (2022). When it comes to running their day-to-day operations, all parts of the global economy deal with environmental concerns. Recent works on green finance have given the concept of green banking (GB) a great deal of attention. The increasing global threat from climate change is the main reason for this. Finding out how environmental governance policies affect bank environmental performance and where private commercial banks (PCBs) in Bangladesh get their green financing was, thus, the main goal of this study. Primary data were gathered from 322 banking staff working for PCBs in Bangladesh using a survey technique. For the purpose of the analysis, this cross-sectional sample was utilised. A technique known as structural equation modelling (SEM) was utilised in order to determine which correlations between the variables under investigation were the most significant. Empirical study revealed that the staff of banks, their day-to-day operations, and the policies connected to green banking practices all contributed considerably to the improvement of green finance. It was not possible to establish statistical significance through the customer-related GB practice of banks. Additionally, the money that financial institutions received for green projects appeared to have a good impact on the environmental performance of these organisations. Moreover, it was demonstrated that the environmental performances of banks were highly influenced by both the day-to-day operations of banks and legislation relating to GB practices. This was established by the findings of the study. However, this stood in sharp contrast to the steps that banks had taken against their customers and employees in relation to the GB scandal. Because of this, we are going to have a discussion about some significant policy consequences as well as prospective routes for additional study in this category.

Hasan, M. M., Al Amin, M., Moon, Z. K., & Afrin, F. (2022). An ethical banking concept known as "green banking" aims to guarantee that financial services are environmentally sensitive by fostering social and environmental sustainability, perceived cognitive efforts, and subjective standards. This is accomplished through the implementation of green banking. On account of this, despite the fact that Bangladesh has witnessed a number of green banking projects, it is still unknown how usage behaviour is impacted by environmental sustainability, perceived cognitive effort, and subjective criteria. Through the use of an extension of the Theory of Reasoned Action (TRA), this study intends to investigate the factors that influenced bankers' adoption of green banking during COVID-19. The goal of this investigation is to fill up that gap.In the SMART PLS 3 programme, a selective sample strategy was utilised to exclude data from 366 bankers in Bangladesh. This was accomplished through the utilisation of structural equation modelling (SEM). Perceived cognitive exertion ($\beta = 0.401$, t-statistics = 3.549, $p < 0.000$) and management support (0.291, t-statistics = 1.978, $p < 0.000$) were shown to be significantly correlated with one another.

Bukhari, S. A. A., Hashim, F., & Amran, A. (2022). The purpose of this research is to examine the factors that lead to green banking's acceptance, the consequences of this adoption, and how the commitment of upper-level management moderates these impacts within the context of corporate environmental ethics. External stakeholder pressures are taken into account as a potential factor in the adoption of green banking. Results like operational efficiency and brand image are being explored in this company proposal. We recast the adoption of green banking as a second-order construct and add four first-order reflecting structures to it. A complete understanding of the idea is guaranteed by doing this.Researchers are now studying green banking practices in Pakistan, a developing country. This study's data comes from 212 bank branch managers in five big cities in Pakistan who were contacted through hard copy communication. A survey that the participants themselves filled out was used to collect the data. A method of partial least square-structured equation modelling in SMART PLS 3.2.9 was used to analyse the data. The study framework's measurement and structural models were both subjected to the two-stage second-order analysis. The findings indicate that when faced with customer and competitive pressure, Pakistani bank branches are more inclined to adopt environmentally friendly banking practices. Banks' adoption procedures are impacted by several environmental ethical considerations, as this phenomenon shows.

According to the data, green banking adoption at the branch level is unaffected by community pressure. Among the analysed stakeholder demands, the link between green banking adoption and top management commitment was positively impacted. The branch's management claims that the implementation of Green Banking has improved the branch's standing in the community and made operations more efficient. By doing an empirical evaluation of the second-order concept of Green Banking, this study intends to fill a notable void in the literature about the adoption of Green Banking. Despite the several facets of green banking adoption, there is now a dearth of research and no empirical study focusing on branch level implementation. This work has important practical implications for green banking and also makes important theoretical and methodological advances.

Research Methodology

Following the conclusion of exploratory interviews and a pilot survey with a number of banks in Hanoi, which is one of the two major hubs in India, this research makes use of a questionnaire survey. Hanoi is one of the two largest hubs in India. Immediately after the pilot survey was over, we went back and looked at the results of the pilot survey. Based on those findings, we made some modifications to the questionnaire. It is divided into two portions: the first section is devoted to fundamental information, and the second section is devoted to the conditions surrounding green banking at banks. Both sections are included in the questionnaire. Questions that deal to general aspects of the banks are included in the first portion of the survey. These questions include the principal field, the year the bank was founded, the specific information of the respondents, and the number of years of experience working in the banking business. In the second section of the survey, there are questions that pertain to the acknowledgement of green banking by the respondents, the current practices of green banking in the banks, the environmental standard that is applied in the process of credit evaluation, the evaluation of the roles that green banking plays in the banks as well as in the entire Indian economy, and the strategies that will be utilised in the future to develop green banking among banking institutions. All of these questions are included in the survey. A variety of various kinds of questions, such as closed-ended and open-ended questions, as well as a Likert scale with five points, have been used in order to guarantee that the responses are correct. This was done in order to ensure that the responses are accurate.

All of the banks that are located in Hanoi participated in the pilot survey that was conducted throughout the month of May in the year 2016. These financial institutions were selected from the following sources: the Indian General Statistics Office, the Banking Strategy Institute of India, and the India Banks Association (the State Bank of India provides a list of financial institutions in India). The following is a list of the criteria that we had established in order to choose the financial institutions that took part in our survey. The selection method, in the first place, gave the greatest amount of consideration to financial institutions that had considerable revenues. The reason for this was due to the fact that green loans require a substantial amount of initial investment (Singh, 2015). Additionally, the selection of both state-owned and non-state-owned banks was selected owing to the fact that prior research has proven that green banking is becoming increasingly widespread regardless of the ownership forms. This was the reason for the selection of both types of finance institutions. Third, in order to ensure the reliability and applicability of the results, the persons who took part in the survey had to be either the directors or vice directors of bank branches or the heads or vice heads of divisions at the head offices. This was done in order to guarantee that the responses would match the requirements.

until the beginning of June 2016 and continuing until the end of August 2016, we disseminated official questionnaire forms to a total of 32 different banks located in India. Those persons who had not responded to the first letter were approached by phone or emailed with reminders after a month had passed since the mailing was sent out. By the time the month of August 2016 came to a close, three hundred and twenty-nine responses had been received from thirty-two commercial banks in India. Specifically, the SPSS 22.0 was utilised for the aim of doing data analysis. Every single person who responded had a minimum of three years of experience working in the banking business for their responses.

The majority of individuals who have between five and seven years of experience make up 83% of the total. Participating in the poll are persons who are either directors or vice directors of bank branches, or heads or vice heads working at head offices. These individuals are either directors or vice directors. In order to ascertain whether or not the results of the survey can be trusted, it is essential to take into account particular characteristics of the individuals who participated in the survey.

Table 1: Variable Description

Independent Variables	Notation	Interpretation
	DEF 3	By shifting to online banking instead of visiting branches, paying bills electronically rather than by mail, etc., we can lessen our impact on the environment and help promote more sustainable banking practices.
	DEF 4	The provision of financing for initiatives that call for the evaluation of sustainable development and environmental implications
	DEF 5	Withholding funding from initiatives that harm the environment
	DEF 6	Creating environmentally friendly banking goods and services and expanding their offerings
	DEF 7	Putting out plans to encourage sustainable development and restore ecological balance
	DEF 8	Providing green investments and projects with favorable circumstances, such as cheaper financing rates and lighter collateral criteria, among other possible benefits

Current activities in green banking	ACT 1 ACT 2 ACT 3 ACT 4	Online banking services Offering financial assistance to initiatives that are concerned with energy efficiency and/or green or clean technology Offering financial assistance to projects that are interested in renewable energy Taking steps to safeguard the environment inside the banks themselves, such as lowering the carbon footprint caused by banking operations, utilizing online banking, and paying bills online rather than sending them through the mail, among other things.
ACT 5		Ensuring that businesses that submit loan applications are in compliance with environmental regulations
ACT 6		Providing assistance to other companies and sectors in order to foster green growth
ACT 7		Providing green investments and green projects with favorable circumstances, such as reduced financing rates and lighter collateral criteria, among other possible benefits

Independent Notation Variables	**Interpretation**
BAR 3 BAR 4 BAR 5 BAR 6 Current barriers to the adoption of BAR 7 green banking	There have been high expenses, lengthy payback times, and considerable hazards associated with initiatives that are environmentally benign. Complexity and difficulty in evaluating environmentally friendly initiatives a lack of staff members who are competent and well-trained in the evaluation of green credits and loans

		When it comes to the evaluation of green credits and loans, the State Bank of India has not offered any explicit instructions. A limited number of internal regulations for the evaluation and evaluation of green credits and loans
	BAR 8	Failure of the government to provide a legislative framework that would enable environmentally responsible banking
	BAR 9	The obligations that Vietnam has made to various international and regional agreements
	BAR 10	Low levels of interest in green credits and loans
	BAR 11	a lack of knowledge among customers on the significance of environmentally responsible banking services
Advantages green banking	ADV 1 ADV 2 ADV 3 of ADV 4 ADV 5	Over the course of time, enhancing the competitiveness and reputation of banks via Being in agreement with India's plans for environmentally responsible growth and sustainable economic development by India Keeping pledges made during India's membership in international organizations by fulfilling obligations Profits that are higher for banks over the long run In order to satisfy the demand of clients for green credits and loans
	ADV 6	Supportive assistance provided by the State Bank of India to financial institutions that facilitate the provision of green credits and loans
	ADV 7	There are favorable assistance provided by international organizations and international financial institutions to the banks that offer green credits and loans.

