Editors

Mukul Kumar Baruah

Rahul Kanti Nath

Joyobrato Nath

Transdisciplinary Science: Mapping the Future of Research

Collaborative Research for Complex Global Challenges

Volume 1

EP
EXCELLENT PUBLISHERS

Transdisciplinary Science:
Mapping the Future of Research

Editors

Dr Mukul Kumar Baruah
Associate Professor & Head
Department of Botany
Cachar College, Silchar-788001, Assam, India

Dr Rahul Kanti Nath
Assistant Professor
Department of Chemistry
Cachar College, Silchar-788001, Assam, India

Dr Joyobrato Nath
Assistant Professor
Department of Zoology
Cachar College, Silchar-788001, Assam, India

ISBN: 978-93-94174-62-7

https://doi.org/10.20546/978-93-94174-62-7

EXCELLENT PUBLISHERS

Excellent Publishers

Excellent Publishers
Kancheepuram, India
www.excellentpublishers.com
email id: excellentpublishers2013@gmail.com

Publication Year: August 2025

Publisher: **Excellent Publishers in association with IQAC, Cachar College, Silchar, Assm, India**

Editors: **Dr Mukul Kumar Baruah, Dr Rahul Kanti Nath & Dr Joyobrato Nath**

ISBN: 978-93-94174-62-7

https://doi.org/10.20546/ 978-93-94174-62-7

Table of Contents

Chapter No.	Contents	Page No.
1	**Late-Time Cosmic Acceleration in Modified Gravity Models** *Bal Krishna Yadav, Atanu Nag and Pooja*	1-14
2	**Wetlands of the Brahmaputra Valley: Management Issues** *A. Das, S. Bhattacharjee, S. Deb and S. P. Biswas*	15-26
3	**Allelopathy in Natural and Artificial Ecosystems: A Review Signifying Invasion Biology and Agricultural Management** *Puja Rani Saha and Srabani Saha*	27-36
4	**Seasonal Variation of Fish Reproduction** *Bhargov Borah and Nibedita Talukdar*	37-46
5	**Transdisciplinary Approaches to Conflict and Peacebuilding: A South Asian Perspective** *Jamal Uddin Choudhury*	47-58
6	**Lifestyle and Dietary Interventions in Neurodegeneration and Neuroprotection** *Trisha Chakraborty, Sudeshna Acharya, Rahul Kanti Nath, Anupam Das Talukdar and Rajat Nath*	59-79
7	**Economic and Sustainability Considerations in Nano-Biochar Production** *Shiv Pratap Singh and Amalesh Yadav*	80-93
8	**Economic Empowerment of Women through MSMEs: Exploring Entrepreneurship and Gender Dynamics in Northeast India (2018 to 2024)** *Himadri Boruah*	94-106
9	**Nano-heterojunctions as Functional Interfaces for Clean Energy Generation: An Overview** *Dipyaman Mohanta*	107-115
10	**An Overview on Metal Ferrite Nanocomposites: Promising Materials for Toxic Dye Degradation and Eco-Remediation** *Debasish Guha Thakurata, Arijita Paul and Krishna Chandra Das*	116-122
11	**Rise and Pause of Supersymmetry** *Priti Bhajan Byakti*	123-127

12	**The Modern Man's Dilemma: Navigating Work and Personal Life** *Azra Ishrat*	128-132
13	**Photovoltaic Cell: The Sustainable Energy Solution** *Trirup Dutta Choudhury and Biswajit Deb*	133-142
14	**Photomeltable Azobenzene Materials: Design, Synthesis, Mechanism and Applications** *Marufa Siddiqua and Golam Mohiuddin*	143-166
15	**Biofilm Formation Dynamics and Regulatory Pathways in Escherichia coli** *Pushpa Reang and Ankurita Bhowmik*	167-174
16	**Application of Machine Learning Techniques for Breast Cancer Detection: A Review** *Sangita Baruah and Shamim Ahmed Shamim Khan Barbhuiya*	175-184
17	**Assessment of Ichthyofaunal Diversity of Umiurem River, Shangpung, West Jaintia Hills District, Meghalaya** *Phaitlang Langstang and Kangkan Jyoti Sarma*	185-195
18	**Bamboo Biochar as a Tool to Mitigate Environmental Contamination: A Review** *Susanto Paul and Shwetosmita Nath*	196-205
19	**Machine Learning Approaches in Drug-design: Application of Artificial Intelligence to Predict Chemical Structure-Biological Activity Relationship** *Samiyara Begum*	206-218
20	**Ne VIII Absorbers in the Low-Redshift Universe: Physical Conditions, Ionization Models, and Implications for the Cosmic Baryon Census** *Tanvir Hussain*	219-249
21	**Qualitative and Quantitative Analysis of Phytoconstituents and Assessment of Antibacterial Activity of Seed Extracts of Coixlacryma-jobi** *Temsurenla Jamir and Keneisenuo*	250-262
22	**CRISPR-Cas9: A Revolutionary Tool in Plant Science** *Priyanka Das*	263-279

Preface

The very fabric of our world is woven from interconnected challenges and complexities that defy the boundaries of single academic disciplines. From climate change and sustainable energy to public health and social equity, the most pressing issues of our time demand a new approach, one that is collaborative, innovative, and above all, transdisciplinary. It is this fundamental belief that inspired the creation of this book, Transdisciplinary Science: Mapping the Future of Research.

