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IEB Bulletin

Issue 2, Vol. 1, 2026

GREEN AND LOW-CARBON ENERGY

SUPPORTING THE UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS





SCIENCE FOR A SUSTAINABLE BORNEO

INFORMING POLICY AND PRACTICE

COLLABORATING FOR A BETTER FUTURE

LOCAL VALUES, GLOBAL IMPACT

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PERPUSTAKAAN NEGARA MALAYSIA



INSTITUTE OF ECOSYSTEM SCIENCE BORNEO (IEB) BULLETIN

INTRO

About The Bulletin

The Institute of Ecosystem Science Borneo (IEB) Bulletin serves as a platform for sharing knowledge, research highlights, innovations, and initiatives related to ecosystem sciences, environmental sustainability, and emerging green technologies. This issue focuses on the theme of Green and Low-Carbon Energy, reflecting the growing global commitment towards sustainable development, climate resilience, and the transition to cleaner energy systems.

As the world faces increasing environmental challenges, the development of low-carbon technologies and renewable energy solutions has become essential in reducing greenhouse gas emissions and supporting a sustainable future. Through this bulletin, IEB aims to promote awareness, scientific understanding, and interdisciplinary collaboration in areas such as renewable energy, carbon management, bioenergy, waste valorisation, green materials, and sustainable environmental practices.

This bulletin also highlights the important role of researchers, industries, policymakers, and communities in advancing innovative solutions that contribute towards environmental protection and the achievement of the Sustainable Development Goals (SDGs). It is hoped that the articles and insights presented in this issue will inspire greater engagement, knowledge exchange, and collective action towards building a greener and more sustainable future for present and future generations.

SUSTAINABLE | INNOVATIVE | COLLABORATIVE | IMPACTFUL



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Foreword By Director



DR. SYEED SAIFUL AZRY OSMAN AL-EDRUS

DIRECTOR
INSTITUTE OF ECOSYSTEM SCIENCE BORNEO (IEB)

It is my pleasure to present Issue 2 of the Institute of Ecosystem Science Borneo (IEB) Bulletin, themed "Green and Low-Carbon Energy." This publication reflects IEB's continued commitment to advancing knowledge, research, and awareness in ecosystem sciences, environmental sustainability, and climate-resilient development.

The theme of this issue is timely and relevant as the world moves towards a more sustainable and low-carbon future. Green energy and low-carbon technologies are essential in addressing climate change, reducing greenhouse gas emissions, and supporting responsible development. For Sarawak, Borneo, and Malaysia, this agenda offers important opportunities to strengthen research, innovation, collaboration, and community engagement.

Through this bulletin, IEB hopes to promote knowledge sharing and encourage greater appreciation of current environmental issues among researchers, academics, students, industries, agencies, and the wider community.

I would like to congratulate the editorial team for their dedication in preparing this issue. My sincere appreciation also goes to all authors, reviewers, contributors, and supporting members who have made this publication possible.

I hope this bulletin will serve as a meaningful reference and inspiration for readers to continue supporting green and low-carbon initiatives towards a more sustainable future.



Foreword By Chief Editor



ENGR. DR. JEFFREY O. OSEH

CHIEF EDITOR, IEB BULLETIN INSTITUTE OF ECOSYSTEM SCIENCE BORNEO (IEB)

The publication of Issue 2 of the IEB Bulletin represents another important effort by the Institute of Ecosystem Science Borneo to promote academic writing, research communication, and knowledge sharing in the field of ecosystem sciences. With the theme "Green and Low-Carbon Energy," this issue brings together contributions that reflect current interests in sustainability, environmental innovation, and low-carbon development.

As Chief Editor, I am pleased to see the continuous support from authors, researchers, academics, students, and collaborators who have contributed their ideas and perspectives to this bulletin. The articles included in this issue cover a range of topics related to sustainable energy, carbon management, environmental technologies, green materials, and ecosystem-based solutions. Each contribution adds value to the broader discussion on how science, innovation, and responsible practices can support a more sustainable future.

The preparation of this bulletin has involved careful coordination, review, editing, and design to ensure that the contents are informative, accessible, and relevant to a wide group of readers. Beyond being a publication platform, this bulletin also serves as a medium to connect research findings with practical awareness and public understanding.

On behalf of the editorial committee, I would like to express my sincere appreciation to all contributors for their valuable submissions. I also extend my gratitude to the reviewers, editors, designers, and technical team for their commitment and cooperation throughout the publication process.

It is our hope that this issue will not only inform readers, but also encourage further discussion, collaboration, and future contributions to the IEB Bulletin.



Editorial Board

MEET THE TEAM BEHIND THIS ISSUE



ChM. Dr. Azrul Nurfaiz Mohd Faizal

His research interests are primarily in chemical and environmental engineering, with a focus on environmental sustainability, wastewater treatment, adsorption technology, biochar and activated carbon materials, biomass valorisation, and low-carbon environmental solutions. His work also explores the development of functional carbon-based materials from waste resources for water purification and sustainable ecosystem applications.



Ts. Dr. Nozieana Khairuddin

Her areas of expertise include bioprocess engineering, food and biomaterial processing, active and smart packaging, food safety, and renewable energy. Her research work also focuses on the development of functional bio-based materials and sustainable technologies for food, agricultural, and environmental applications.



ChM. Dr. Alvin Lim Teik Zheng

His research interests focus on analytical chemistry, material chemistry, catalysis, environmental pollution control technology, and nanotechnology. His current research work also explores the development of carbon-based nanomaterials and functional materials for wastewater treatment, pollutant degradation, electrochemical sensing, and sustainable environmental applications.



Editorial Board

MEET THE TEAM BEHIND THIS ISSUE



ChM. Dr. Sivasangar Seenivasagam

His areas of expertise include renewable energy, catalysis, biomass conversion, and value-added chemical synthesis. His research work focuses on the development of catalytic and sustainable chemical processes for converting biomass and renewable resources into value-added products, supporting cleaner energy and green technology applications.



Dr. Sharon Ong Yong Yee

Her areas of expertise include entrepreneurship, business management, women entrepreneurship, ICT adoption, and business performance. Her research work focuses on entrepreneurial practices, digital technology adoption, and organisational performance, particularly in supporting sustainable business development and innovation among entrepreneurs.



Dr. Ahmad Zaidi Ismail

His areas of expertise include synthesis, catalysis, inorganic chemistry, and material chemistry. His research interests focus on the design, synthesis, and characterisation of functional chemical materials, with emphasis on catalytic systems and inorganic-based materials for chemical and sustainable technology applications.



IEB's University Driven Research Program (UDRP)

The Institute of Ecosystem Science Borneo (IEB) serves as the lead responsibility centre for Universiti Putra Malaysia's University Driven Research Program (UDRP) on Climate Change Mitigation and Adaptation. Positioned under the EcoHealth Framework, the programme contributes to the university's strategic outcome of "Uphold Planetary Health." The programme is led by Dr. Syeed Saifulazry Osman Al-Edrus, Director of IEB.

A Transdisciplinary Platform for Climate Action

The UDRP strengthens UPM's high-impact research ecosystem by bringing together researchers from diverse disciplines to address the complex and interconnected challenges associated with climate change. Its transdisciplinary approach encourages the integration of scientific, technological, environmental, socioeconomic and policy perspectives in developing practical and sustainable solutions.

Through this platform, research findings are expected to extend beyond academic publications and generate meaningful benefits for communities, industries, policymakers and sustainable socioeconomic development. Researchers remain affiliated with their respective faculties or institutes while contributing their expertise to IEB's broader research community.

The programme comprises 15 appointed researchers from IEB and five faculties across Universiti Putra Malaysia and Universiti Putra Malaysia Sarawak. Their combined expertise covers ecosystem science, social and management sciences, agriculture and forestry, chemistry, physics, environmental and occupational health, and engineering.

Strategic Research Priorities

i) High-Impact Publications
Producing quality research outputs, particularly publications in reputable Q1 and Q2 journals.



ii) Competitive Research Funding
Strengthening researchers' roles as principal investigators and securing grants from national, international and industrial sources.

iii) Innovation and Technology Translation
Transforming research findings into intellectual property, innovative products, commercialisation opportunities and technology-transfer outcomes.

iv) Strategic Collaboration
Expanding interdisciplinary partnerships with industries, government agencies, communities and international research institutions.

Programme at a Glance

University Outcome	**Uphold Planetary Health**
Research Framework	**EcoHealth**
Lead PTJ	**Institute of Ecosystem Science Borneo**
Research Programme	**Climate Change Mitigation and Adaptation**
Programme Leader	**Dr. Syeed Saifulazry Osman Al-Edrus**
Research Community	**15 appointed researchers across six research and academic units**

From Research to Impact

Through the UDRP, IEB aims to generate integrated, actionable and scalable climate solutions that strengthen environmental and societal resilience, support sustainable development and reinforce the Institute's role as a catalyst for research excellence in Borneo and beyond. The programme also provides a progressive pathway towards recognition as a Research Centre and, ultimately, a Research Centre of Excellence, subject to demonstrated research performance and impact.



From Napier Grass to Smart Indicator Film for Food Spoilage Monitoring: A Step Towards Climate Change Mitigation

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Introduction

The increased use of food packaging systems has caused severe environmental concerns worldwide. Conventional plastics are highly resistant to degradation and are primarily derived from petroleum-based resources. As a result, they accumulate in landfills and natural ecosystems over time, contributing to long-term environmental damage (Figure 1). Furthermore, substantial greenhouse gas emissions are produced during the production and disposal of plastic materials, increasing the problems associated with global climate change (Verma et al., 2025). Plastic waste degrades over time into microplastics, which can contaminate soil and water and enter the food chain, endangering ecosystems and human health. Thus, the development of sustainable, biodegradable, and functional alternatives for food monitoring systems is important. Materials derived from biomass have drawn interest as eco-friendly and sustainable materials for smart food monitoring applications. Napier Grass has emerged as a useful raw material due to its high cellulose content, rapid development rate, and widespread availability in tropical climates. Its application promotes agricultural waste valorisation while reducing reliance on fossil fuels.

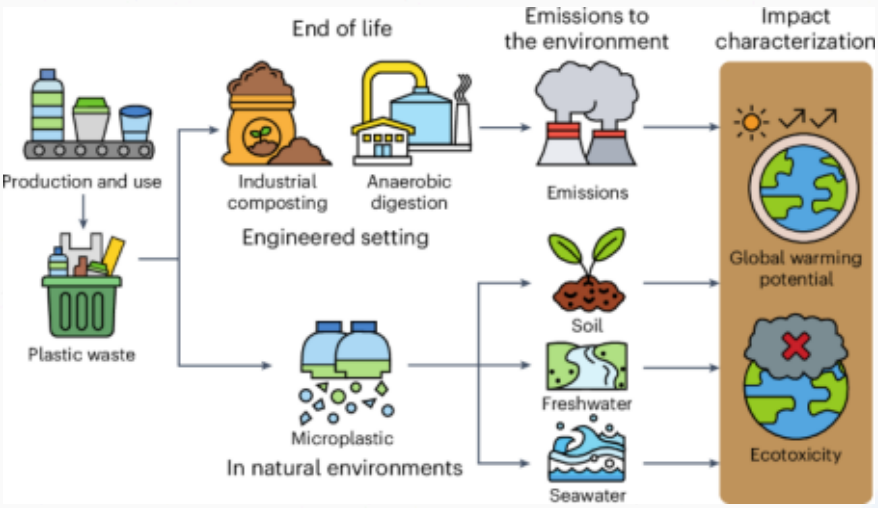

Figure 1. Environmental challenges associated with conventional plastic packaging (Source: Piao et al., 2024)

Napier Grass as a Renewable Biomass Source

Napier Grass is a perennial grass that grows quickly and is commonly grown in tropical and subtropical areas. It is notable for its high biomass output, minimal agricultural input requirements, and quick regrowth immediately after harvesting. These properties make it an environmentally friendly and cost-effective resource for biopolymer synthesis. Napier grass also helps mitigate climate change by absorbing carbon dioxide during photosynthesis. Napier grass's main structural component is cellulose, a natural polymer that is frequently employed in the manufacture of biodegradable materials (Figure 2). The mechanical strength, biodegradability, and renewability of cellulose make it valuable. When extracted and purified, it can be converted into functional materials suitable for biodegradable film and sensing material development. According to recent research, cellulose-based materials outperform traditional plastics in terms of mechanical strength, flexibility, and barrier performance (Liu et al., 2023). Additionally, by turning waste into valuable goods, agricultural biomass valorization aligns with the concepts of the circular economy (Kossalbayev et al., 2025). Drying, grinding, dewaxing, alkaline treatment, and bleaching are common steps in the extraction of cellulose from Napier grass. By removing lignin and hemicellulose, these procedures provide refined cellulose that can be used to make films.



Figure 2. Raw Napier grass biomass was collected for cellulose extraction in biodegradable film development

Development of Biopolymer-Based Films

Napier grass cellulose can be combined with natural polymers like potato starch to create biodegradable films. Glycerol acts as a plasticizer in this system, increasing elasticity and decreasing brittleness, while potato starch acts as a film-forming matrix that enhances structural integrity and flexibility (Figure 3). Cellulose, starch, and glycerol combine to form a flexible biopolymer film that can be used as a biodegradable indicator film attached to packaging lids for food spoilage monitoring. According to Kumar and Yadav (2022), natural polymer-based solutions are becoming more popular due to their biodegradability and sustainability advantages over petroleum-based polymers. Furthermore, it has been demonstrated that nanocellulose reinforcement greatly enhances the mechanical strength and barrier qualities of biocomposites (Ting et al., 2021).



Figure 3. Casting of film-forming solution in a petri dish

pH-Sensitive Indicator Functionality

The primary cause of food spoiling is microbial activity, which generates volatile substances like amines and ammonia. These substances raise the pH of the environment, which makes pH-sensitive indicators helpful for detecting freshness. Methyl Red and Bromothymol Blue are examples of synthetic indicators that are incorporated into the biodegradable indicator film used on packaging lids in this technique. Bromothymol blue turns from yellow to blue as pH rises, whereas methyl red turns from red in acidic conditions to yellow in neutral and basic conditions. According to Păușescu et al. (2022), pH-sensitive indicator films can successfully detect food spoilage when exposed to packaging headspace gases by observing color changes, offering a simple and cost-effective monitoring technique without the need for electronic sensors.

Biodegradable and Intelligent Film Concept

Biodegradable film is made of materials that can spontaneously degrade into harmless components when exposed to the environment. When paired with functional additives such as pH indicators, these materials can function as intelligent indicator systems when integrated with packaging, providing information regarding food quality. The biodegradability, renewability, and compatibility of cellulose-based films with natural polymers make them potential materials for environmentally friendly packaging. According to Liu et al. (2023), cellulose-based films have a great potential to function as indicator layers in smart packaging applications. The incorporation of functional indicators into biodegradable films is a significant step toward intelligent packaging systems that not only preserve food but also track its freshness in real time.

Environmental and Climate Change Impact

The development of Napier grass-based indicator films helps to mitigate climate change in several ways (Figure 4). First, it reduces the need for plastics derived from fossil fuels, which lowers greenhouse gas emissions from their manufacturing and disposal. Second, biodegradable materials prevent long-term environmental damage since they degrade naturally. Additionally, Napier Grass promotes the circular economy and the benefits of agricultural waste (Kossalbayev et al., 2025). Furthermore, better food freshness monitoring helps reduce food waste, which is a major source of methane emissions in landfills. As a result, this strategy indirectly lowers greenhouse gas emissions from food waste and plastic waste systems.



Figure 4. Circular economy concept for sustainable food packaging (Source: Bharat & Datta, 2024)

Challenges and Future Outlook

Despite its potential, creating biodegradable films based on Napier grass still faces several obstacles. Moisture sensitivity, which impacts mechanical strength and stability, is one significant drawback. Therefore, increasing water resistance is crucial for real-world applications. Another problem is maintaining the stability and safety of synthetic pH indicators within biodegradable matrices. Further research is required to address issues like migration, deterioration, and long-term performance. It is anticipated that future studies will concentrate on enhanced crosslinking methods, polymer blending optimization, and nanocellulose reinforcement. These developments could improve the materials' mechanical, thermal, and functional qualities, increasing their suitability for large-scale industrial uses.

Conclusion

Biodegradable films made from Napier grass offer a sustainable substitute for conventional plastic-based indicators and enhance smart packaging systems. Environmentally friendly materials can be produced through combining natural polymers like potato starch with renewable biomass like Napier grass. The addition of pH-sensitive indicators such as Methyl Red and Bromothymol Blue improves functionality by allowing for visual monitoring of food freshness. Overall, this technique promotes sustainability by reducing plastic pollution, greenhouse gas emissions, and improving food waste management, all of which help to mitigate climate change.

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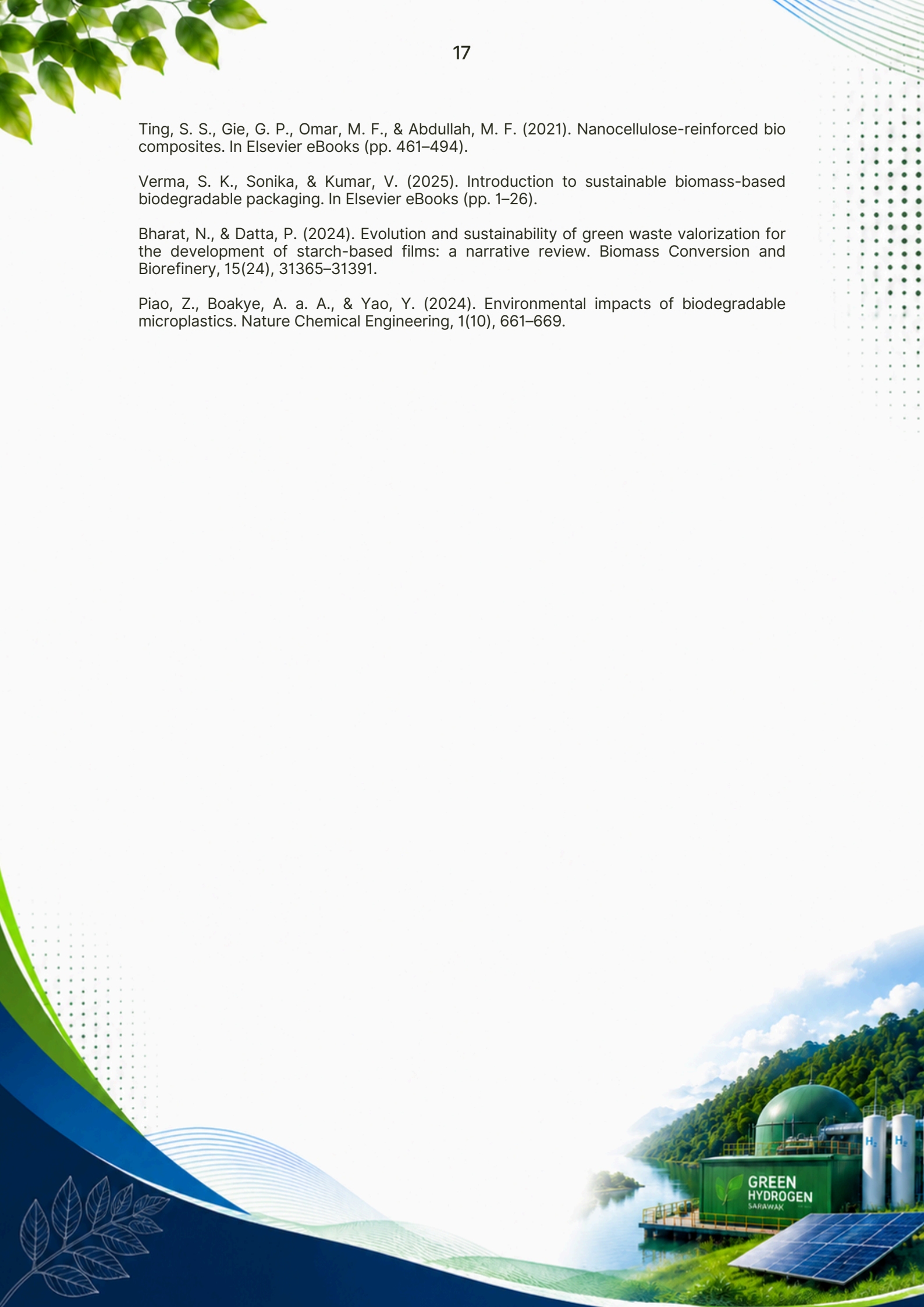

Membrane Contactors as a Viable Option for CO2 Capture towards Environmental Sustainability

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Introduction

The global climate, besides the ecosystems, has been adversely impacted on account of the swift industrial and economic growth. Human-engineered problems such as acidic rain, in addition to the effects of greenhouse gases, are linked closely to energy utilization and industrial outputs (Nieminen et al., 2020). It is on record that emission of CO_2 is exponentially increasing at a global alarming rate, and CO_2 concentrations in the ecosystem have attained a new concern level of four hundred and forty-one ppm. The increasing CO_2 concentrations within the atmosphere, leading to the phenomenon of global warming, are linked to the global growth of CO_2 emissions. In the desire to capture and separate CO_2 from the source of emissions, including from the environment, different technological methods have been explored to provide short-term mitigation to suppress the harmful impacts of CO_2 emissions (Liu et al., 2024). Within industrial space, the existence of acid gases like CO_2 causes severe issues. For example, the existence of CO_2 in natural gases reduces the heating values due to its acidic nature and causes corrosion within pipelines. Hence, stimulating economic development and complying with ecosystem protection, CO_2 capture from natural gases is vital (Mamah et al., 2022).

The different technologies that have been applied for capturing CO_2 include cryogenic-distillation, membrane separation, carbon molecular sieve absorption, solid adsorption, and chemical and physical absorption. The technology involves absorbing into alkano-lamine solutions via usage of conventional contacting devices like tray/packed columns. However, this approach is energy-intensive and complex to function on account of challenges like foaming, channeling, and flooding. The utilization of membrane-contactors in managing and controlling the emission of CO_2 is attracting renewed attention. As a desired alternative, membrane contactor technology that uses combinations of chemical absorptions as well as membrane separation is viewed as leading technology for controlling CO_2 emissions for environmental sustainability (Stepanova et al., 2025). Though separation of gases by membrane has been systematically researched for over a century, membrane development technology combined with asymmetric membrane fabrications only significantly advanced in the 1970s (Yang et al., 2025).

Polymeric membranes' wetting is considered a major setback because membranes' wetting can increase the membrane's mass transfer resistance, hence reducing the mass transfer efficiency of the process. Wetting takes place when liquid absorbent enters the pores of the membrane over a long period of operation. This offers a serious bottleneck to the application of PVDF-based membranes for CO_2 capturing for environmental sustainability. The PVDF membrane's performances are associated greatly to the hydrophobicity of its surface (Rehman et al., 2025). PVDF membrane's modification can mitigate this challenge. Surface modifying is a viable pathway to incorporate hydrophobic-functional groups onto PVDF membranes, thereby enhancing the quality of the membranes. The popular approaches in PVDF-based membranes' modifications are physical blending, coating, chemical, and layer-by-layer, all geared towards improving the performance of the membrane towards CO_2 capturing.

Overview of Membrane Contactors

Membrane contactors are devices possessing polymeric or ceramic porous membranes that actualize purifications or separations of two different phases through applying concentrations, activity, and temperature as driving forces without dispersing one phase into another (Hou et al., 2025). They are utilized in the separation process due to several merits, like the capacity to provide large gas to liquid contact areas that facilitate a decrease in contactor weights and sizes, exhibiting compacting configurations, and, most remarkably, is that its driving-force is the variation in concentration gradients, hence removing the need to use external pressure (Cormos, 2025).



The compatibility between membrane material and absorbents is crucial for the entire efficiency of the systems. The membrane is expected to be chemically and physically stable in long-term contact with the absorbent to prevent degradation. Specifically, a high degree of hydrophobicity is the most desirable quality to ensure the anti-wetting status of the resultant membrane during operations. Absorbent is required to display high surface tensions as well as a high degree of affinity towards the gases to improve its absorption capability, besides its selectivity. There are several types of membrane contactors, such as temperature-swing membrane absorption processes, spiral-wound/tubular modules, crossflow and woven fiber membrane modules, and longitudinal-flow modules.

Membrane Used for Membrane Contactors: Criteria and Properties

To obtain extremely efficient and stable CO_2 capture with a membrane contactor, the material and liquid absorbent solutions must be properly chosen. In addition to CO_2 capture, research has been ongoing to determine the optimal membrane material, liquid absorbents, and maximum operating parameters for high mass transfer rates. flux. Dense membranes, microporous membranes with pore diameters less than 1 μm, and composite membranes are the three types of membranes used in membrane contactors. Micro-porous membranes for CO_2 capturing can be described as thin-walled structures possessing open-spongy morphology of precisely controlled pore dimensions, ranging from 0.03 μm to 10 μm (Luqmani et al., 2023). A micro-porous membrane depends on an interconnected network of small pores embedded by various means within an otherwise non-permeable polymeric structure. The pores provide narrow networks for sieving of molecules as well as micropore connectivity for rapid transportation of gases, giving significantly enhanced gas-separating performances. The dense membranes inhibit the phenomenon of wetting, yet offer low mass transfers. Composite membranes are an attractive alternative to provide membranes possessing prolonged stability, besides high mass transfers (Ahmadi et al., 2018).

Effects of Modifications on PVDF Membrane for CO_2 Capturing

Surface modification and functionalizations can viably influence the microstructure of PVDF membrane, that enventually improve flux in addition to anti-wetting qualities of PVDF membrane for CO_2 capturing. Previously, studies have shown that features of PVDF membrane could be tailored through different types of surface or structural modifications. The need for modification of PVDF membranes used for CO_2 capture is as dramatically summarized in Figure 1.

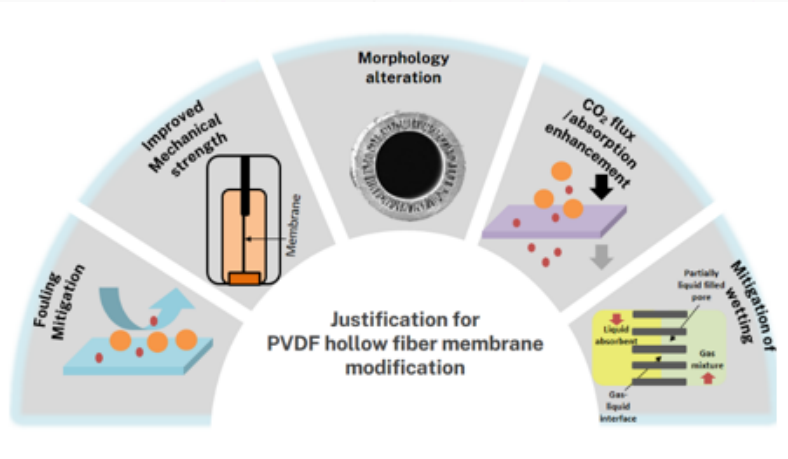

Figure 1. Diagrammatic depiction of justification for PVDF membrane modification for CO_2 capturing

Performance Evaluation of Surface-Modified PVDF Membrane Contactor

Phase separation techniques that are either thermally activated or non-solvent induced are used to create PVDF-based membranes. Unusually, electrospinning has been used to create hydrophobic nanofiber membranes with contact angles more than 150 o (Makanjuola et al., 2018). The best method for creating dimensional porous nanofibrous materials that are ideal for membrane contactors is electrospinning. By varying the dope's characteristics and electrospinning conditions, electrospinning allows for the fabrication of membrane topologies. PVDF membranes can be structurally, or surface changed to achieve the necessary features for CO_2 collection applications, regardless of the fabrication techniques used. Figure 2 illustrates the methods of PVDF membrane modification for enhanced CO_2 capture. The methods include coating, grafting, adding compounds, and integrating nanoparticles.

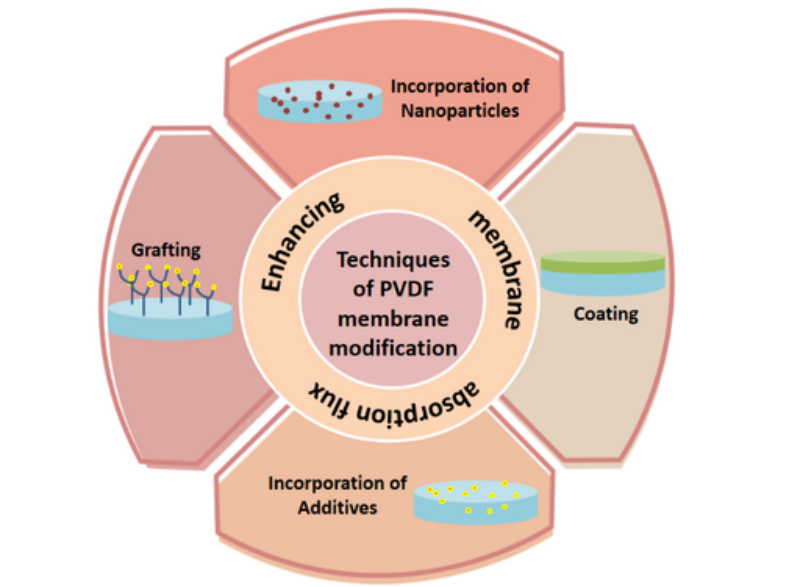

Figure 2. The techniques of PVDF membrane modification for improved CO_2 capturing

Performance Evaluation of Surface-Modified PVDF Membrane Contactor

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Conclusion

The innovations and development of separation technology based on membrane contacting processes for CO_2 can provide desirable environmental remediation solutions to various complicated bottlenecks facing the ecosystem. The alluring property offered by membrane contacting technology can resolve the intrinsic challenges, thereby possessing the potential to be an alternative to conventional technology. The PVDF membrane alteration for increased hydrophobicity, wetting mitigation, and overall better membrane contactor performance for CO_2 capture has been made public by this publication. In order to realize optimum potentials and the practical potentiality of PVDF-based membranes in real-world CO_2 capturing applications, it is anticipated that the adoption of the highlighted modification approaches and solutions to the associated inadequacies will be crucial.