Results and Discussions

1.1. Reliability Analysis of the Data

As stated by Anderson et al. (2010), the Cronbach's alpha is a statistical instrument that is used to ascertain the level of dependability that the data possesses. Given this, we will start by doing an examination of the reliability of the data by using Cronbach's alpha test in order to analyse the internal consistency of the five components. This will be done in order to determine whether or not the data are reliable. Cronbach's alpha values that are more than or equal to 0.6 will be considered appropriate for use in our research (Ritter, 2010). In particular, the scales that have these values will be allowed for usage. By utilising the item-total correlation, it is feasible to ascertain the degree of correlation that exists between a single variable and other variables that are measured on the same scale. It is decided that the value that contributes more than 0.3 to the overall correlation of the items will be accepted, while the value that contributes less than 0.3 will be rejected. It is possible that the data may be considered legitimate due to the fact that the findings of the Cronbach's alpha test that was performed using the data from the Indian banks have been officially released. As a result of the fact that every single one of the five components possesses a Cronbach's alpha value that is higher than 0.6, it is possible to draw the conclusion that they possess a high level of dependability and might be utilised for further exploration.

1.2. Exploratory Factor Analysis

Second, exploratory factor analysis (EFA) is performed in order to evaluate the pattern of convergence among variances in order to re-confirm the efficacy of the theoretical framework. This is done in order to ensure that the framework is accurate. The exploratory factor analysis, often known as EFA, is a statistical technique that is employed to reduce the quantity of data to a number of variables that are more manageable and to study the structure of the data that lies under the surface. The KMO measure states that it is also utilised for the goal of determining the structure of the relationships that exist between the variables. This is one of the reasons why it is utilised. In light of this, it may be concluded that the factor analysis is satisfactory (DeCoster, 1998), given that the KMO values are within the range of 0.5 to 1.0 and the significance level is lower than 0.5. Due to the fact that their KMO values are less than 0.5, two variables, namely BAR 1 and CON 5, are ignored after the first essential factor analysis. In the analysis, these factors are not taken into consideration. We will not accept DEF5 for the same reason that we did not accept it at the end of the second EFA contest. There was then the third and final EFA examination. With a significance value of 0.000 correspondingly, the KMO value is used to quantify the adequacy of the sample, which accounts for a total of 91.6% of the sample. Because the factor loadings values for each of these variables are more than 0.5, it can be concluded that all of these variables, which are all displayed in Table 3, are acceptable.

1.3. The future of green banking in Vi- As shown in Figure 1, a high percentage of etnam respondents (75%) agree that green bank.

We have requested that the selected Indian bank, which is considered to be a key component, review the strategy of their individual banks in order to evaluate the future of green banking in the medium- and long-term expansion of the banking sector in India. This is important because we want to take into account the future of green banking. Only eleven percent of these respondents are of the opinion that green banking is considered to be of essential relevance in India's medium- and long-term banking sector in the future. This is in reference to the growth plan of their respective banks. Taking everything into consideration, this result suggests that green banking is something that Furthermore, we enquired of the respondents as to whether there are any specific economic sectors in India that ought to be the major focus of green banking. A representation of the replies to the questions may be found in Figure 2. The waste management industry is the one that receives the highest degree of agreement, as indicated by the mean score of 3.782, which suggests that it is the winner. The second position goes to solar energy, which had a mean score of 3.76. This is followed by biological energy, agriculture, forestry, and fishing, as well as products that are efficient in terms of energy consumption, among other things. When compared to all other industries, the oil refinery and hydroelectricity industries are ranked the lowest. It is possible to draw the conclusion from this that the banking system in India has a comprehensive understanding of the sectors that are harmful to the natural world and the environment. In spite of the fact that hydroelectricity has recently been seen as a source that does not contribute to pollution, it does in reality have important effects for the environment. These implications include contributing to the modification of the environment and having an impact on the land use, housing, and natural ecosystems in the region that is around the area.

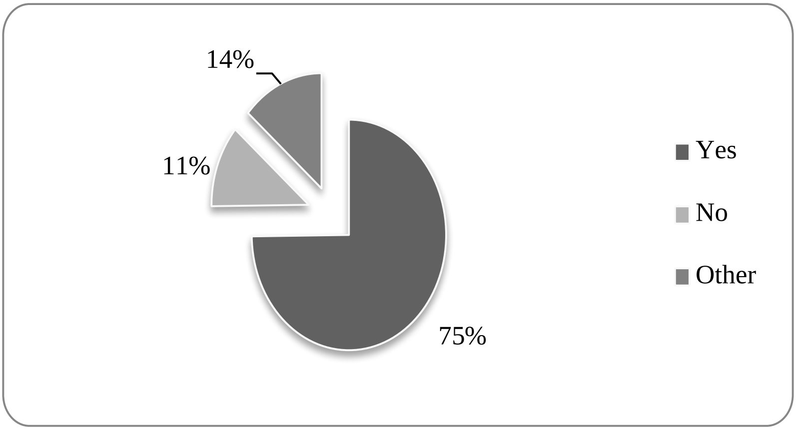

Figure 1: In terms of banks' plans for medium- and long-term growth, green banking includes

Furthermore, we enquired of the respondents as to whether there are any specific economic sectors in India that ought to be the major focus of green banking. A representation of the replies to the questions may be found in Figure 2. The waste management industry is the one that receives the highest degree of agreement, as indicated by the mean score of 3.782, which suggests that it is the winner. The second position goes to solar energy, which had a mean score of 3.76. This is followed by biological energy, agriculture, forestry, and fishing, as well as products that are efficient in terms of energy consumption, among other things. When compared to all other industries, the oil refinery and hydroelectricity industries are ranked the lowest. The conclusion that can be drawn from this is that Indian banks have a general understanding of the businesses that are harmful to the natural world and the environment. In spite of the fact that hydroelectricity has recently been seen as a source that does not contribute to pollution, it does in reality have important effects for the environment. These implications include contributing to the modification of the environment and having an impact on the land use, housing, and natural ecosystems in the region that is around the area.

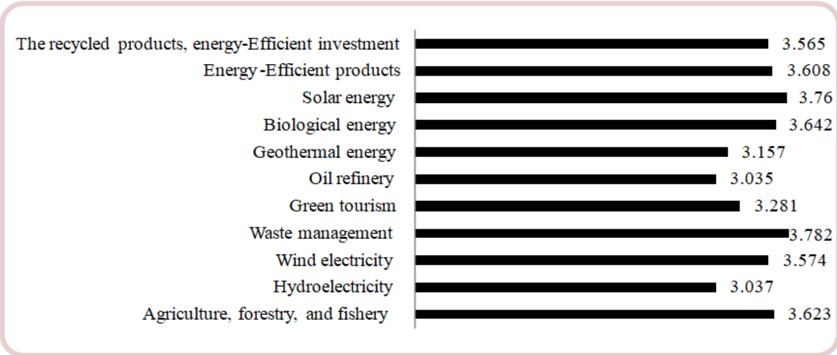

Figure 2: Subsets of environmentally conscious banking

As can be seen in Figure 3, one of the other goals of our research is to identify the different kinds of help that Indian banks will need in order to advance green banking in the years to come. It has been determined by the persons who took part in the survey that the most significant source of communication about credit policies and desired interest rates originates from the Government of India and the State Bank of India. The second and third most significant types of help are, respectively, aid from international organisations on green banking in India and assistance from the Indian government on green growth policies. Both of these types of support are quite important. The significance of both of these forms of assistance is regarded as being greater than that of the first approach.