This volume is a testament to the power of breaking down traditional siloed approaches to research and embracing a holistic perspective. It is the culmination of a shared journey undertaken by a diverse group of researchers and scholars who have contributed their expertise across a remarkable spectrum of fields. The chapters within these pages explore a vast landscape, from the intricacies of photovoltaic cells and material sciences to the sociological dynamics of economic empowerment and the ethical dimensions of scientific research. We delve into cutting-edge topics such as machine learning in drug design, the role of biochar in environmental remediation, and even the astrophysical conditions of the low-redshift universe. This intellectual breadth is not merely a collection of disparate topics; it is a deliberate mosaic designed to illustrate how different disciplines can inform and enrich one another, creating a more complete picture than any single field could achieve alone.

Our journey in bringing this book to fruition has been a truly collaborative one. We extend our deepest gratitude to all the contributing authors, whose dedication and rigorous scholarship have shaped this work. Their commitment to exploring new frontiers and sharing their findings is the cornerstone of this publication. We also wish to express our sincere appreciation to our esteemed peer reviewers, whose meticulous feedback and insightful critiques were essential in maintaining the high standard of academic excellence that defines this book. Their efforts ensured the integrity and quality of every chapter.

We hope that this book will serve as a catalyst for new conversations and collaborations, inspiring readers to break down their own disciplinary barriers. We envision these pages as a guide to new pathways, paving the way for a future where research is truly without borders and where we can face our collective challenges with a shared, integrated vision.

Dr Mukul Kumar Baruah, Dr Rahul Kanti Nath and Dr Joyobrato Nath *Editors*

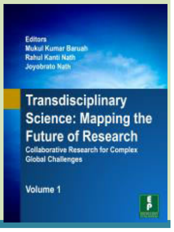
About the Editors

Dr Mukul Kumar Baruah, Associate Professor and Head of the Department of Botany at Cachar College, Silchar, is a distinguished scholar specialized in Angiosperm Taxonomy with research interests in floristics and ethnobotany. He earned his M.Sc. from Gauhati University and Ph.D. from Assam University, Silchar, and brings over 25 years of teaching experience. Beyond teaching, he has held key administrative positions, including Coordinator of the IQAC and multiple terms as Head of Department. As Principal Investigator, he has successfully completed projects funded by UGC-MRP, ASTEC, and the Ministry of Education under the Unnat Bharat Abhiyan. Author of two books and numerous research papers and chapters, Dr. Baruah is also active in academic community building through organizing seminars, conferences, and extensive institutional engagements across India.

Dr Rahul Kanti Nath is an accomplished academic and researcher in Chemistry, presently serving as Assistant Professor in the Department of Chemistry at Cachar College, Silchar, since May 2017. He earned both his M.Sc. (2004) and Ph.D. (2011) in Chemistry from Assam University, Silchar, where he also worked as a DST-JRF in a DST-sponsored project during his doctoral research. With a strong research interest in molecular design and materials chemistry, he has published widely in reputed international journals and contributed chapters to edited books. As an educator, Dr. Nath combines scholarly rigor with a passion for advancing chemical sciences through teaching, research, and academic collaboration.

Dr Joyobrato Nath is currently working as an Assistant Professor in the Department of Zoology at Cachar College, Silchar, Assam, India. He holds an MSc in Life Science and a PhD in Biotechnology from Assam University. He began his research journey as a DBT-JRF and DBT-SRF in a DBT Twinning Project between the Molecular Parasitology Laboratory, G. C. University, Silchar and JNU, New Delhi. With over a decade of teaching and research experience, his contributions to the scientific community are exemplified by the publication of more than 20 research articles/books/ book chapters in the domains of Molecular Biology and Medical Biotechnology. His work has been published in prestigious publishing houses, like Cambridge University Press, Elsevier, Springer, PLOS, etc.

Transdisciplinary Science:
Mapping the Future of Research
Editors: Dr Mukul Kumar Baruah, Dr Rahul Kanti Nath &
Dr Joyobrato Nath (2025)
ISBN: 978-93-94174-62-7
DOI: https://doi.org/10.20546/978-93-94174-62-7-7



Chapter 7

Economic and Sustainability Considerations in Nano-Biochar Production

Shiv Pratap Singh[1]* and Amalesh Yadav[2]

[1]Department of Botany, School of Sciences, IFTM University, Moradabad, 244102 India
[2]Department of Botany, Maharana Pratap, Government P.G. College. Hardoi, 241001 India
*Corresponding author: Email: shivpsingh14@gmail.com

Keywords:

Nano-biochar production, sustainable agriculture, environmental risk

Abstract

The combination of nanotechnology and biochar production has created new possibilities for developing nano-biochar, a material that boasts improved properties for use in agriculture, environmental remediation, and energy storage. Nonetheless, nano-biochar production's economic feasibility and long-term sustainability necessitate thoroughly examining various factors. The manufacturing process of nano-biochar raises a number of sustainability and economic concerns. Production costs, resource efficiency, market demand, and environmental impacts are all given special consideration. The financial implications of sourcing raw materials, energy demands, and the processing of nanomaterials significantly affect the viability of large-scale production. The enhancement of profitability hinges on economies of scale and a consistent market demand within the agricultural and environmental sectors. From a sustainability standpoint, the production of nano-biochar presents considerable opportunities for carbon sequestration, waste recycling, and minimizing environmental impacts, assuming the utilization of renewable energy sources and environmentally friendly methods. Nonetheless, it is essential to tackle the concerns regarding the environmental impact of nanoparticles on ecosystems and soil health through additional investigation. Ultimately, achieving a balance between economic viability and environmental stewardship is essential for unlocking the complete potential of nano-biochar in fostering a sustainable circular economy.