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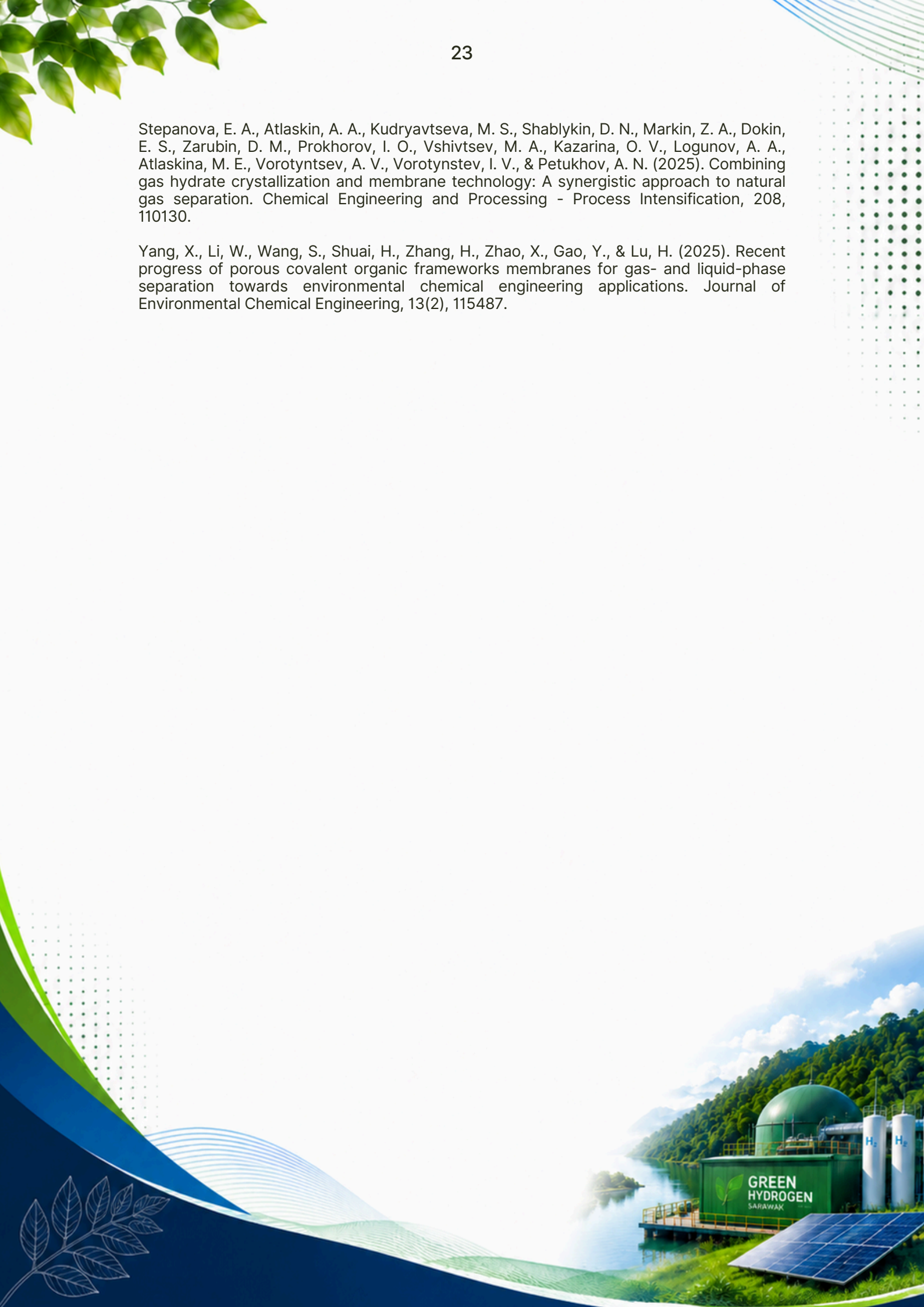

Implications of Drilling Operations for Wellbore CO_2 Leakage Pathways and Remediation Strategies

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Introduction

Geological carbon storage (GCS) has emerged as a critical strategy for mitigating atmospheric carbon dioxide (CO_2) emissions and achieving global climate targets (Torsæter et al., 2017). However, the long-term integrity of storage systems remains a central concern, particularly regarding the potential for CO_2 leakage through wellbores. Active and abandoned wellbores represent one of the most significant human-caused pathways for CO_2 migration due to their direct penetration of subsurface formations (Ahammad & Azadbakht, 2025). Among the various factors influencing wellbore integrity, drilling operations play a foundational role in determining the structural and chemical stability of the well system over time.

Drilling activities introduce complex mechanical, thermal, and chemical disturbances to the subsurface environment. These disturbances can alter formation properties, compromise cement bonding, and create micro-annuli or fractures that may later serve as preferential leakage pathways (Nguyen et al., 2026). Despite advancements in drilling technologies and well completion practices, inconsistencies in drilling fluid design, casing installation, and cementing operations continue to pose risks to long-term containment.

This study examines the implications of drilling operations on the formation and evolution of CO_2 leakage pathways within wellbores. It further explores how these pathways can be effectively mitigated through targeted remediation strategies. By integrating insights from drilling engineering, geomechanics, and geochemistry, this work aims to provide a comprehensive understanding of how early-stage operational decisions influence long-term storage security.



Key Discussions

Drilling operations influence wellbore integrity through several interconnected mechanisms. One of the primary concerns is the interaction between drilling fluids and formation materials (Nguyen et al., 2026). Improperly designed drilling muds can lead to formation damage, such as clay swelling, fines migration, or pore blockage, which may weaken the formation structure and affect cement bonding (Su et al., 2023). Additionally, the invasion of drilling fluids into the formation can alter permeability and create heterogeneities that later facilitate CO_2 migration (Su et al., 2023). Many factors influence CO_2 leakage in the wellbore, which develops over time, as illustrated in Figure 1.

Mechanical stresses induced during drilling also play a critical role. The process of drilling alters the in-situ stress regime, potentially causing microfractures or enlarging existing natural fractures (Anya et al., 2020). These fractures, if not properly sealed during cementing, can act as conduits for CO_2 leakage (Anya et al., 2020). Furthermore, poor casing centralization and inadequate mud removal before cementing can result in incomplete zonal isolation, leaving behind channels or micro-annuli along the casing-cement or cement-formation interfaces (Anya et al., 2020).

Thermal effects are another important factor. Temperature variations during drilling and subsequent CO_2 injection can induce thermal stresses in the wellbore system (Ahammad & Azadbakht, 2025). These stresses may lead to debonding at interfaces or the development of microcracks within the cement sheath. Over time, repeated thermal cycling exacerbates these defects, increasing the likelihood of leakage (Schimel et al., 2000).

From a chemical perspective, the interaction of CO_2 with wellbore materials introduces additional challenges. CO_2, particularly in its supercritical form, can react with cement and formation minerals, leading to carbonation and potential degradation of mechanical properties. While some degree of carbonation may reduce permeability, excessive reactions can weaken the cement matrix and enlarge existing pathways (Wang et al., 2021).

Importantly, these factors do not act independently. Instead, they interact in complex ways, creating a dynamic system where initial drilling-induced conditions evolve under the influence of CO_2 injection (Wang et al., 2021). This underscores the need for an integrated approach that considers the entire lifecycle of the well (from drilling to abandonment).

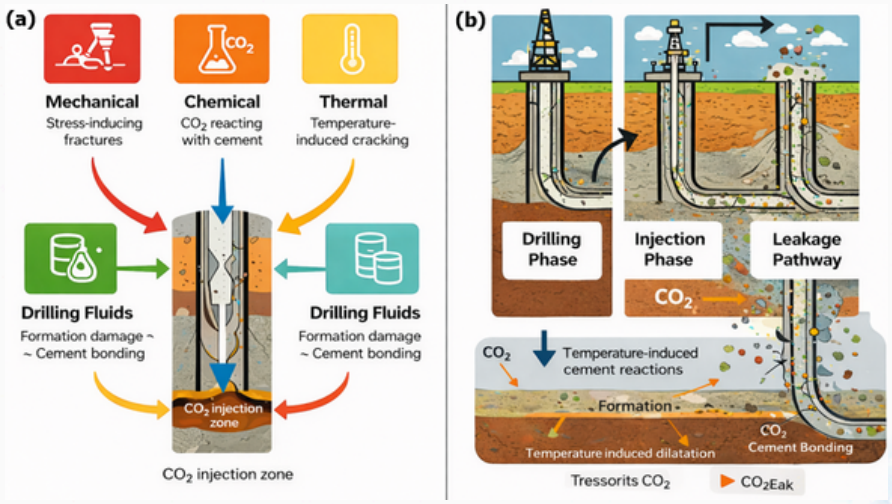


Figure 1. CO_2 leakages through the wellbores: (a) influencing factors and (b) developmental stages

Case Example / Evidence

Field and experimental studies provide compelling evidence of the impact of drilling operations on CO_2 leakage pathways. One notable example comes from CO_2 storage projects in the North Sea, where legacy wells have been identified as potential leakage risks (Phelps et al., 2015). Investigations revealed that many of these wells exhibited poor cement bonding and micro-annuli formation, largely attributed to suboptimal drilling and cementing practices during their original construction (Phelps et al., 2015).

In laboratory studies, researchers have simulated drilling fluid invasion and its effects on cement bonding. Results show that the presence of residual drilling mud on formation surfaces significantly reduces the bond strength between cement and rock. This weak interface becomes a preferential pathway for fluid migration under pressure gradients typical of CO_2 injection scenarios (Torsæter et al., 2017).

Another example can be drawn from enhanced oil recovery (EOR) operations using CO_2. In several cases, leakage along wellbores was traced back to inadequate zonal isolation caused by poor mud displacement and channeling during cementing. These observations highlight how drilling-phase decisions can have long-term consequences, even in wells not originally designed for CO_2 storage (Anya et al., 2020).

Advanced imaging techniques, such as X-ray computed tomography (CT), have further revealed the presence of microcracks and voids within cement sheaths that originated from drilling-induced stress and improper cement placement. These microstructural defects, though initially small, can coalesce and form continuous pathways under prolonged exposure to CO_2-rich environments (Gan et al., 2022). Collectively, these examples demonstrate that drilling operations are not merely preparatory steps but are integral to the long-term performance and safety of CO_2 storage systems.

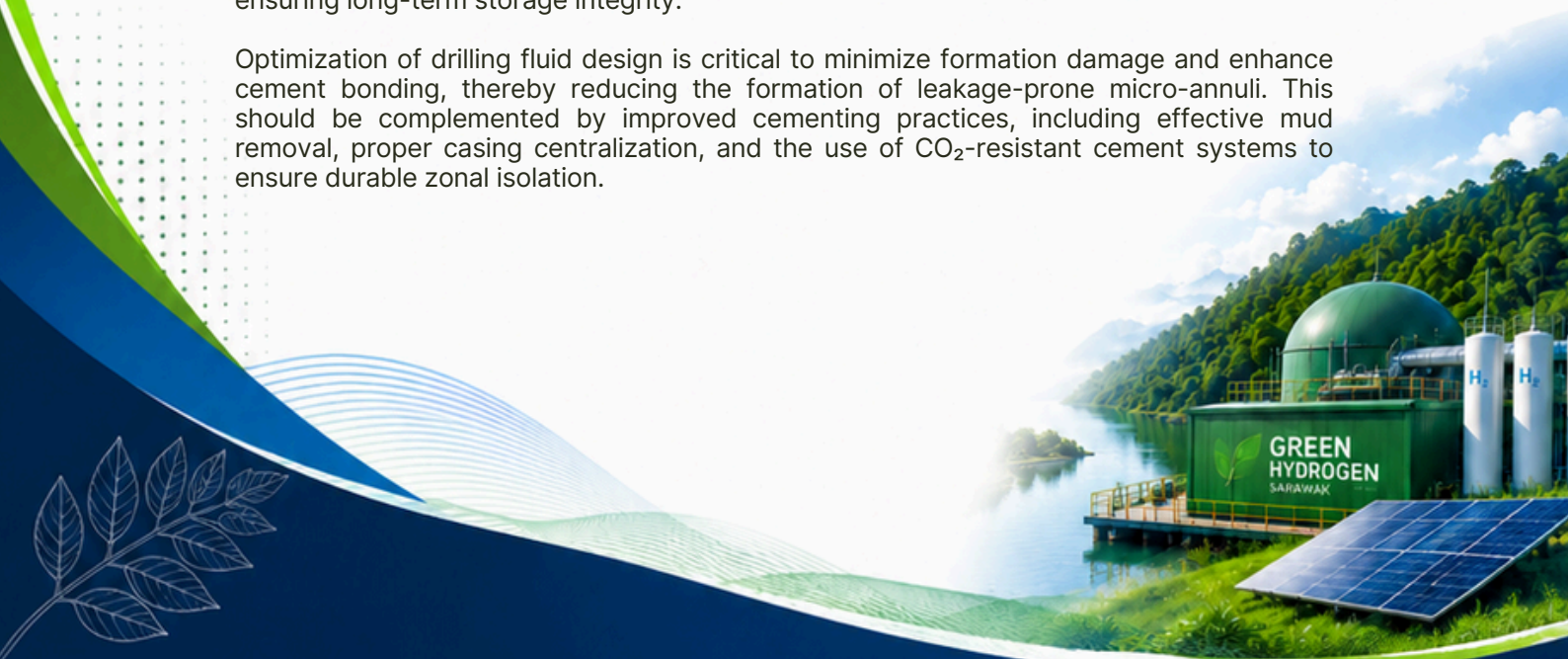
Conclusion

Drilling operations play a pivotal role in shaping the integrity of wellbores and their susceptibility to CO_2 leakage. Mechanical disturbances, chemical interactions, and thermal effects introduced during drilling collectively contribute to the formation of potential leakage pathways. These pathways, often initiated at the micro-scale, can evolve into significant conduits for CO_2 migration if not properly managed. The evidence clearly indicates that many wellbore integrity issues associated with CO_2 leakage can be traced back to deficiencies in drilling and cementing practices. As such, ensuring the quality and compatibility of drilling operations is essential for the success of GCS initiatives. Addressing these challenges requires a holistic understanding of the interactions between drilling processes, material properties, and long-term subsurface conditions.

Implications / Recommendations

To support the transition toward a low-carbon energy system and a sustainable, carbon-neutral environment, mitigating drilling-induced CO_2 leakage pathways is essential for ensuring long-term storage integrity.

Optimization of drilling fluid design is critical to minimize formation damage and enhance cement bonding, thereby reducing the formation of leakage-prone micro-annuli. This should be complemented by improved cementing practices, including effective mud removal, proper casing centralization, and the use of CO_2-resistant cement systems to ensure durable zonal isolation.



In addition, real-time monitoring and diagnostic tools during drilling and cementing should be adopted to detect and address integrity issues early. The integration of geo-mechanical and thermal modeling into well design further enables the prediction of stress-induced failures, which is vital for maintaining wellbore stability under long-term CO_2 injection conditions. Finally, targeted remediation strategies, such as squeeze cementing, polymer sealants, and self-healing materials, should be deployed to address existing leakage pathways to enhance wellbore integrity, strengthen the reliability of carbon storage systems, and advance the realization of a sustainable, low-carbon future.

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Tribo-reaction and mechanism of MWCNT additives under AISI E-52100

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Introduction

To save the environment from noise pollution from machine operations, lubricants are used in industry (machine operations) and other moving activities to lessen wear and friction on related surfaces. This prolongs the machine's life and improves its effectiveness (Prasannakumar et al., 2025; Li et al., 2022). On the concept of lowering wear and friction, lubricants also help in heat evacuation, power delivery, corrosion inhibition, and the formation of a liquid stopper at affected contacts. It is also used in a variety of apparatus, from huge machinery to small equipment, to ensure consistent machine performance. Early in the process of solving the lubricating issues, mineral oil, a product made possible by petroleum sources was manufactured and utilized. However, enhancement using various additives was used because base lubricants cannot resist high/long running working circumstances (Opia et al., 2025, 2026a, 2026b). This necessitated a detailed study of the behavior of the mixtures to achieve a synergistic effect.

However, some vegetable oils have good tribological qualities; their functioning is restricted by their inherent qualities and can be improved by adding appropriate additives and making other compositional changes. Furthermore, compared to their edible siblings, non-edible vegetables require greater research and application due to cost conflicts and competitiveness between food and energy. The use of bio-lubricants as alternatives in lubrication applications has been the subject of extensive research over the last few decades. Based on our knowledge, none of these studies has thoroughly examined and evaluated various bio-lubricants to understand how they work in connection to lowering wear and friction through film formation and tribo-chemical processes. Thus, the purpose of this work is to assess the organic carbon nanotube tribo reaction and mechanism under AISI E-52100 steel lubrication. As illustrated in Figure 1, these tribo-chemical reactions of lubricant additives under Gibbs free energy require three conditions: the surface energy from the lubricant-lubricated material interface, the mechanical and thermal issues from the friction force, and the change in free energy due to shear stress.

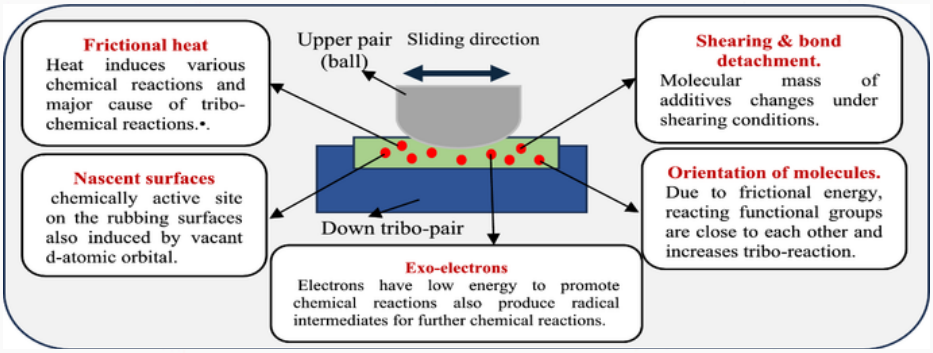

Figure 1. Factors influencing the production of films during lubrication by chemical reactions at tribo-contact

Materials and Methods

In this study, commercially available SAE 15W-40 and neem were bought from the market. Considering its good lubricity in tribological tests, the SAE 15W-40 lubricant was chosen for use in this investigation. Additionally, neem oil was used to assess the tribological effectiveness of the various fatty acid concentrations. To ascertain whether the SAE 15W-40 could be replaced, it was contrasted with two different vegetable lubricants. According to the manufacturer's presentations, Table 1 shows some typical properties of the basic oils employed for this experimental study.

Table 1. A few features of neem oil

Sample physicochemical features	Fatty acid composition, %	SAE 15W-40
Saturation %	3–6	-
Unsaturation %	91–95	-
Cloud point, °C	26	-
Flash point, °C	274	227
Pour point, °C	17	-
Melting point, °C	19	-

Tribological Tests

The study chose an alternative motion tribo-apparatus to obtain a thorough investigation of the oil's performance over a wide range of relative velocities. To assure reproducibility, friction tests were performed using a ball-on-flat machine (Ducom 2010, Instruments, USA), following a proven test technique (Opia et al., 2026b). Each test was repeated three times. A schematic illustration of the device is shown in Figure 2. In accordance with ASTM D4172, the tribological behaviour towards wear-prevention and friction-reducing qualities was evaluated. A 40 mm by 40 mm by 5 mm flat piece of AISI E-52100 steel slid against a 10 mm-diameter ball of X210Cr12 steel. The concentration of 1 wt.% additive was selected based on recommendations from other studies. Consequently, neem and jatropha are used as base lubricants to manufacture a specific 1 wt.% of PTFE nanoparticles. The variations in lubricating properties have been investigated using tribometers. Vegetable oils frequently have good lubricating properties, given the correct lubrication regime.



Figure 2. The four-ball tester apparatus

Frictional Analysis

When a load of 100 N is applied as shown in Figure 3, the varying COF and wear scar diameter of the various lubricant samples are utilized at different frequencies (3 Hz and 5 Hz). According to the study, adding 1 weight percent PTFE to the different selected base oils reduced the COF at 3 and 5 Hz. The COF of base neem and neem + 1 wt.% MWCNT under 3 Hz were 0.1197 and 0.0879, respectively, according to Fig. 7(a). But SAE 15W-40 had the lowest COF (0.0737). Compared to the SAE15W-40 value of 0.0883, the study found that the COF values for base neem and neem + 1 wt.% MWCNT were 0.1459 and 0.0953, respectively, at a frequency of 5 Hz as indicated in Fig. 7(b). The study revealed that each sample's COF increased as frequency climbed from 3 to 5 Hz. Further research showed that, except for SAE 15W-40, neem + 1 wt.% produced superior tribological responses compared to their base neem equivalent.

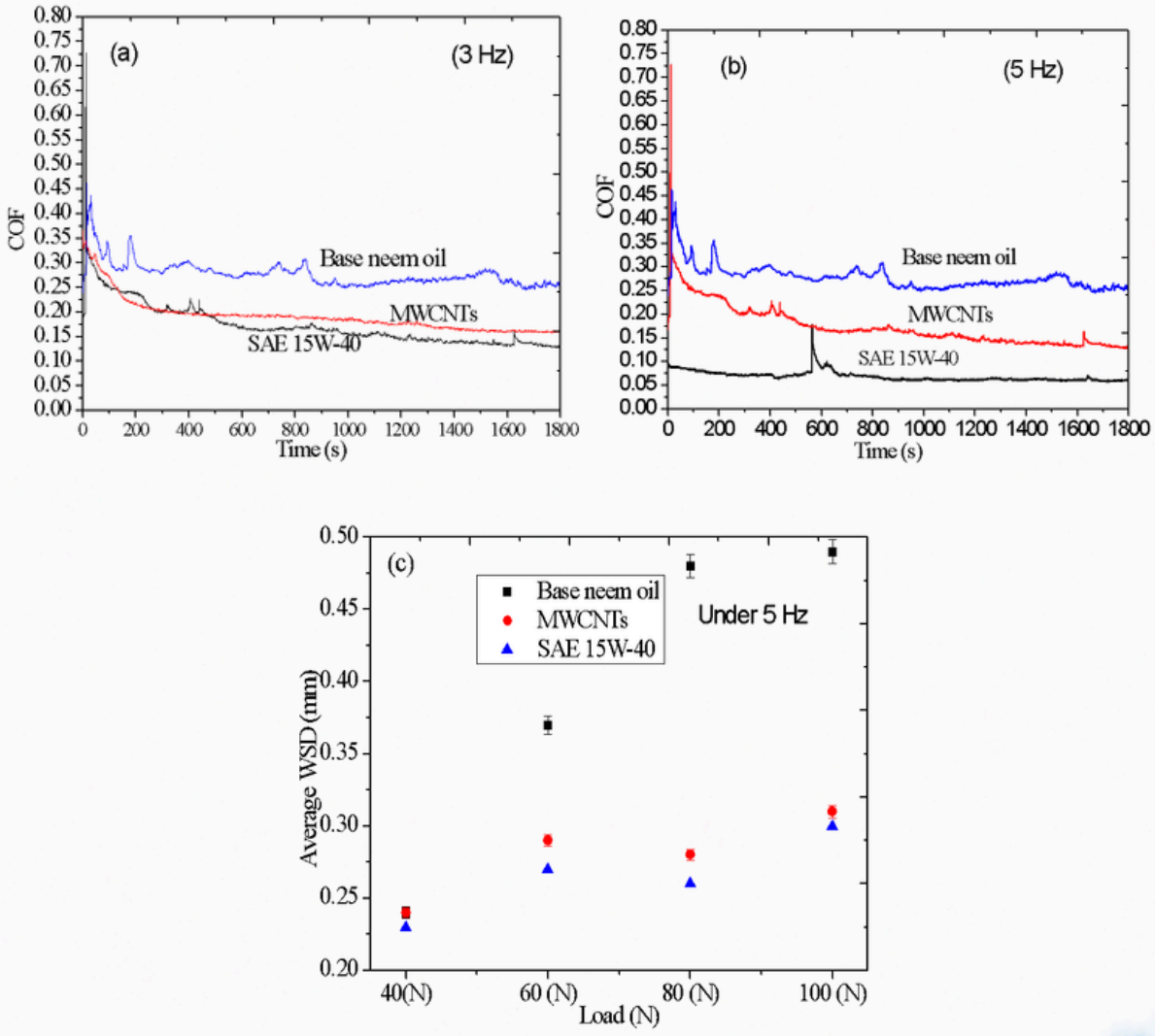

Figure 3. (a and b) COF & (c) wear scar diameter recorded from neem lubricant (at 75 °C, 3, 5 Hz, and under 100 N)

Neem Nanolubricant Tribo-Reaction and Mechanism

Based on the test results and the study, the tribo-chemistry process of neem + 1 wt.% MWCNT may be explained as follows. The tribo-reaction operation toward tribo-film generation for friction and wear decrease is thus modeled in Figure 4. Because of its polarity, MWCNT first competes with the vegetal base fluid to adsorb onto the metal surface. The study found that Neem 1wt.% MWCNT additions can adsorb more quickly due to the electron-rich conjugated structure of its straight alkyl carbon chain, which enables it to form large bonds with the polar metal. As seen in Figure 3 (b and c), the large number of electrons in this enormous connection makes it easier for a dense adsorption coating to form on the metal surface.

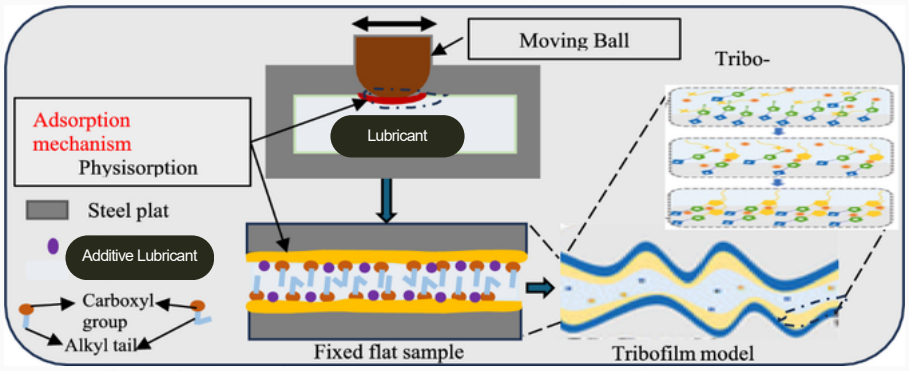

Figure 4. Neem nanolubricant tribo-reaction and mechanism during service

Conclusions

The present study uses steel materials and various operating conditions to investigate the tribological properties of neem vegetable lubricants with MWCNT. It is possible to reach the following conclusions:

1. The inclusion of MWCNT in the vegetable lubricants achieved better results under an advanced frequency of 5 Hz compared to lower frequencies, in contrast to neem base lubricants using a ball on a flat surface.
2. The EDS revealed that MWCNT was involved in lubrication, generating a third body that assisted in contact separations, by identifying extra elements and decreasing the contact of the iron (Fe) steel material. Additionally, an efficient layer that functioned as a healing mechanism was found to be formed by appropriate tribo-reactions between the lubricant and substrate.

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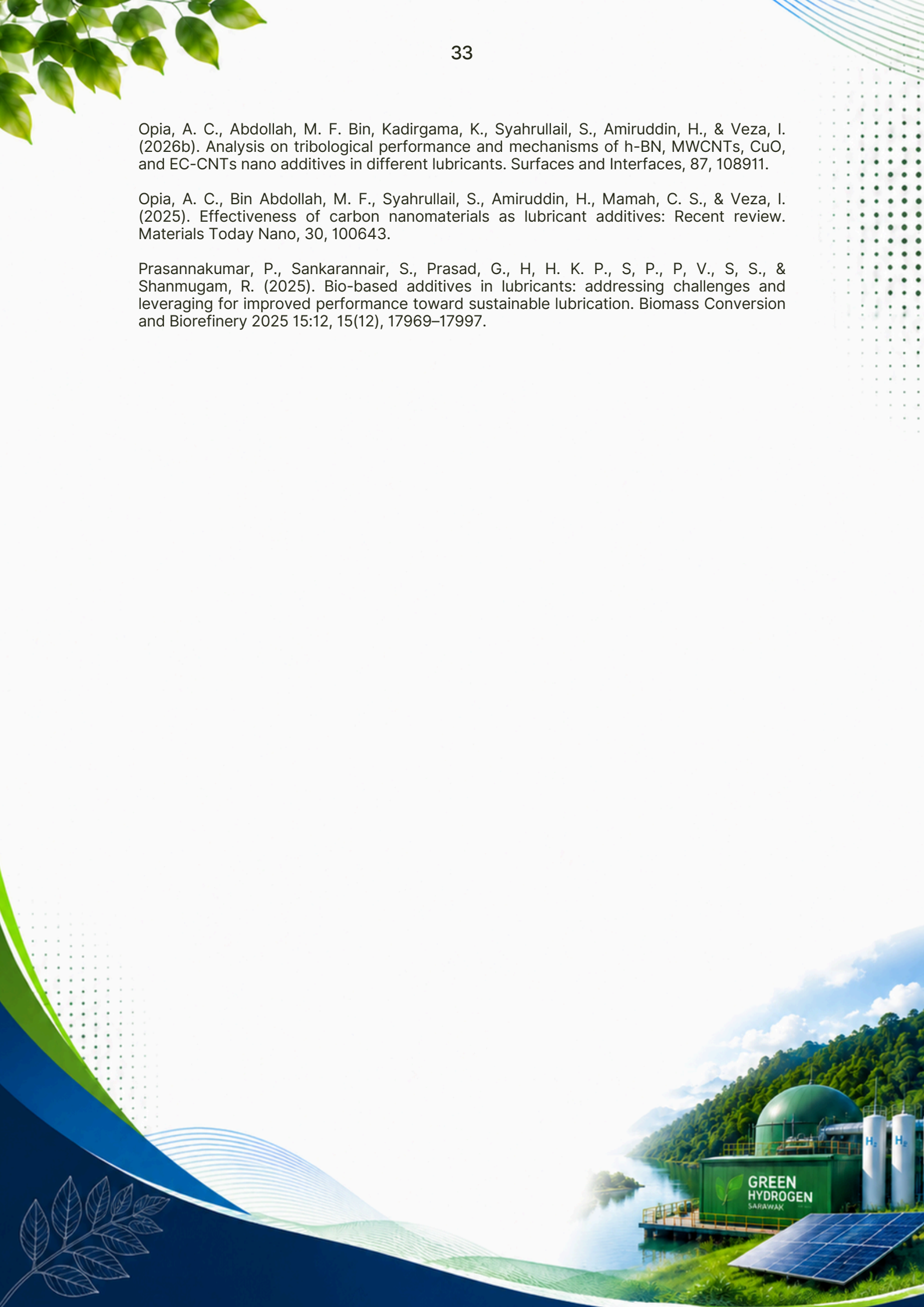

Valorization of Cocoa Pod Husk for Sustainable Biochar Production

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Introduction

Cocoa pod husk (CPH) is a plentiful lignocellulosic biomass produced as a by-product of cocoa production, generally comprising around 70-80% of the total weight of cocoa fruit (Nascimento et al., 2025; Iwuozor et al., 2024). The cocoa fruit and its primary parts are seen in Figure 1.



Figure 1. The structure of lignocellulose and how cellulose, hemicellulose, and lignin interact (Salcedo-Puerto et al., 2022)

The global cocoa industry produces millions of tons of cocoa powder annually, predominantly in West Africa's key cocoa-producing countries, including Côte d'Ivoire, Ghana, Nigeria, and Cameroon. Angbé et al. (2026) reported that over 20 years, about 578 million tonnes of CPH were produced in seven West African nations, with Côte d'Ivoire and Ghana accounting for most of the output, as shown in Figure 2. This considerable biomass volume becomes a valuable resource if effectively utilized.

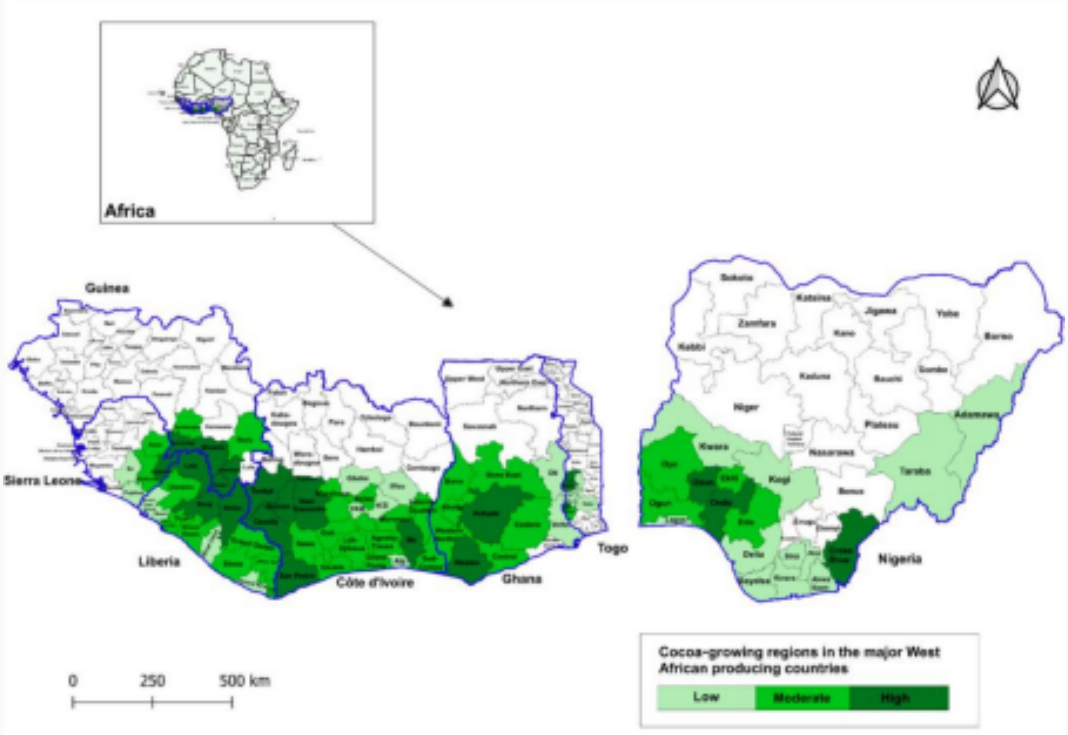

Figure 2. Cocoa-producing regions in seven West African nations, categorized by the relative scale of cocoa cultivation based on available data regarding cultivated area or production metrics (Angbé et al., 2026)

Traditionally, CPH has been underutilized, with large amounts discarded or left to decompose on farms, posing ecological risks and environmental pollution (Awogbemi & Kallon, 2023; Salcedo-Puerto et al., 2025). The open decomposition of CPH releases greenhouse gases, notably methane (CH_4) and carbon dioxide (CO_2), contributing substantially to agricultural sector methane emissions in Africa (Angbé et al., 2026). This mismanagement not only undermines local environmental quality but also restricts opportunities for circular bioeconomy development in cocoa-growing communities. Figure 3 below shows the integrated biomass conversion pathway for cocoa pod husk residues.