As a consequence of this, it is reasonable to arrive at the conclusion that in order to encourage ecologically responsible banking in the future, the Indian banks will need assistance on a macro level from the government and the SBV. Furthermore, among these sorts of investments, the pioneer investments made by companies on green projects are considered to be the item that obtained the lowest rating in terms of its capacity to stimulate the expansion of green banking among banks. This is because these investments are considered to be the most environmentally conscious. Another way of putting this is to say that the criteria that companies have for green banking will not have a substantial influence on the green banking activities that Indian banks will engage in in the future.

Conclusion

When it comes to the development plan of India's commercial banks, it is possible to reach the conclusion that the adoption of environmentally friendly banking practices is an inescapable trend that cannot be avoided. The reason for this is that the level of understanding of this model in India's commercial banking system is still quite low, and the actual extent to which it has been applied is also rather low. Not only is it vital for commercial banks to make real efforts in order to successfully handle the situation, but it is also required for the government to give support, and it is especially important for businesses and consumers to make contributions. For the purpose of enhancing the degree of knowledge of the green banking model among the management of commercial banks: Increasing the level of awareness among managers, particularly senior executives, of commercial banks that are now functioning in India, where green banking is being implemented, is the first necessity for the successful implementation of green banking. This is especially important for top executives. The degree of understanding of green banking that is displayed by bank managers and executives is the component that has the strongest relationship with the preparedness of banks to provide green banking services, according to the findings of our employee finance study. This is the component that has the strongest link. Unless the managers of commercial banks in India have a better understanding of the definitions and different levels of the green banking model, they will not be able to provide the necessary assistance for the construction of action plans and acceptable business strategies at each level of specialised green bank development. This lack of understanding will prevent them from being able to provide the necessary assistance. Financial institutions should support green banking as a green development strategy for all of their business strategies and banking services in order to achieve the most advanced level of green banking. This is because green banking is the most advanced level of green banking. In particular, the leadership of financial institutions is a group that ought to realise the relevance of environmentally responsible banking.

References

1. Bukhari, S. A. A., Hashim, F., & Amran, A. (2022). Pathways towards Green Banking adoption: moderating role of top management commitment. International Journal of Ethics and Systems, 38(2), 286-315.
2. Hasan, M. M., Al Amin, M., Moon, Z. K., & Afrin, F. (2022). Role of environmental sustainability, psychological and managerial supports for determining bankers' green banking usage behavior: an integrated framework. Psychology research and behavior management, 3751-3773.
3. Chen, J., Siddik, A. B., Zheng, G. W., Masukujjaman, M., & Bekhzod, S. (2022). The effect of green banking practices on banks' environmental performance and green financing: An empirical study. Energies, 15(4), 1292.
4. Aslam, W., & Jawaid, S. T. (2023). Green banking adoption practices: improving environmental, financial, and operational performance. International Journal of Ethics and Systems, 39(4), 820-840.
5. Shafique, O., & Majeed, A. (2020). Factors influencing bankers' intention to adopt green finance in Pakistan. Review of Economics and Development Studies, 6(4), 773-785.
6. Guang-Wen, Z., &Siddik, A. B. (2022). Do corporate social responsibility practices and green finance dimensions determine environmental performance? An Empirical Study on Bangladeshi Banking Institutions. Frontiers in Environmental Science, 10, 890096.

7. Abbas, J., Hussain, I., Hussain, S., Akram, S., Shaheen, I., & Niu, B. (2019). The impact of knowledge sharing and innovation on sustainable performance in Islamic banks: a mediation analysis through a SEM approach. Sustainability, 11(15), 4049.

8. Abbas, J., Hussain, I., Hussain, S., Akram, S., Shaheen, I., & Niu, B. (2019). The impact of knowledge sharing and innovation on sustainable performance in Islamic banks: a mediation analysis through a SEM approach. Sustainability, 11(15), 4049.

9. Stauropoulou, A., Sardianou, E., Malindretos, G., Evangelinos, K., & Nikolaou, I. (2023). The effects of economic, environmentally and socially related SDGs strategies of banking institutions on their customers' behavior. World Development Sustainability, 2, 100051.

10. Shahzad, M., Qu, Y., Zafar, A. U., &Appolloni, A. (2021). Does the interaction between the knowledge management process and sustainable development practices boost corporate green innovation?. Business Strategy and the Environment, 30(8), 4206-4222.

11. Igbudu, N., Garanti, Z., & Popoola, T. (2018). Enhancing bank loyalty through sustainable banking practices: The mediating effect of corporate image. Sustainability, 10(11), 4050.

12. Zhang, J., Ouyang, Y., Philbin, S. P., Zhao, X., Ballesteros-Pérez, P., & Li, H. (2020). Green dynamic capability of construction enterprises: Role of the business model and green production. Corporate Social Responsibility and Environmental Management, 27(6), 2920-2940.

13. Wang, S., Abbas, J., Sial, M. S., Álvarez-Otero, S., &Cioca, L. I. (2022). Achieving green innovation and sustainable development goals through green knowledge management: Moderating role of organizational green culture. Journal of innovation & knowledge, 7(4), 100272.

14. Ma, L., Ali, A., Shahzad, M., & Khan, A. (2022). Factors of green innovation: the role of dynamic capabilities and knowledge sharing through green creativity. Kybernetes.

15. Sun, H., Rabbani, M. R., Ahmad, N., Sial, M. S., Cheng, G., Zia-Ud-Din, M., & Fu, Q. (2020). CSR, co-creation and green consumer loyalty: Are green banking initiatives important? A moderated mediation approach from an emerging economy. Sustainability, 12(24), 106880.

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ISBN: 978-81-975412-4-7

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Eco-Conscious Commerce: Bridging Green Marketing and Sustainable Development

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Contents

6.1 Introduction

The emergence of green marketing represents a paradigm shift in the way businesses approach marketing, emphasizing environmental sustainability and social responsibility alongside economic objectives. Unlike traditional marketing, which primarily focuses on maximizing profits and market share, green marketing seeks to promote products and services that minimize environmental impact and contribute to sustainable development goals. This research paper aims to explore the distinctive features of green marketing compared to traditional marketing practices, analyzing their respective impacts on sustainable development across environmental, social, and economic dimensions.

6.2 Green Marketing: Shaping Eco-Friendly Consumerism

The motion, an ecological marketing workshop conducted by the American Marketing Association (AMA) was one of the first ones held in 1975. The market of green marketing appeared in 1980. AMA defines green marketing is conveying message of products which are supposed to safe for the environment. Business Dictionary understands green marketing to be the communication and promotion means of companies that follow the interests of the consumer towards their brand. When an American survey run, Gutfield found that 80% of the consumers had responded that they were environmentalists as per the citation of Grove,'et al' (1996). According to Mainieri and Barnett, 1997, as cited in Juwaheer, 2005, the environment has faced massive destructive changes: decrease in natural resource, damage to the ozone layer and loss of ex-sertion-here agriculture land. In recent years, as world companies abuse the environment to the tune of pollution in the too great extent, increasing people have become more clear of the environmental issues. In a result, because of social attention, many companies, following environmental changes, have begun to accept their role in the world (Chen, 2010). A parallel line of thinking is represented by the article of Kangun et al., 1991, in Martin &Simintiras '95. They claim that firms trying to make a positive environmental impact by creating environmentally friendly products to meet consumers' growing concerns about the environment. Thus, the proportional number of firms began to use the image of a green industry in their commercials by manufacturing and selling products and services in a way that harms nature as naked as possible (minimally). Multiple researches show that whereas green marketing implies some differences from the traditional marketing regarding consumer buying behavior and market dynamics, it is however universal that marketing discipline is equally the same. Such as the finding that Menon et al (2017) showed, today, consumers are highly concerned about the environment and they are willing to pay more for brands with sustainability practices at the core of their business. CSR also including green marketing initiatives, is another factor a study of Chabowski et al. (2011) found to increase consumers' positive perceptions and purchase intentions.

Objectives

1. To study the green marketing and know about the how green marketing is different to Traditional Marketing.
2. To know the current status of adapting green marketing in India and Their benefits.

6.3 Methodology

In this research study we are using a comparative analysis method, we are using the existing literature, empirical studies, and market data, to compare green marketing with the conventional methods of marketing. The analysis would involve bringing together and critically discussing pertinent study findings, theoretical models, and case studies as a way to identify the exceptional attributes and consequences that the specific approaches bring forth in the context of sustainable development.

6.4 Meaning of Green Marketing

Green marketing, or short termed ecological marketing and sustainable marketing, is the process of creating and promoting products and services that are ecological or sustainable respectively. The process usually contains three aspects of marketing such as designing, manufacturing, getting the product to the customer and the communication strategy. The main goal of green marketing is the limitation of footprint that businesses create which is comparably preferable for the consumers who are erring on the side of caution

Example:

The use of EVs is a good illustration of the green marketing, which is a case of the auto companies. Electric vehicles are a good pillar to environmental vice that causes low emissions produced similar to petrol-powered vehicles that lead the air quality improvement and reducing carbon footprints in the air production. Compared to the automakers producing traditional vehicles, electric vehicle manufacturers are more likely to use green marketing principles when launching promotional campaigns.