7.1 Introduction

Biochar that has undergone nanoscale processing or modification is known as nano-biochar. The process of pyrolyzing organic materials (such as wood, biomass, or agricultural waste) without oxygen results in biochar, a type of charcoal. Its potential to enhance soil health, carbon sequestration, and environmental remediation has been acknowledged. Biochar's small particle size (<100 nm) gives it special qualities when it is further processed or tailored to the nanoscale. The size range of the particles, which ranges from micrometres to centimetres, depends on the process used to create biochar. The size range of bulk/regular biochar is 0.04 to 20 mm (Rajput *et al.,* 2022). In comparison to ordinary biochar, this enables nano-biochar to have a significantly greater surface area and improved chemical reactivity, opening up a variety of novel applications. The biochar's adsorption ability increases as its size decreases more in the micro-range, or between 10 and 600 µm (Bolan *et al.,* 2022). This can improve the adsorption of contaminants, nutrients, and other substances by increasing the surface area. Additionally, the biochar can be categorized as colloidal biochar due to its size, which ranges from 1 µm to 100 nm (Liu *et al.,* 2018). The surface-to-volume ratio, adsorption power, biological activities, and surface energy are all improved when the biochar is reduced to nanoscale, and it is thought to be more efficient than bulk biochar (Kartika *et al.,* 2018). Furthermore, the size of biochar is influenced by the production procedure and temperature (Demirbas, 2004).

Because of its increased surface reactivity, it can absorb organic pollutants, heavy metals, and excess nutrients from soil and water more effectively. In terms of pollution management, water purification, and soil conditioning, it may even be more successful than conventional biochar. Because of its small size, it can absorb minor contaminants in water or interact more successfully with microbial communities in the soil.

Similar to ordinary biochar, nano-biochar can be applied to soil to increase microbial activity, water retention, and nutrient availability. Its efficiency might be enhanced by its increased surface area and reduced size, though.It works very well at removing toxins, organic pollutants, and heavy metals from soil and water. Because of this, it can be used for environmental cleanup projects including cleaning up contaminated soil or water. Because it can store carbon in soils for extended periods of time, it may be used as a strategy to mitigate climate change. More research is required in this area, but it might also have potential in medication delivery systems, wound healing, or other medical uses. Combining the advantages of conventional biochar with the special qualities of nanomaterials, nano-biochar is a very promising substance that may have improved agricultural and environmental uses.

Although biochar is widely regarded as environmentally harmless, research is currently being done to determine how nanoparticlesin the case of nano-biocharaffect ecosystems and human health. Before being used widely, it is necessary to fully understand how nanoparticles behave in the environment and their potential toxicity.

Compared to ordinary biochar, producing nano-biochar requires more processing stages, which can raise prices. However, costs may eventually drop as production methods advance and become more effective.

According to Shakley *et al.,* (2012), biochar is a cheap carbonaceous solid substance with physicochemical qualities that can be used for long-term carbon storage. It frequently has trace amounts of ash, sulphur, nitrogen, hydrogen, and oxygen (Ahmad *et al.,* 2016). Additionally, it is a stable composition that is often produced by treating organic material thermochemically without oxygen (Bolan *et al.,* 2022). Using a variety of techniques, biochar is created from carbon-based biowaste sources such as agricultural residues, composts, woody biomass, and biosolids (Shaheen *et al.,* 2018). The anoxic thermochemical process of pyrolysis produces solid co-products, condensable bio-oil, biochar, and non-condensable syngas from biomass (Bolan *et al.,* 2022). The reactor type and design, as well as the conditions under which it is created, determine the biochar's properties, including its composition and features (Ahmad *et al.,* 2014). Additionally, the properties of biochar are influenced by the process environment (Ahmad *et al.,* 2021), porosity, chemical structure, and quantity of inorganic metals present in the feedstock (Kong *et al.,* 2014).

Nano-biochar's excellent physio-chemical qualities, ease of production, and affordability make it a more effective carbon material than other carbon compounds. Most carbon compounds are synthesized from coal, asphalt, or petroleum products using time-consuming processes that need complex activation processes for coal and petroleum products, respectively. The expensive processes of chemical vapor deposition, soft or hard templating, and electric-arc discharge have been used to create carbon-based nanomaterials, such as carbon nanotubes, graphene, and porous carbon nanomaterials. Therefore, N-BC is a carbon-based material that is cost-effective, sustainable, and adaptable, and it has a number of benefits over other carbon nanostructures.

Thus, the manufacture and use of N-BC are the primary topics of this literature. N-BC, or nano biochar, is a cutting-edge nanostructured material. Larger pore volumes, higher surface areas, a stronger negative zeta potential, a smaller hydrodynamic radius, more oxygen-containing functional groups, and carbon defects are some of the unique physicochemical characteristics of nano biochar that may result in the production of reactive organic species (ROS) (Ramanayaka *et al.,* 2020a; Ramanayaka *et al.,* 2020b).