Figure 3. Integrated biomass conversion pathway for cocoa pod husk residues (Belwal et al., 2022)

Given these challenges, adopting sustainable waste management strategies to convert cocoa pod husks into valuable by-products has become a priority. Among such strategies, biochar technology has emerged as a promising pathway for sustainable CPH valorization. Biochar is a charred biomass material produced from the thermochemical conversion of organic feedstocks under limited oxygen conditions, primarily via pyrolysis (Jayakumar et al., 2023; Xie et al., 2022). This process converts lignocellulosic residues, such as CPH, into carbon-rich, porous materials with multifaceted applications, including soil amendment, pollutant adsorption, and catalysis. Figure 4 below shows the structure of lignocellulose and how cellulose, hemicellulose, and lignin interact.

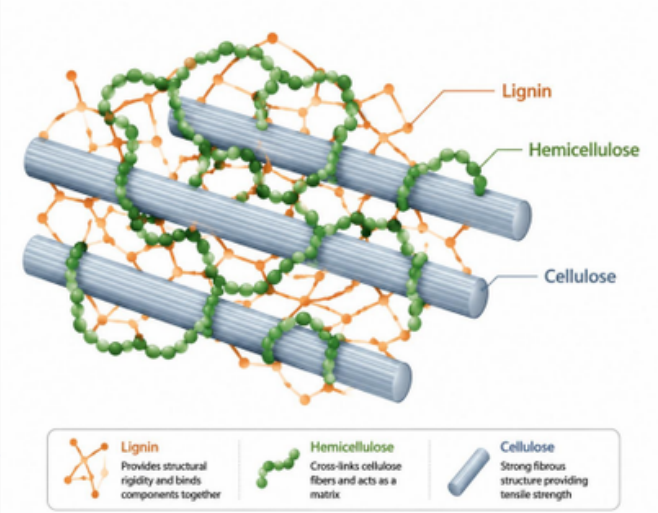

Figure 4. The structure of lignocellulose and how cellulose, hemicellulose, and lignin interact (Mendoza-Meneses et al., 2021)



The development and application of CPH-derived biochar address two critical issues. First, it presents an eco-friendly approach to managing large volumes of agricultural waste, mitigating environmental pollution and greenhouse gas emissions (Angbé et al., 2026). Second, it offers opportunities to enhance soil fertility and promote sustainable agricultural productivity, an urgent need in many cocoa cultivation areas faced with nutrient depletion and soil degradation (Gopal et al., 2025; Mwafulirwa et al., 2024).

Cocoa Pod Husk Disposal Remains A Major Challenge

Notwithstanding the vast annual yield of cocoa pod husk, its application has been markedly inadequate. The common practice of on-farm abandonment or cremation of CPH produces substantial methane emissions, a powerful greenhouse gas with a global warming potential significantly exceeding that of CO_2 (Angbé et al., 2026). The environmental impact of this mismanagement is significant: roughly 17 million tonnes of CO_2-equivalent methane are emitted annually from CPH decomposition in West Africa, representing nearly 3% of Africa's agricultural methane emissions (Angbé et al., 2026).

Furthermore, traditional disposal and use methods, such as composting, are often inefficient at reducing toxic metal contaminants inherent in CPH and other agro-industrial residues, thereby compromising soil and water quality (Awogbemi & Kallon, 2023). Limited processing infrastructure and knowledge dissemination also constrain the utilization of CPH for value-added applications (Dachs et al., 2025). This knowledge scarcity is especially pronounced in the organization and dissemination phases of circular economy practices within cocoa production networks.

Simultaneously, soil nutrient deficiencies, particularly of potassium and phosphorus, have become a growing concern in cocoa cultivation systems due to intensive farming and inadequate replenishment (Gopal et al., 2025; Mwafulirwa et al., 2024). Potassium deficiency affects about 20% of global agricultural lands and is prevalent in major cocoa-producing soils, impeding cocoa productivity and quality (Gopal et al., 2025). The negative impacts of soil degradation compel the exploration of sustainable soil amendment options derived from local waste resources, such as CPH biochar, which can supply critical nutrients and improve soil physicochemical characteristics.

The contamination of water bodies with antibiotics and heavy metals originating from agricultural runoff poses additional health and environmental risks (Hung et al., 2026; Correa Abril et al., 2024). Hence, there is a pressing need for environmentally safe, economically viable treatment methods that leverage agricultural biochar for water pollution remediation.

Overview Of Biochar: Definition And Properties

Biochar is a carbon-rich solid material produced through the thermochemical conversion of biomass under limited oxygen conditions, typically via pyrolysis, but also through microwave-assisted pyrolysis (MAP) or hydrothermal carbonization (HTC) (Shaheen et al., 2023; Švarc Gajić et al., 2023; Marsolla et al., 2025). The production technique and process parameters including temperature, residence time, and activation processes critically influence biochar's physical and chemical properties, such as surface area, porosity, elemental composition, functional groups, and stability (A. Mekuiko et al., 2023; Bednárek et al., 2024). Shaheen et al. (2023) and Marsolla et al. (2025) observed that higher pyrolysis temperatures typically decrease biochar yield but improve aromaticity, porosity, and surface functionalities, thereby enhancing adsorption and catalytic activity. Microwave-assisted pyrolysis is noted for its energy efficiency and uniform thermal profile, enabling engineering of biochar with tailored properties for specific applications (Shirvanimoghaddam et al., 2026; Correa-Abril et al., 2024). 1. Figure 5 below shows the Scanning electron microscopy (SEM) of CPH and CPH char, which undergo pyrolysis at 400 °C.



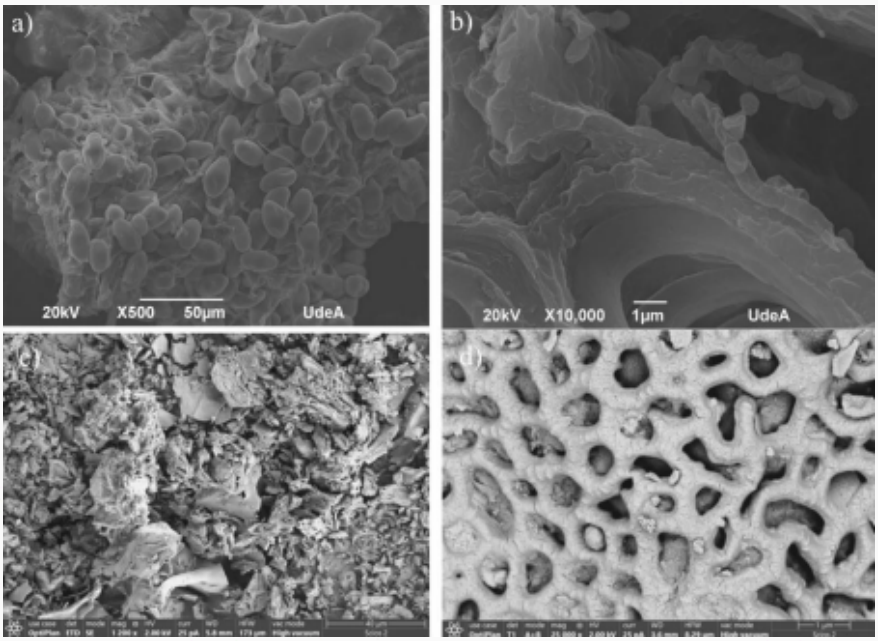

Figure 5. SEM images of feedstock cocoa pod husk (CPH) (a and b) and B400 (c and d) (Carrillo et al., 2026)

Role of Biochar in Sustainable Agriculture

Biochar application in agriculture offers multifaceted benefits, including improved soil fertility, nutrient retention, water-holding capacity, and the enhancement of beneficial soil microbial communities (Tan, 2023; Mwafulirwa et al., 2024). The alkaline nature of biochar, its high cation exchange capacity, and its provision of essential nutrients, such as potassium, make it an attractive amendment, particularly for acidic and nutrient-depleted soils typical of cocoa-producing regions (M. Gopal et al., 2025). Ecotoxicity and biocompatibility studies have confirmed the safety of CPH-derived Biochars. Hung et al. (2026) demonstrated that metal-free cocoa pod husk biochar catalytically activated peroxymonosulfate for antibiotic degradation without embryotoxic effects on zebrafish models, assuring eco-responsible applications.

Cocoa Pod Husk Biochar

Specific to CPH biochar, studies have shown its effectiveness as an adsorbent for heavy metals and organic pollutants. Correa-Abril et al. (2024) reported a maximum adsorption capacity of approximately 14.7 mg/g for Cd(II) ions with microwave-assisted pyrolysis-derived CPH biochar, highlighting the role of oxygen-containing active sites and the formation of stable complexes such as CdCO3. Similarly, other studies have noted the high potassium content of CPH biochar (10.9% with 60% water-soluble potassium), rendering it especially beneficial as a potash source in organic agriculture (Gopal et al., 2025). Research on activated and iron-doped variants of CPH biochar has further expanded its utility. John et al. (2025) synthesized an iron-doped CPH biochar that exhibited strong catalytic activity for the oxygen reduction reaction, demonstrating promise as a cathode catalyst in microbial fuel cell-driven Fenton processes for dye degradation. Beyond pollutant adsorption, Iwuozor et al. (2024) demonstrated that activated biochar derived from cocoa waste can be used for biogas upgrading due to its CO_2 adsorption selectivity, thereby advancing energy recovery technologies.

In summary, coco pod husk biochar combines rich physicochemical properties and tailored surface chemistries to support its diverse environmental remediation, soil amendment, and catalytic applications. However, continuous optimization of production conditions and activation strategies remains crucial to maximize performance for targeted end uses.

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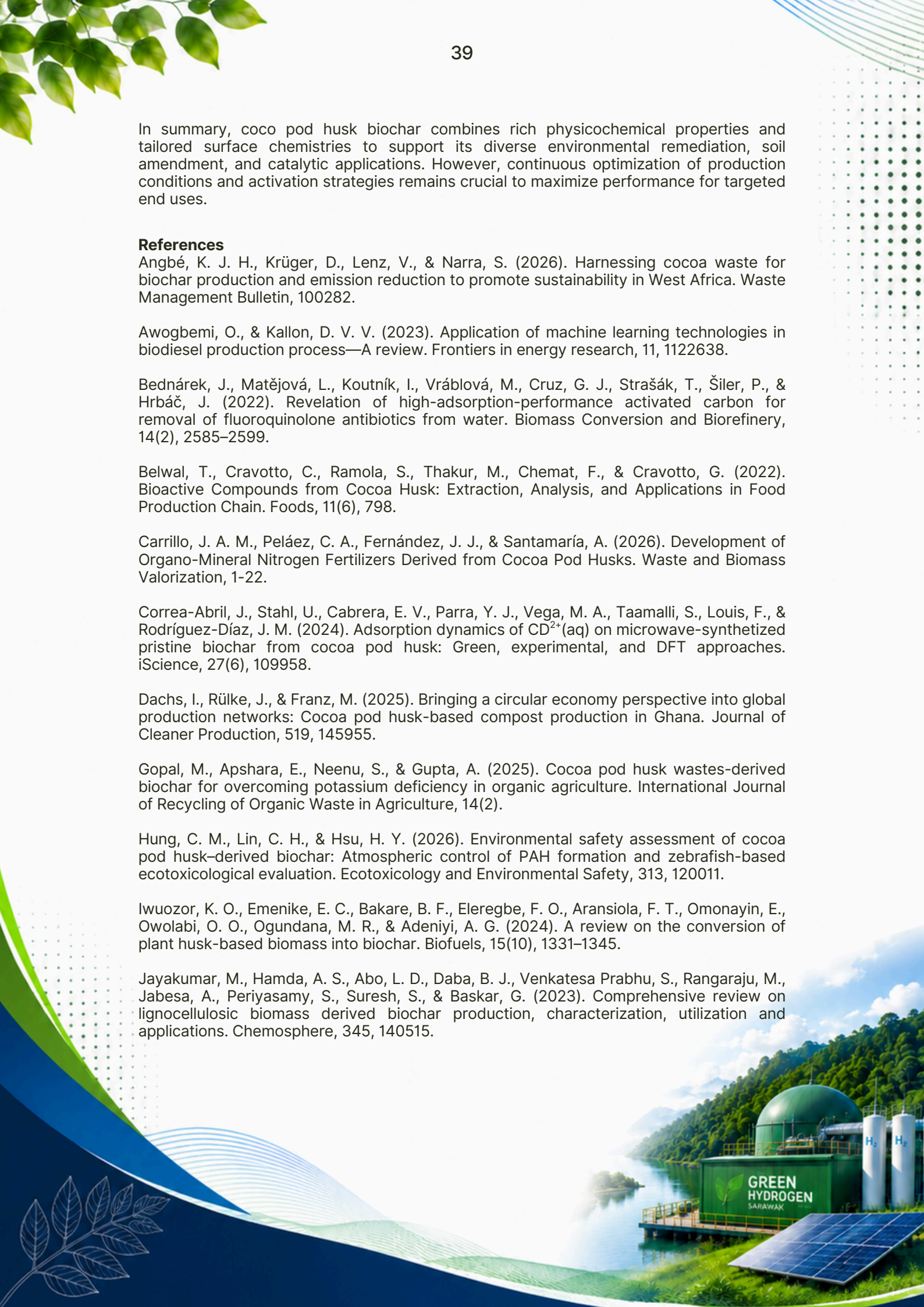

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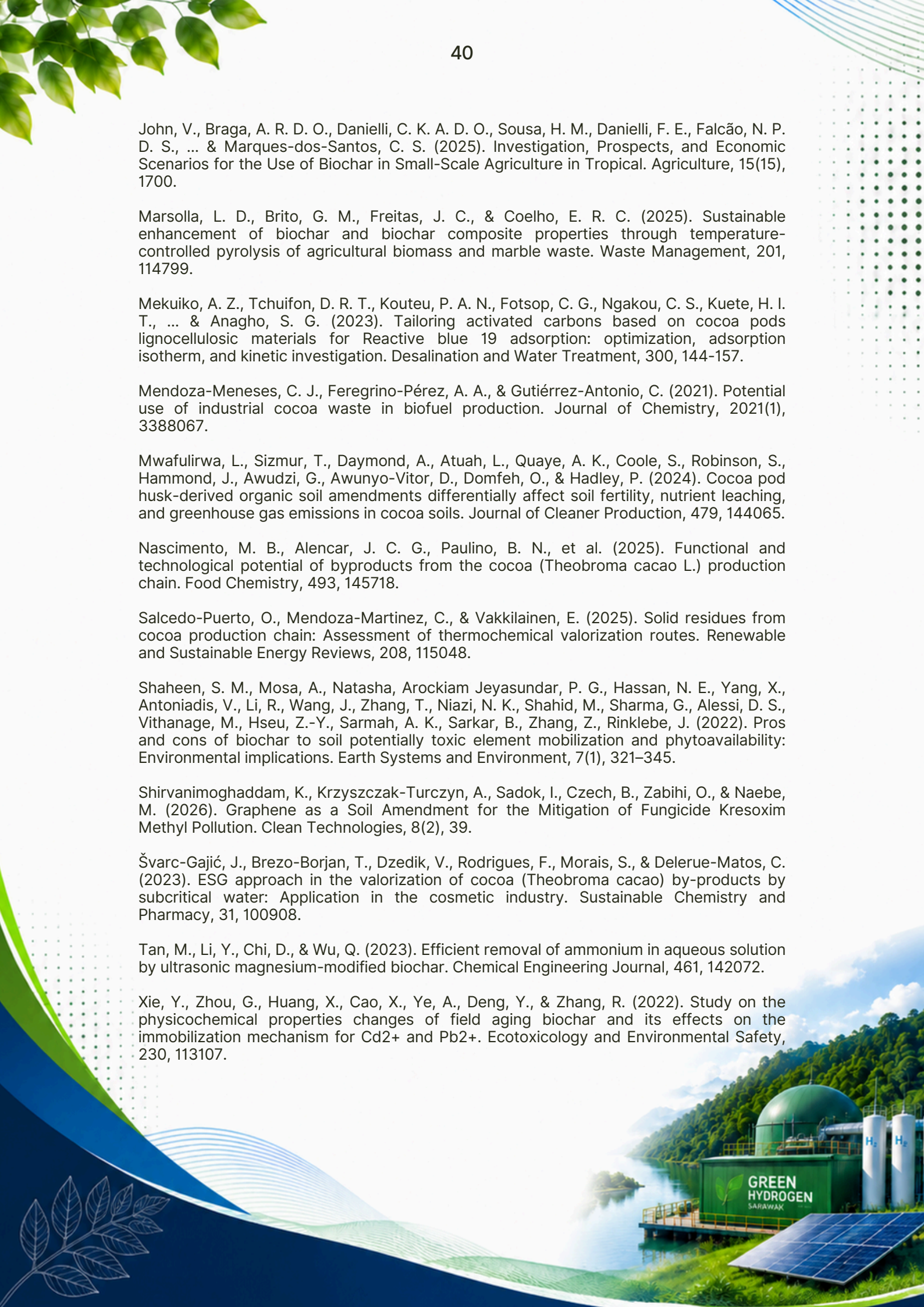

The Role of Nanoparticles in Improving CO_2 Trapping Mechanisms during Geological Storage

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Introduction

Climate change, driven by the rise of greenhouse gases, is still one of the biggest environmental challenges of the 21st century. Carbon dioxide (CO_2) is the most significant greenhouse gas since it is most extensively used for industrial processes, power generation, and transportation. Carbon capture and storage (CCS) is a promising method to reduce CO_2 levels in the atmosphere by capturing the emissions of industrial processes and storing them in geological formations, for example, deep saline aquifers, depleted oil and gas fields, and unmineable coal seams (Hatami et al., 2021). However, there are technical issues that limit the efficiency and long-term security of CO_2 sequestration. In recent years, nanotechnology has introduced nanoparticles to improve the performance of CO_2 sequestration by changing the fluid properties, trapping structures, and storage security (Zandahvifard et al., 2021). Nanoparticles are small, typically ranging from 1 to 100 nanometers. Because they are extremely small and have a high surface area to volume ratio, nanoparticles can be extremely sensitive to fluids and porous geological media, and therefore have special physicochemical properties that enable them to be used in CO_2 sequestration Ngouangna et al., 2023). In CO_2 sequestration, nanoparticles can enhance the storage capacity of CO_2, stabilize the foams, encourage mineralization, and minimize the leakage (Yekeen et al., 2017). This bulletin will present the mechanisms of nanoparticles and their applications to enhance the efficiency and safety of geological CO_2 storage.

Key Discussions

Nanoparticles play several important roles in enhancing CO_2 sequestration. Due to their ability to change fluid characteristics, rock-fluid interactions, and chemical reactions in geological formations (Nik et al., 2020). These modifications can significantly improve the efficiency of carbon capture and storage processes, leading to more effective mitigation of climate change. Additionally, the tailored properties of nanoparticles can enhance the stability and longevity of CO_2 stored underground.



Enhanced CO_2 Trapping Mechanisms

The key mechanisms through which nanoparticles can increase the sequestration of CO_2 are the enhancement of various trapping processes within geological formations (Hamed, 2026). CO_2 is typically stored in subsurface reservoirs through four main trapping mechanisms: structural trapping, residual trapping, solubility trapping, and mineral trapping (Cui et al., 2026). Nanoparticles can enhance these reservoirs in many ways (Figure 1). Nanoparticles can change rock wettability and interfacial tension between CO_2, brine, and rock surfaces. This modification will lead to residual trapping (Punnam et al., 2021). CO_2 becomes immobilized as disconnected droplets in the pore spaces of rock. Greater residual trapping significantly reduces the probability of CO_2 migration and leakage (Zhao et al., 2024). And some nanoparticles can act as catalysts to catalyze chemical reactions that convert dissolved CO_2 into stable carbonate minerals. This is known as mineral trapping and is one of the most permanent ways to store CO_2 (Zhao et al., 2024).

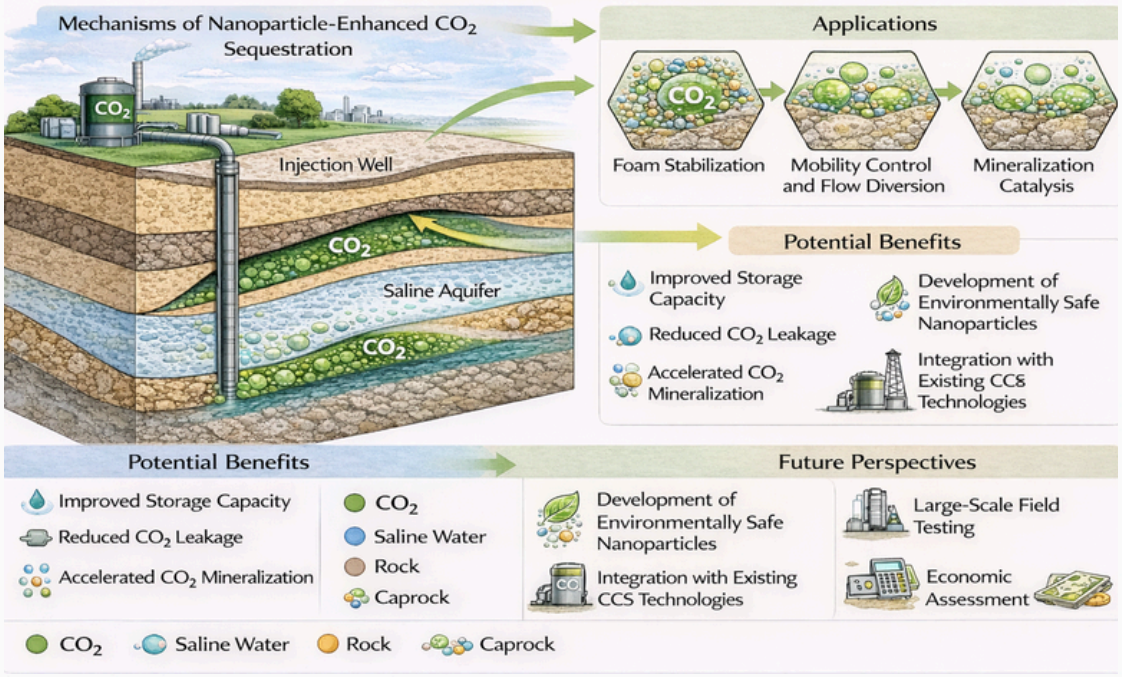

Figure 1. Schematic representation of nanoparticle-assisted CO_2 sequestration in geological formations

Improvement of CO_2 Foam Stability

Nanoparticles are widely used to stabilize CO_2 foams in porous media. CO_2 foams are formed when gas interacts with surfactants or stabilizing agents to form gas bubbles in liquids(Taylor et al., 2014). Foam systems help control gas mobility and improve sweep efficiency in CO_2 sequestration and enhanced oil recovery applications. Nanoparticles adsorb at gas-liquid interfaces and form strong barriers to gas bubbles, preventing bubble coalescence and collapse. Therefore, CO_2 mobility is reduced, allowing the injected gas to spread more evenly across the reservoir. As a result, improved foam stability increases the contact between CO_2 and reservoir fluids and promotes dissolution and mineralization (Zhao et al., 2024).

Mobility Control and Flow Diversion

Another important problem for CO_2 sequestration is the poor mobility ratio of CO_2 and reservoir fluids. Because CO_2 is typically less viscous than brine, it can rapidly travel through high-permeability channels and hence create viscous fingering and can bypass much of the reservoir Patel et al., 2018). Nanoparticles can enhance mobility control by increasing the viscosity of injected fluids and reducing gas mobility (Guerrini et al., 2018). In nanoparticle-stabilized foam systems, nanoparticles help to eliminate high-permeability channels and move CO_2 to previously upswept regions of the reservoir (Singh & Mohanty, 2015). This improved flow distribution improves the areal and vertical sweep efficiency, and CO_2 can occupy a greater volume of the storage formation.

Enhancement of CO_2 Solubility and Mineralization

Nanoparticles can also accelerate chemical reactions between CO_2 and reservoir minerals. Some metal oxide nanoparticles, like magnesium oxide (MgO), calcium oxide (CaO), and iron oxide (Fe_2O_3), may be catalysts for carbonation reactions. In saline aquifers, CO_2 dissolves into formation brine and is then converted into carbonic acid, which reacts with minerals in the reservoir rock to form stable carbonate minerals like calcite, magnesite, and dolomite (Matter & Kelemen, 2009). Nanoparticles can increase the rate of these reactions by providing reactive surfaces that can be used to precipitate minerals. This enhanced mineral trapping mechanism improves long-term storage security by converting CO_2 into solid mineral forms.

Improvement of Reservoir Conformance

The heterogeneity of reservoirs affects CO_2 sequestration efficiency. Geological formations are known to have several layers of permeability that differ, and so CO_2 is distributed in different patterns. Nanoparticles can be used to make the reservoir conformance better by plugging into high-permeability zones. When the nanoparticles are injected into the formation and deposited in larger pore channels, the permeability of the formation decreases. For this reason, CO_2 flows into smaller-permeability zones that, if not weeded, would not be cleaned. As a result, the reservoir storage capacity is increased.

Conclusion

Nanoparticles are an emerging technological tool to optimize CO_2 sequestration efficiency and safety. Due to their unique physicochemical properties, they are highly efficient at trapping, stabilizing CO_2 foams, improving mobility and mineralization reactions, and enhancing reservoir sweep efficiency. Although significant advances have been made in laboratory research, the transport of nanoparticles and the long-term effects on CO_2 have yet to be fully established. As nanoparticle-assisted CO_2 sequestration is developed and tested in the field, it will become an important tool to reduce carbon emissions in the atmosphere and curb climate change.

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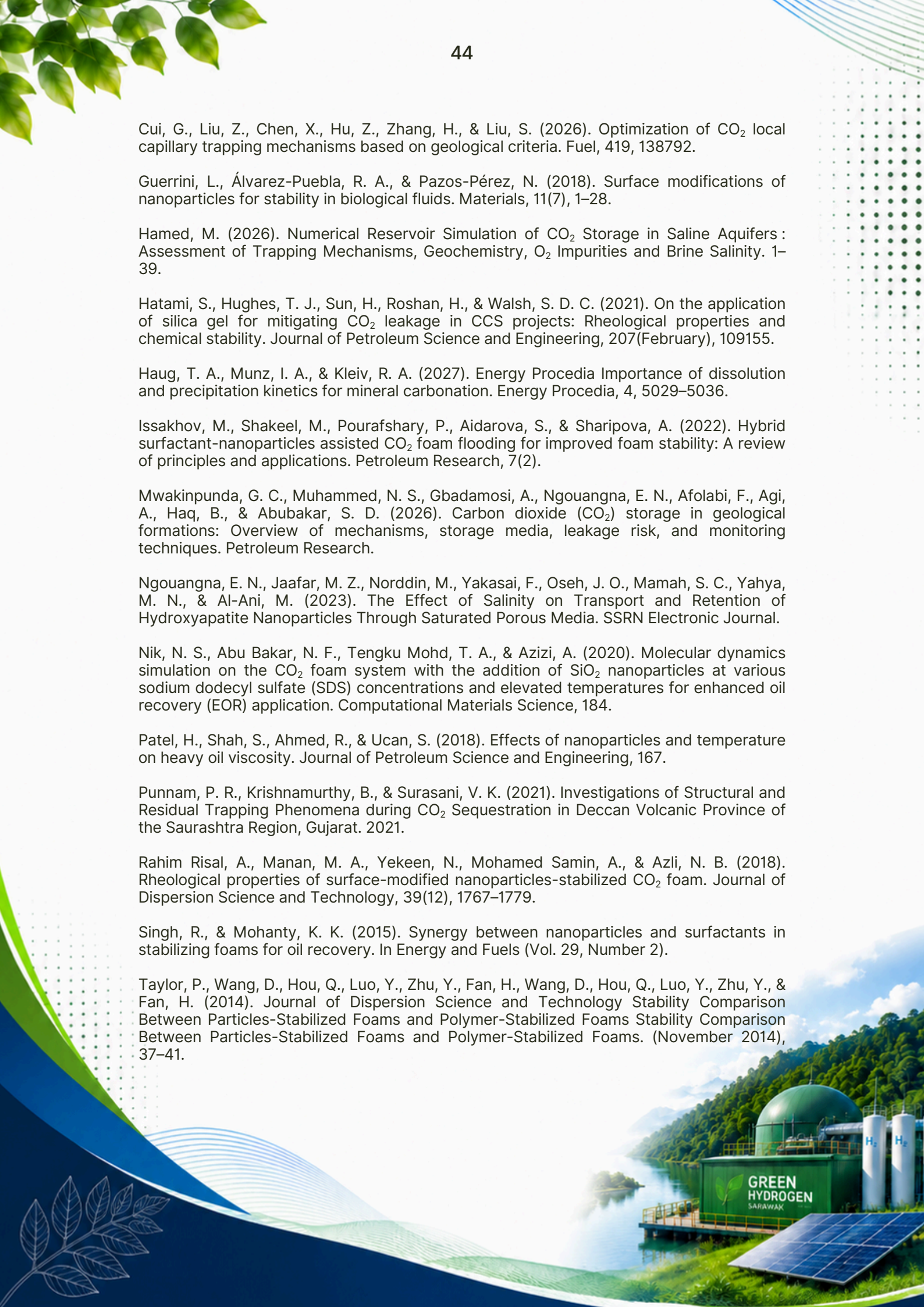

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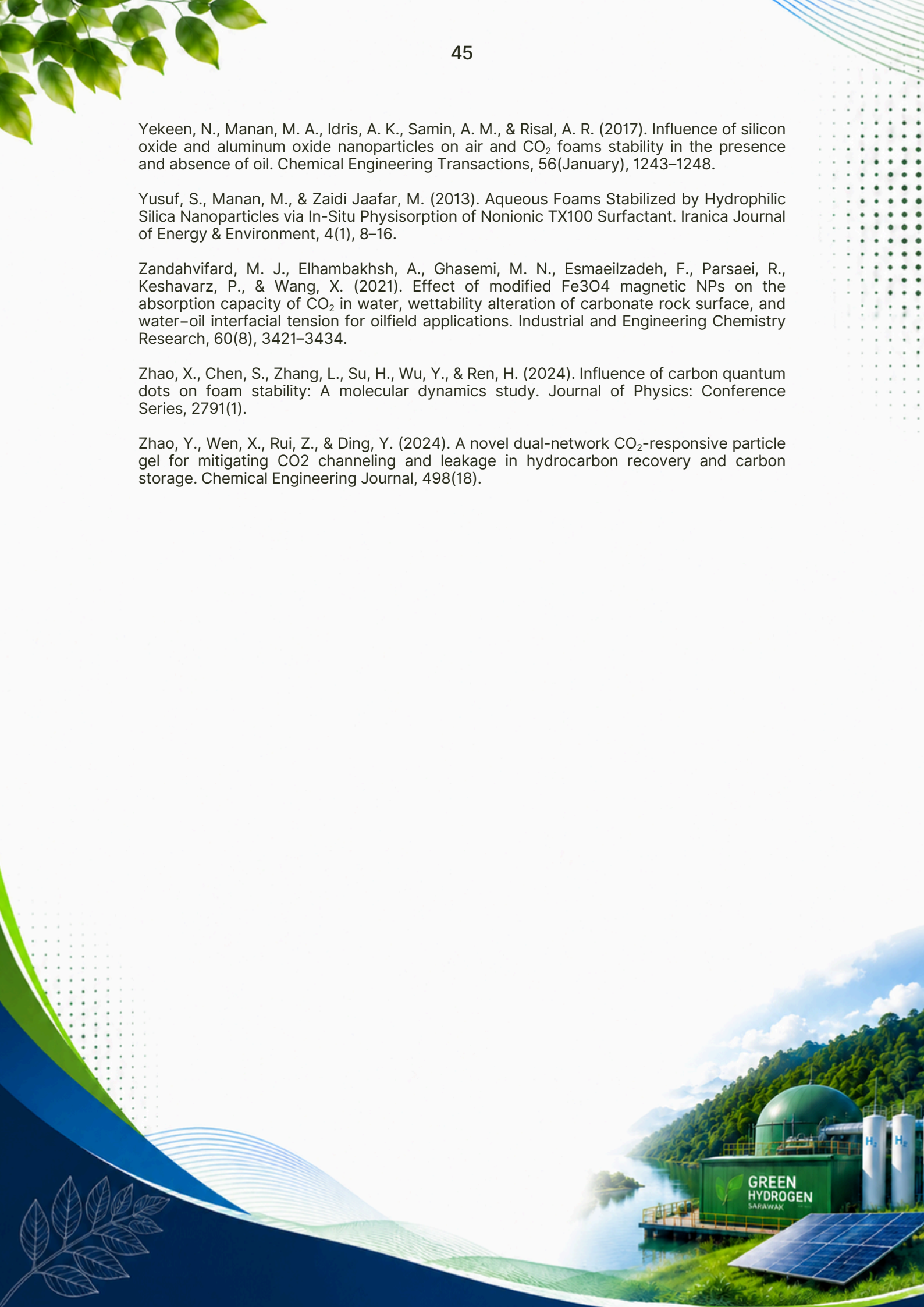

Sustainable Hydrogen Storage Technologies for Clean Energy and Decarbonization

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Introduction

The growing global demand for sustainable and environmentally friendly energy has increased interest in green and low-carbon energy systems. Hydrogen has emerged as a promising clean energy carrier because it produces only water during fuel cell operation and can support the integration of renewable energy sources such as solar and wind power (Liu & Wang, 2025). Despite its advantages, one of the major limitations of hydrogen utilization is the challenge of safe, efficient, and economical storage.