6.5 Evolution of Green Marketing

The discussion about green marketing started at a seminar on Ecological Marketing,‖ held in the American Marketing Association,‖ while ecological marketing was a newly defined term and was a hotted topic then. The green marketing phrase was in its infancy in the 1980s and became prevalent in the 1990s. Green Marketing which emerged in 1980s was the introduction. The manifestation of the first wave of green marketing was found in the book titles Green Marketing, meant as a term for sustainable marketing. His 1992 book was called "The Good and the Green" in the UK and "How to Be a Green Consumer" for the United States. Peattie (2001) sees green marketing development through three stage’s.

First phase was, thusly, called "Ecological" green marketing, and during this period any consideration of environmentally problematic solutions and environmentally helpful help emerged. The second phase was the Environmental or Green Marketing approach, during which the focus was placed on the creation of green technology, which was design oriented and was efficient, clean, safe, and off-waste. In the third branch, the green marketing underlined the sustainable issue. It was the next dominating trend of the late 1990s and early 2000s which was participatory promise and the focus was on quality, timing, price and convenience within the green environment.

6.6 Features of Green Marketing

- **Environmental Focus:** Green marketing that targets green marketing claims about the environmental benefits of products and services is a shrewd move. This may include characteristics as the energy efficiency, use of renew able resources, low waste and low carbon footprint.
- **Transparency:** The campaign that goes green usually incorporates open communication and product or service environmental impacts disclosure. The implementations of activities are rising, which starts with the provision of true and clear details about the eco-friendly characteristics as well as practices.
- **Innovation:** Green marketing helps sustainable product design by reducing unnecessary resources and manufacturing processes, creating green packaging, and minimizing destruction of the environment. Companies might fund research to ensure that they develop items which have less impact on the environment compared to traditional ones.
- **Consumer Education:** The green marketing process essentially comprises of creating an engrossing platform for the consumers to apprise them about the significance of environmental preservation and the benefits of choosing sustainability products. To illustrate this, may include: raising more awareness about environmental problem; giving detailed information about environmentally-friendly products and their features; and providing advisory about ways of minimizing environmental impact.
- **Social Responsibility:** The essence of green marketing is that any company's readiness to carry out the practice of corporate social responsibility considers environmental and social aspects of its operations. Companies advertising conservation efforts in their activities continuously strive at minimizing negative impact on the environment and support local conservation programs, often contributing to global sustainable development goals.

- **Certification and Labeling:** The green marketing process may encompass earning certifications or ecopermits from established organizations, this will ensure that the product manufactures show environmental proof. These standard certifications give a confidence to buyers that the goods adhere to particular environmental criteria.
- **Long-term Perspective:** Eco/green marketing indulges in long sustainable approach in business practices where it is understood that it is critical for the long-term profitability and viability of a business by focusing on environmental sustainability. The organizations realizing the green marketing purpose realize that they have to promote environmental actions as not a fleeting trend only but as a real need of future generations.

Along such lines green marketing aims to remain consistent while cultivating the image of environmental responsibility amongst customers whose ethical perception of the environment is high.India, with the fastest-growing economy and the highest population growth, faces environment challenges extremely high today. Addressing era of impairing environmental consciousness and consumer awareness extraordinary concern, there has been a spike in respect to green marketing across various domains the nation at large. The article deals with the situation of marketing with regard to ecology, current status of adoption of green marketing in India, and the advantages it has, from business and social point of view.

6.7 Why are Firms using Green Marketing

- **Consumer Demand:** Green marketing is picked up by companies on the basis of the increasing fascination of customers towards green products/services. It has been found out that consumers adopt their environmental awareness and willing to spend extra money garneys the products identified as sustainable or eco-friendly by their functionality (Kotler et al., 2017). And to meet the consumer's demand towards green marketing, firms are primarily using this approach as a strategic positioning in the market (Polonsky, 2011).

- **Regulatory Pressures:** Aside form other factors, the role of green marketing in responding to market pressures tied to environmental issues is becoming increasingly prominent. Across nations governments along with others are trying to form stricter regulations and make policies which are designed to reduce the carbon emission as well as the conservation and minimization of pollution (Chabowski et al., 2011). Green marketing practices, which help ensure companies' compliance with this legislation and make them more trustworthy, can help businesses improve their reputation as responsible organizations.
- **Cost Savings:** Besides, green marketing allows saving money for enterprises by means of smart and resource-efficient technology and minimizing waste. To achieve eco-friendly activities such as energy conservation, recycling, and waste minimization during the course of their operations, companies can reduce energy bills and improve the performance of their businesses (Menon et al, 2017). As an illustration, the replacement of fossil fuels with green energy sources or reduction of excess packaging materials can produce even larger savings over time.
- **Competitive Advantage:** Green marketing doesn't only help a company gain a competitive edge in the marketplace, but it also allows the company to stay ahead of the curve and be proactive in their environmental efforts. Clean and green companies that deliver sustainable products or adopt eco-sensitive operational procedures can win the trust and loyalty of environmentally concerned customers (Kotler et al., 2017). Be it more, green marketing can serve firms as a unique tool to make a difference in competitors and stand out as a firm at the top in sustainability (Polonsky, 2011).
- **Reputation Management:** Green marketing can as well contribute to the building of the brand image of firms in which the reputation management often stands at a pinnacle of their success. People are always spend more of their time thinking

about the effects on the environment as a result of company involvement and never forgetting to appreciate the efforts of companies (Chabowski et al., 2011). Through participation in green marketing initiatives and by letting consumers know about firm's environmental awareness, the firms will develop a good reputation, mutually trust with their stakeholders, and reduce the risks to their reputation associated with environmental issues.

With this in mind, firms are using green marketing to satisfy consumer demand, conform to regulatory limitations, and reduce cost centeredness, escape competition and get a good name as Eco friendly organizations.

6.8 Comparison between Green and Traditional Marketing

Aspect	Green Marketing	Traditional Marketing
Focus	Emphasizes environmental sustainability and social responsibility alongside economic goals	Primarily focused on maximizing profits and market share
Objectives	Seeks to promote products and services with environmental benefits, such as energy efficiency, recyclability, and reduced carbon footprint	Focuses on short-term profitability and market dominance
Target Audience	Targets environmentally conscious consumers who are willing to pay a premium for sustainable products	Targets a broad consumer base with varied preferences and priorities
Communication	Emphasizes transparent and honest communication about environmental benefits and sustainable practices	Often relies on traditional advertising techniques and may prioritize persuasion over transparency

Product Development	Integrates environmental considerations into product design and manufacturing processes	May prioritize cost and convenience over environmental concerns in product development
Brand Image	Enhances brand image by positioning the company as environmentally responsible and socially conscious	Brand image may be focused on product features, price, or perceived value
Consumer Behaviour	Influences consumer behaviour by tapping into growing environmental awareness and concerns	May rely on traditional consumer behaviour models and market segmentation
Competitive Advantage	Provides a competitive advantage by meeting consumer demand for sustainable products and fostering brand loyalty	Competitive advantage may be based on factors such as price, quality, or distribution channels
Innovation	Drives innovation in product design, packaging, and business practices to minimize environmental impact	Innovation may be focused on product performance, features, or market positioning
Long-Term Perspective	Takes a long-term perspective on business strategies, aiming to create value for stakeholders and society as a whole	May prioritize short-term gains and market fluctuations over long-term sustainability

This comparison table highlights the fundamental differences between green marketing and traditional marketing in terms of their objectives, target audience, communication strategies, product development approaches, brand image, consumer behaviour influence, competitive advantage, innovation focus, and long-term perspective.

6.9 Current Status of Green Marketing Adoption

Green marketing adoption in India has witnessed significant growth in recent years, driven by several factors:

- **Government Initiatives:** To retain green business practices, the Indian government has rolled out number of policies and initiatives to guarantee the environmental sustainability. For example; the National Action Plan on Climate Change and the Swachh Bharat Abhiyan were the initiatives taken which have raised awareness about environmental issues and have also encouraged the businesses to go for green marketing strategies.
- **Consumer Awareness:** With the growing awareness of the public and sustainability in landscape, one may observe a significant boost. Consumers rather choose manufacturers who produce and/or service eco-friendly goods and do not mind shelling out additional money for this, if the company stands for environmental preservation.
- **Corporate Social Responsibility (CSR):** Many firms that are engaged in green marketing in India do this as part of their corporate social responsibility (CSR) endeavors. Companies can introduce environmental friendly practices, that is coupled with green products promotion, as a public relations medium to grow brand equity, urban green consumers base and to achieve positive social and environmental effects.
- **Competitive Advantage:** Competition is driving companies to shift towards green marketing as they identify the potential to differentiate themselves from the others. Implementation of sustainable strategies could be a crucial additional feature of the companies giving them an edge in the market and creating strong customer loyalty, which in turn would ensure growth and longevity.