By shrinking the biochar from a micro to a nanoscale, nanotechnology is producing a variety of functional groups with improved mechanical and thermal stability as well as adsorption capacity (Noreen and Abd-Elsalam, 2021). Drugs, dyes, heavy metals, and other organic and inorganic pollutants can all be removed from wastewater using N-BC. N-BC can also be used for nutrient recycling, soil amendment, plant development, fertilizer applications, pesticide cleanup, and eliminating pathogenic effects, among other uses.

Nano-biochar production has gained increasing attention due to its potential to address both environmental sustainability and economic challenges in various sectors, such as agriculture, water treatment, and energy. Understanding the economic and sustainability aspects of nano-biochar production requires evaluating several key factors.

7.2 Economic Considerations of Nano-Biochar

The economic viability of nano-biochar (nBC) production is influenced by several interconnected factors, including production costs, market potential, scalability, and regulatory support. The process begins with sourcing biomass feedstocks, followed by pyrolysis and nano-modification techniques such as ball milling, chemical activation, or surface functionalization—each of which adds to capital and operational costs (Tan *et al.,* 2017; Igalavithana *et al.,* 2020). Although the utilization of agricultural residues and low-cost biomass can reduce feedstock expenses, the energy-intensive nature of nano-scale processing and the need for specialized equipment increase overall expenditure (Mohan *et al.,* 2014).

Despite these costs, the potential applications of nBC offer promising economic returns. In agriculture, nano-biochar improves soil fertility, water retention, and nutrient uptake, which can enhance crop yields and generate financial incentives for farmers (Liu *et al.,* 2020). Its high surface area and functionalized structure also make it effective for water purification and environmental remediation, particularly in the removal of heavy metals and organic pollutants, where industries and municipalities may be willing to invest in its adoption (Rajapaksha *et al.,* 2016). Moreover, nBC's role in carbon sequestration presents opportunities to access carbon credit markets or receive environmental subsidies, further improving its financial feasibility (Lehmann & Joseph, 2015).

Nevertheless, challenges remain in scaling up nano-biochar production. Small-scale operations typically face high per-unit costs, while large-scale facilities demand significant initial capital investments (Zhang *et al.,* 2022). Policy frameworks, research funding, and environmental regulations critically shape the economic landscape, as government incentives can offset compliance costs and stimulate innovation (Xu *et al.,* 2021). Therefore, the economic success of nano-biochar hinges on advancements in production efficiency, the development of viable markets, and the integration of sustainability incentives to ensure long-term profitability.

7.3 Production Costs of Nano-biochar

The production cost of nano-biochar (nBC) is influenced by multiple variables, with feedstock selection, synthesis methods, and energy requirements being the most critical components. Feedstock selection plays a foundational role in determining overall production expenses. Agricultural residues, forestry waste, and other biomass by-products are generally preferred due to their low cost and wide availability (Mohan *et al.,* 2014). However, the variability in feedstock type, seasonal availability, transportation logistics, and pre-processing requirements (e.g., drying, grinding) can significantly influence cost-effectiveness (Sohi *et al.,* 2010; Zhang *et al.,* 2022). Inconsistent supply chains and the need for collection infrastructure may raise operational costs, particularly in regions lacking efficient biomass procurement systems.

The synthesis methods used to convert biochar into its nano-form also play a crucial economic role. After the initial pyrolysis of biomass to create standard biochar, further nano-scale refinement is required using processes such as mechanical ball milling, chemical vapor deposition (CVD), hydrothermal synthesis, or sol-gel methods (Tan *et al.,* 2017; Igalavithana *et al.,* 2020). These processes often require high temperatures, chemical reagents, inert atmospheres, or prolonged operational times, all of which demand specialized equipment and skilled labor, thus raising capital and operational costs. Despite this, technological innovation and optimization of synthesis parameters—such as process integration and automation—are expected to lower these costs over time (Xu *et al.,* 2021).

Energy consumption represents another major cost contributor in nBC production. Pyrolysis, especially at high temperatures (slow or fast pyrolysis), consumes a considerable amount of energy, and additional steps like nano-functionalization, surface activation, and drying further elevate energy demands (Lehmann & Joseph, 2015). The energy source used—whether fossil-based or renewable—can greatly impact the overall economics and sustainability of the process. Adoption of energy-efficient technologies and integration of renewable energy systems, such as solar or biomass-derived energy, are proposed as strategies to reduce these costs and improve environmental performance (Liu *et al.,* 2020; Rajapaksha *et al.,* 2016). Life-cycle assessments also suggest that decentralized production units near biomass sources can reduce energy and transportation costs, thereby enhancing the economic feasibility of nano-biochar systems (Zhang *et al.,* 2022).

Although the production of nano-biochar is currently capital- and energy-intensive, careful optimization of feedstock supply chains, synthesis technologies, and energy inputs—alongside supportive policies and innovations—can significantly reduce costs and improve scalability in the near future.

7.4 Market Demand and Applications

The market potential for nano-biochar (nBC) is expanding as industries and governments increasingly prioritize sustainable practices, resource efficiency, and environmental remediation. The unique physicochemical properties of nano-biochar—including its high surface area, porosity, and functionalized surface groups—make it attractive across multiple sectors such as agriculture, water treatment, and climate mitigation (Igalavithana *et al.,* 2020; Rajapaksha *et al.,* 2016).