Researchers have therefore investigated different hydrogen storage technologies to improve energy efficiency, reduce carbon emissions, and support the transition toward cleaner energy systems. Existing studies classify hydrogen storage methods into compressed gas storage, liquid hydrogen storage, solid-state storage, and underground geological storage (Tarkowski et al., 2021). This review discusses these major hydrogen storage systems and their relevance to green and low-carbon energy development. Figure 1 illustrates the major hydrogen storage systems and their integration with sustainable green energy production, clean energy applications, and decarbonization goals.



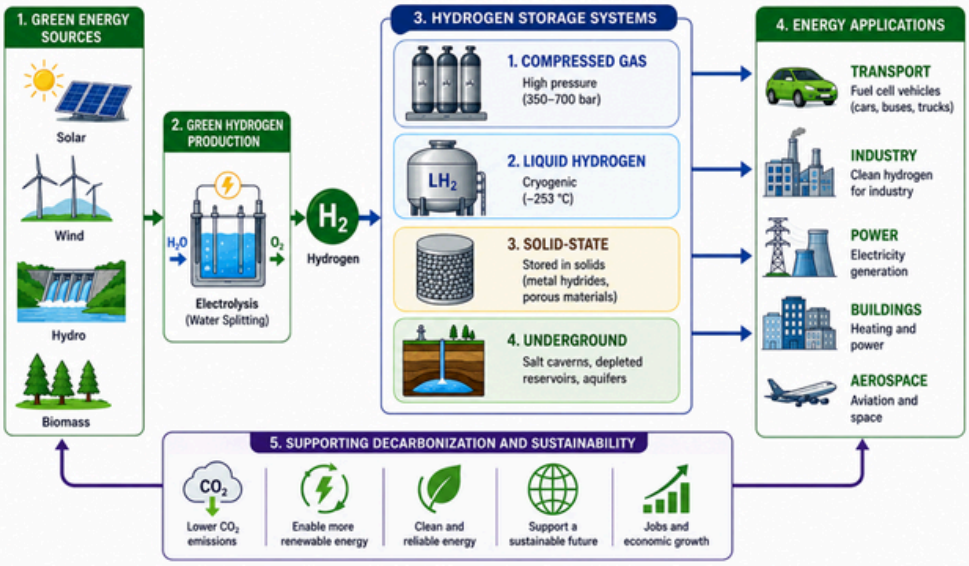


Figure 1. Hydrogen storage systems for green energy and decarbonization applications

Key Discussions

Compressed gas storage is one of the most mature and commercially applied hydrogen storage technologies. According to recent studies, hydrogen is commonly stored at pressures between 350 and 700 bar in high-pressure cylinders and composite tanks (Oni et al., 2021). Researchers have reported that Type III and Type IV composite storage tanks are increasingly used because of their lightweight nature and high mechanical strength. Several authors noted that compressed hydrogen storage is widely applied in fuel cell electric vehicles due to its relatively simple operation and rapid charging capability (Louza et al., 2026). Studies also showed that carbon fiber reinforced composite tanks improve structural performance while reducing tank weight, thereby enhancing transportation efficiency and lowering energy consumption. However, literature reports indicate that hydrogen leakage and permeability through polymer liners remain important challenges. Researchers further observed that high compression energy requirements and safety concerns associated with high-pressure operation continue to limit broader deployment (Dagdag & Kim, 2024).

Liquid hydrogen storage has also received significant attention in low-carbon energy research because liquefied hydrogen possesses a higher volumetric energy density than compressed gas. Studies showed that hydrogen must be cooled to approximately −253°C to achieve liquefaction. Several researchers explained that cryogenic liquid hydrogen systems are particularly important in aerospace and large-scale transport applications. Literature findings indicate that liquid hydrogen storage allows larger quantities of hydrogen to be transported efficiently over long distances (Yadav & Xu, 2012). Despite these advantages, previous studies highlighted several technical challenges, including boil-off losses, high liquefaction energy demand, and the need for sophisticated thermal insulation systems. Researchers therefore emphasized the importance of improving cryogenic insulation technologies and reducing liquefaction costs to support sustainable hydrogen economies.

Solid-state hydrogen storage has been extensively studied as a safer alternative to conventional compressed and liquid hydrogen systems. Literature reports show that hydrogen can be stored within solid materials such as metal hydrides, complex hydrides, and porous adsorbent materials. Researchers observed that solid-state systems provide improved volumetric storage density and lower operational pressures, thereby reducing leakage risks and enhancing safety performance. Some studies further demonstrated that nanostructured materials and advanced hydrides can significantly improve hydrogen absorption and desorption characteristics (Dun et al., 2024). However, many authors identified limitations such as slow kinetics, high material cost, thermal management problems, and low hydrogen release rates. Current research, therefore, focuses on developing advanced nanomaterials and lightweight storage media capable of improving storage efficiency in green energy applications.

Underground hydrogen storage has recently emerged as an important technology for supporting renewable energy integration and large-scale low-carbon energy systems. Existing literature indicates that hydrogen can be stored in salt caverns, depleted oil and gas reservoirs, and deep saline aquifers. Researchers explained that underground storage provides very large storage capacities and can support seasonal energy balancing in renewable energy systems (Zivar et al., 2021). Studies conducted in Europe and North America demonstrated that salt caverns are particularly suitable because of their low permeability and excellent sealing characteristics. Nevertheless, several studies identified concerns related to hydrogen leakage, microbial reactions, geochemical interactions, and long-term storage stability. Researchers therefore recommended further geological investigations and monitoring systems to improve operational safety and environmental sustainability. The various hydrogen storage technologies differ in their operating principles, applications, benefits, limitations, and future development potential. Understanding these differences is important for selecting suitable storage systems that can support sustainable energy utilization, clean energy transition, and decarbonization goals. Table 1 presents a comparison of the major hydrogen storage systems currently used or under development.

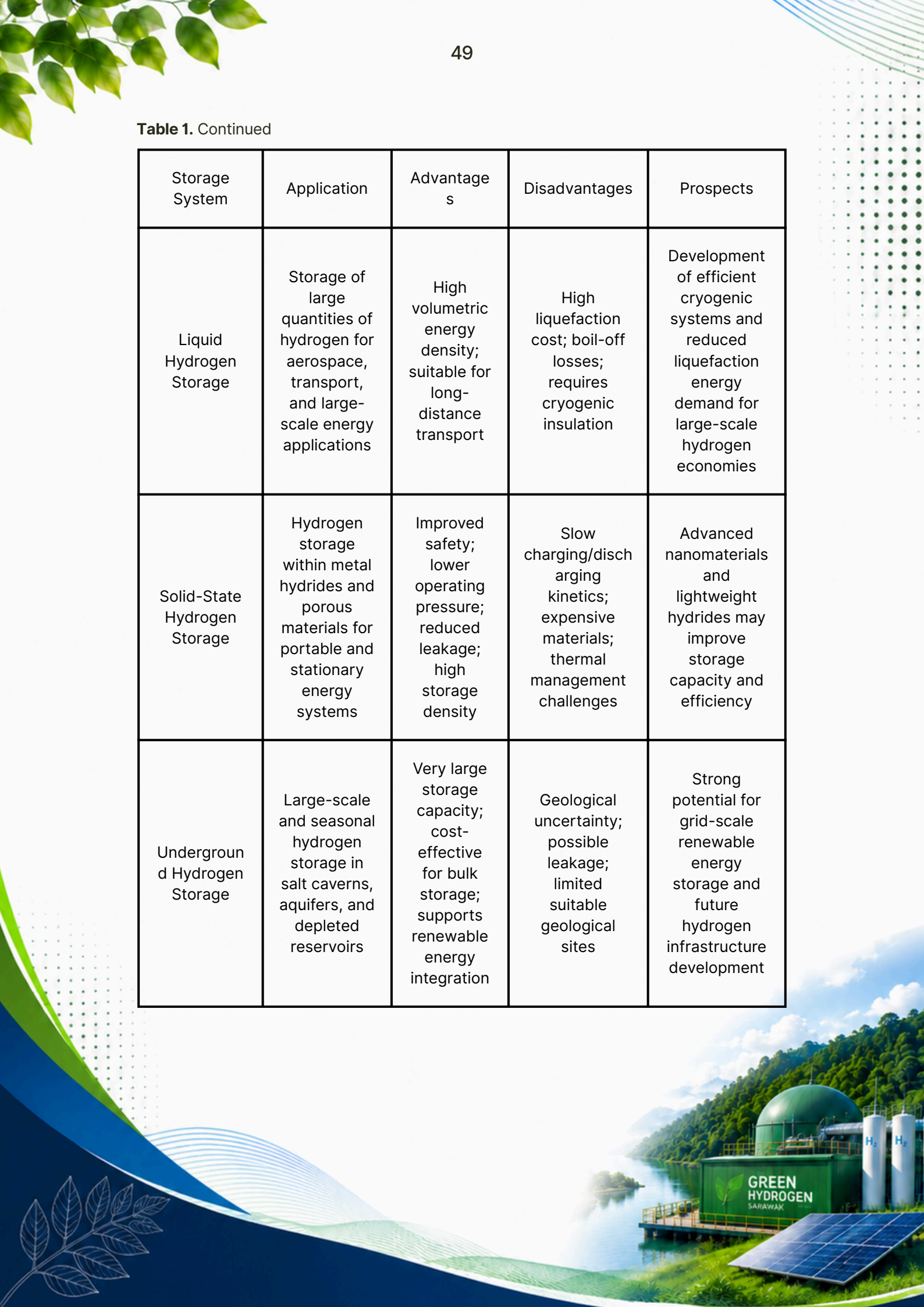
Table 1. Comparison of major hydrogen storage systems for sustainable energy and decarbonization applications

Storage System	Application	Advantages	Disadvantages	Prospects
Compressed Gas Storage	Storage and transport of hydrogen in high-pressure cylinders for fuel cell vehicles and industrial applications	Mature technology; fast charging and discharging; widely commercialized	High compression energy requirement; hydrogen leakage risk; high-pressure safety concerns	Improved composite tanks, lightweight materials, and safer high-pressure systems for transportation and refueling infrastructure



Table 1. Continued

Storage System	Application	Advantages	Disadvantages	Prospects
Liquid Hydrogen Storage	Storage of large quantities of hydrogen for aerospace, transport, and large-scale energy applications	High volumetric energy density; suitable for long-distance transport	High liquefaction cost; boil-off losses; requires cryogenic insulation	Development of efficient cryogenic systems and reduced liquefaction energy demand for large-scale hydrogen economies
Solid-State Hydrogen Storage	Hydrogen storage within metal hydrides and porous materials for portable and stationary energy systems	Improved safety; lower operating pressure; reduced leakage; high storage density	Slow charging/discharging kinetics; expensive materials; thermal management challenges	Advanced nanomaterials and lightweight hydrides may improve storage capacity and efficiency
Underground Hydrogen Storage	Large-scale and seasonal hydrogen storage in salt caverns, aquifers, and depleted reservoirs	Very large storage capacity; cost-effective for bulk storage; supports renewable energy integration	Geological uncertainty; possible leakage; limited suitable geological sites	Strong potential for grid-scale renewable energy storage and future hydrogen infrastructure development



Case Example / Evidence

Recent industrial developments demonstrate the growing importance of hydrogen storage technologies in green and low-carbon energy systems. For example, Toyota and Hyundai have successfully implemented high-pressure hydrogen storage tanks in fuel cell vehicles, promoting low-emission transportation (Kojima & Fukazawa, 2015). In addition, NASA has long utilized liquid hydrogen storage systems in aerospace propulsion because of their high energy efficiency. European countries such as Germany are also investing in underground hydrogen storage within salt caverns to support renewable electricity storage and future hydrogen-based energy networks (Schöb et al., 2023). These developments indicate that hydrogen storage technologies are becoming increasingly important in achieving carbon neutrality and sustainable energy transition goals.

Conclusion

The literature shows that hydrogen storage technologies are essential components of green and low-carbon energy systems. Compressed gas storage currently dominates commercial applications because of its technological maturity, while liquid hydrogen storage provides higher storage density for large-scale transport and aerospace applications. Solid-state storage offers promising safety advantages, whereas underground hydrogen storage provides opportunities for grid-scale renewable energy integration.

Although significant progress has been achieved, several technical and economic challenges remain, including hydrogen permeability, energy losses, material degradation, and high infrastructure costs. Continued research and technological innovation are therefore necessary to improve storage efficiency, safety, and sustainability.

Implications and Recommendations

- Researchers should continue developing advanced low-permeability materials for hydrogen storage systems.
- Greater investment is needed in green hydrogen infrastructure and renewable energy integration.
- Nanomaterials and advanced composite systems should be explored for safer and more efficient hydrogen storage.
- Governments should strengthen policies and funding aimed at supporting low-carbon hydrogen technologies.
- Further studies on underground hydrogen storage are required to ensure long-term environmental and operational safety.

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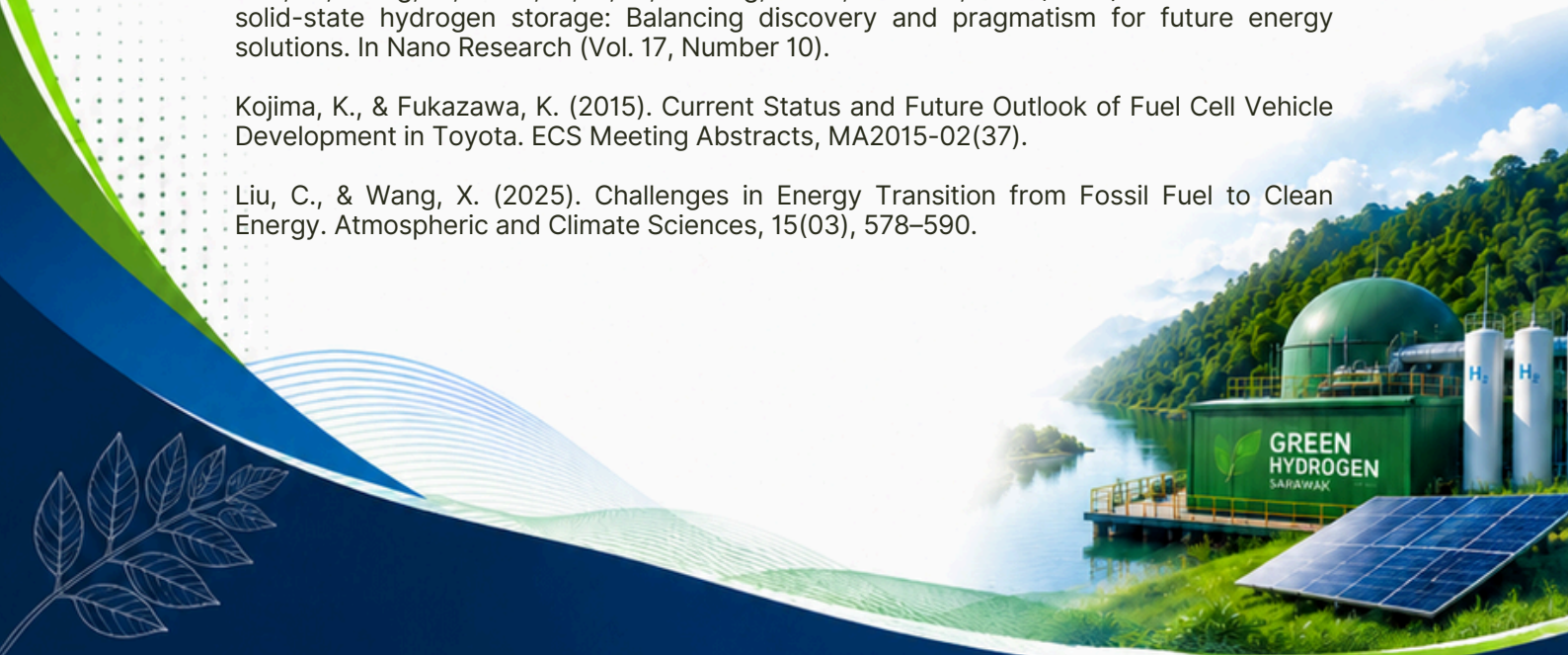

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Production of Pometia Pinnata Seed Biochar for Sustainable Wastewater Treatment Applications

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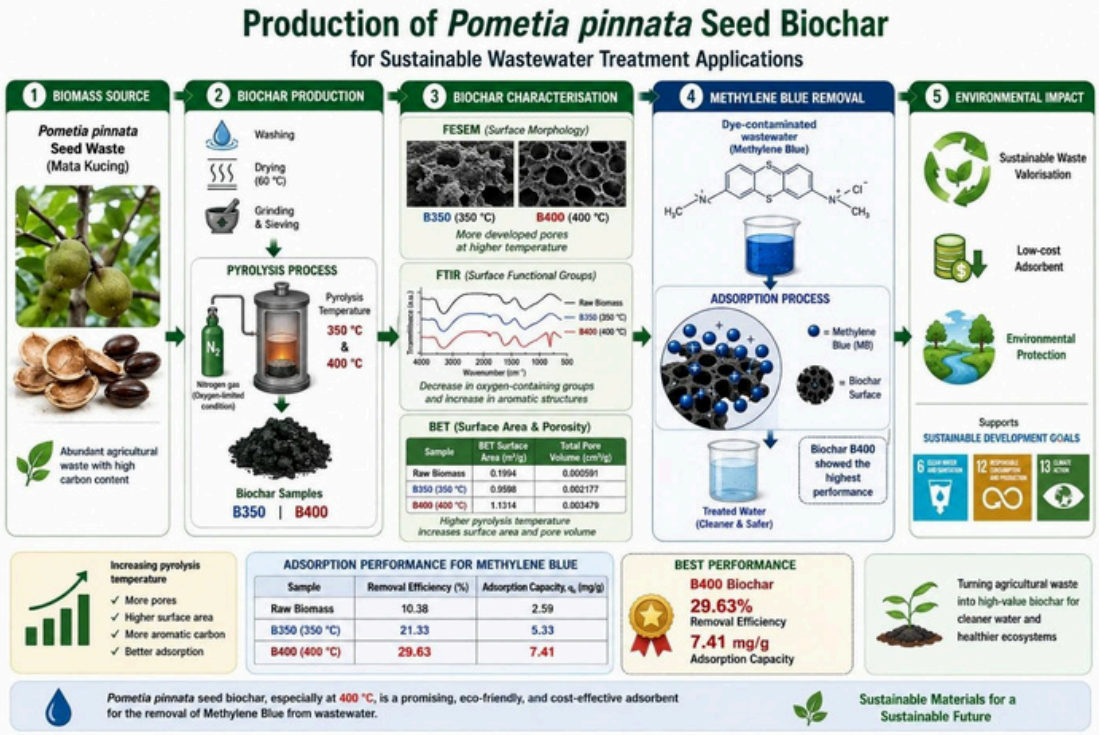


Figure 1. The overview of production of pometia pinnata seed biochar for sustainable wastewater treatment applications.

Introduction

Water pollution caused by industrial activities has become one of the major environmental issues worldwide. Among various pollutants, synthetic dyes released from textile, printing, and laboratory industries are highly concerning due to their stability, toxicity, and resistance to degradation. The presence of dyes in aquatic systems reduces light penetration, affects photosynthesis, and disrupts aquatic ecosystems (Adeoye et al., 2025; Sutar et al., 2024). Even at low concentrations, coloured wastewater can significantly affect water quality and ecosystem balance.

Methylene Blue (MB) is a commonly used cationic dye widely applied in textile and laboratory industries. Due to its aromatic ring structure and high chemical stability, MB is difficult to remove through conventional biological and chemical treatment processes (Zhu et al., 2024). As a result, adsorption has emerged as one of the most effective and economical methods for dye removal from wastewater.

In recent years, biochar has gained increasing attention as a sustainable adsorbent material. Biochar is a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions. Biochar possesses desirable characteristics such as porous structure, surface functional groups, and high adsorption potential, making it suitable for environmental remediation applications (Tomczyk et al., 2020).

Agricultural and biomass wastes are increasingly explored as biochar precursors because they are abundant, renewable, and inexpensive. One potential biomass source is Pometia pinnata seed, locally known as “mata kucing”. These seeds are often discarded as agricultural waste despite containing high carbon content and lignocellulosic components suitable for biochar production. Converting such waste into functional adsorbent materials supports sustainable waste management and circular economy practices.

Therefore, this study focuses on the production of biochar derived from Pometia pinnata seeds at different pyrolysis temperatures and evaluates its performance for Methylene Blue removal from aqueous solution. The study also examines the influence of pyrolysis temperature on the physicochemical properties and adsorption behaviour of the produced biochar. Figure 1 shows the overview of production of pometia pinnata seed biochar for sustainable wastewater treatment applications.

Biochar and Sustainable Waste Management

Biochar is produced through thermal decomposition of biomass under limited oxygen conditions. Depending on the feedstock and pyrolysis temperature, biochar may exhibit different physicochemical characteristics such as pore structure, surface area, and surface chemistry (Leng et al., 2021). These characteristics strongly influence its adsorption performance for pollutants.

Compared to conventional activated carbon, biochar offers several advantages including lower production cost, simpler preparation process, and sustainable utilisation of biomass waste. Biochar production also contributes to waste valorisation by converting agricultural residues into useful environmental materials (Wang et al., 2021).
Different biomass feedstocks such as rice husk, coconut shell, corn cob, and fruit seeds have been investigated for biochar production. Recent studies reported that seed-derived biochar exhibits promising adsorption performance due to its porous structure and high carbon content (Mutolib et al., 2023). However, studies involving Pometia pinnata seed biochar remain limited.



The use of biomass waste for wastewater treatment aligns closely with ecosystem sustainability and environmental protection strategies. Sustainable utilisation of agricultural waste not only reduces solid waste disposal problems but also provides low-cost solutions for pollution control. Thus, biochar technology represents an environmentally friendly approach that integrates waste management and water treatment simultaneously.

Production of Pometia pinnata Seed Biochar

The Pometia pinnata seeds used in this study were first washed thoroughly to remove impurities and dirt. The cleaned seeds were oven-dried at 60 °C until constant weight was achieved. After drying, the seeds were ground into smaller particles and sieved to obtain uniform particle size.

Biochar production was conducted using the pyrolysis method under oxygen-limited conditions. The prepared biomass was heated in a muffle furnace at two different temperatures: 350 °C and 400 °C. Nitrogen gas was supplied continuously during pyrolysis to maintain an inert environment and prevent combustion.

After the pyrolysis process, the produced biochar samples were washed with distilled water until neutral pH was obtained. The biochar was then dried and stored in airtight containers prior to characterisation and adsorption experiments.

Pyrolysis temperature plays an important role in determining the characteristics of biochar. Higher pyrolysis temperatures generally promote carbonisation, pore development, and removal of volatile compounds, resulting in improved adsorption properties (Ge et al., 2023).

Characterisation of Biochar

The produced biochar samples were characterised using Field Emission Scanning Electron Microscopy (FESEM), Fourier Transform Infrared Spectroscopy (FTIR), and Brunauer–Emmett–Teller (BET) surface area analysis.

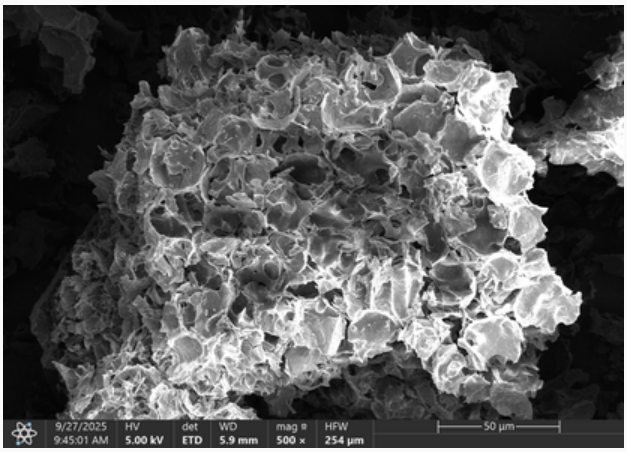
Surface Morphology Analysis

FESEM analysis (Figure 2.) revealed significant changes in the surface morphology of biochar after pyrolysis. Biochar produced at 350 °C showed rough and irregular surfaces with initial pore formation. Meanwhile, biochar produced at 400 °C exhibited more developed pores and rougher surface texture.

The increase in pore development at higher pyrolysis temperature is associated with greater decomposition of biomass components and volatilisation processes during carbonisation. The porous structure is important because it increases the available surface area for adsorption.



a)



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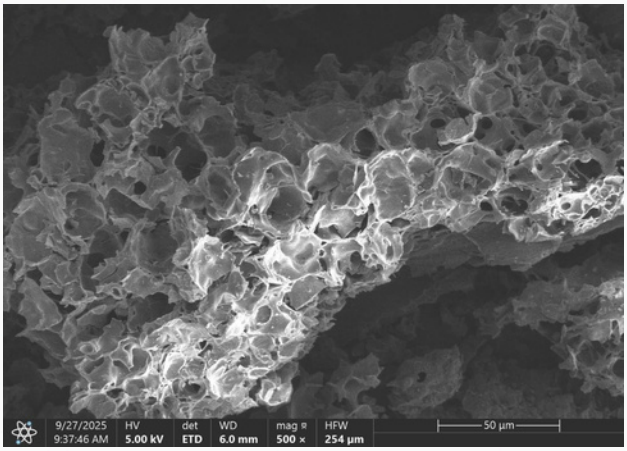

Figure 2. FESEM image of a) Pometia pinnata seed-derived biochar produced at 350 °C (magnification: 500x) and b) FESEM image of Pometia pinnata seed-derived biochar produced at 400 °C (magnification: 500x)

Functional Group Analysis

FTIR analysis (Figure 3) was conducted to identify the surface functional groups of the biochar samples. The raw biomass showed strong hydroxyl (-OH), carbonyl (C=O), and aliphatic C-H functional groups.

After pyrolysis, the intensity of oxygen-containing functional groups decreased significantly, especially for biochar produced at 400 °C. At the same time, aromatic C=C structures became more dominant, indicating increased carbonisation and aromaticity. These chemical changes influence the interaction between biochar surface and dye molecules during adsorption processes.

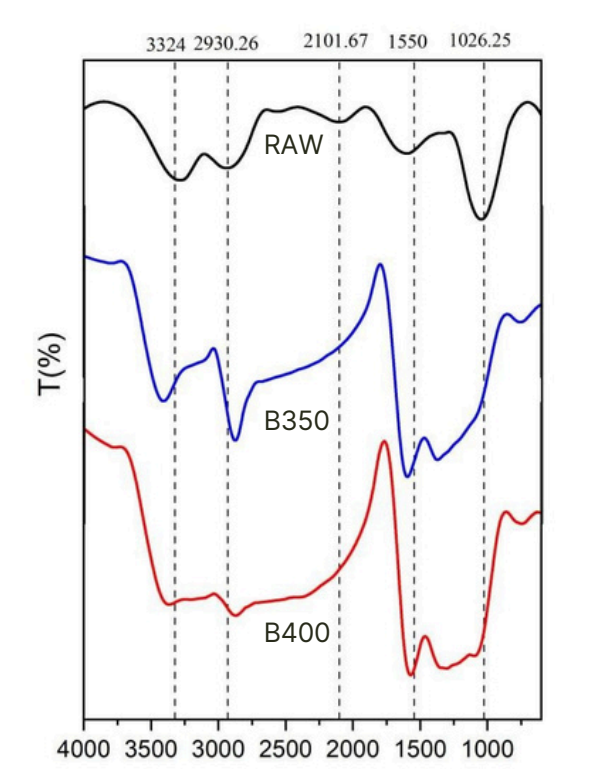

Figure 3. FTIR spectra of raw biomass and biochar samples

BET Surface Area Analysis

BET analysis (Table 1) showed that pyrolysis temperature significantly affected the surface area and pore volume of biochar.

Table 1. BET Surface Area and Pore Characteristics

Sample	BET Surface Area (m^2/g)	Total Pore Volume (cm^3/g)
Raw Biomass	0.1994	0.000591
B350	0.9598	0.002177
B400	1.1314	0.003479

Biochar produced at 400 °C exhibited the highest surface area and pore volume. The enhanced porosity and surface area contribute to improved adsorption performance because more active sites become available for pollutant interaction.

Adsorption Performance for Methylene Blue Removal
The adsorption performance of the biochar samples (Table 2) was evaluated using batch adsorption experiments with Methylene Blue solution at an initial concentration of 50 mg/L. The experiments showed that adsorption performance improved with increasing pyrolysis temperature. Biochar produced at 400 °C (B400) achieved the highest removal efficiency and adsorption capacity compared to B350 and raw biomass.

Table 2. Adsorption Performance of Biochar Samples

Sample	Removal Efficiency (%)	Adsorption Capacity, q_e (mg/g)
Raw Biomass	10.38	2.59
B350	21.33	5.33
B400	29.63	7.41

The improved adsorption performance of B400 is associated with its larger surface area, higher pore volume, and enhanced aromatic carbon structures. These characteristics promote stronger interaction between the biochar surface and Methylene Blue molecules through electrostatic attraction and π–π interactions. The results indicate that increasing pyrolysis temperature within the studied range improved the physicochemical properties and adsorption capacity of the biochar.

Environmental and Ecosystem Implications
The utilisation of Pometia pinnata seed waste for biochar production demonstrates a sustainable strategy for biomass waste management. Agricultural waste materials are often discarded without proper utilisation, contributing to environmental pollution. Converting these wastes into functional adsorbent materials supports circular economy principles and sustainable resource management.

In addition, biochar technology provides an environmentally friendly approach for wastewater treatment applications. The use of low-cost biomass-derived adsorbents may reduce dependence on expensive commercial activated carbon while promoting sustainable environmental remediation technologies.