6.9.1 Countries Ranked According to their Response Level

Table No. 1 Countries ranked according to their response level on Green Marketing

Rank	Countries
1	India
2	UK
3	US
4	Thailand
5	Australia

Source: International Journal of Management Research

6.10 Benefits of Green Marketing Adoption

The adoption of green marketing in India offers numerous benefits to businesses, consumers, and society as a whole:The adoption of green marketing in India offers numerous benefits to businesses, consumers, and society as a whole:

- **Environmental Conservation:** Green marketing which is also called eco-marketing interpret environmentally-oriented behavior like using renewable sources, reducing waste & conserving energy. They are undertaking the ecological practices and thus saving the natural habitats and other systems like water reservoirs, forest, and farmland.
- **Public Health:** Green marketing can actually change people's behavior by reducing production and consumption of the products which are less heathy to everyone. One of the most apparent demonstrate is the advocacy of organic food products that help reduce the contact with pesticides and chemical elements and thus facilitate better public health qualities.
- **Cost Savings:** A green marketing effort will enable businesses for the cost burden reduction. As example, installing energy efficient equipment helps cut energy consumption and operational cost down in a course of time.
- **Brand Reputation:** Those businesses that have committed to environmental sustainability through eco marketing programs have an advantage over other companies who might believe they are more ethical. Consumers are likely to have social trust and loyalty if a brand emphasizes the environmentally friendly advisable.

- **Competitive Advantage:** Green marketing establishes a competitive advantage by putting forward environmentally concerned users as buyers as well as by distinguishing brands from the market. Companies which demonstrate financial commitment towards green marketing grab the market and retain their loyal customers.
- **Regulatory Compliance:** Green marketing leads businesses to adapt to enviromental regulations and standards. Through adherence to regulatory criteria, businesses are able to lower risk of legal penalties and project a good corporate image.

6.11 Findings of the Study: Green Marketing and Innovation

The study reveals a significant gap between green marketing and traditional marketing, especially when it comes to addressing sustainable development. Green marketing places a strong emphasis on ecological sustainability, social responsibility, and long-term value creation. In contrast, traditional marketing often focuses on short-term profits and market expansion, frequently disregarding the ecological and social consequences of its actions. As businesses and consumers grow increasingly aware of environmental issues, the importance of eco-marketing becomes more pronounced. This shift, driven in part by government initiatives and CSR pledges, reflects a growing recognition of the benefits of green marketing in India. These benefits include ecological preservation, improved public health, cost reduction, enhanced brand reputation, increased competitiveness, and regulatory compliance (Polonsky, 2011).

The transition to green marketing is closely tied to changing consumer behavior. As highlighted by Polonsky (2011), there is a rising number of consumers who prioritize environmentally friendly products and value corporate social responsibility. These consumers are now the driving force behind the demand for sustainable marketing practices. As businesses respond to these changes, green marketing provides them with a competitive edge by meeting the demands of eco-conscious consumers. Enterprises that adopt green marketing strategies not only satisfy customer preferences but also improve brand reputation and foster loyalty, which is crucial for long-term success.

Furthermore, green marketing has the potential to stimulate innovation within companies, pushing them to adopt sustainable practices across their entire value chain—from product design to manufacturing. This is where the role of green marketing in promoting resource-efficient technologies and the circular economy comes into play. As Rakesh et al. (2024) point out, the willingness of consumers to pay more for sustainable brands encourages firms to innovate in ways that align with both environmental and market demands.

In contrast, traditional marketing is largely driven by immediate sales and market coverage, often relying on price, quality, and convenience as the primary factors influencing consumer behavior. However, green marketing introduces a transformative approach by promoting the environmental benefits of products and emphasizing long-term relationships with environmentally responsible consumers. This shift fosters greater brand loyalty, as consumers become more aware of and aligned with companies that prioritize sustainability. Unlike traditional marketing, which tends to focus on heterogeneous preferences and short-term goals, green marketing encourages innovation and positions businesses as leaders in social and environmental responsibility (Chabowski et al., 2011).

Green marketing is thus emerging as a key player in driving the shift towards sustainability, acting as an accelerator for environmental and societal change. By focusing on long-term sustainable value creation, green marketing helps businesses achieve economic goals while simultaneously promoting ecological preservation and social welfare (Chen et al., 2014). As companies increasingly recognize the importance of environmental sustainability, green marketing is expected to continue shaping consumer preferences, driving innovation, and setting the stage for a sustainable future.

6.12 Conclusion

To sum up, green marketing reflects a holistic approach in marketing which aims at delivery of environmental sustainability, social responsibility, and future valuation. Different from traditional marketing techniques, the latter mostly miss the positive aspects of the impact on health and environment in the pursuit of short-term earnings and increasing market share. In the foreseeable future, ad campaigns and consumers' preferences are most likely to become the main tools which would enable businesses to contribute to environmental and societal sustainability. Green marketing in this case will act as an accelerator of such change. An eco-marketing strategy is how environmental consciousness and promoting social values are stressed over just building the economy, while the traditional approach prioritizes profit maximization and market share expansion. this component of the table pinpoints the main discrepancies in green marketing and conventional marketing. Green marketing tends towards the preservation of the environment, along with the social welfare while continuing to seek economic goals that have an individualization of the environmentally conscious consumers in mind, and this is achieved by ensuring that they are well informed about environmental benefits. It results in the incorporation of innovation in the product development and business strategies. These form part of long-term sustainable value creation and competitive advantage to build up the market for green products. While traditional marketing concentrates on single-term sales and market coverage with heterogeneous preference consumers and typical advertising media, referral marketing resembles new marketing strategy in long-term orientation and relationship building tactics. Unlike the classic marketing which is based on the criteria of price, quality or convenience, eco marketing approach is created so that the brand could be outstanding and brings attention to customers among the environmental responsible people by promoting environmental benefits and fostering brand loyalty. Ultimately, green marketing is a transformative paradigm of marketing that reflects the growing awareness and demands about environmental safety which gives companies the benefit of acting in a way that accomplishes economic goals while at the same time promoting social and environmental change. As business become more aware of environmental sustainability green marketing will keep playing the same crucial role in directing consumer purchase choices, creating innovations and the setting up of a sustainable future not only for India

References

1. Chabowski, B. R., Mena, J. A., & Gonzalez-Padron, T. L. (2011). The role of corporate social responsibility in consumer evaluation of firm performance. Journal of Business Ethics, 104(1), 133-148.
2. Polonsky, M. J. & Rosenberger, P. J. (2001). Reevaluating green marketing: a strategic approach. Business Horizons, 44(5), pp 21-30.
3. R. Shrikanth Et al, Contemporary green marketing-brief reference to Indian scenario, International journal of social science and interdisciplinary research, vol. I, Jan.2012.26-38.
4. Dr.Sarawade W.K. Conceptual development of green marketing in India, Excel journal of engineering technology and management science, vol. I, June 2012.1-6.
5. K. Uday Kiran, Opportunity and challenges of green marketing with special reference to Pune, international journal of management and social science research, vol.I, Oct. 2012.18-24.
6. Rahul Singal Et al, Green marketing: challenges and opportunity, International journal of innovation Engineering and technology, vol II, Feb. 2013.470-474.
7. Cherian, J. and Jacob, J (2012) "Green Marketing- Astudy of consumer's attitude towards environment friendly products" "Canadian Center of Science and Education" Vol.8, No. 12, pp-117-126.
8. Mohanasundaram, V (2012) "Green marketing- Challenges and Opportunities" "International Journal of Multidisciplinary Research" Vol-2, Issue 4, pp-66-73.
9. Nagaraju, B and H.D, Thejaswini (2014) "Consumer Perception Analysis- Market Awareness towards eco Friendly FMCG products- A case study of Mysore District" "IOSR Journal of Business and Management" Vol. 16, Issue. 4, pp-64-71.

10. Sachdev.S (2011) "Eco friendly products and consumer perception" "International Journal of Multidisciplinary Research" Vol.1, Issue 5, pp- 279-287.
11. Singh.G (2013) "A study of evolution and practice of Green Marketing By Various Companies in India" "International Journal of Management and Social Sciences Research" Vol. 2, No.7, pp- 49-56. 0
12. Fowler, A. R., Close, A. G. (2012) It aint easy being greed: Macro, Meso, and Micro
13. Green Advertising Agendas. Journal of Advertising, 41(4): 119-132.
14. Garg, A. (2015) Green Marketing for Sustainable Development: an Industry
15. Perspective. Sustainable Development, 301-316.
16. Gheorghiu, A., Vidraşcu, P.A., Niculescu, M.D. (2013) The Deveopment of the Ecomarketing, Green Performance and Corporate Responsibility in a Competetive
17. Economy. Quality - Access to Success, p. 373.
18. Gliedt, T., Parker, P. (2007) Green community entrepreneurship: creative destruction
19. in the social economy. International Journal of Social Economics, 34(8): 538-553.
20. Jotanović, S.R. (2017) Marketing sadruštvenimciljemiekološkiodgovornoponašanje
21. potrošačasaprostorabivšeJugoslavije (doktorskadisertacija). Ekonomskifakultet:
22. Subotica.
23. Li, H., Cai W. (2009) Green Marketing and Sustainable Development of Garment
24. Industry-A Game between Cost and Profit. International Journal of Business and
25. Management, 3(12): 81-85.