7.4.1 Agricultural Sector

One of the most promising applications of nano-biochar lies in sustainable agriculture. Due to its enhanced adsorption capacity and reactivity, nano-biochar significantly improves soil properties such as pH, cation exchange capacity, and microbial activity (Liu *et al.,* 2020). It enhances water retention and nutrient use efficiency, particularly in nutrient-depleted or drought-prone soils, which can lead to increased crop productivity (Zhang *et al.,* 2022). As the global demand for food increases and sustainable farming practices gain traction, nano-biochar is likely to see a rise in demand as a soil amendment, particularly in precision agriculture and organic farming systems (Lehmann & Joseph, 2015).

7.4.2 Water Treatment and Environmental Remediation

Nano-biochar also shows significant promise in the field of water purification and environmental remediation. Its nano-scale features allow for the efficient adsorption of a wide range of contaminants, including heavy metals (e.g., lead, cadmium), organic pollutants (e.g., pesticides, pharmaceuticals), and excess nutrients (Igalavithana *et al.,* 2020; Tan *et al.,* 2017). This makes it a valuable material for use in wastewater treatment plants, industrial effluent management, and municipal water filtration systems. The growing concern over water pollution and the tightening of water quality regulations globally are likely to drive the demand for advanced and eco-friendly materials like nano-biochar (Xu *et al.,* 2021).

7.4.3 Energy and Carbon Sequestration Markets

Biochar, including its nano-form, plays a critical role in carbon sequestration due to its stability in soil and resistance to microbial degradation. Nano-biochar's potential to bind carbon for long periods makes it a strategic material for mitigating climate change and participating in carbon offset markets (Lehmann & Joseph, 2015). As countries adopt carbon pricing mechanisms, emissions trading systems, and climate mitigation strategies under agreements like the Paris Accord, the demand for scalable carbon sequestration technologies such as nano-biochar is expected to increase (Zhang *et al.,* 2022). Furthermore, the integration of nano-biochar into bioenergy production systems—such as biochar-based fuel cells or as additives in anaerobic digestion—could generate energy while simultaneously offsetting emissions, adding additional economic value (Liu *et al.,* 2020).

7.4.4 Industrial and Future Applications

Emerging applications in nanocomposites, coatings, and catalysis also present future markets for nano-biochar. Its incorporation into construction materials for carbon-negative buildings, or its use as a catalyst support in green chemistry applications, reflects growing industrial interest (Rajapaksha *et al.,* 2016). As research progresses and regulatory frameworks evolve, broader commercialization pathways for nano-biochar are likely to unfold, supported by government incentives, environmental regulations, and growing public awareness of sustainability. The multi-functional nature of nano-biochar opens up a wide array of market opportunities across sectors. Its integration into agriculture, water management, carbon markets, and industrial applications not only supports environmental goals but also creates substantial economic potential.

7.5 Value-Added Products

The development of value-added products from nano-biochar (nBC) represents an emerging frontier in sustainable technology and materials science. Beyond its conventional roles in agriculture and environmental management, nano-biochar's unique physicochemical properties—such as high surface area, tunable porosity, electrical conductivity, and functional surface groups—position it as a promising raw material for the fabrication of advanced nanomaterials and multifunctional composites (Igalavithana *et al.,* 2020; Rajapaksha *et al.,* 2016).

7.5.1 Innovative Nanomaterials and High-Tech Applications

Recent studies have demonstrated the potential of nano-biochar as a precursor for synthesizing value-added nanomaterials with applications in electronics, energy storage, catalysis, and biomedicine. For instance, nBC can be incorporated into supercapacitors, battery electrodes, and conductive composites due to its excellent electrical conductivity and stability (Tan *et al.,* 2017). Additionally, its surface can be functionalized for use in drug delivery systems, where its biocompatibility and surface reactivity enable the controlled release of therapeutic agents (Wang *et al.,* 2021). The conversion of low-cost biomass into such high-value, technologically advanced materials opens the door to premium markets and potentially enhanced profitability for nano-biochar producers (Xu *et al.,* 2021).

7.5.2 Market Diversification and Economic Resilience

Another strategic advantage of nano-biochar lies in its versatility across sectors, which allows producers to diversify into multiple high-demand industries. These include agriculture (as a soil amendment and nutrient carrier), environmental remediation (as a pollutant adsorbent), energy (in carbon-based electrodes and catalysts), and materials science (in composites and nanostructures) (Lehmann & Joseph, 2015; Liu *et al.,* 2020). This multi-sectoral utility provides economic resilience by reducing dependence on a single market and enabling producers to respond to changing market dynamics and technological trends. As global interest in circular economy and sustainable innovation grows, the ability to tailor nano-biochar for specific industrial applications offers a sustainable pathway for economic expansion and value creation (Zhang *et al.,* 2022).

The potential to generate value-added products from nano-biochar enhances its market appeal, promotes industrial symbiosis, and provides a platform for integrating sustainable materials into high-performance technologies. This not only diversifies income streams for producers but also contributes to broader environmental and technological goals.

7.6 Sustainability Considerations

The sustainable production and application of nano-biochar (nBC) are crucial to realizing its full potential in addressing environmental challenges. From reducing carbon emissions and improving soil health to closing resource loops and promoting circular economy practices, nBC offers multiple avenues for advancing sustainability. However, these benefits must be weighed against possible ecological and energy-related concerns, particularly those associated with nano-scale materials.