The findings of this study also contribute to ecosystem science by highlighting the importance of integrating waste management and pollution control strategies. Sustainable wastewater treatment is essential for protecting aquatic ecosystems and maintaining environmental quality.



Conclusion

This study successfully produced biochar from Pometia pinnata seeds using pyrolysis at 350 °C and 400 °C and evaluated its adsorption performance for Methylene Blue removal. The results showed that increasing pyrolysis temperature improved the physicochemical properties of the biochar, including surface area, pore development, and aromatic carbon structures. Biochar produced at 400 °C exhibited the best adsorption performance with the highest removal efficiency and adsorption capacity. Overall, Pometia pinnata seed biochar shows strong potential as a sustainable and low-cost adsorbent material for wastewater treatment applications. The study also highlights the environmental benefits of converting agricultural waste into valuable materials for ecosystem protection and sustainable water management.

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Carbon Capture, Utilisation and Storage (CCUS): Sarawak's Pathway Towards a Low-Carbon Economy

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Introduction

Climate change has become one of the most critical environmental challenges facing the world today due to the increasing concentration of greenhouse gases, particularly carbon dioxide (CO_2), in the atmosphere. Industrialisation, fossil fuel combustion, transportation activities, and energy-intensive manufacturing sectors continue to contribute significantly to global carbon emissions (IPCC, 2023). The accumulation of atmospheric CO_2 is closely associated with rising global temperatures, sea-level rise, ecosystem degradation, and increasingly frequent extreme weather events that threaten environmental sustainability and human wellbeing.

As countries intensify efforts to achieve net-zero carbon emissions, Carbon Capture, Utilisation and Storage (CCUS) has emerged as one of the most important technological solutions for reducing industrial carbon emissions while supporting economic growth and energy security. CCUS refers to the process of capturing carbon dioxide emissions from industrial sources before they are released into the atmosphere, followed by utilisation for industrial applications or permanent storage within deep geological formations (Global CCS Institute, 2024).

Globally, CCUS is increasingly recognised as an essential mitigation strategy for hard-to-abate sectors such as oil and gas, cement, steel, and petrochemical industries, where complete decarbonisation remains technically challenging (IEA, 2024). In Malaysia, Sarawak is rapidly positioning itself as a strategic hub for CCUS development due to its extensive geological storage potential, established energy infrastructure, and proactive commitment towards low-carbon development.

Sarawak's ambition to become a regional leader in sustainable energy technologies is further strengthened through initiatives such as the Sarawak Hydrogen Economy Roadmap (SHER), renewable energy expansion, and offshore carbon storage projects. These initiatives reflect the state's long-term commitment towards balancing industrial development with environmental sustainability and climate resilience.



Understanding Carbon Capture, Utilisation and Storage (CCUS)
CCUS is an integrated technology designed to reduce carbon emissions by capturing CO_2 from industrial processes and preventing its release into the atmosphere. The process generally consists of three major stages: carbon capture, carbon utilisation, and carbon storage.

1. Carbon Capture
Carbon capture involves separating CO_2 from industrial emission sources such as power plants, natural gas processing facilities, petrochemical industries, and manufacturing sectors. Several technologies are currently used for carbon capture, including post-combustion capture, pre-combustion capture, and oxy-fuel combustion systems.

Among these technologies, post-combustion capture is widely applied because it can be integrated into existing industrial facilities with relatively lower infrastructure modification. Captured CO_2 is then compressed for transportation to utilisation or storage sites.

2. Carbon Utilisation
Captured CO_2 may be utilised for various industrial applications including enhanced oil recovery (EOR), chemical manufacturing, synthetic fuel production, carbonated beverages, and construction materials. Recent technological advancements have also explored the conversion of CO_2 into value-added products such as methanol, sustainable aviation fuels, and industrial chemicals.

Carbon utilisation not only reduces emissions but also supports the development of a circular carbon economy where carbon resources are reused productively rather than released into the environment.

3. Carbon Storage
Carbon storage involves injecting compressed CO_2 into deep underground geological formations such as depleted oil and gas reservoirs or saline aquifers. These geological formations are capable of trapping CO_2 safely for thousands of years through structural, residual, and mineral trapping mechanisms. Long-term monitoring and geological assessment are essential to ensure storage integrity and environmental safety throughout the storage period.

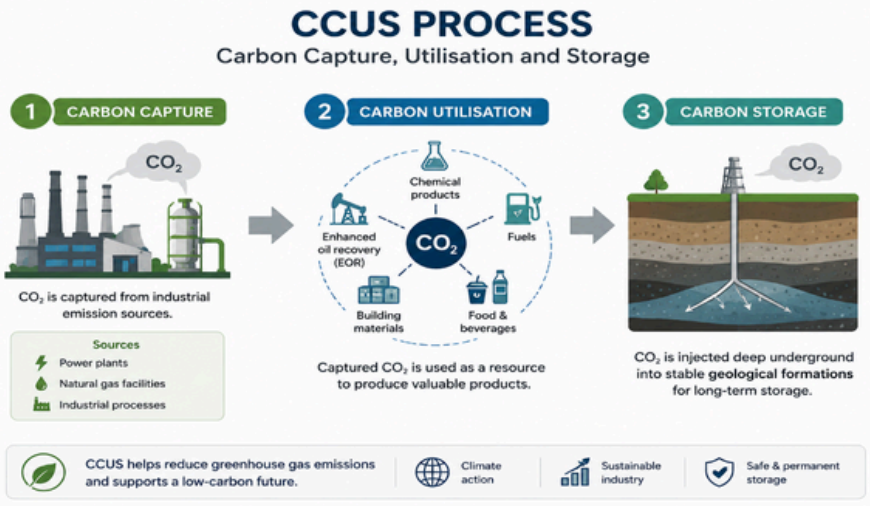

Figure 1. Simplified Overview of Carbon Capture, Utilisation and Storage (CCUS) Process

Sarawak's Potential as a Regional CCUS Hub

Sarawak possesses several strategic advantages that make the state highly suitable for CCUS implementation. One of the major strengths is the availability of extensive offshore geological formations within the Central Luconia region, which are considered highly promising for long-term carbon storage applications (Hassan et al., 2025).

The offshore reservoirs in Sarawak have previously stored hydrocarbons naturally for millions of years, indicating favourable geological characteristics for permanent CO_2 sequestration. Studies have suggested that Sarawak may contain a significant proportion of Malaysia's potential geological carbon storage capacity (Abdullah et al., 2024).

Apart from favourable geological conditions, Sarawak also benefits from a mature oil and gas industry supported by well-established infrastructure including offshore platforms, subsea pipelines, processing facilities, and liquefied natural gas (LNG) plants. The availability of such infrastructure may reduce future development costs associated with CO_2 transportation and injection systems.

Sarawak's strategic location within Southeast Asia further enhances its potential to become a regional carbon storage hub capable of supporting neighbouring countries and international industries seeking carbon management solutions.

The Sarawak Government has also demonstrated strong commitment towards low-carbon development through strategic initiatives involving renewable energy, hydrogen economy expansion, and sustainable industrial transformation. Petroleum Sarawak Berhad (PETROS) has been appointed as the resource manager for carbon storage activities within the state, strengthening the governance and regulatory framework for future CCUS projects.

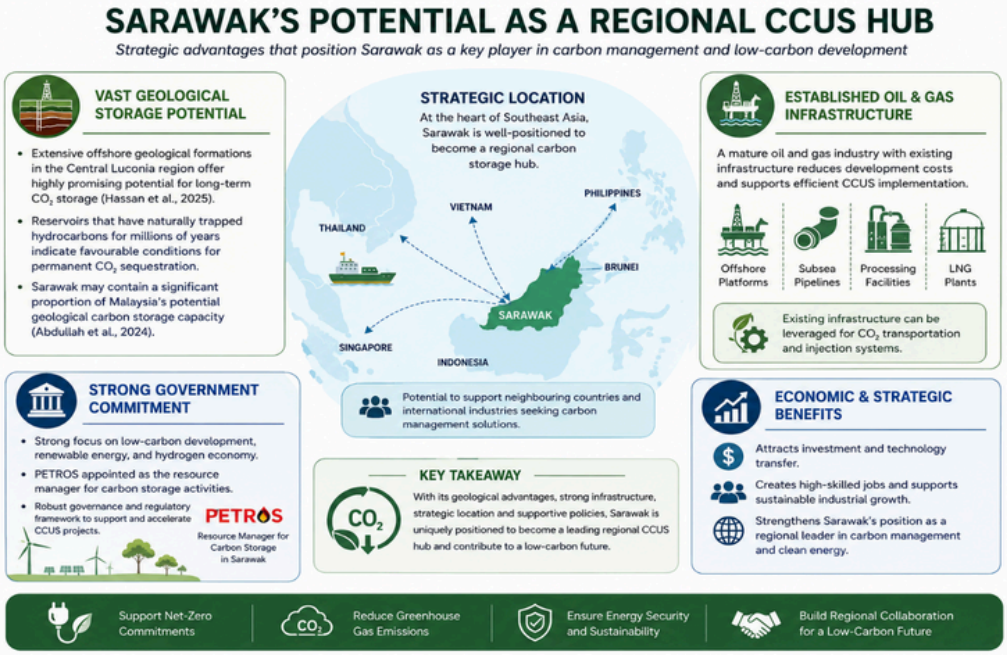

Figure 2. Sarawak's Strategic Potential as a Regional Carbon Capture, Utilisation and Storage (CCUS) Hub

Government Policies and Strategic Initiatives
The Sarawak Government has introduced several important policies and initiatives to support the development of CCUS technologies and low-carbon economic transition.

One of the major milestones was the implementation of the Land (Carbon Storage) Rules 2022, which established legal and regulatory frameworks governing carbon storage activities within Sarawak. The regulation provides guidance related to licensing procedures, environmental monitoring, operational safety, and long-term management of storage sites.

In addition, the Sarawak Hydrogen Economy Roadmap (SHER) outlines the state's long-term strategy for becoming a regional leader in hydrogen production and clean energy technologies (MEESty, 2024). CCUS technologies play an important role in supporting hydrogen production, particularly for blue hydrogen systems where carbon emissions generated during hydrogen production are captured and stored.

Recent offshore carbon storage bid rounds organised by PETROS have also attracted significant international interest from energy companies and investors seeking to participate in Sarawak's emerging carbon management sector. These developments indicate growing confidence in Sarawak's potential as a future regional hub for CCUS and sustainable energy industries.

Environmental and Economic Benefits of CCUS
1. Reduction of Greenhouse Gas Emissions
One of the primary environmental benefits of CCUS is its ability to significantly reduce CO_2 emissions from industrial sectors. By preventing carbon emissions from entering the atmosphere, CCUS contributes directly towards climate change mitigation and supports Malaysia's commitment to achieving net-zero greenhouse gas emissions by 2050. This technology is particularly important for hard-to-abate industries where alternative low-carbon technologies remain limited or economically challenging.

2. Sustainable Industrial Development
CCUS enables industries to continue operating while reducing environmental impacts associated with carbon emissions. This allows industrial sectors such as oil and gas, petrochemicals, cement manufacturing, and energy production to transition gradually towards more sustainable operations without compromising economic productivity.

3. Economic Growth and Investment Opportunities
The development of CCUS technologies may also generate substantial economic opportunities, including:

- Attraction of international green investments
- Development of new industrial sectors
- Creation of high-skilled employment opportunities
- Expansion of carbon management services
- Technology transfer and innovation growth

Sarawak's potential role as a regional carbon storage hub may further strengthen the state's competitiveness within the global low-carbon economy.

4. Support for Circular Carbon Economy
CCUS supports the concept of a circular carbon economy where captured carbon is reused, recycled, or stored responsibly instead of being released into the atmosphere. This approach aligns closely with sustainable resource management and long-term environmental protection strategies.



Challenges in CCUS Implementation

1. High Operational Costs

Carbon capture systems require substantial investment due to complex engineering processes, high energy consumption, and infrastructure development costs. Large-scale deployment therefore requires strong financial support and long-term investment strategies.

2. Technical and Infrastructure Requirements

CCUS projects involve sophisticated engineering systems, specialised expertise, and continuous monitoring technologies to ensure safe and efficient operations. Long-term geological monitoring is particularly important to maintain storage integrity and minimise environmental risks.

3. Regulatory and Policy Coordination

Effective implementation of CCUS requires close coordination between federal agencies, state governments, industries, and international stakeholders. Clear policies and regulatory consistency are essential to improve investment confidence and facilitate project development.

4. Public Awareness and Acceptance

Public understanding regarding CCUS technologies remains relatively limited. Therefore, transparent communication, public engagement programmes, and scientific awareness initiatives are important to improve public confidence regarding the safety and environmental benefits of carbon storage technologies.

Role of Universities and Research Institutions

Universities and research institutions in Sarawak can play an important role in supporting CCUS development through scientific research, technological innovation, and human capital development.

Potential research areas include:

- Carbon adsorbent materials
- Biochar and activated carbon technologies
- CO_2 adsorption systems
- Geological storage monitoring
- Environmental risk assessment
- Sustainable energy systems
- Carbon utilisation technologies
- Waste-to-resource conversion technologies

Research collaboration between universities, industries, and government agencies can accelerate technological advancement while strengthening local expertise in carbon management and sustainability. The integration of ecosystem science, environmental engineering, and sustainable technology research is essential to ensure that CCUS development remains environmentally responsible and socially sustainable.



Future Outlook of CCUS in Sarawak

Sarawak's future in CCUS development appears highly promising due to favourable geological conditions, strong policy support, and increasing global demand for carbon management solutions.

As industries worldwide continue transitioning towards sustainability and net-zero targets, Sarawak has the potential to emerge as:

- A regional carbon storage hub
- A leader in hydrogen and clean energy technologies
- A centre for sustainable industrial innovation
- A strategic destination for green investments

Continuous collaboration among government agencies, industries, universities, and international stakeholders will be crucial in ensuring the successful implementation of CCUS technologies in the state.

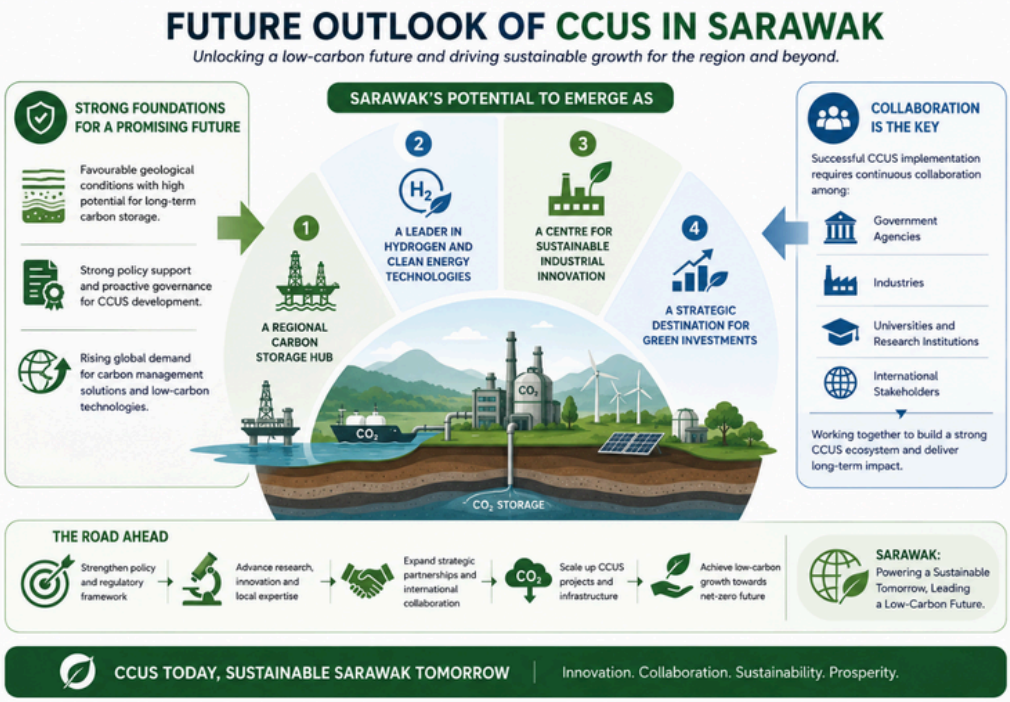

Figure 3. Future Outlook of Carbon Capture, Utilisation and Storage (CCUS) Development in Sarawak

Conclusion

Carbon Capture, Utilisation and Storage (CCUS) represent a transformative opportunity for Sarawak to lead the transition towards a sustainable and low-carbon economy. Supported by extensive geological storage potential, established industrial infrastructure, and proactive government initiatives, Sarawak is strategically positioned to become a major regional hub for carbon management and clean energy development.

The successful implementation of CCUS technologies offers multiple environmental and economic benefits, including greenhouse gas reduction, industrial sustainability, green investment attraction, and technological innovation. However, continued collaboration among government agencies, industries, research institutions, and local communities remains essential to address technical, economic, and regulatory challenges associated with CCUS deployment.

Overall, the development of CCUS in Sarawak reflects the growing importance of integrating environmental sustainability, technological advancement, and economic resilience in achieving long-term climate goals and ecosystem protection.

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Slag Beyond Waste: Advancing Circular Economy and Environmental Sustainability

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Introduction

Industrial development has played a major role in supporting economic growth, urbanisation, infrastructure expansion, and technological advancement worldwide. However, rapid industrialisation has also resulted in increasing environmental concerns, particularly regarding industrial waste generation. Among the major industrial by-products generated globally is slag, a solid residue produced during metal smelting and refining processes. For decades, slag was often considered an unwanted waste material and disposed of in landfills or open dumping areas. Nevertheless, increasing awareness regarding environmental sustainability and resource conservation has transformed the perception of slag from industrial waste into a potentially valuable secondary resource.

Today, slag is increasingly recognised for its beneficial properties and wide range of applications in environmental management, construction industries, wastewater treatment, carbon management, and sustainable material development. Instead of occupying landfill space and posing long-term environmental risks, slag can be reused, recycled, and valorised into functional products that support circular economy practices.
The growing interest in slag utilisation is strongly aligned with global sustainability goals, particularly in reducing industrial waste, conserving natural resources, minimising greenhouse gas emissions, and promoting cleaner industrial production. In Malaysia, including Sarawak, the exploration of sustainable industrial waste management strategies has become increasingly important due to ongoing industrial expansion and the nation's commitment towards environmental sustainability.

The increasing concern over industrial waste generation has encouraged many countries to reconsider how industrial by-products are managed and utilised. Rather than viewing industrial residues as unwanted waste materials, researchers and industries are now exploring methods to convert these by-products into valuable resources that can support sustainable development. Among the industrial by-products receiving growing attention worldwide is slag. In recent years, slag has emerged as an important material in environmental engineering, sustainable construction, wastewater treatment, and carbon management applications.



The global transition towards greener industries and circular economy practices has accelerated interest in slag valorisation technologies. This shift is driven by increasing environmental regulations, rising landfill limitations, climate change concerns, and the need for more sustainable resource management strategies. According to recent studies, slag-based applications can contribute significantly towards reducing industrial waste disposal while simultaneously generating economic and environmental benefits (Li et al., 2024; Zhao et al., 2025).

The utilisation of slag is particularly relevant in the context of sustainable industrial development because many industrial sectors continue to generate substantial quantities of solid waste annually. Traditionally, these materials were disposed of in landfills or stockpiled in open areas, creating long-term environmental burdens and increasing waste management costs. However, advancements in material science and environmental engineering have demonstrated that slag possesses valuable physical and chemical characteristics that make it suitable for a wide range of industrial and environmental applications.

In many countries, slag is now considered a secondary raw material capable of supporting low-carbon technologies, sustainable infrastructure development, and resource recovery systems. The growing body of research related to slag valorisation indicates that industrial waste materials may play an important role in future green technology development and circular economy implementation. This article discusses the formation and characteristics of slag, environmental concerns associated with slag disposal, sustainable utilisation approaches, and future opportunities for slag valorisation in supporting green and low-carbon development.

Overview of Industrial Slag

Slag is a non-metallic by-product generated during metallurgical and industrial processes involving high temperatures. It forms when impurities present in ores, fuels, and raw materials react with fluxing agents during smelting or refining operations. These impurities separate from molten metals and solidify into slag.

Depending on the industrial process involved, slag may contain varying proportions of calcium oxide, silicon dioxide, aluminium oxide, magnesium oxide, iron oxide, and trace metals. The physical and chemical properties of slag differ according to the raw materials used, furnace operating conditions, and cooling methods.

Several major types of slag are commonly produced worldwide:

1. Blast Furnace Slag

Blast furnace slag is produced during iron manufacturing in blast furnaces. It is one of the most widely utilised slags due to its cementitious properties and suitability for construction applications.





Figure 1. Blast Furnace Slag and Its Sustainable Applications

2. Steel Slag

Steel slag is generated during steel refining processes. It often contains higher concentrations of iron, calcium, and magnesium compounds.



Figure 2. Steel Slag and Its Sustainable Applications

3. Copper Slag
Copper slag is produced during copper smelting operations and is commonly investigated for abrasive materials, construction aggregates, and environmental applications.



Figure 3. Copper Slag and Its Sustainable Applications

4. Nickel Slag
Nickel slag is generated during nickel extraction and processing industries. Sarawak and other regions with industrial metal processing activities may potentially generate nickel-related industrial by-products in the future.



Figure 4. Nickel Slag and Its Sustainable Applications

5. Electric Arc Furnace Slag
Electric arc furnace slag is produced during electric steelmaking operations and possesses strong mechanical properties suitable for road construction and pavement applications.



Figure 5. Electric Arc Furnace Slag and Its Sustainable Applications

The characteristics of slag vary significantly depending on its origin. Some slags exhibit high hardness and durability, while others possess porous structures and adsorption capabilities useful for environmental remediation.

Environmental Issues Associated with Slag Disposal
Although slag can provide useful industrial applications, improper disposal and management may create environmental challenges. Large quantities of untreated slag deposited in open environments may contribute to long-term ecological impacts. One major concern is the potential leaching of heavy metals and hazardous compounds into surrounding soil and groundwater systems. Certain slags may contain trace amounts of chromium, lead, cadmium, arsenic, or other metals that can migrate into the environment under specific conditions.

In addition, extensive slag disposal areas may occupy valuable land resources, alter surrounding landscapes, generate dust pollution, affect nearby ecosystems, increase environmental monitoring costs and contribute towards long term waste management burdens. Another concern involves the increasing accumulation of industrial waste due to rapid industrial growth. Traditional disposal approaches are becoming less sustainable because of rising landfill limitations and stricter environmental regulations.

As industries move towards Environmental, Social, and Governance (ESG) practices, sustainable slag management is becoming increasingly important. Rather than viewing slag solely as waste, industries and researchers are now exploring methods to transform slag into useful products that minimize environmental impact while generating economic value.

Slag in Construction and Infrastructure Development

The increasing use of slag in construction and infrastructure industries reflects the growing demand for sustainable building materials and environmentally responsible industrial practices. Construction industries worldwide consume enormous quantities of raw materials every year, including cement, sand, gravel, and natural aggregates. The extraction and processing of these materials contribute significantly towards environmental degradation, greenhouse gas emissions, and depletion of natural resources.

As a result, researchers and industries have intensified efforts to identify alternative materials capable of reducing dependence on virgin raw materials while maintaining engineering performance and structural durability. Slag has become one of the most promising alternatives because of its favourable mechanical properties, chemical stability, and cementitious characteristics.

Recent studies have reported that incorporating slag into construction materials not only improves material performance but also contributes towards lower environmental impacts through waste minimisation and carbon emission reduction (Biava et al., 2024; Wang et al., 2026).

1. Cement and Concrete Production

Ground granulated blast furnace slag (GGBFS) is commonly used as a supplementary cementitious material in concrete. When incorporated into cement mixtures, it can improve long-term strength, durability, workability, and resistance to chemical attack. More importantly, the use of slag in cement and concrete production can help reduce dependence on ordinary Portland cement, which is associated with high carbon dioxide emissions.

2. Road Construction and Pavement Materials

Steel slag and electric arc furnace slag are also suitable for road construction and pavement applications. Their strong mechanical properties make them useful as aggregates in asphalt mixtures and road base materials. In this context, slag can enhance pavement durability while reducing the extraction of natural stone and gravel.

3. Sustainable Building Materials

Beyond cement and road construction, slag is also being investigated for bricks, ceramic products, geopolymer materials, lightweight aggregates, and eco-friendly concrete blocks. These applications demonstrate how industrial by-products can be converted into practical building materials that support sustainable construction practices.

Slag for Wastewater Treatment Applications

Slag has also gained attention as a potential low-cost material for wastewater treatment. Its mineral composition, porous structure, and reactive surface properties allow it to interact with various pollutants in contaminated water. Several studies have shown that slag-based materials can remove pollutants through adsorption, precipitation, ion exchange, and surface complexation mechanisms (Qiao et al., 2020; Zhao et al., 2025).

1. Heavy Metal Removal

Certain slag materials are capable of removing heavy metals such as lead, cadmium, copper, zinc, and chromium from wastewater. This makes slag a promising material for treating industrial effluents, especially from mining, electroplating, and metal-processing industries.



2. Dye and Organic Pollutant Removal
Slag-based adsorbents have also been studied for the removal of dyes and organic pollutants from industrial wastewater. This is particularly relevant to textile and manufacturing industries, where coloured wastewater can affect aquatic ecosystems if discharged without proper treatment.

3. Phosphorus Removal
Some slags containing calcium and iron compounds can help remove phosphorus from wastewater. Since excessive phosphorus can contribute to eutrophication in rivers and lakes, slag-based filtration systems may offer a useful approach for improving water quality and reducing nutrient pollution.

Slag and Carbon Capture Potential
As climate change remains a global concern, Carbon Capture, Utilisation, and Storage (CCUS) technologies are increasingly important for reducing carbon dioxide emissions. Recent studies have shown that certain slags, especially those rich in calcium and magnesium, can react with carbon dioxide through mineral carbonation processes (Kothari et al., 2025; Loncnar et al., 2026).

1. Mineral Carbonation
Mineral carbonation occurs when carbon dioxide reacts with calcium- or magnesium-rich materials to form stable carbonate minerals. Through this process, slag can potentially store carbon dioxide in a solid and stable form. This approach is attractive because it combines carbon reduction with industrial waste utilisation, making it relevant to low-carbon industrial development.

Slag in Agriculture and Soil Improvement
Another possible application of slag is in agriculture and soil management. Some slags contain beneficial minerals such as calcium, magnesium, silicon, and iron, which may help improve soil properties. In certain cases, slag may be used as a soil conditioner or liming material to reduce soil acidity and improve nutrient availability.

However, agricultural use must be carefully assessed because some slags may contain trace metals. Proper environmental monitoring and regulatory compliance are essential before slag can be safely applied to agricultural land.

Slag and Circular Economy Principles
The circular economy concept encourages waste reduction, recycling, reuse, and resource recovery. Slag valorisation supports this concept by transforming industrial by-products into useful materials for construction, water treatment, agriculture, and carbon management.

Instead of following the conventional “take, use, and dispose” approach, slag utilisation promotes a more sustainable pathway where industrial waste is recovered and reused. This can help industries reduce disposal costs, conserve natural resources, improve environmental performance, and strengthen ESG-related practices.



Future Opportunities in Malaysia and Sarawak

Malaysia has strong potential to expand slag valorisation initiatives due to continuous industrial development, infrastructure growth, and increasing awareness of sustainability. In Sarawak, future opportunities may include the development of slag-based construction materials, environmental remediation technologies, carbon capture applications, and waste-to-resource industries.

The state's growing focus on green technology, renewable energy, and sustainable industrial development provides a suitable platform for future slag-related research. Collaboration among universities, industries, government agencies, and environmental authorities will be important to ensure that slag utilisation is technically feasible, environmentally safe, and economically practical.

Challenges and Limitations

Although slag has promising potential, several challenges need to be considered. The composition of slag can vary depending on raw materials and industrial processes, which may affect its performance and environmental safety. In addition, public perception remains a challenge because slag is still commonly viewed as waste rather than a useful resource.

Regulatory requirements, environmental monitoring, processing costs, and transportation issues may also influence the commercial application of slag. Therefore, continuous research, proper characterisation, and risk assessment are necessary before slag can be widely adopted in different sectors.

Conclusion

Slag is no longer merely an industrial waste material. With appropriate treatment, characterisation, and application, it can become a valuable secondary resource for sustainable development. Its potential use in construction, wastewater treatment, carbon capture, agriculture, and circular economy systems demonstrates its importance in future green industrial practices.

For Malaysia and Sarawak, slag valorisation may support waste reduction, resource conservation, low-carbon development, and environmental protection. With strong collaboration among researchers, industries, and policymakers, slag can contribute meaningfully towards sustainable industrial ecosystems and future green technology development.