26. Mishra, P., Sharma, P. (2014) Green Marketing: Challenges and Opportunities for

27. Business. Management Edge, 7(1): 78-86.

28. Ottman, J. A. (2011) The New Rules of Green Marketing: Strategies, Tools, and

29. Inspiration for Sustainable Branding. Greenleaf Publishing: UK.

30. Padhy, N., Vishnoi, P. (2015) Green Marketing Mix and Sustainable Development.

31. International Journal of Research in Commerce and Management, 6(07): 34-37.

32. Pantić, O., Đuričin, S. (2015) Značajreciklažneindustrijeiupravljanja

33. poljoprivrednimotpadom u ciljuzaštiteživotnesredine. Ecologica, 22(80): 613-616.

34. Sungchul, C., Alex, N. (2011) Environmental and Economic Dimensions ofSustainability and Price Effects on Consumer Responses. Journal of Business Ethics,104(2): 269.

35. Tolušić, Z., Dumančić, E., Bogdan, K., (2014) Društvenoodgovornoposlovanjeizeleni marketing. AgroeconomiaCroatica, 4(1): 25-31.

Zhang, J. (2010) Green Marketing Strategy Analysis of Real Estate Based on Low Carbon Economy. International Journal of Business & Management, 5(12): 177.

 ISBN: 978-81-975412-4-7

7

Photogalvanic Cells for Sustainable Development: A Renewable Energy Perspective

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Contents

7.1 Renewable Energy Generation

Renewable energy generation refers to the process of producing electricity or other forms of energy using naturally replenishing resources such as sunlight, wind, rain, tides, waves, and geothermal heat. Unlike fossil fuels, which are finite and contribute to environmental pollution and climate change, renewable energy sources are sustainable and environmentally friendly.

Some common forms of renewable energy generation include:

i) **Solar Power:** This involves capturing sunlight using photovoltaic cells or solar panels to generate electricity or using solar thermal collectors to heat water or air for residential or commercial use.

ii) **Wind Power:** Wind turbines capture the kinetic energy of the wind and convert it into electricity. Wind farms are often built in areas with consistent wind patterns, such as coastal regions or plains.

iii) **Hydropower:** This involves harnessing the energy of flowing water, typically by building dams or using the kinetic energy of rivers and streams to turn turbines and generate electricity.

iv) **Biomass:** Biomass energy is generated from organic materials such as wood, agricultural residues, and municipal solid waste. These materials are burned or converted into biogas through processes like anaerobic digestion to produce heat or electricity.

v) **Geothermal Energy:** Geothermal power plants utilize heat from the Earth's interior to generate electricity. This heat can be accessed through geothermal reservoirs, hot springs, or by tapping into the Earth's heat through geothermal heat pumps.

vi) **Tidal and Wave Energy:** Tidal energy is generated by capturing the kinetic energy of ocean tides, while wave energy is produced by converting the motion of ocean waves into electricity using specialized devices.

7.2 Types of Solar Technologies

Solar technology encompasses various methods of harnessing solar energy for different purposes. Here are some types of solar technologies:

i) **Photovoltaic (PV) Solar Cells**: PV cells directly convert sunlight into electricity using semiconductor materials like silicon. These cells are commonly seen in solar panels on rooftops, in solar farms, or integrated into building materials like solar shingles.

ii) **Solar Thermal Systems**: Solar thermal technology uses sunlight to generate heat, rather than electricity. There are two main types:

- **Concentrated Solar Power (CSP)**: CSP systems concentrate sunlight using mirrors or lenses onto a small area, heating a fluid to produce steam, which then drives a turbine to generate electricity.
- **Solar Water Heating Systems**: These systems use solar collectors to absorb sunlight and heat water for residential or commercial use, such as heating water for showers or space heating.

iii) **Concentrator Photovoltaics (CPV)**: CPV systems use lenses or mirrors to focus sunlight onto small, highly efficient PV cells, increasing the amount of electricity generated per unit area of solar panels.

iv) **Solar Air Conditioning**: Solar air conditioning systems use solar thermal energy or PV electricity to power air conditioning units, reducing electricity consumption from the grid.

v) **Solar Desalination**: Solar desalination systems use solar energy to desalinate seawater or brackish water, providing a sustainable source of freshwater in regions with water scarcity.

vi) **Solar-Powered Transportation**: Solar-powered vehicles, such as solar cars, boats, and airplanes, use solar panels to generate electricity to power their propulsion systems.

vii) **Solar-Powered Gadgets**: Portable solar chargers and solar-powered lights are examples of small-scale solar technologies designed for personal use, often in outdoor or off-grid settings.

viii) **Building-Integrated Photovoltaics (BIPV)**: BIPV systems integrate solar panels into building materials like windows, facades, or roofing tiles, allowing structures to generate electricity while maintaining aesthetic appeal.

ix) **Floating Solar Farms**: These are solar power plants installed on water bodies like reservoirs, ponds, or lakes, utilizing floating solar panels to generate electricity while conserving land space.

x) **Solar Cooking**: Solar cookers and ovens use sunlight to cook food, offering an environmentally friendly alternative to conventional cooking methods that rely on fossil fuels.

xi) **Photogalvanic cells**: Photogalvanic cells, a unique intersection of photochemical and electrochemical processes, have emerged as promising tools in this endeavor. Harnessing Solar Energy: Photogalvanic cells, leveraging photoelectrochemical processes, efficiently convert solar energy into electrical power**.**

7.3 Introduction to Photogalvanic Cells

In the wake of environmental challenges and the pressing need for sustainable energy solutions, researchers are exploring novel technologies to harness renewable energy sources. Photogalvanic cells, a unique intersection of photochemical and electrochemical processes, have emerged as promising tools in this endeavor. Harnessing Solar Energy: Photogalvanic cells, leveraging photoelectrochemical processes, efficiently convert solar energy into electrical power. This direct conversion mechanism from light to electricity holds immense promise for sustainable energy generation This article delves into the role of photogalvanic cells in sustainable development, highlighting their potential applications and contributions to a greener future **[1].**

Photogalvanic cells, also known as photoelectrochemical cells or light-driven cells, utilize light energy to induce redox reactions at electrode surfaces. These cells typically consist of a semiconductor electrode immersed in an electrolyte solution. When exposed to light, the semiconductor absorbs photons, generating electron-hole pairs. These charge carriers then participate in electrochemical reactions, leading to the generation of electrical energy. The key advantage of photogalvanic cells lies in their ability to directly convert solar energy into electricity, offering a renewable and clean power source **[2-6].**

In a scientific study published in 1839, Becquerel elucidated the "Becquerel effect." Electrode potential arises when light initiates photochemical and photoelectric reactions at the surface layer of an electrode. The "photogalvanic effect" denotes the photochemical process that induces electrode potential in the electrolyte solution upon illumination. The alteration in the equilibrium of redox reactions is likely the primary cause of most photogalvanic effects**[2-6].**

The photogalvanic effect was discovered in 1949 by physicist Rabinowich, a trailblazer in the field of energy. By employing an Fe+2-Thionine solar cell, they effectively harnessed solar energy. Since Rabinowitch's seminal work, photogalvanic cells have been widely employed as converters of solar light into electricity **[2-6].**

The development of solar power transformation and storage has recently been focused on PG cells. These cells use an electrochemical solution that contains photosensitizers like dyes, surfactants, reductants, and alkalis. The solution is filled into a glass beaker and both electrodes (cathode and anode) are dipped in the solution **[2-6].**

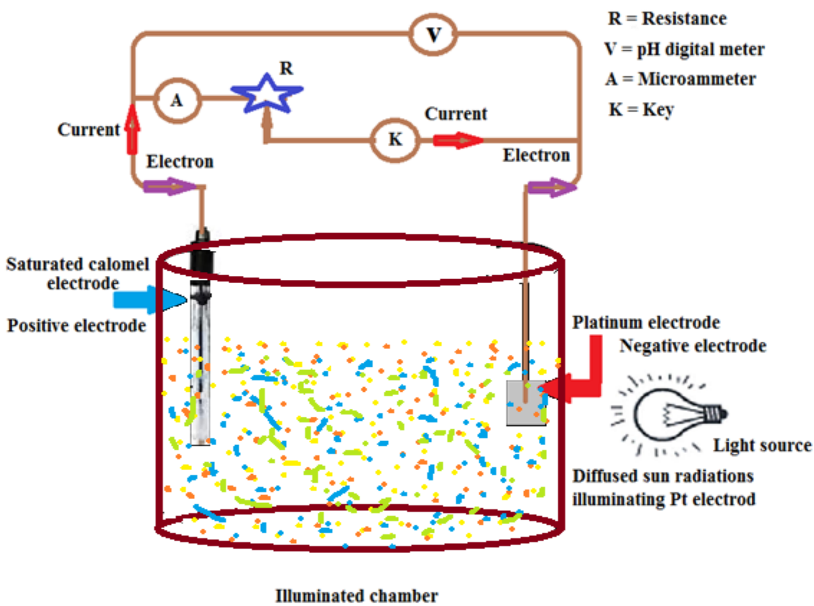

Figure 1: The photogalvanic cell.