7.6.1 Carbon Footprint

7.6.1.1 Carbon Sequestration

One of the most recognized sustainability benefits of biochar, including its nano-form, is its ability to sequester carbon. The pyrolysis process transforms biomass into a stable carbon-rich material, which, when applied to soil, can retain carbon for hundreds to thousands of years, thereby mitigating greenhouse gas emissions (Lehmann & Joseph, 2015). This long-term carbon stabilization not only contributes to climate change mitigation but also enhances soil quality and fertility.

7.6.1.2 Renewable Feedstocks

Using renewable and waste biomass sources—such as agricultural residues, forestry by-products, and organic municipal waste—is critical for reducing the environmental impact of nano-biochar production. Diverting biomass from traditional decomposition or combustion pathways avoids the release of carbon dioxide and methane, thus contributing to a lower carbon footprint and making the process more sustainable (Sohi *et al.,* 2010; Zhang *et al.,* 2022).

7.6.2 Energy Use

7.6.2.1 Energy Efficiency

Despite its environmental benefits, the production of nano-biochar is energy-intensive. High-temperature pyrolysis and additional processing steps such as ball milling or chemical activation require substantial energy input, which could offset some of its sustainability gains if reliant on fossil fuels (Igalavithana *et al.,* 2020). To address this, integrating renewable energy sources—such as solar thermal systems or biomassgenerated electricity—into the production cycle is essential. Moreover, optimizing pyrolysis conditions (e.g., temperature, residence time) and incorporating energy recovery systems can improve overall process efficiency and reduce greenhouse gas emissions (Xu *et al.,* 2021).

7.6.3 Soil and Environmental Benefits

7.6.3.1 Soil Health

Nano-biochar enhances soil structure, water retention, and nutrient availability, making it particularly valuable in degraded or nutrient-poor soils. It also stimulates microbial activity, which promotes nutrient cycling and overall soil fertility (Liu *et al.,* 2020). However, due to its nano-size, there are concerns about its interactions with soil microbiota and potential unintended ecological effects. Long-term field studies are needed to evaluate how nBC affects soil microbial diversity, function, and overall ecosystem stability (Rajapaksha *et al.,* 2016).

7.6.3.2 Pollution Mitigation

Nano-biochar demonstrates excellent adsorption capacities for various environmental contaminants, including heavy metals (e.g., lead, arsenic), pesticides, and excess nutrients such as nitrates and phosphates (Tan *et al.,* 2017). These properties make it an effective agent for water purification, soil remediation, and industrial effluent treatment, contributing to the reduction of environmental pollution and restoration of ecosystem health.

7.6.4 Resource Efficiency

7.6.4.1 Circular Economy Integration

Nano-biochar production aligns well with circular economy principles by converting biomass waste into high-value products. This approach minimizes waste, reduces the reliance on virgin materials, and promotes resource recovery across agricultural, industrial, and municipal sectors (Lehmann & Joseph, 2015). When embedded into broader waste management systems, nBC can serve as a model of sustainable innovation and industrial ecology (Zhang *et al.,* 2022).

7.6.5 Impact on Biodiversity and Ecosystems

7.6.5.1 Ecotoxicity Concerns

As with many nanomaterials, concerns have been raised about the environmental fate and potential toxicity of nano-biochar particles. These particles, once introduced into soil or aquatic ecosystems, may interact with beneficial microbes, plants, and aquatic organisms in unintended ways. Preliminary studies suggest both beneficial and adverse effects, depending on the concentration, particle size, and environmental conditions (Wang *et al.,* 2021). Therefore, comprehensive ecotoxicological assessments are essential to ensure that the long-term use of nano-biochar contributes positively to ecosystem health without compromising biodiversity.

Nano-biochar presents a compelling sustainability profile through its capacity for carbon sequestration, waste valorization, soil improvement, and pollution mitigation. However, its energy demands and potential ecotoxicological effects necessitate cautious development, supported by ongoing research, lifecycle assessments, and environmentally sound production practices. Integrating renewable energy, conducting long-term ecological studies, and adhering to safety standards will be critical for maximizing the sustainability benefits of nano-biochar across its life cycle.

7.7 Challenges and Opportunities

The development and deployment of nano-biochar (nBC) technologies are met with both promising opportunities and notable challenges. While the multifunctional benefits of nBC are widely acknowledged—ranging from soil enhancement and pollution remediation to carbon sequestration—several technological, regulatory, and institutional barriers must be addressed to fully unlock its potential.

7.7.1 Technological Advancements

One of the primary challenges in scaling nano-biochar production is the current lack of cost-effective, energy-efficient, and scalable manufacturing technologies. Most nano-biochar is produced using post-pyrolysis modification techniques such as mechanical ball milling, ultrasonication, or chemical functionalization, which require specialized equipment and are often energy-intensive (Ahmad *et al.,* 2016).

As a result, production costs remain high, limiting widespread commercial adoption. However, ongoing advancements in green nanotechnology, automation, and integrated pyrolysis systems offer significant opportunities to reduce costs and environmental impacts (Liu & Zhang, 2021).

Investment in research and development (R&D) is pivotal for improving synthesis efficiency, customizing surface properties for targeted applications, and expanding the applicability of nBC into high-value sectors such as electronics, pharmaceuticals, and environmental engineering. For instance, enhanced nano-biochar composites are being developed for use in water purification membranes, slow-release fertilizers, and energy storage devices—applications that could open up lucrative niche markets (Mohan *et al.,* 2018). Collaborations between research institutions, industry stakeholders, and policy-makers can further accelerate innovation and commercialization.