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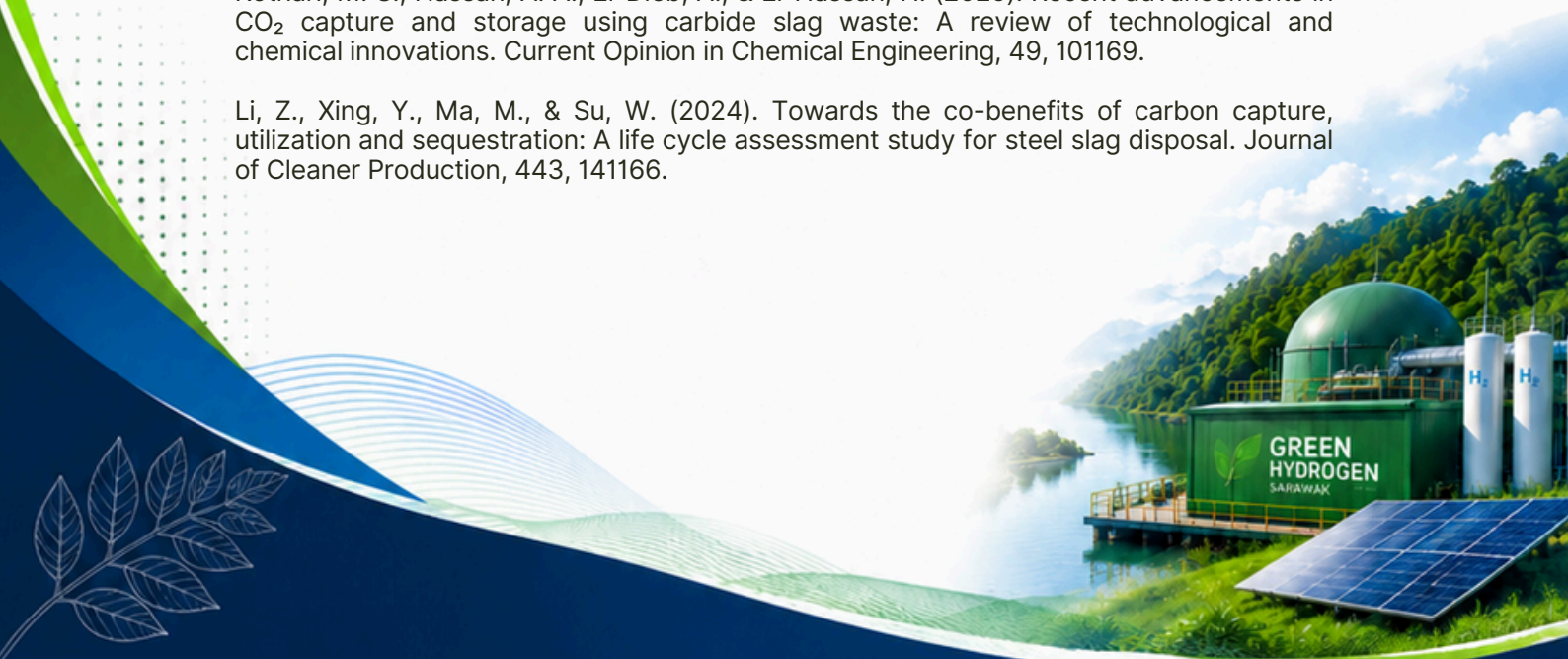

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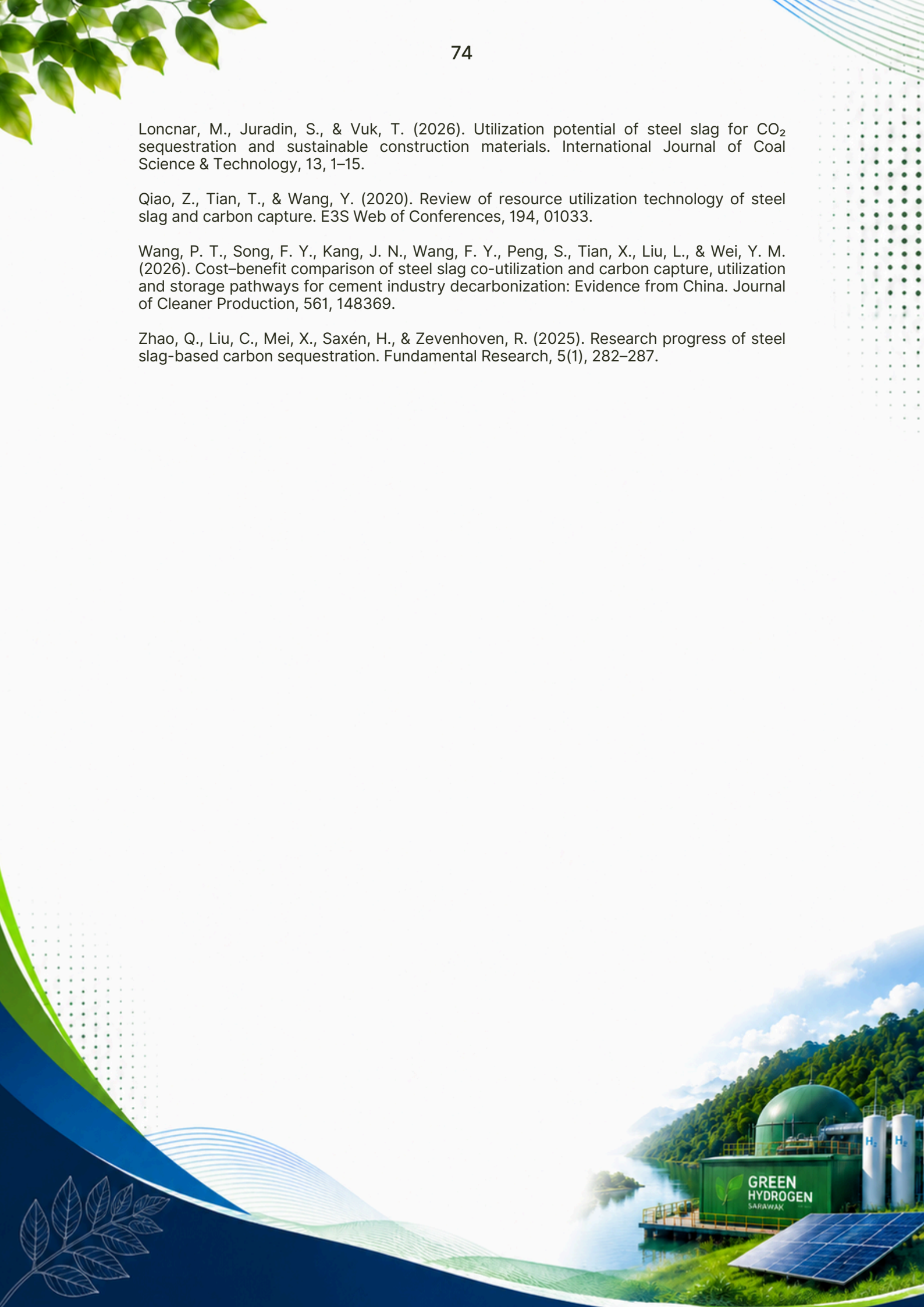

Biomass-Derived Carbon Sensors For Sustainable Detection Of Environmental Pollutants

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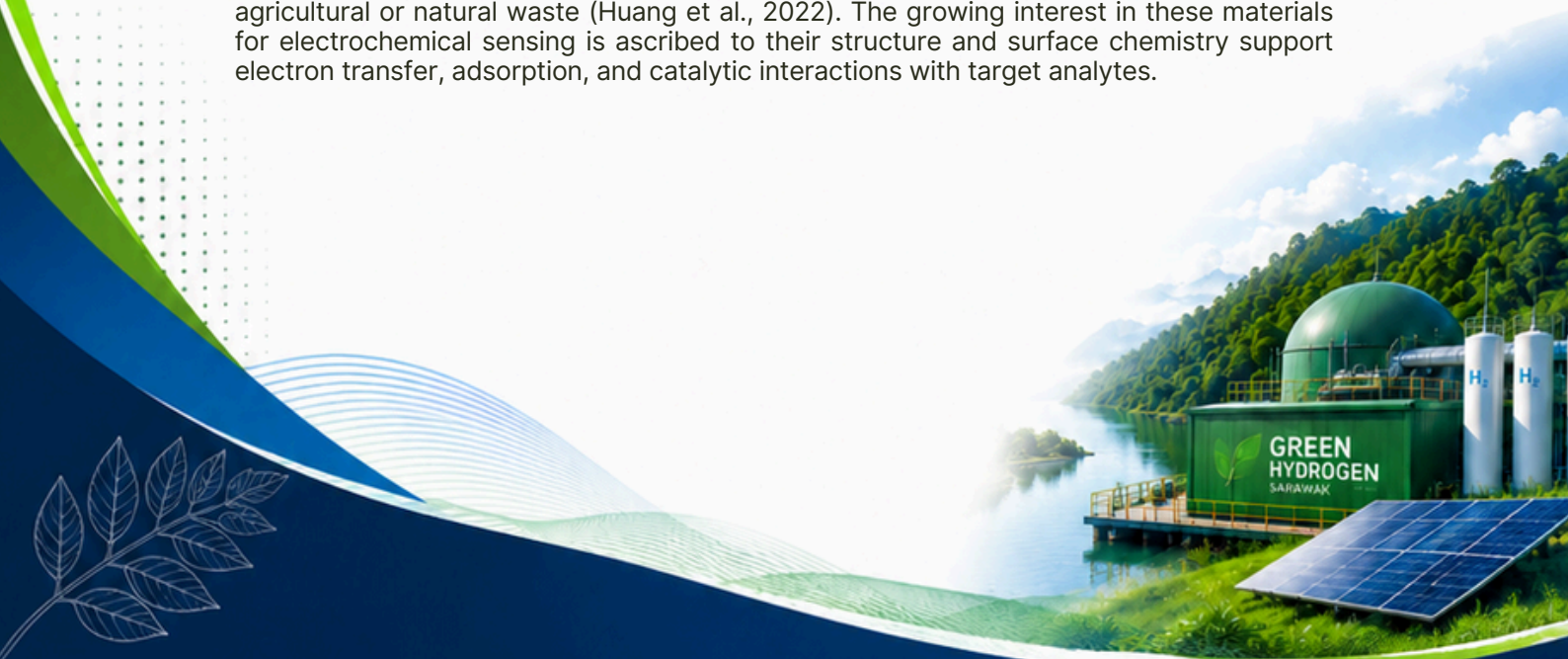
Introduction

Healthy ecosystems depend on clean water, stable soil quality, balanced nutrient cycles, and low pollutant pressure. Yet many ecosystems now face continuous exposure to contaminants from urbanization, agriculture, aquaculture, mining, pharmaceutical use, and industrial discharge. Pollutants such as heavy metals, antibiotics, pesticides, dyes, endocrine-disrupting compounds, and phenolic residues persist in the environment and affect aquatic organisms, soil microorganisms, plants, animals, and humans (Nassri et al., 2023). Monitoring these pollutants forms an essential part of ecosystem protection. Traditional pollutant analysis often relies on laboratory-based techniques such as chromatography, mass spectrometry, and atomic absorption spectroscopy (de Andrade et al., 2025). These methods remain important because they provide strong sensitivity and accuracy. Their use, however, requires expensive equipment, skilled analysts, stable laboratory infrastructure, and complex sample processing. This creates a gap between scientific detection capacity and field-level ecosystem monitoring. In many environmental settings, especially rural areas, plantations, rivers, farms, and remote catchments, monitoring must be rapid, portable, affordable, and repeatable.

Electrochemical sensors offer a practical solution. They convert chemical interactions at an electrode surface into measurable electrical signals. Their main strengths include low sample volume, fast response, simple operation, and compatibility with portable devices (Qiao et al., 2024; Zabitler et al., 2026). Recent advances in screen-printed electrodes and modified carbon electrodes have strengthened the possibility of field-based detection. Reviews on screen-printed electrodes describe their advantages in low cost, small size, portability, and mass production, which support environmental and point-of-need sensing applications (Liang et al., 2022).

Within this field, biomass-derived carbon has gained attention as a green electrode material or electrode modifier (Abdullah, 2017). Biomass-derived carbon refers to carbon-rich materials obtained from renewable biological sources through thermal, hydrothermal, or chemical conversion. Examples include BC, activated carbon, graphene-like carbon, porous carbon, heteroatom-doped carbon, and carbon composites derived from agricultural or natural waste (Huang et al., 2022). The growing interest in these materials for electrochemical sensing is ascribed to their structure and surface chemistry support electron transfer, adsorption, and catalytic interactions with target analytes.



Why Biomass-Derived Carbon Fits Sustainable Sensing

Biomass-derived carbon fits sustainable sensing for three main reasons: resource circularity, material functionality, and low-carbon design.

First, it transforms waste into functional materials. Agricultural residues and lignocellulosic wastes often create disposal problems. Burning or open dumping contributes to air pollution, greenhouse gas release, and land contamination. Converting these residues into carbon materials gives waste a second function. In regions with strong agricultural activity, including Borneo and Malaysia, biomass residues from rice husk, oil palm waste, coconut shell, wood residue, fruit peel, and other plant-based sources provide abundant feedstock for carbon material production (Saharudin et al., 2024).

Second, biomass-derived carbon has useful electrochemical properties. Depending on the precursor and preparation method, it possesses porous structures, oxygen-containing functional groups, graphitic domains, defect sites, and heteroatom content such as nitrogen, sulfur, phosphorus, or oxygen. These features increase the number of active sites on the electrode surface. They also improve pollutant adsorption, charge transfer, and signal response. Third, the material supports low-carbon monitoring. Environmental monitoring itself should not create unnecessary environmental burdens. Conventional electrode modifiers such as noble metals, synthetic nanomaterials, or energy-intensive materials often raise cost and sustainability concerns. Biomass-derived carbon offers a lower-cost and renewable alternative. Although carbonization still requires energy, the use of waste biomass and simple preparation routes reduces material cost and supports a more circular research pathway.

Sensing Mechanism of Biomass-Derived Carbon Electrodes

Electrochemical sensing depends on the interaction between the pollutant and the electrode surface. When biomass-derived carbon modifies an electrode, it improves detection through several linked mechanisms summarized in Figure 1.

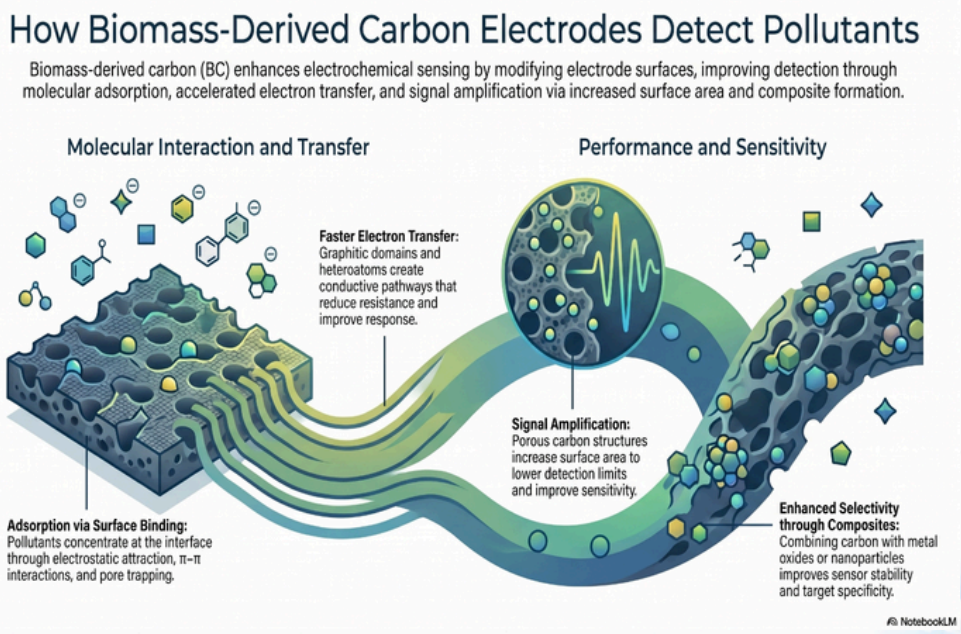


Figure 1. Schematic illustration of pollutant detection by biomass-derived carbon electrodes.

The first mechanism is adsorption. Pollutant molecules or ions interact with the carbon surface through electrostatic attraction, π–π interactions, hydrogen bonding, complexation, or pore trapping. For example, aromatic pollutants such as dyes, phenols, and some antibiotics interact with graphitic domains through π–π interactions. Metal ions interact with oxygen-, nitrogen-, or sulfur-containing groups on the carbon surface. These interactions concentrate the analyte near the electrode interface and strengthen the electrical response. These interactions concentrate the analyte near the electrode interface and strengthen the electrical response. For instance, sulfur-containing carbon nanofibers (S-CNF), exhibited enhanced metal detection capabilities due to the presence of various functional groups. These include sulfur-bearing groups (e.g., S-O, S-S, C-S-C, and C-S) and oxygen- and nitrogen-containing groups, which facilitate strong interactions with lead ions (Kumar et al., 2025).

The second mechanism is faster electron transfer. A suitable carbon structure provides conductive pathways between the pollutant and the electrode. Graphitic domains, defect sites, and interconnected pores reduce resistance and improve current response. When the carbon surface contains heteroatoms, the electronic structure changes. This improves active sites and strengthens catalytic behavior.

The third mechanism is signal amplification. Porous carbon increases the effective surface area of the electrode. A larger active surface gives more space for analyte interaction (Cheng et al., 2016). This improves sensitivity and lowers the detection limit. Composite formation with metal oxides, polymers, enzymes, or nanoparticles further improves selectivity and stability. Recent reviews emphasize the role of functionalization and composite design in improving the performance of BC-based electrochemical sensors and biosensors (Min et al., 2025).

Detection of Key Environmental Pollutants

1. Heavy Metals

Heavy metals such as lead, cadmium, mercury, copper, and arsenic pose serious risks to ecosystems because they persist, accumulate, and enter food chains. Electrochemical detection of heavy metals often uses stripping voltammetry, where metal ions deposit on the electrode surface and then strip back into solution to generate a measurable current. Biomass-derived carbon improves this process by offering binding sites and conductive surfaces. This direction has strong relevance for monitoring mining discharge, industrial wastewater, agricultural runoff, and river systems affected by metal contamination.

2. Antibiotics and Pharmaceutical Residues

Antibiotic residues have become important emerging pollutants. Their presence affects microbial communities and contributes to wider concerns about antimicrobial resistance. Biomass-derived carbon sensors offer a sustainable approach for detecting antibiotics such as tetracycline, ciprofloxacin, sulfamethoxazole, and chloramphenicol. Many antibiotics contain electroactive functional groups that undergo oxidation or reduction at modified electrodes (Sarakatsanou et al., 2023). For ecosystem science, this application matters because antibiotic contamination links water quality, microbial ecology, aquaculture safety, and public health. A portable sensor that detects antibiotic residues in river water or aquaculture effluent would support faster decision-making and reduce dependence on delayed laboratory results.



3. Pesticides

Pesticides protect crops but also create risks when they leach into soil, rivers, and groundwater. Organophosphates, carbamates, herbicides, and organochlorine pesticides affect aquatic organisms, beneficial insects, soil microorganisms, and human health. Screen-printed electrodes have been widely explored for pesticide detection because they are portable, low-cost, and suitable for disposable field testing(Nageib et al., 2023; Zheng et al., 2025). Biomass-derived carbon adds a green material component to this platform. When used as an ink component or electrode modifier, it improves surface area and supports analyte accumulation. This area fits agricultural ecosystems. Farmers, plantation managers, and environmental agencies need practical tools to monitor pesticide residues in irrigation water, drainage channels, and nearby rivers. Biomass-derived carbon sensors provide a promising route toward low-cost monitoring in such settings.

4. Dyes and Phenolic Compounds

Dyes and phenolic compounds often originate from textile, printing, plastic, pharmaceutical, and industrial activities. Many of these compounds show toxicity, persistence, and strong color or odor effects in water. Electrochemical sensors detect these pollutants through oxidation or reduction reactions. Biomass-derived carbon is suitable for these analytes because many dye and phenolic molecules contain aromatic structures. These structures interact well with graphitic and porous carbon surfaces. The carbon material adsorbs the pollutant and enhances signal generation. One previous study demonstrates that biomass-derived carbon from date leaves is effective for detecting phenolic contaminants like 1-naphthol and 2-naphthol due to its submicron and nanometer sizes, which enhance interaction with aromatic structures in these pollutants (Mahfoz et al., 2024). The modified glassy carbon electrode utilizes both direct oxidation and redox peaks from quinone formation, leading to superior sensitivity and selectivity. The carbon material's porous nature facilitates adsorption of the analytes, significantly improving signal generation for electrochemical detection.

This approach supports rapid screening of industrial discharge before pollutants enter river systems.

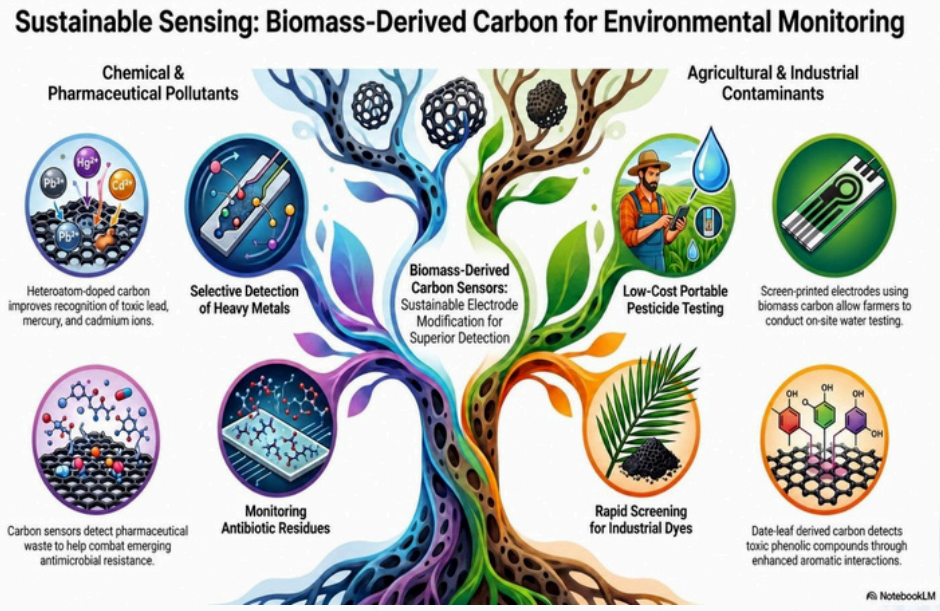


Figure 2. Sustainable environmental monitoring using biomass-derived carbon sensors.



Link to Green and Low-Carbon Energy

Green energy systems, sustainable agriculture, clean water technologies, and climate-resilient ecosystems all require reliable monitoring tools. Sensors provide the data needed to track pollution, assess intervention success, and reduce unnecessary resource use.

Biomass-derived carbon sensors relate to green and low-carbon energy in several ways. First, they use renewable waste feedstock instead of relying fully on synthetic or expensive materials. Second, they support low-power detection because electrochemical measurements require small energy input. Third, they enable decentralized monitoring, reducing the need to transport samples repeatedly to centralized laboratories. Fourth, they support clean water and ecosystem protection, which are essential components of sustainable development.

Biomass-derived carbon also connects with energy storage and conversion research. Reviews on biomass-derived graphene and nanostructured carbons report their application across energy conversion, energy storage, and electrochemical sensing technologies (Adeola et al., 2025; Feng et al., 2023; Khandaker et al., 2025). This means a single material platform supports both green energy devices and environmental sensors. Such overlap strengthens the case for biomass-derived carbon as a cross-cutting material in low-carbon technology.

Challenges in Practical Application

Despite strong promise, biomass-derived carbon sensors still face several limitations. The first limitation is material variability. Biomass differs by source, age, composition, moisture content, mineral content, and pretreatment. Rice husk, coconut shell, oil palm biomass, and fruit peel produce carbon materials with different structures and functional groups. This affects sensor reproducibility. Researchers need standardized preparation conditions and clear reporting of biomass source, carbonization temperature, activation method, yield, and surface properties. The second limitation is selectivity. Environmental samples contain many interfering ions and organic compounds. A sensor that performs well in standard solutions may show weaker performance in river water, wastewater, soil extract, or aquaculture effluent. Selectivity must be tested using realistic matrices. Recovery studies, interference tests, and comparison with established analytical methods are needed.

The third limitation is long-term stability. Modified electrodes may lose activity due to surface fouling, oxidation, detachment of modifier layers, or changes in surface chemistry (Fathimath Sanooba & Alwarappan, 2025). This is especially important for field use, where humidity, temperature, and sample complexity vary. The fourth limitation is scale-up. Many studies remain at the laboratory stage using glassy carbon electrodes. For real-world use, sensor design should move toward screen-printed electrodes, flexible electrodes, paper-based devices, and portable potentiostat systems (Anzar et al., 2022; Yamanaka et al., 2016). Screen-printed electrochemical sensors have already shown value as sensitive, rapid, and affordable platforms for moving laboratory sensing toward in-field testing. Biomass-derived carbon should be integrated into these practical platforms.



Future Prospects

Pollutant-specific sensor design: Biomass-derived carbon sensors should be tailored to the chemistry of target pollutants. Heavy metal sensing requires surface complexation sites, while antibiotics and dyes require suitable aromatic interactions and pore structures. Pesticide detection requires separate design strategies for enzyme-free and enzyme-based systems.

Use of local biomass resources: Agricultural and forestry residues from Malaysia and Borneo should be prioritized as carbon precursors. This links waste valorization with ecosystem monitoring and low-carbon material development.

Portable sensing platforms: Future systems should focus on field-ready formats, including screen-printed electrodes, smartphone-based readout, mini potentiostats, and disposable testing strips.

Life-cycle sustainability: Green material claims should consider energy demand, chemical use, waste generation, and regeneration potential. Sustainable sensing requires both strong analytical performance and environmental responsibility.

Conclusion

Biomass-derived carbon sensors provide a practical and sustainable approach for detecting environmental pollutants. They link renewable waste resources with electrochemical sensing, ecosystem monitoring, and low-carbon environmental management. Their porous structure, surface functional groups, conductivity, and compatibility with electrode modification make them suitable for detecting heavy metals, antibiotics, pesticides, dyes, and phenolic compounds. For ecosystem science, their value lies not only in pollutant detection but also in supporting faster decision-making, cleaner water systems, circular resource use, and decentralized monitoring. Future progress depends on reproducible material synthesis, stronger selectivity, real-sample validation, device integration, and life-cycle assessment. With careful design, biomass-derived carbon sensors may become key tools for sustainable ecosystem protection, especially in regions where biomass residues are abundant and environmental monitoring needs are growing.

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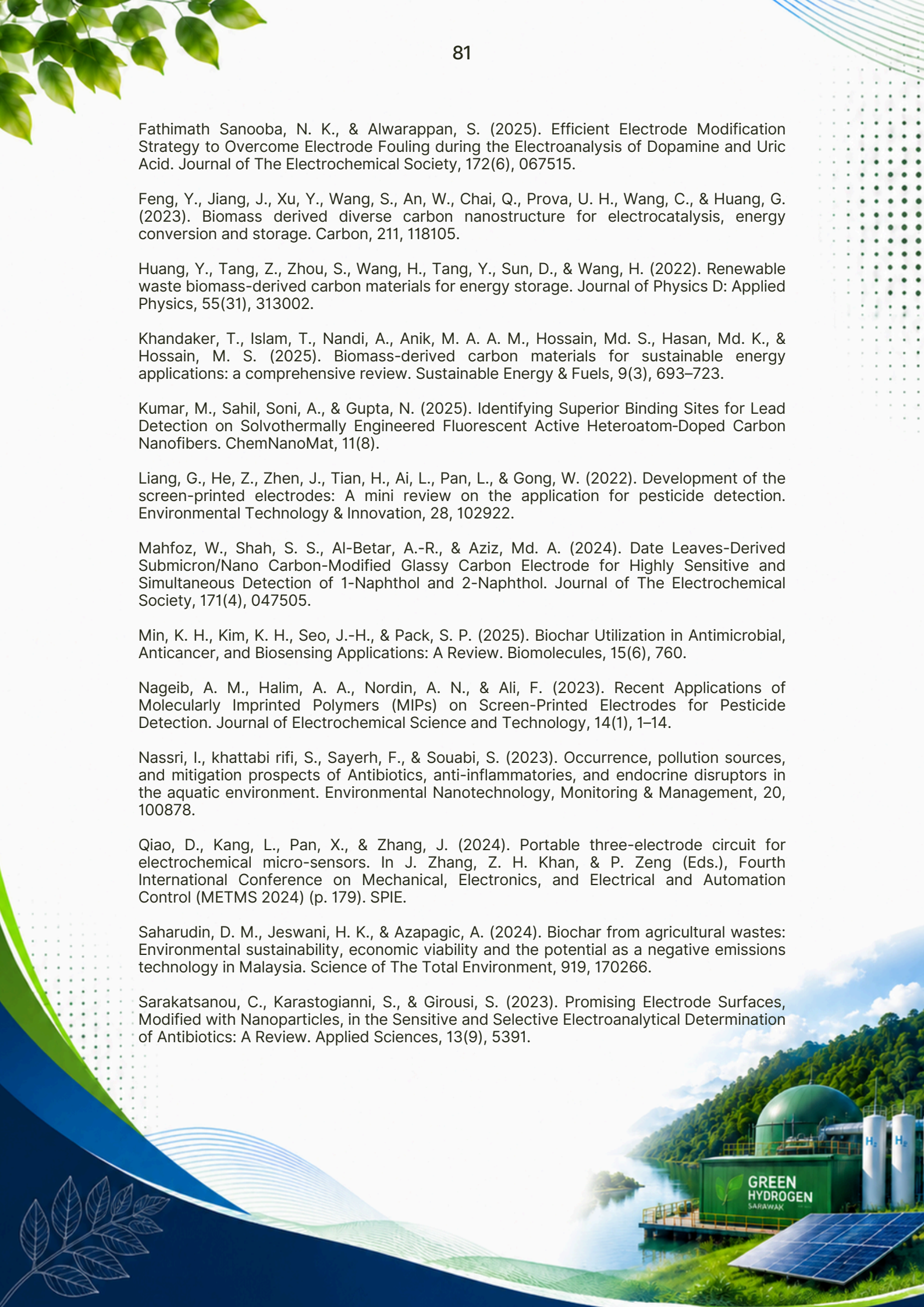

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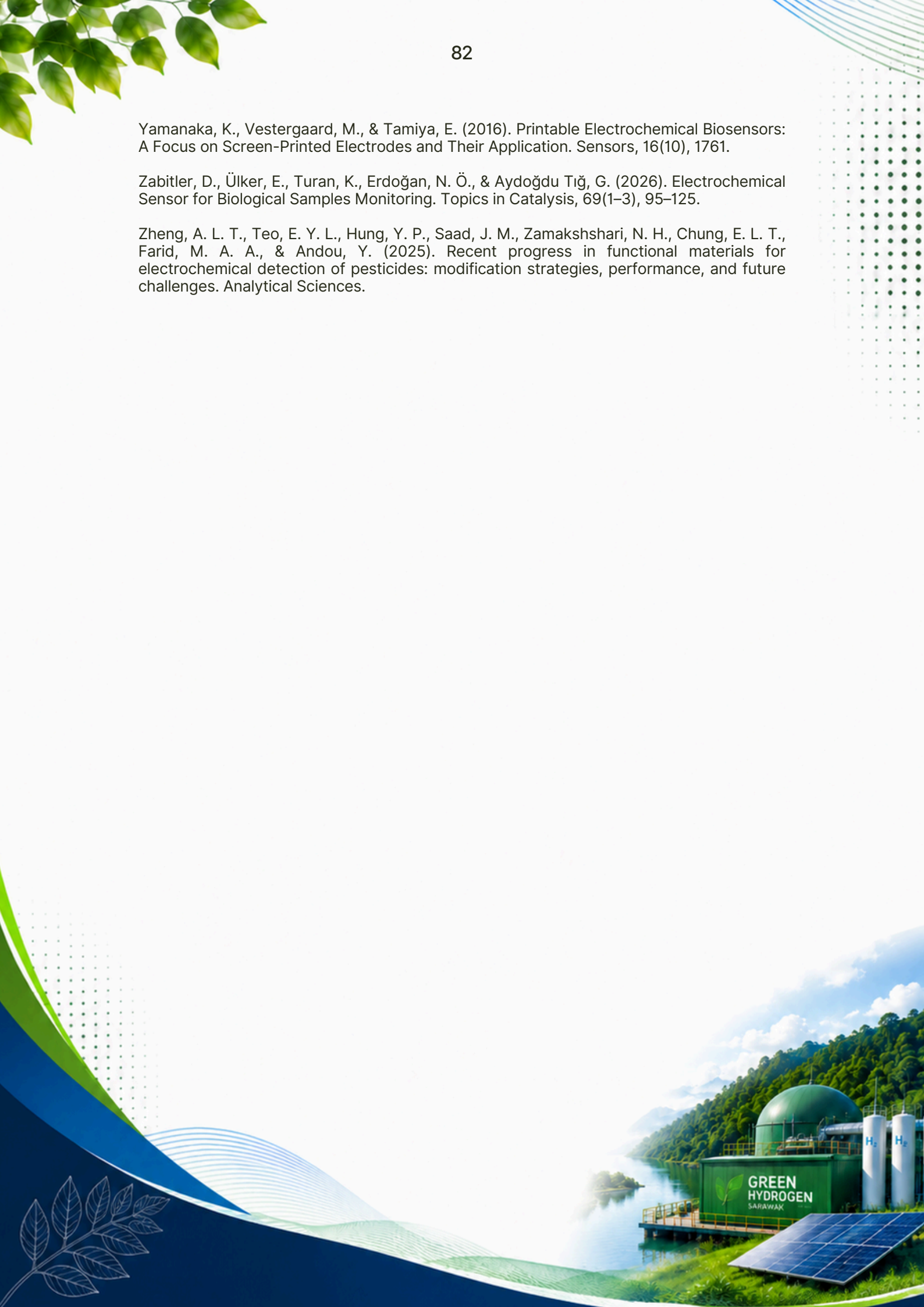

Integration Of Nanocellulose Composites And Anthocyanin In Smart Packaging

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Introduction

Food packaging is the most important aspect in food protection, maintaining quality, extend shelf life, and support safe distribution from producers to consumers. It includes food wrap and food cover during storage, transportation and sale. However, due to increasing consumer demand for safer and higher-quality food, packaging requirements are shifting from traditional packaging to smart packaging (Yan et al., 2022). Osmólska et al. (2022) stated that smart packaging is an advanced packaging system that incorporates active and intelligent technologies to improve food quality, safety, shelf life, and consumer communication, whereas intelligent packaging specifically focuses on monitoring and providing information about the condition of the packaged product as shown in Figure 1.