First ensure that the device key is not connected. Initially the PG cell setup is kept in dark conditions. When a stable potential is observed, this potential is referred to as the dark potential (Vdark). After some time, the cell is charged with artificial sunlight, and then the potential is identified at different time intervals. Vmax represents the maximum potential, while the open circuit potential (Voc) indicates the stable potential when the cell is fully charged (with the circuit key not connected). Next, the circuit key is connected. The maximum current value is obtained immediately after connecting the circuit, with the highest possible current (imax) being recorded when the circuit resistance value is zero (short circuit condition). Once the current stabilizes, the value is referred to as the short circuit current (isc). Changes are also made in the resistance circuit using a potentiometer to study the cell's i-V property. The maximum power at the power point is determined by the product of the current and accompanying potential (Vpp). The potential at the power point (Vpp) and the current at the power point (ipp) are the respective names given to the potential and current at the power point

- **The charging time** = (time of Voc collection) – (time of illumination initiation).
- **Fill factor of (FF)** = (ipp×Vpp)/(isc×Voc).
- **Conversion efficiency (CE)** = (ipp×Vpp×FF×100%)/(A×P),

Where "A" and "P" represents the area of the Pt electrode in square centimeters and the average artificial intensity of the sun in $mWcm^{-2,}$ respectively.

Photogalvanic cells represent a promising avenue in renewable energy technology, offering a unique approach to harnessing solar energy for electricity generation. Unlike traditional photovoltaic cells, which rely on semiconductor materials to directly convert light into electricity, photogalvanic cells utilize photochemical and electrochemical processes to achieve the same goal. First introduced in the early 20th century, photogalvanic cells have undergone significant advancements, particularly in materials science and engineering, leading to improved efficiency and stability. The basic principle underlying photogalvanic cells involves the generation of electron-hole pairs within a semiconductor electrode upon exposure to light. These charge carriers then participate in electrochemical reactions at the electrode-electrolyte interface, resulting in the production of electrical current. One of the key advantages of photogalvanic cells lies in their versatility and scalability. Unlike conventional photovoltaic technologies, which often rely on complex and costly semiconductor materials, photogalvanic cells can utilize a wide range of materials, including metal oxides, perovskites, and organic compounds. This flexibility enables the development of low-cost and environmentally friendly photogalvanic cell configurations, suitable for diverse applications. Furthermore, photogalvanic cells hold promise for integration into existing infrastructure, such as building-integrated photovoltaics and portable electronic devices, thereby expanding the reach of solar energy utilization. Additionally, ongoing research efforts aim to enhance the performance and durability of photogalvanic cells, paving the way for their widespread adoption in renewable energy systems **[1].**

7.4 Socio-Economic Impact of Photogalvanic Cells

Photogalvanic cells have significant socio-economic implications, particularly in regions where access to reliable and affordable energy is limited. By providing clean and renewable electricity, photogalvanic cells can catalyze socio-economic development, empower communities, and enhance livelihoods.

A study by *Shafiee and Topal* (2009) discusses the potential socio-economic benefits of renewable energy technologies, including photogalvanic cells, in improving energy access and supporting economic growth. The study highlights how off-grid photogalvanic systems can provide electricity to remote or underserved communities, thereby facilitating the development of small-scale industries, improving educational and healthcare services, and enhancing overall quality of life.

Furthermore, the deployment of photogalvanic cells can create employment opportunities and stimulate economic activity. Local manufacturing, installation, and maintenance of photogalvanic systems can generate jobs and promote skills development within communities. Additionally, the use of photogalvanic cells for off-grid power solutions can reduce reliance on costly and polluting energy sources such as diesel generators, thereby freeing up financial resources for other productive investments.

Moreover, photogalvanic cells enable energy independence and resilience, particularly in areas prone to energy shortages or disruptions. By providing decentralized electricity generation, photogalvanic systems can mitigate the impact of power outages and improve community resilience to environmental disasters and socio-economic shocks.

In conclusion, photogalvanic cells have significant socio-economic implications, ranging from improving energy access and livelihoods in underserved communities to fostering economic development and resilience. Continued investment in photogalvanic technology and supportive policies is essential to unlock its full potential in advancing socio-economic progress and achieving sustainable development objectives **[8].**

7.5 Technological Advancements in Photogalvanic Cells

Technological advancements play a crucial role in enhancing the efficiency, stability, and scalability of photogalvanic cells, thereby expanding their applicability and impact in sustainable development. In recent years, significant progress has been made in various aspects of photogalvanic cell technology, driving innovation and paving the way for further advancements.

A review by *G. Wang et al.* (2017) provides insights into recent progress in metal oxide photocathodes for photoelectrochemical water splitting, a field closely related to photogalvanic cell technology. The review discusses novel materials, fabrication techniques, and device architectures aimed at improving the performance and durability of photocathodes, which are key components of photogalvanic cells.

One notable technological advancement in photogalvanic cell technology is the development of advanced semiconductor materials with enhanced light absorption and charge transport properties. Researchers have explored a wide range of materials, including metal oxides, perovskites, and organic compounds, to optimize the efficiency and stability of photogalvanic cells under various operating conditions.

Furthermore, advancements in nanostructuring and surface engineering have enabled the fabrication of high-performance photogalvanic cell architectures. Nanostructured electrodes, such as nanowires, nanotubes, and nanoporous films, provide large surface areas and efficient charge carrier transport pathways, leading to improved light harvesting and conversion efficiency.

In addition to materials and device design, advancements in fabrication and manufacturing processes have contributed to the scalability and cost-effectiveness of photogalvanic cell technology. Techniques such as solution processing, roll-to-roll manufacturing, and additive manufacturing enable the mass production of photogalvanic cells at reduced costs, making them more accessible for widespread deployment.

Moreover, research efforts continue to focus on improving the stability and durability of photogalvanic cells for long-term operation in harsh environmental conditions. Strategies such as surface passivation, protective coatings, and interface engineering aim to mitigate degradation mechanisms and extend the lifespan of photogalvanic cell devices.

Overall, ongoing technological advancements in photogalvanic cell technology hold promise for enhancing their performance, reliability, and cost-effectiveness, thereby accelerating their adoption in renewable energy systems and environmental applications **[9].**

7.6 Applications in Sustainable Development

- **Solar Energy Conversion:** Photogalvanic cells play a crucial role in solar energy conversion systems. By efficiently converting sunlight into electricity, these cells contribute to the proliferation of solar power technologies. Their low-cost fabrication and scalability make them viable candidates for large-scale solar energy deployment, facilitating the transition towards renewable energy-driven economies **[2-6].**
- **Water Splitting for Hydrogen Production:** Another significant application of photogalvanic cells is in photoelectrochemical water splitting for hydrogen generation. By utilizing sunlight to drive the electrolysis of water, these cells offer a sustainable pathway for producing hydrogen, a clean fuel with diverse applications in transportation, industry, and energy storage. Integrating photogalvanic cells into water-splitting devices holds promise for achieving carbon-neutral hydrogen production and mitigating greenhouse gas emissions **[10].**
- **Environmental Remediation:** Beyond energy generation, photogalvanic cells demonstrate potential in environmental remediation applications. Through photocatalytic processes, these cells can facilitate the degradation of organic pollutants and the reduction of toxic metal ions in wastewater. By harnessing solar energy to drive pollutant degradation reactions, photogalvanic cells contribute to mitigating environmental pollution and promoting water sustainability.