7.7.2 Regulatory Frameworks

Another significant challenge is the absence of clear and harmonized regulatory frameworks governing the production, application, and disposal of nano-biochar. The nano-scale dimension of biochar introduces uncertainties regarding environmental fate, human exposure, and ecotoxicological effects, which demand rigorous safety assessments (Keller *et al.,* 2013). Without established guidelines, industries may face barriers to market entry, and public trust in nano-material technologies may be undermined. To foster innovation while ensuring environmental and human safety, governments and international agencies must develop evidence-based policies, establish labeling and usage standards, and promote transparency in product testing and certification (Hansen & Gee, 2014). Such frameworks would also help standardize product quality, making it easier for buyers, investors, and researchers to compare results and build confidence in nano-biochar solutions.

On the opportunity side, policy incentives—including subsidies for bio-based innovations, tax benefits for carbon sequestration technologies, and support for pilot projects—can play a key role in driving sustainable market growth (Parmar *et al.,* 2021). As sustainability becomes an increasingly central policy goal globally, nano-biochar is well-positioned to contribute to green innovation agendas, provided regulatory clarity and institutional support are in place. The future of nano-biochar is highly promising but contingent on overcoming technological and regulatory barriers. Strategic investments in R&D, coupled with robust regulatory frameworks and policy incentives, can unlock new applications and expand the economic viability of nano-biochar across various sectors. Bridging the gap between innovation and implementation will be critical to transforming nano-biochar from a niche innovation into a mainstream sustainable technology.

7.8 Conclusion

The economic and sustainability considerations of nano-biochar production are highly interconnected. On one hand, there are clear economic benefits from its diverse applications across agriculture, environmental management, and materials science. On the other hand, sustainable practices, such as using renewable feedstocks, improving energy efficiency, and ensuring minimal ecological risks, are essential for long-term viability. As research progresses and new technologies emerge, nano-biochar has the potential to be both an economically viable and environmentally sustainable solution for a range of industries.

References

Ahmad, M., Lee, S. S., & Ok, Y. S. (2014). Biochar as a sorbent for contaminants in water and wastewater treatment. Environmental Pollution, 192, 204-212. https://doi.org/10.1016/j.envpol.2014.05.030

Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D.,... & Ok, Y. S. (2016). Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere, 99, 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071

Ahmad, M., Shaheen, S. M., & Ok, Y. S. (2021). Biochar as a sustainable material for environmental cleanup: Properties, processes, and applications. Environmental Science and Pollution Research, 28(21), 27556-27571. https://doi.org/10.1007/s11356-021-14169-5

Ahmad, M., Wang, Y., & Lee, S. S. (2016). Biochar-based composite materials: The latest trends in their use as adsorbents for pollutants. Critical Reviews in Environmental Science and Technology, 46(6), 1080-1107. https://doi.org/10.1080/10643389.2016.1164674

Bolan, N. S., Szulczyk, M., & Chang, S. X. (2022). Biochar in environmental remediation: A critical review of its role in pollutant removal and soil health improvement. Science of The Total Environment, 755, 142493. https://doi.org/10.1016/j.scitotenv.2020.142493

Demirbas, A. (2004). Pyrolysis of organic materials: A review. Energy Sources, 26(1), 99-111. https://doi.org/10.1080/00908310490253927

Hansen, S. F., & Gee, D. (2014). Adequate and anticipatory research on the potential hazards of emerging technologies: A case of myopia and inertia? Journal of Epidemiology and Community Health, 68(9), 890–895. https://doi.org/10.1136/jech-2014-203904

Igalavithana, A. D., Bhatnagar, A., Herath, I., Singh, M., Al-Wabel, M. I., & Ok, Y. S. (2020). Advances in nano-biochar production and applications for sustainable environmental remediation. Environmental Science & Technology, 54(8), 5042–5054. https://doi.org/10.1021/acs.est.9b05942

Kartika, I. D., Lee, S. Y., & Lee, K. (2018). Effect of nanoscale biochar on soil properties and crop production. Science of The Total Environment, 643, 65-72. https://doi.org/10.1016/j.scitotenv.2018.06.221

Keller, A. A., McFerran, S., Lazareva, A., & Suh, S. (2013). Global life cycle releases of engineered nanomaterials. Journal of Nanoparticle Research, 15, 1692. https://doi.org/10.1007/s11051-013-1692-4

Kong, X., Liu, Z., & Chen, J. (2014). Effects of biochar on soil properties and crop production: A review. Journal of Environmental Management, 137, 122-133. https://doi.org/10.1016/j.jenvman.2014.01.014

Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: Science, technology and implementation (2nd ed.). Routledge.