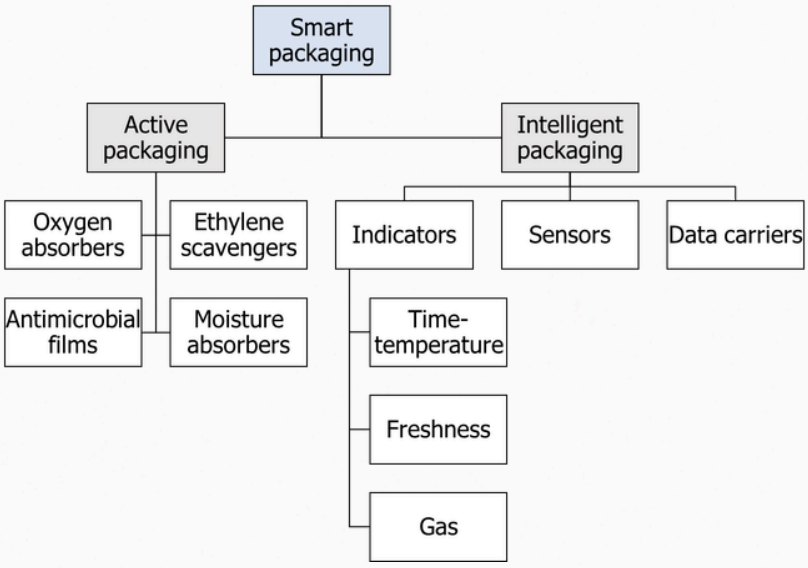


Figure 1. Components of smart packaging

Intelligent packaging has the ability to monitor changes in food and give real-time feedback on food quality has made it a popular trend in the industry (Drago et al., 2020). It provides producers, sellers, and consumers with the freshness or deterioration of food by sensing, detecting, and recording changes in the internal and external environments of the packaged food, and providing dynamic feedback and early warning on potential food safety. Besides, active packaging has also gained attention since it interacts directly with packaged product to prolong the shelf life of food and maintain the quality. Absorbers and emitters are the two types of active packaging which are important in preserving the taste, nutritional value, and freshness of food. Product migration from packaging to food is also a critical matter which refers to the transfer of chemical substances such as plasticizers, heavy metals, inks, and adhesives from the container into the food product. It is a crucial food safety concern governed by strict regulations to protect consumer health.

Biopolymers For Food Packaging Application

Starch and cellulose are the most abundant and easily available biopolymers. Thermoplastic starch (TPS) is a biodegradable polymer material produced by processing starch with plasticizers under heat and shear, allowing it to behave like conventional thermoplastic materials. The main content of TPS are starch, water, plasticizer, and additives or fibres to improve strength and stability. Common starch sources are corn starch, potato starch, cassava starch and tapioca starch.

The additives are the most important factor need to be considered to improve the properties and qualities of the film. Fibres such as nano cellulose fibre (CNF) has been actively explored for its application in food packaging. CNFs are nanoscale, plant-derived fibers that measure less than 100 nm in diameter. The abundance of nanocellulose fibers in agricultural waste such as from oil palm empty fruit bunches can be utitlized for food packaging films. Moreover, nanocellulose-based film has gained popularity because of its extraordinary properties of air and oxygen barriers, which protect the food from undesirable entities. The characteristics of nano-based films are similar to natural poly bags. The excellent oxygen tolerance capability of nano-film arises due to the high crystallinity of nanocellulose. Other properties such as tolerability, style flexibility, and processability making it suitable to be applied in automotive, packaging, electronics, and biotechnology sectors. In packaging sector, it is undeniably an excellent material to replace petroleum-based plastics as it can improve barrier properties (like reducing water vapor permeability) in biodegradable food packaging.

Anthocyanin For Smart Packaging

Most pH-responsive freshness indicators are prepared with synthetic colorants. However, due to their toxicity, and some of them are even carcinogenic, they may pose a serious threat to life and the environment Kurek et al. (2022). Hence, it is crucial to find non-toxic and safe colorants for the preparation of pH-responsive freshness indicators. The application of natural colorants could improve food safety, while also meeting consumer expectations for food safety. Anthocyanins have been widely studied due to their noticeable and rich color variations over a wide range of changes in pH, high safety, easy availability, and other functional properties such as antioxidant and antibacterial activity (Yuan et al., 2020). Most natural colorants can be obtained from agricultural waste and food processing plant wastes such as fruit peel, pressed residue, etc. Consequently, research into pH-responsive freshness indicators not only promotes the rational utilization of waste but also provides a green substitute for synthetic dyes for monitoring food quality.



Plant-derived anthocyanins such as from purple sweet potato, and red cabbage which offer natural, safe, and pH-sensitive colour transitions, aligning with the growing demand for eco-friendly food packaging. For instance, the application of anthocyanin in Food Freshness Indicator (FFI) can monitor real-time freshness and deterioration of food products throughout their shelf life. The indicator provides a color shift that corresponds to changes in food freshness or quality, thereby enabling non-destructive and real-time monitoring of spoilage (Luo et al., 2022). Thus, the indicator enables consumers to visually identify changes in food quality quickly and non-destructively. It is applicable for highly perishable foods such as meats and seafoods due to their high moisture content, protein richness, and susceptibility to microbial spoilage and enzymatic degradation. It is an effective tool for detecting spoilage metabolites such as volatile amines (TVB-N), hydrogen sulfide (H2S), biogenic amines (histamine, putrescine), and pH changes.

The mechanism of the indicator started when the nutrients in food such as protein and fat decompose under the action of enzymes and microorganism and produce various acidic and alkaline gases (trimethylamine (TMA), dimethylamine (DMA), ammonia (NH3), hydrogen sulfide, carbon dioxide, etc.), which are then released into the confined space during the process of food freshness change. As the storage period increases, volatile acidic and basic compounds become denser in the package headspace and are further adsorbed by the freshness indicator attached to the inside of the package. These compounds lead to an increase in hydroxyl ions in the indicator. Accordingly, the deprotonation of hydroxyl groups changes the structure of the natural dyes, which then exhibit color changes (Rodrigues et al., 2021).

Preparation Methods

Yusof et al. (2026) reported that packaging films containing anthocyanins can be prepared by solvent casting, electrospinning, melt extrusion, and 3D printing. As for nano cellulose fiber (CNF) preparation, there are several important steps need to be performed. The preparation of nanocellulose involves several important processing steps, including pretreatment, purification, and fibrillation or hydrolysis. Alkaline treatment and bleaching processes are the first step to remove lignin and hemicellulose. Then, hydrolysis treatment will further isolate the nanocellulose by removing non-cellulosic components and separates cellulose fibers from the plant cell wall. These processes reduce the dimensions of cellulose to the nanoscale, producing nanocellulose with a high aspect ratio, large specific surface area, and excellent mechanical properties (Ditta et al., 2024; Wang et al., 2024).

Challenges Of Anthocyanin In Films

1. Degradation and migration

Freshness indicator with anthocyanin has the problems of low stability and the colour rendering domain could not effectively cover the shelf life of food. Therefore, it is crucial to improve the effectiveness of natural pigment freshness indicators in practical applications. Various optimization strategies have been employed to enhance the sensitivity and stability, including chemical modification, co-pigmentation, pigment blending, encapsulation, and metal-ion complexation. These methods enhance pigment functionality through structural modification, protective encapsulation, or interactions with co-pigments and metal ions, thereby improving color stability and responsiveness (Huang et al., 2024)



Anthocyanins are highly sensitive to environmental factors, including light, oxygen, temperature, and pH changes, which can lead to rapid degradation, color fading, and reduced sensing performance. To address these limitations, anthocyanins are commonly encapsulated within biopolymer-based film matrices prior to incorporation into packaging films (Gao et al., 2025). This protective barrier reduces direct exposure to external conditions, thereby minimizing oxidative degradation and improving thermal and photostability. In addition, encapsulation can also control the release behavior of pigments and maintain their structural integrity during processing and storage. As a result, encapsulated pigments exhibit improved color retention and more stable responsiveness, making them more suitable for use in freshness indicators and smart packaging systems. Recent studies have consistently reported that encapsulation significantly enhances the functional lifespan of natural pigments compared to their free forms, confirming its importance as a key stabilization strategy in intelligent food packaging applications (Huang et al., 2025)

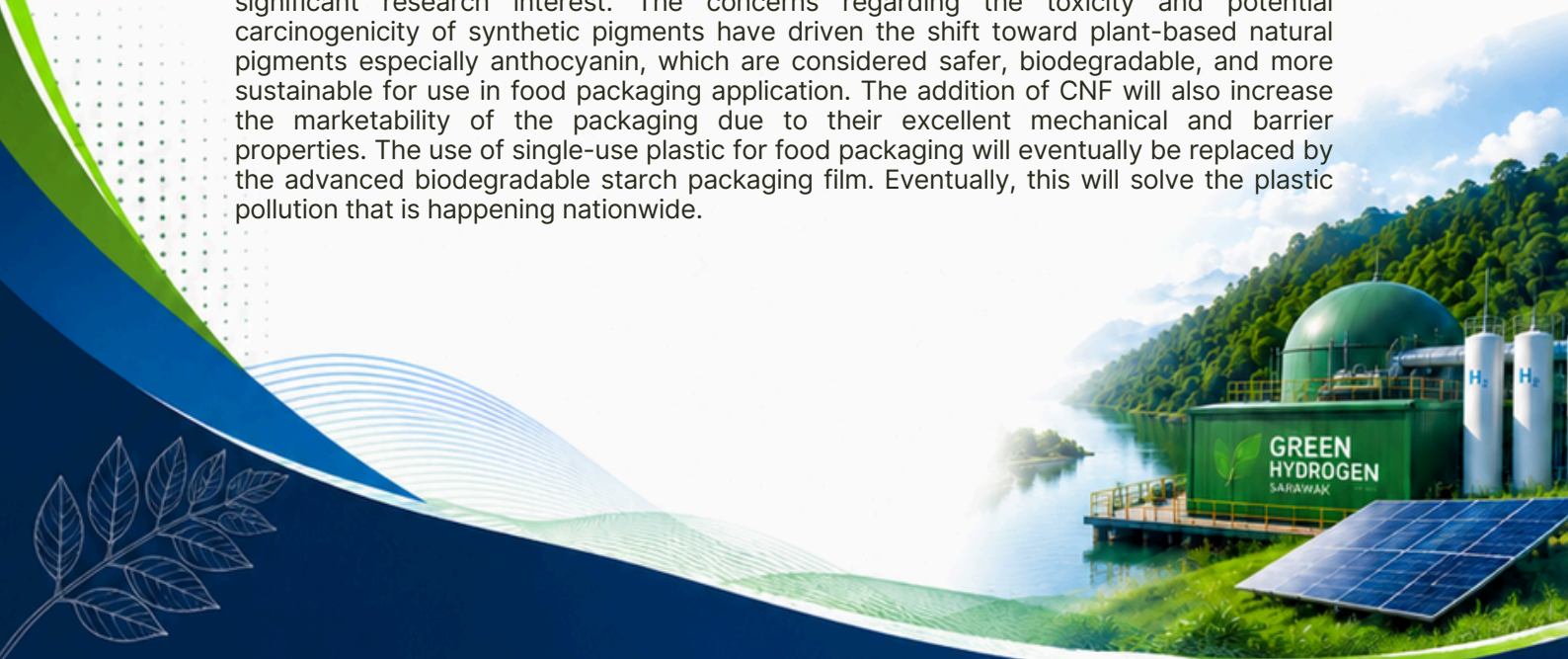
In addition to encapsulation, acylation is an important molecular modification approach used to improve anthocyanin stability and color properties. Acylation is the enzymatic or chemical process of introducing acyl groups into anthocyanin molecules, typically through esterification with organic acids, to enhance their structural stability and color properties. It has been widely reported that acylation enhances the color intensity and stability of anthocyanins by promoting intramolecular co-pigmentation, where aromatic acyl groups facilitate molecular stacking and steric shielding of the flavylium cation structure and reducing susceptibility to degradation caused by environmental factors such as pH, light, temperature, and oxygen (Yañez-Apam et al., 2023).

Future Perspectives

Traditional date labels are still useful, but it is becoming more clear that they do not accurately represent the freshness of the goods. Freshness indicators are being more widely used in a variety of food categories, especially those that are more likely to deteriorate quickly, as a result of this increased awareness. The fundamental components of smartness, such on-pack indications, are becoming commonplace, even though fully functional smart packaging with IoT connectivity is still developing. Sustainability is another increasingly important factor. Manufacturers are being forced to implement sophisticated packaging solutions that go beyond simple expiration dates due to the growing customer demand for food quality assurance and transparency. They are actively looking for freshness indicators that don't significantly increase the volume or complexity of the packaging and are biodegradable and eco-friendly. This supports the industry's larger effort to cut down on packaging waste. According to reports, a crucial field of study is the creation of bio-based and compostable indicator materials, which are motivated by both consumer demand and legal requirements.

Conclusions

In response to increasing consumer awareness of food safety and freshness, smart packaging film is capable of visually signalling food quality changes have attracted significant research interest. The concerns regarding the toxicity and potential carcinogenicity of synthetic pigments have driven the shift toward plant-based natural pigments especially anthocyanin, which are considered safer, biodegradable, and more sustainable for use in food packaging application. The addition of CNF will also increase the marketability of the packaging due to their excellent mechanical and barrier properties. The use of single-use plastic for food packaging will eventually be replaced by the advanced biodegradable starch packaging film. Eventually, this will solve the plastic pollution that is happening nationwide.



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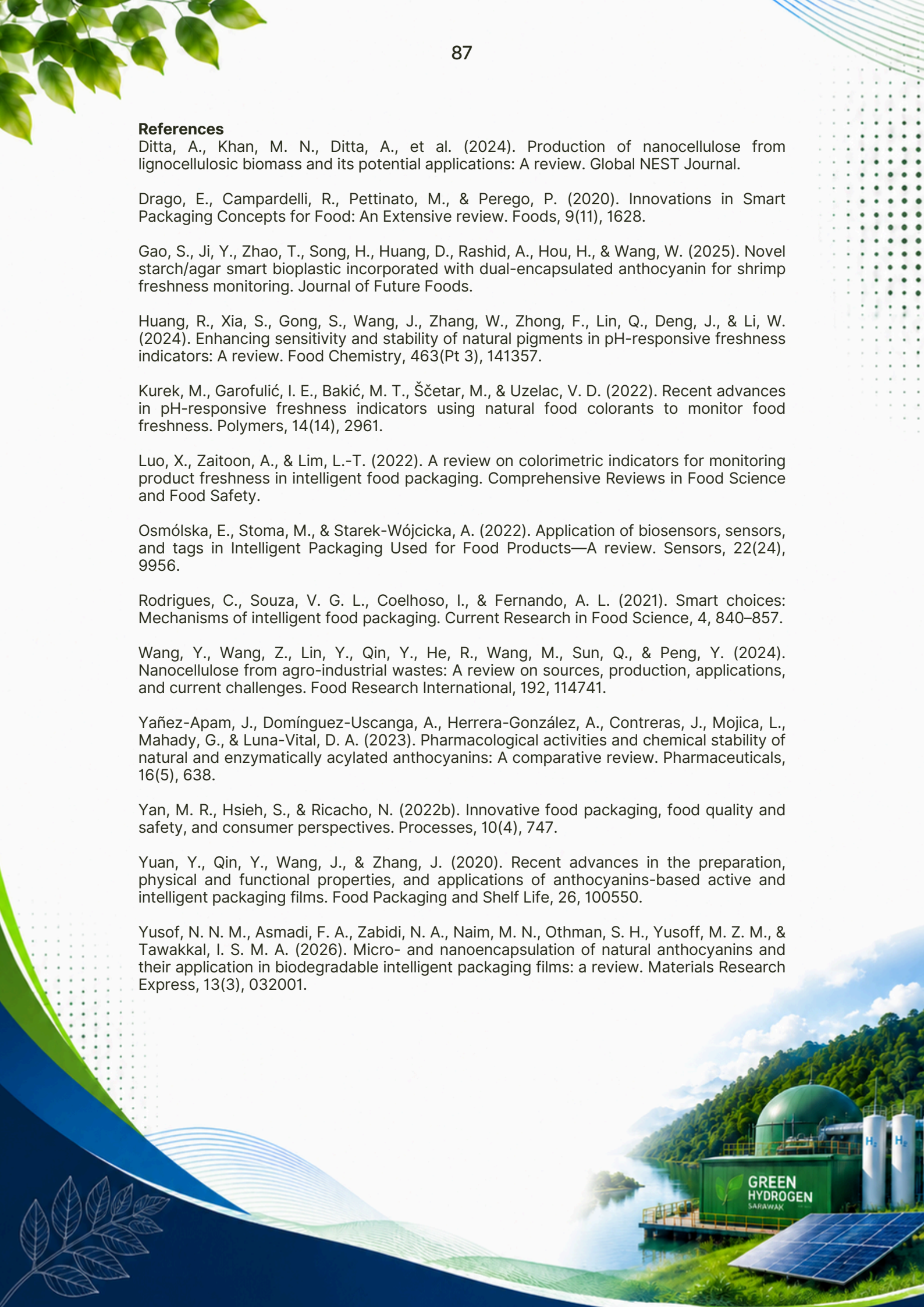

Preliminary Study On The Conversion Of Coconut Shell Waste Into Sustainable Charcoal Briquettes Using Starch And Paper Binders

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Introduction

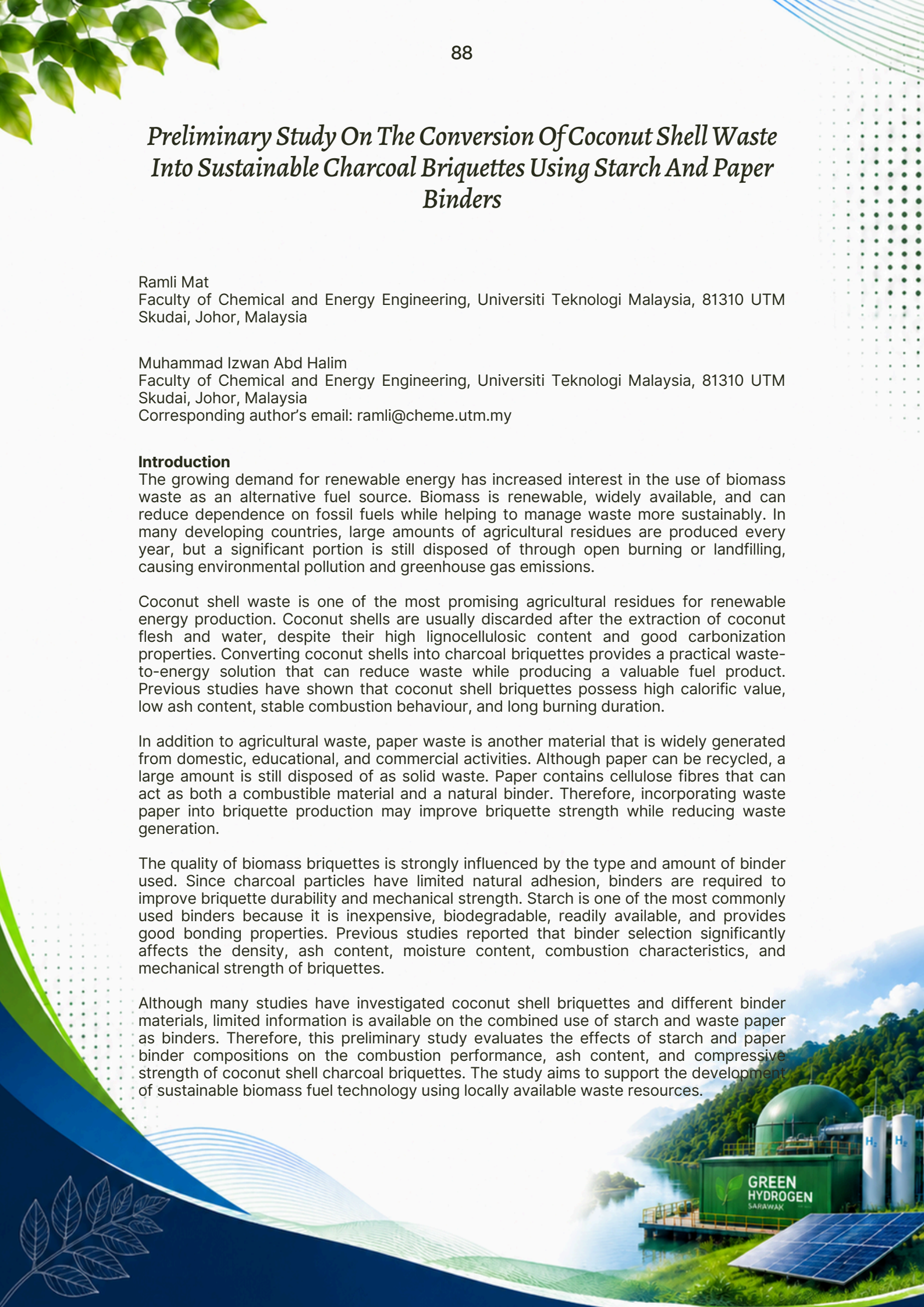
The growing demand for renewable energy has increased interest in the use of biomass waste as an alternative fuel source. Biomass is renewable, widely available, and can reduce dependence on fossil fuels while helping to manage waste more sustainably. In many developing countries, large amounts of agricultural residues are produced every year, but a significant portion is still disposed of through open burning or landfilling, causing environmental pollution and greenhouse gas emissions.

Coconut shell waste is one of the most promising agricultural residues for renewable energy production. Coconut shells are usually discarded after the extraction of coconut flesh and water, despite their high lignocellulosic content and good carbonization properties. Converting coconut shells into charcoal briquettes provides a practical waste-to-energy solution that can reduce waste while producing a valuable fuel product. Previous studies have shown that coconut shell briquettes possess high calorific value, low ash content, stable combustion behaviour, and long burning duration.

In addition to agricultural waste, paper waste is another material that is widely generated from domestic, educational, and commercial activities. Although paper can be recycled, a large amount is still disposed of as solid waste. Paper contains cellulose fibres that can act as both a combustible material and a natural binder. Therefore, incorporating waste paper into briquette production may improve briquette strength while reducing waste generation.

The quality of biomass briquettes is strongly influenced by the type and amount of binder used. Since charcoal particles have limited natural adhesion, binders are required to improve briquette durability and mechanical strength. Starch is one of the most commonly used binders because it is inexpensive, biodegradable, readily available, and provides good bonding properties. Previous studies reported that binder selection significantly affects the density, ash content, moisture content, combustion characteristics, and mechanical strength of briquettes.

Although many studies have investigated coconut shell briquettes and different binder materials, limited information is available on the combined use of starch and waste paper as binders. Therefore, this preliminary study evaluates the effects of starch and paper binder compositions on the combustion performance, ash content, and compressive strength of coconut shell charcoal briquettes. The study aims to support the development of sustainable biomass fuel technology using locally available waste resources.



Methodology

1. Raw Material Preparation

Coconut shell waste was collected from Kampung Sungai Gerisek and Taman Anjung Permai, Johor, Malaysia. The collected coconut shells were dried under sunlight to reduce their moisture content before the carbonization process. Waste paper was collected from residential areas and students around Universiti Teknologi Malaysia (UTM) and used as an additional binder material.

The dried coconut shells were carbonized using a self-fabricated steel furnace for approximately 3 h to produce coconut shell charcoal. After cooling, the charcoal was crushed into smaller particles suitable for briquette production.

Two types of binders were used in this study, namely starch and paper pulp. The starch binder was prepared by mixing starch flour with water until a uniform mixture was obtained. The paper binder was prepared by soaking waste paper in hot water until a pulp-like consistency was formed.

2. Briquette Preparation

The briquettes were produced using coconut shell charcoal with different binder compositions. In the first stage, starch binder concentrations of 10%, 20%, and 30% were investigated. In the second stage, paper pulp was added together with starch at charcoal–starch–paper ratios of 90:5:5, 80:10:10, and 70:15:15, respectively. The compositions of the briquette samples are presented in Table 1.

The charcoal and binder materials were manually mixed until a homogeneous mixture was obtained. The mixture was then compressed using a self-fabricated compression tool to form briquettes. Each briquette weighed approximately 45–50 g. The prepared briquettes were first dried under sunlight and then oven-dried before characterization.

Table 1. Composition of briquette samples

Sample	Composition Ratio
A	90:10 (charcoal:starch)
B	80:20 (charcoal:starch)
C	70:30 (charcoal:starch)
D	90:5:5 (charcoal:starch:paper)
E	80:10:10 (charcoal:starch:paper)
F	70:15:15 (charcoal:starch:paper)



3. Briquette Characterization
This preliminary study focused on three main parameters, namely ash content, combustion performance, and compressive strength.

3.1 Ash Content
Ash content was determined by measuring the residual ash remaining after complete combustion. The ash residue was weighed using a calibrated digital balance and expressed as a percentage of the original briquette mass.

3.2 Combustion Test
Combustion performance was evaluated using a water boiling test. Approximately 60 g of briquette sample was ignited and used to heat 50 mL of water. The time required for the water to reach 100°C was recorded as the boiling time.

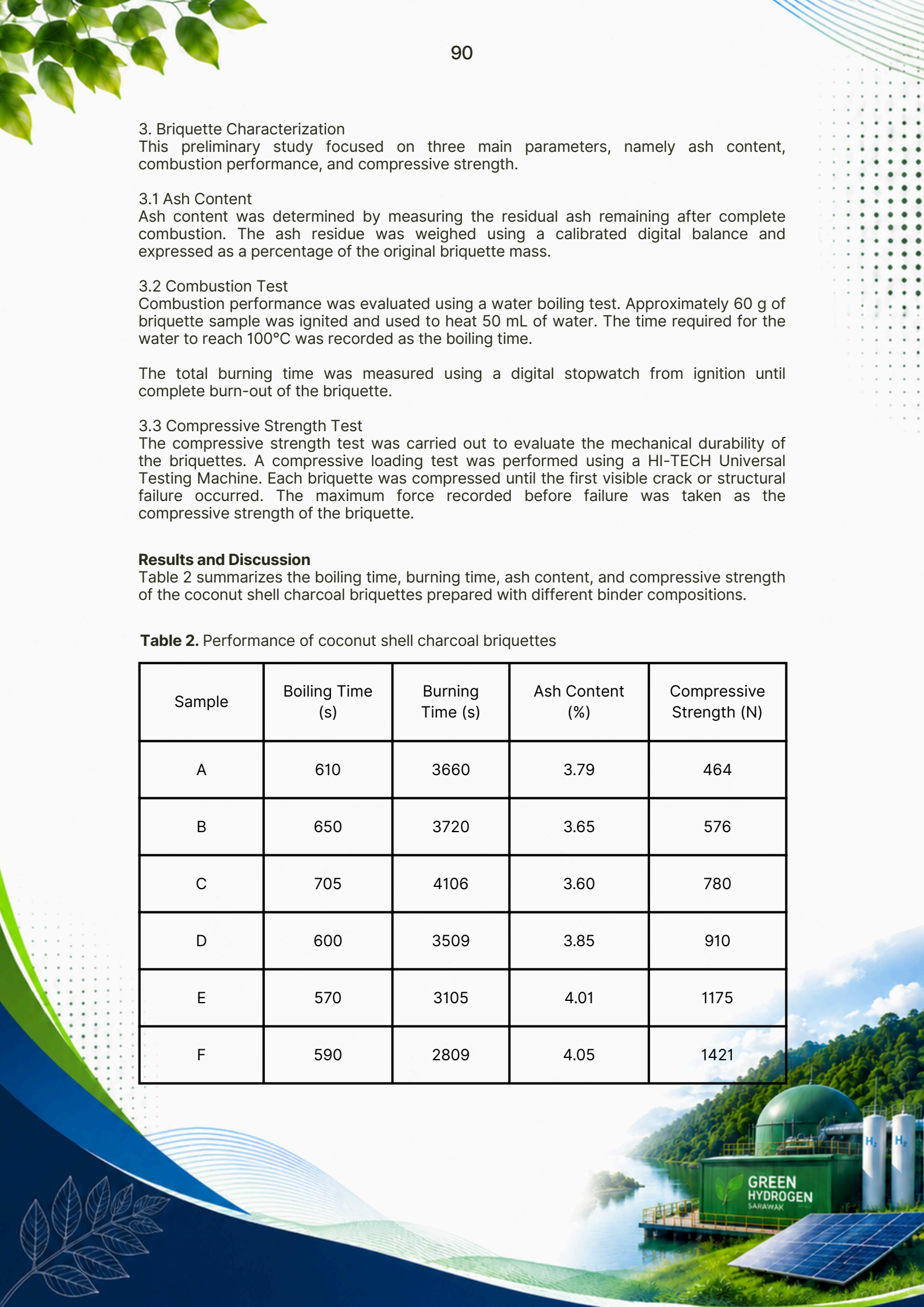
The total burning time was measured using a digital stopwatch from ignition until complete burn-out of the briquette.

3.3 Compressive Strength Test
The compressive strength test was carried out to evaluate the mechanical durability of the briquettes. A compressive loading test was performed using a HI-TECH Universal Testing Machine. Each briquette was compressed until the first visible crack or structural failure occurred. The maximum force recorded before failure was taken as the compressive strength of the briquette.

Results and Discussion
Table 2 summarizes the boiling time, burning time, ash content, and compressive strength of the coconut shell charcoal briquettes prepared with different binder compositions.

Table 2. Performance of coconut shell charcoal briquettes

Sample	Boiling Time (s)	Burning Time (s)	Ash Content (%)	Compressive Strength (N)
A	610	3660	3.79	464
B	650	3720	3.65	576
C	705	4106	3.60	780
D	600	3509	3.85	910
E	570	3105	4.01	1175
F	590	2809	4.05	1421



1. Effect of Starch Binder
Samples A, B, and C were prepared using 10%, 20%, and 30% starch binder, respectively. The results show that increasing the starch content increased the boiling time from 610 s for Sample A to 705 s for Sample C. This trend suggests that a higher binder content reduced the relative amount of charcoal in the briquette, resulting in lower heat release and slower water heating.

The burning time increased from 3660 s to 4106 s as the starch content increased. This behaviour may be attributed to the denser structure formed by the additional starch binder. A denser briquette limits oxygen penetration, resulting in a slower combustion rate and a longer burning duration.

Compressive strength increased significantly from 464 N to 780 N with increasing starch content. This improvement indicates stronger particle bonding and better structural integrity due to the adhesive properties of starch.

A slight reduction in ash content was also observed, decreasing from 3.79% to 3.60%. The low ash values indicate that coconut shell charcoal is a good-quality fuel that produces only a small amount of solid residue after combustion.

2. Effect of Paper Addition
The addition of paper binder further improved briquette performance. Samples D, E, and F achieved compressive strengths of 910 N, 1175 N, and 1421 N, respectively, which were considerably higher than those of the starch-only briquettes. This improvement can be attributed to the cellulose fibres in the paper pulp, which enhanced particle bonding and reinforced the briquette structure.

The incorporation of paper also reduced the boiling time compared to the starch-only briquettes. Sample E recorded the shortest boiling time of 570 s. This may be due to the higher volatile matter content of paper fibres, which promotes easier ignition and faster combustion, resulting in more rapid heat release during the early stages of burning.

However, increasing the paper content reduced the burning time from 3509 s for Sample D to 2809 s for Sample F. Since paper burns more readily than coconut shell charcoal and generally has a lower energy content, higher paper concentrations accelerated fuel consumption and shortened the combustion duration.

Ash content increased slightly from 3.85% to 4.05% with increasing paper content. This increase may be associated with mineral fillers commonly found in paper products, such as calcium carbonate and kaolin clay. These inorganic materials remain as ash after combustion. Nevertheless, all ash contents remained below 5%, indicating acceptable combustion quality for biomass briquettes.

3. Overall Performance
The results demonstrate that binder composition plays an important role in determining briquette performance. Increasing starch content improved briquette strength and prolonged burning duration but increased boiling time. In contrast, the addition of paper binder enhanced ignition characteristics and significantly improved compressive strength, although it reduced burning duration and slightly increased ash content.



Among all formulations tested, Sample F (70:15:15) achieved the highest compressive strength of 1421 N, while Sample E (80:10:10) recorded the shortest boiling time. Overall, the combined use of starch and paper binders successfully improved the mechanical and combustion properties of coconut shell charcoal briquettes, demonstrating the potential of utilizing coconut shell and paper waste as sustainable resources for renewable solid fuel production.