- **Off-Grid Power Solutions:** In remote or off-grid areas with limited access to conventional electricity infrastructure, photogalvanic cells offer a decentralized energy solution. These cells can power autonomous devices, such as sensors, communication systems, and remote monitoring equipment, enhancing connectivity and resilience in underserved communities. Additionally, their portability and ease of deployment make them suitable for disaster relief efforts and emergency response scenarios.
- **Environmental Remediation**: Photogalvanic cells play a crucial role in environmental remediation through photocatalytic processes. *Wang et al.* (2019) demonstrated the effectiveness of solar-driven photothermal and photophotocatalytic conversion using plasmonic copper sulfide heterostructure nanoparticles, highlighting the potential of photogalvanic cells in addressing water pollution and promoting sustainable water management practices. By harnessing solar energy, photogalvanic cells facilitate the degradation of pollutants and the detoxification of wastewater, contributing to environmental sustainability **[11].**
- **Socio-Economic Empowerment**: Photogalvanic cells have the potential to empower communities by providing access to clean and affordable energy. Studies have shown that off-grid photogalvanic systems can improve energy access in remote or underserved areas, enhancing livelihoods and stimulating economic development. Moreover, the deployment of photogalvanic technologies creates opportunities for local job creation and skills development, contributing to socio-economic resilience and inclusive growth **[8].**

7.7 Challenges and Future Directions in Photogalvanic Cell Technology

While photogalvanic cells hold great promise for sustainable development, several challenges must be addressed to fully realize their potential. Additionally, future research directions are essential to overcome these challenges and further advance the field. Here, we explore the key challenges and potential future directions in photogalvanic cell technology.

- **Challenges**
  i) **Efficiency and Stability**: Enhancing the efficiency and stability of photogalvanic cells remains a significant challenge. Improvements are needed in materials design, device architectures, and interface engineering to minimize energy losses and prevent degradation over time.
  ii) **Materials Availability and Cost**: Many advanced materials used in photogalvanic cells, such as rare earth elements and noble metals, are costly and may face supply chain constraints. Developing alternative materials with comparable performance and lower cost is crucial for widespread adoption.
  iii) **Scalability and Manufacturing**: Scaling up the production of photogalvanic cells to commercial levels presents technical and economic challenges. Manufacturing processes must be optimized for high throughput and cost-effectiveness while maintaining device performance and reliability.
  iv) **Integration and System Design**: Integrating photogalvanic cells into existing energy systems and infrastructure requires careful consideration of system compatibility, grid integration, and regulatory frameworks. Interdisciplinary collaboration is needed to address technical, economic, and policy challenges.
- **Future Directions**
  i) **Advanced Materials Design**: Continued research into novel materials, including nanomaterials, quantum dots, and perovskites, holds promise for improving the efficiency, stability, and scalability of photogalvanic cells.
  ii) **Multifunctional Devices**: Exploring the integration of additional functionalities, such as energy storage and

catalysis, into photogalvanic cells can enhance their versatility and applicability in integrated energy systems.

iii) **Smart Grid Integration**: Developing smart grid technologies and energy management systems that leverage the intermittent nature of solar energy can enhance the reliability and flexibility of photogalvanic cell-based energy systems.

iv) **Environmental Sustainability**: Emphasizing sustainability in materials selection, manufacturing processes, and end-of-life disposal is essential for minimizing the environmental impact of photogalvanic cell technology and promoting circular economy principles.

v) **Policy and Regulatory Support**: Establishing supportive policies, incentives, and standards for renewable energy technologies, including photogalvanic cells, can accelerate their deployment and market penetration, driving innovation and investment.

By addressing these challenges and pursuing future research directions, photogalvanic cell technology can play a significant role in advancing sustainable development and addressing global energy and environmental challenges **[12].**

7.8 Policy and Regulatory Considerations for Photogalvanic Cells

The successful integration and deployment of photogalvanic cells into the energy landscape require supportive policy frameworks and regulatory measures. Policy and regulatory considerations play a crucial role in shaping market incentives, investment decisions, and technological innovation in the renewable energy sector. Here, we delve into key policy and regulatory aspects relevant to photogalvanic cells.

- **Renewable Energy Targets and Mandates**: Setting ambitious renewable energy targets and mandates at the national, regional, and local levels creates a favorable market environment for photogalvanic cell deployment. Clear policy signals signalize long-term commitment to renewable energy and drive investment in photogalvanic infrastructure.

- **Financial Incentives and Subsidies**: Providing financial incentives, such as tax credits, grants, and low-interest loans, can offset the upfront costs of installing photogalvanic systems and accelerate market adoption. These incentives reduce the financial barrier to entry and encourage investment in renewable energy projects.
- **Grid Integration and Interconnection Standards**: Developing grid integration and interconnection standards ensures seamless integration of photogalvanic systems into the existing electricity grid. Clear technical requirements and streamlined permitting processes facilitate grid interconnection and minimize regulatory hurdles for photogalvanic system owners.
- **Environmental Regulations and Permitting**: Compliance with environmental regulations, such as air quality standards and water discharge limits, is essential for ensuring the environmental sustainability of photogalvanic cell manufacturing and operation. Streamlined permitting processes and environmental impact assessments help mitigate potential environmental risks and ensure compliance with regulatory requirements.
- **Research and Development Funding**: Investing in research and development (R&D) funding for photogalvanic cell technology promotes innovation and technological advancement. Public-private partnerships, research grants, and innovation incentives stimulate R&D activities and drive cost reduction and performance improvement in photogalvanic cell technology.
- **International Cooperation and Collaboration**: International cooperation and collaboration on renewable energy policy frameworks, standards, and best practices facilitate knowledge sharing and technology transfer. Harmonizing regulatory approaches and fostering cross-border cooperation accelerate the

global transition to renewable energy and advance sustainable development goals **[13].**

7.9 Conclusion

photogalvanic cells represent a promising technology with significant potential to drive sustainable development and address pressing energy and environmental challenges. Through their ability to harness solar energy and convert it into electricity, photogalvanic cells offer a clean, renewable, and scalable solution for powering a wide range of applications, from off-grid electricity generation to environmental remediation. Despite facing challenges such as efficiency improvements, materials availability, and policy support, photogalvanic cells continue to show promise as a key enabler of a sustainable energy future. photogalvanic cells hold immense promise as a transformative technology that can help address the dual challenges of climate change and energy access while driving socio-economic progress and environmental sustainability. With concerted efforts from researchers, policymakers, industry stakeholders, and civil society, photogalvanic cells can play a pivotal role in shaping a brighter and more sustainable future for generations to come.

7.10 References

[1]. B. O'Regan, & M. Grätzel. A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films. *Nature*.353(6346), (1991), 737-740.

[2]. E. Rabinowitch. The photogalvanic Effect-I The Photochemical Properties of the Thionine Iron System. *The Journal of Chemical Physics*. 8 (1940) 551-559.

[3]. J. R. Bolton. Photochemical conversion and storage of solar energy. *Annual Review of Energy*. 4 (1979) 353-401.

[4]. P. Koli, Y. Dayma, R. K. Pareek, R. Kumar,&M. Jonwal. Simplified photogalvanic cell design with promise for enhanced solar electricity generation and storage. *Energy Storage*. (2021) e287.

[5]. P. Koli, A. Meena, R. Kumar, A. Chran, J. Saren, Dheerata. Titan Yellow dye sensitized and Ethylenediaminetetraacetate photoreduced photogalvanic system. *Energy Reports*.10(2023)2817–2825

[6]. P. Gangotri, & K. M. Gangotri. Studies of the micellar effect on photogalvanics: solar energy conversion and storage-EDTA-Safranine O-CTAB system. *Arabian Journal for Science & Engineering*. 35(1), (2010) 19-28.

[7]. M. A. Green, K. Emery, Y. Hishikawa, W. Warta, & E. D. Dunlop. Solar cell efficiency tables (version 54). Progress in Photovoltaics: *Research and Applications*, 27(1) (2019) 3-12.

[8]. S. Shafiee, & E. Topal. When will fossil fuel reserves be diminished. *Energy Policy*. 37(1), (2009) 181-189.

[9]. Y. Yang, S. Niu, D. Han, T. Liu, G. Wang, and Y. Li. Progress in Developing Metal Oxide Nanomaterials for Photoelectrochemical Water Splitting. *Advanced Energy Mater*. 1700555 (2017), 1- 26.

[10]. A. Abdurakhmanov, Y. Sabirov, S. Makhmudov, D. Pulatova, T. Jamolov, N. Karshieva and S. Ochilov. Hydrogen production using solar energy. *IOP Conf. Series: Earth and Environmental Science*. 937 (2021) 042042.

[11]. W. N. Wang, Z. Zhang, Sun, L. D., & Yan, C. H. Solar-driven photothermal and photophotocatalytic conversion over plasmonic copper sulfide heterostructure nanoparticles. *ACS Nano*. 13(10), (2019) 11499-11507.

[12]. K. Sivula, & R. V. D. Krol. Semiconducting materials for photoelectrochemical energy conversion. *Nature Reviews Materials*. 1(5), (2016) 15010.

[13]. B. K. Sovacool, & M. H. Dworkin. Energy justice: Conceptual insights and practical applications. *Applied Energy*. 142, (2015) 435-444.