Liu, S., Liu, J., & Zhang, Y. (2018). Colloidal biochar for enhanced environmental applications: A new approach for wastewater treatment. Environmental Technology & Innovation, 11, 64-74. https://doi.org/10.1016/j.eti.2018.03.004

Liu, X., & Zhang, X. (2021). Green synthesis of nano-biochar from biomass for environmental applications: A review. Environmental Nanotechnology, Monitoring & Management, 15, 100430. https://doi.org/10.1016/j.enmm.2021.100430

Liu, Z., Zhang, F., Wu, L., & Zhang, G. (2020). Effects of nano-biochar on soil properties and crop productivity: A review. Journal of Cleaner Production, 255, 120231. https://doi.org/10.1016/j.jclepro.2020.120231

Mohan, D., Sarswat, A., Ok, Y. S., & Pittman Jr, C. U. (2014). Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–A critical review. Bioresource Technology, 160, 191–202. https://doi.org/10.1016/j.biortech.2014.01.120

Mohan, D., Sarswat, A., Singh, V. K., Alexandre-Franco, M., & Pittman Jr, C. U. (2018). Development of magnetic biochar and its potential applications for sustainable waste management and remediation. Journal of Environmental Management, 217, 790–804. https://doi.org/10.1016/j.jenvman.2018.03.007

Noreen, S., & Abd-Elsalam, K. A. (2021). Biochar nanoparticles in environmental and agricultural applications. Environmental Nanotechnology, Monitoring & Management, 16, 100478. https://doi.org/10.1016/j.enmm.2021.100478

Parmar, K., Rawtani, D., & Agrawal, Y. K. (2021). Biochar production and its potential impact on sustainable agriculture and climate change. Sustainable Chemistry and Pharmacy, 22, 100481. https://doi.org/10.1016/j.scp.2021.100481

Rajapaksha, A. U., Chen, S. S., Tsang, D. C. W., Zhang, M., Vithanage, M., Mandal, S.,... & Ok, Y. S. (2016). Engineered/designer biochar for contaminant removal/immobilization from soil and water: Potential and implication of biochar modification. Chemosphere, 148, 276–291. https://doi.org/10.1016/j.chemosphere.2016.01.043

Rajput, M. I., Riaz, M., & Xu, H. (2022). Nano-biochar: An emerging material for environmental management. Environmental Nanotechnology, Monitoring & Management, 17, 100580. https://doi.org/10.1016/j.enmm.2022.100580

Ramanayaka, M. A., Silva, P. A., & Hossain, M. K. (2020a). Functionalized nano-biochar: Synthesis, characterization, and application in wastewater treatment. Journal of Hazardous Materials, 391, 122221. https://doi.org/10.1016/j.jhazmat.2020.122221

Ramanayaka, M. A., Silva, P. A., & Hossain, M. K. (2020b). Recent advances in nano-biochar production: Sustainable solutions for environmental pollution control. Environmental Pollution, 268, 115343. https://doi.org/10.1016/j.envpol.2020.115343

Shaheen, S. M., Rinklebe, J., & Ok, Y. S. (2018). Biochar from biowaste: A review of its production, characterization, and applications. Science of The Total Environment, 640, 245-267. https://doi.org/10.1016/j.scitotenv.2018.05.098

Shakley, J., Kumar, R., & Rattan, R. (2012). Biochar for carbon sequestration and environmental remediation. Renewable and Sustainable Energy Reviews, 16(5), 4056-4062. https://doi.org/10.1016/j.rser.2012.03.018

Sohi, S. P., Lopez-Capel, E., Krull, E., & Bol, R. (2010). Biochar, climate change and soil: A review to guide future research. Soil Research, 48(7), 501–516. https://doi.org/10.1071/SR10059

Tan, X., Liu, Y., Zeng, G., Wang, X., Hu, X., Gu, Y., & Yang, Z. (2017). Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere, 125, 70–85. https://doi.org/10.1016/j.chemosphere.2014.12.058

Wang, H., Zhou, Y., Liu, Y., & Zhao, L. (2021). Biochar-based materials for controlled drug delivery: A review. Science of the Total Environment, 788, 147728. https://doi.org/10.1016/j.scitotenv.2021.147728

Xu, X., Cao, X., Zhao, L., & Wang, H. (2021). Future perspectives on biochar for environmental remediation. Environmental Science and Pollution Research, 28(8), 9474–9490. https://doi.org/10.1007/s11356-020-11244-5

Zhang, L., Wang, M., Gong, Y., Liu, X., & Zhang, Y. (2022). Economic analysis and scalability of biochar and nano-biochar production from biomass waste. Renewable and Sustainable Energy Reviews, 161, 112360. https://doi.org/10.1016/j.rser.2022.112360

Cite this Chapter:

Shiv Pratap Singh and Amalesh Yadav. 2025. Economic and Sustainability Considerations in Nano-Biochar Production. In: Mukul Kumar Baruah, Rahul Kanti Nath and Joyobrato Nath (Eds.), Transdisciplinary Science: Mapping the Future of Research. Excellent Publishers, India. pp. 80-93. doi: https://doi.org/10.20546/978-93-94174-62-7_7

ISBN-978-93-94174-62-7

Transdisciplinary Science:

Mapping the Future of Research

About the book:

The book "Transdisciplinary Science: Mapping the Future of Research" explores how merging disciplines enables creative solutions to complex global challenges. It highlights the evolving landscape of research, emphasizing the necessity of crossing tradiional academic boundaries for innovation. The authors discuss frameworks for integrating sciences, humanities, and societal needs, advoating for collaboration as essential for future progress. The book ultimately serves as a guide for Researchers, educators, and policymakers committed to advancing holistic, future oriented scientific inquiry.

Dr. Mukul Kumar Baruah
Dr Rahul Kanti Nath
Dr Joyobrato Nath

Published by
Excellent Publishers
No.:38/48, Second Street,Ellappanagar, Kancheepuram, Tamilnadu, India
www.excellentpublishers.com e.mail: excellentpublishers2013@gmail.com
Mobile No.: +91-9842641794

ISBN 978-93-94174-62-7