Conclusion

This preliminary study investigated the production of sustainable charcoal briquettes from coconut shell waste using starch and paper binders. The results showed that binder composition significantly influenced combustion performance, ash content, and compressive strength.

Increasing the starch content improved briquette strength and extended the burning duration, although it increased the boiling time. The addition of paper binder enhanced ignition performance and significantly increased compressive strength due to the reinforcing effect of cellulose fibres.

Among the formulations studied, Sample E (80:10:10) exhibited the most balanced overall performance, combining good combustion behaviour with relatively high compressive strength. These findings indicate that coconut shell waste and waste paper have strong potential as sustainable biomass resources for renewable fuel production.
Overall, the study demonstrates that the conversion of agricultural and paper waste into briquettes can contribute to waste reduction, renewable energy development, and sustainable fuel production for small-scale community applications.

Recommendations

As this work represents a preliminary investigation, further studies are recommended to provide a more comprehensive evaluation of briquette quality. Future research should include analyses of calorific value, volatile matter, fixed carbon, density, moisture content, and emissions.

The effects of different binder types, particle sizes, and compression pressures should also be investigated to optimize briquette performance. In addition, better control of drying and carbonization conditions may help reduce moisture content and improve combustion efficiency.

Future studies may also evaluate the economic feasibility and large-scale production potential of coconut shell charcoal briquettes for sustainable community-based energy applications.

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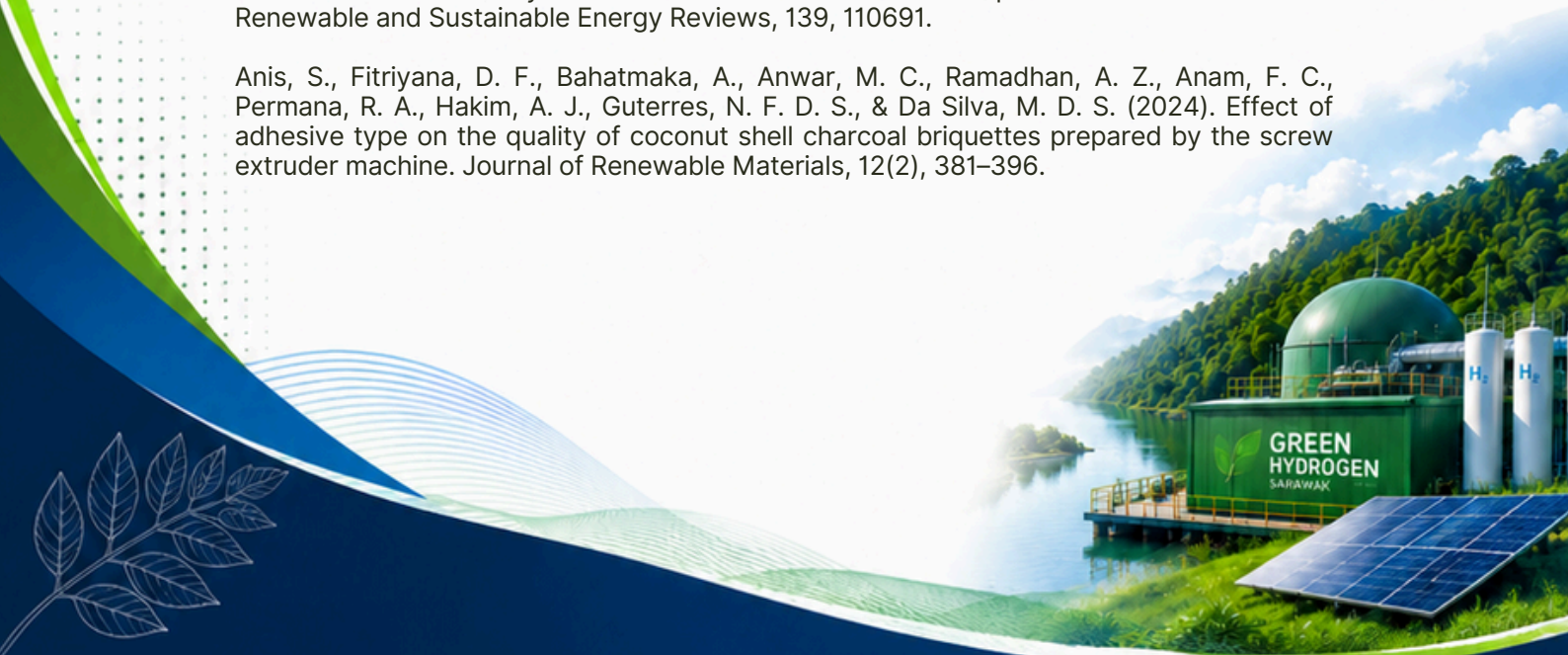

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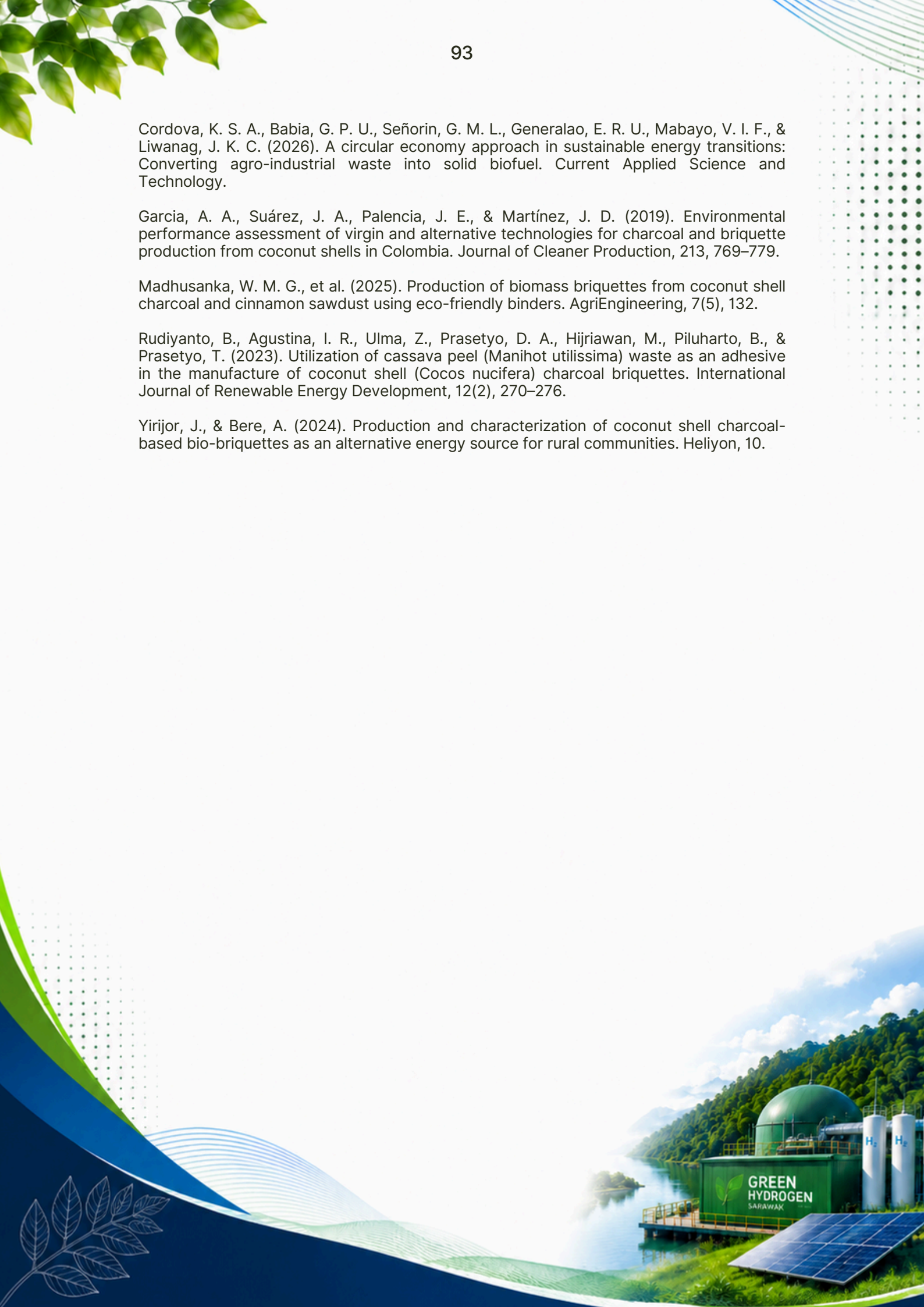

Biogenic Bandgap Engineering: From Phytochemical Capping To Lattice Doping And Z-Scheme Assembly For Solar Water Purification

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Introduction

Green and low-carbon water treatment has become a priority because conventional remediation methods often shift pollution from one phase to another or require high chemical and energy inputs. Semiconductor photocatalysis offers a cleaner pathway by using solar energy to generate reactive species that mineralize or transform organic contaminants (Al Miad et al., 2024; Jabbar et al., 2024). Yet many conventional photocatalysts still depend on harsh synthesis conditions, expensive precursors, or ultraviolet light activation. This creates a mismatch between the green promise of photocatalysis and the material routes used to produce it. Biogenic synthesis addresses part of this problem. Plant extracts, algae, bacteria, fungi, and biomolecules contain polyphenols, flavonoids, proteins, alkaloids, chlorophylls, amino acids, and carbohydrates that can reduce metal ions, control nucleation, and stabilize nanoparticles (El-Seedi et al., 2024). In semiconductor photocatalysis, performance depends on light absorption, charge separation, surface reactions, and redox potential. These properties are controlled by lattice defects, dopant states, band alignment, and interfacial charge pathways (Zuo et al., 2024). Biological metabolites can influence these features during synthesis and thermal treatment. Therefore, the biogenic route should be understood as an electronic design strategy, not only as a green preparation method.

The biogenic interface is the region where biological molecules meet inorganic semiconductor growth. At this interface, three processes occur together. First, functional groups such as hydroxyl, carboxyl, amine, and thiol groups bind metal ions and regulate nucleation (Yugay & Shkryl, 2026). Second, organic residues remain on the particle surface and influence hydrophilicity, adsorption, and interfacial charge movement. Third, some biological elements can enter the semiconductor lattice or generate vacancies after calcination (Fuziki et al., 2023).



These events determine whether the material is simply capped or electronically modified. Bio-reduction and bio-doping must be separated clearly. Bio-reduction refers to the conversion of metal ions into oxides, sulfides, or metallic particles through biological reducing agents. Bio-doping refers to the entry of atoms such as nitrogen, sulfur, or carbon into the lattice or near-surface structure. This distinction matters because surface capping mainly affects dispersion and adsorption, whereas doping and defects can narrow the bandgap, create mid-gap states, or improve visible-light response. A second transition involves carbon. During controlled calcination, organic caps may be removed, converted into carbonaceous layers, or transformed into carbon quantum dot-like domains. These carbon residues can improve electron mobility, increase visible-light harvesting, and create conductive bridges between semiconductor components (Zhang et al., 2021). Excess carbon, however, can block active sites or shield light. The challenge is to retain enough carbon for charge transport without suppressing surface reactions.

Bandgap Tuning through Biological Chemistry

Biogenic bandgap tuning begins with non-metal doping. Amino acids, proteins, alkaloids, and sulfur-containing metabolites can supply nitrogen and sulfur species during thermal treatment (Brif et al., 2014). When incorporated into oxide semiconductors such as TiO_2, ZnO, Bi_2O_3, WO_3, or mixed metal oxides, these dopants may introduce localized energy states above the valence band or below the conduction band. This narrows the optical transition needed for excitation and shifts the response toward visible light. Carbon from sugars and phenolics can also sensitize the surface or create interfacial states that support electron transfer (Simanullang et al., 2024).

Transition metal co-doping offers another route. Some plants naturally accumulate Fe, Cu, Mn, Ni, or Zn, and their extracts can introduce trace metal species during synthesis. In controlled systems, these metals may act as dopants or form secondary oxide phases that improve charge separation (Disha et al., 2025). The benefit depends on concentration. Low levels can trap charges and reduce recombination, whereas excessive metal loading can become recombination centers. Therefore, biogenic co-doping requires chemical profiling of extracts and careful optimization rather than simple claims of natural composition.

Residual phytochemicals also provide sensitization. Chlorophyll, anthocyanins, tannins, and conjugated phenolics absorb visible light and may inject electrons into the conduction band of a semiconductor when the energy alignment is favorable. This process resembles dye sensitization, but the natural dye layer is formed during synthesis. The limitation is stability. Natural chromophores may degrade under long irradiation. Stable performance requires either strong anchoring, partial carbonization, or integration into a heterojunction that protects the sensitizer from rapid photobleaching.

Defect Engineering and Z-Scheme Assembly

Defects are central to solar photocatalysis. Oxygen vacancies can increase visible-light absorption, improve adsorption of oxygen or water, and provide active sites for reactive oxygen species generation (Cui et al., 2025). Biogenic synthesis may favor vacancy formation because rapid nucleation, uneven ligand binding, and mild reducing conditions disturb ideal crystal growth. Defect-rich materials are not automatically better. Too few vacancies give limited electronic benefit, while too many vacancies accelerate recombination. The aim is controlled defect density, not maximum disorder. Heterojunction design gives biogenic engineering its strongest value. In a conventional type-II system, electrons move to the semiconductor with the lower conduction band, while holes move to the semiconductor with the higher valence band.



This improves separation but weakens redox potential (Yuan et al., 2024). A Z-scheme system keeps the stronger electrons and stronger holes on different semiconductors, allowing pollutant degradation to proceed with stronger oxidative and reductive power. For water purification, this matters because pharmaceutical pollutants and persistent organic compounds often require high redox capacity, not charge separation alone (Pirhashemi & Habibi-Yangjeh, 2021). Biogenic routes can assist Z-scheme assembly in three ways. First, biological molecules can anchor two semiconductor phases closely, reducing interfacial resistance. Second, bio-reduced Ag or Au nanoparticles can form Schottky barriers that capture electrons and suppress recombination. Third, biological templates such as pollen, bacterial cells, cellulose, or viral capsids can guide porous architecture, improving light scattering and mass transfer. These features help move photocatalysts from isolated nanoparticles toward organized solar-active structures.

Application in Solar Water Purification

The most meaningful target for biogenic photocatalysts is not simple dye removal, but the degradation of antibiotics, endocrine-disrupting compounds, pesticides, and other persistent organic pollutants, as shown in Figure 1. Dyes are useful for early screening because they are easy to monitor, but they may undergo photosensitization and overstate photocatalytic performance. Recalcitrant pollutants provide a more realistic test of bandgap design, charge transfer, and reactive species formation.

One recent study reports the sustainable, green synthesis of a novel Z-scheme SnS_2/HAp photocatalyst utilizing Ocimum tenuiflorum (tulsi) leaf extract as a stabilizing agent (Gadore et al., 2024). To promote circular waste management, hydroxyapatite (HAp) was upcycled from discarded Labeo rohita fish scales. Following comprehensive structural, morphological, and optical characterization, the composite's performance was evaluated through the degradation of gentian violet (GV) dye and other emerging organic pollutants. Under optimized conditions, the SnS2/HAp photocatalyst achieved a maximum GV degradation efficiency of 97.49% (k = 0.0494 min-1) and maintained over 70% efficiency against other contaminants across diverse water matrices. This enhanced performance is driven by a proposed Z-scheme electron transport mechanism that accelerates charge separation and delays recombination.

Mechanism validation should move beyond removal percentage. A strong solar purification study should report dark adsorption, photolysis control, catalyst stability, mineralization through total organic carbon analysis, and reusability. Scavenger studies can identify whether superoxide radicals, hydroxyl radicals, or holes dominate the reaction. In a Z-scheme pathway, the simultaneous presence of strong oxidative holes and reduction-driven superoxide formation gives stronger evidence than efficiency alone. Band edge positions, radical trapping, and photoluminescence or photocurrent data should support the proposed pathway. Water matrix effects also require attention. Natural waters contain chloride, carbonate, phosphate, nitrate, humic substances, and competing organic matter. These species may scavenge radicals or occupy active sites. A photocatalyst that performs well in deionized water may fail in river water or wastewater effluent. For this reason, future studies should test biogenic photocatalysts under simulated sunlight in real or synthetic water matrices and report degradation intermediates where possible.



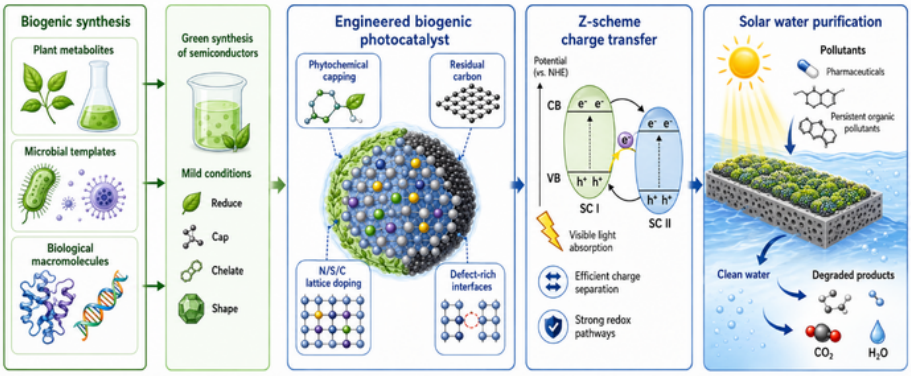

Figure 1. Schematic illustration of biogenic bandgap engineering for solar water purification

Critical Assessment and Roadmap

The main weakness of biogenic photocatalyst research is reproducibility. Plant extracts vary with species, season, location, solvent, extraction time, and storage condition (Nabi et al., 2026). Two extracts with the same plant name may contain different levels of phenolics, proteins, sugars, and trace metals. This variability directly affects nucleation, capping, doping, and defect formation. Future work should report extract preparation in detail and include basic metabolite profiling, such as total phenolic content, FTIR fingerprints, UV-visible spectra, or chromatographic markers. Calcination is the second challenge. Higher temperature improves crystallinity and removes unstable organic residues, but it may also destroy useful carbon, collapse porous templates, reduce surface area, and alter dopant states. Lower temperature preserves biological residues but may leave poorly crystalline materials with weak charge transport (Chen & Tang, 2024). The optimal condition depends on whether the design goal is crystallinity, carbon sensitization, defect formation, or heterojunction construction. Reporting only the final degradation percentage hides this trade-off. The third challenge is deployment. Powder photocatalysts are difficult to recover and may create secondary contamination. Practical systems need immobilized materials on membranes, glass, fibers, ceramics, hydrogels, or coated reactors. Immobilization reduces loss but may lower surface area and light penetration. The next generation of biogenic photocatalysts should therefore combine material design with reactor thinking. A low-carbon material has limited value if it cannot be recovered, reused, and operated under sunlight in real water conditions.

Conclusion

Biogenic synthesis should no longer be viewed only as a safer way to make nanoparticles. Its larger potential lies in bandgap engineering through phytochemical capping, lattice doping, defect formation, carbon-mediated charge transport, and Z-scheme heterojunction assembly. These mechanisms connect biological chemistry with semiconductor physics. When controlled properly, biogenic routes can produce solar-active photocatalysts that are greener to synthesize and better suited for water purification. The field now needs stronger evidence: standardized extracts, verified dopant and defect states, realistic pollutant testing, mechanism validation, and immobilized systems. This shift will move biogenic photocatalysis from descriptive green synthesis toward low-carbon material engineering for clean water applications.

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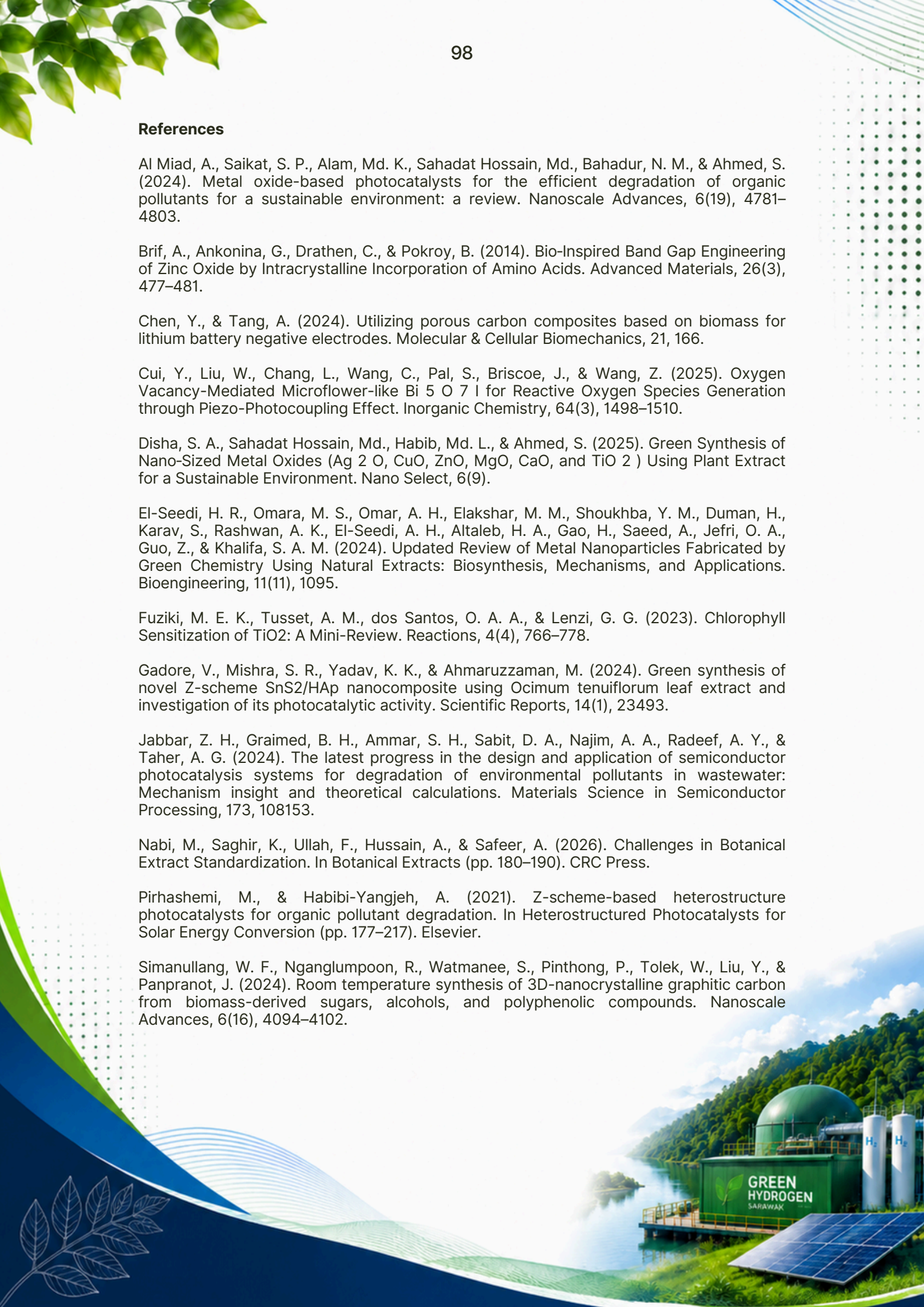

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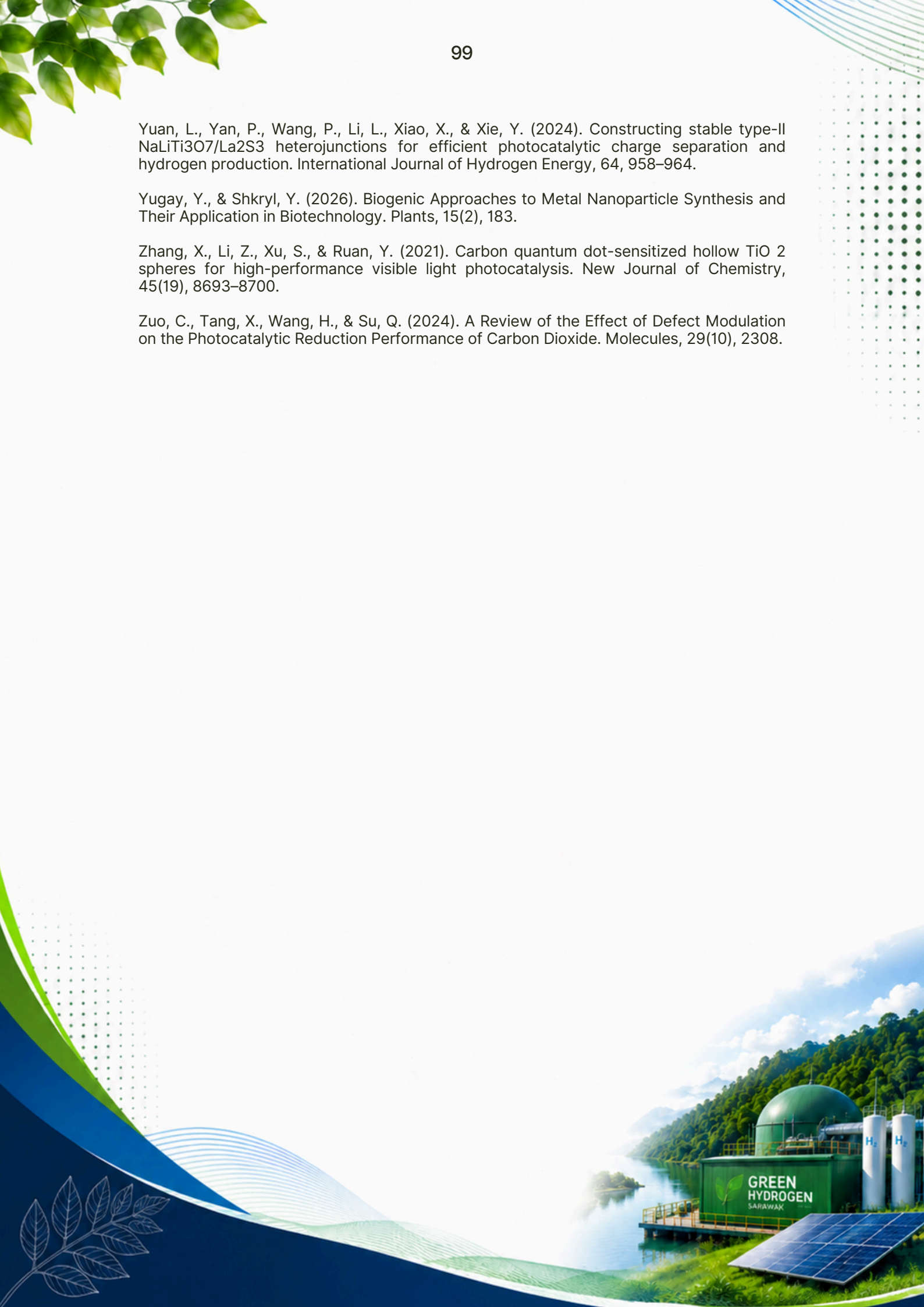

From Kitchen Waste to Jet Fuel: Unlocking the Potential of Waste Cooking Oil for Sustainable Aviation

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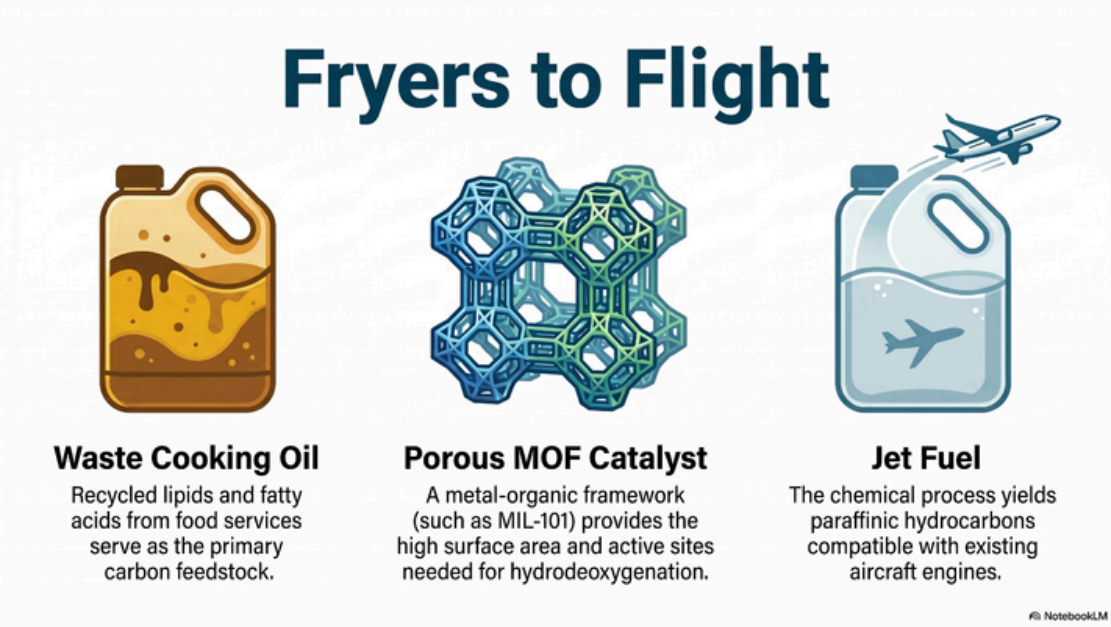


Introduction

The aviation sector plays an important role in supporting global mobility, trade, tourism, and economic development. However, the industry remains highly dependent on fossil-derived aviation fuels, which are mainly composed of hydrocarbon molecules ranging from C8 to C15. Unlike fuels used in land and maritime transportation, aviation fuel is a highly specialised petroleum product designed to meet strict aircraft performance and safety requirements (Wang et al., 2024).



Despite its importance, aviation contributes significantly to global greenhouse gas emissions. Current estimates indicate that the aviation industry accounts for approximately 2% of global greenhouse gas emissions, making it one of the sectors requiring urgent decarbonisation strategies (Wang et al., 2024). As air travel continues to grow, reducing carbon emissions from aviation has become increasingly important in supporting global climate change mitigation efforts.

One of the most promising short-term approaches for reducing aviation-related emissions is the use of Sustainable Aviation Fuel (SAF). SAF refers to renewable liquid fuel produced from sustainable feedstocks such as biomass, organic waste, waste oils, and carbon-based resources. Compared with conventional aviation fuel, SAF has the potential to reduce life-cycle carbon emissions by up to 80%, depending on the feedstock and production pathway used (Abrantes et al., 2021).

Among the various feedstocks available for SAF production, waste cooking oil (WCO) has gained increasing attention due to its abundance, low cost, and strong sustainability potential. WCO is generated from households, restaurants, hotels, food industries, and catering establishments after repeated use of edible vegetable oils for frying. Instead of being discarded into drainage systems or landfills, WCO can be recovered and converted into renewable fuels, including biodiesel, renewable diesel, and sustainable aviation fuel.

This article discusses the potential of waste cooking oil as a sustainable feedstock for aviation fuel production, the chemical pathways involved in its conversion, and the role of advanced catalysts, particularly Metal–Organic Frameworks (MOFs), in improving the efficiency of hydrodeoxygenation-based fuel production.

Overview of Sustainable Aviation Fuel

Sustainable Aviation Fuel is a renewable alternative to conventional jet fuel. It can be produced from several sources, including vegetable oils, animal fats, agricultural residues, municipal waste, biomass, and captured carbon dioxide. The main objective of SAF development is to reduce the dependence of the aviation sector on fossil resources while lowering greenhouse gas emissions across the fuel life cycle.

SAF is particularly important because aviation is considered a hard-to-abate sector. Unlike road transport, where electrification is rapidly advancing, aircraft require fuels with high energy density, excellent thermal stability, and strict safety performance. Therefore, liquid hydrocarbon fuels will continue to be important for aviation in the near future.

The development of SAF offers several environmental and industrial benefits:

1. Reduction of Carbon Emissions

SAF can significantly reduce life-cycle carbon dioxide emissions compared with fossil-based aviation fuel. The reduction depends on the type of feedstock, production process, hydrogen source, and supply chain efficiency. When produced from waste-based feedstocks such as WCO, SAF can provide substantial environmental benefits because it converts waste into valuable fuel while avoiding competition with food-based resources.

2. Lower Particulate Emissions

SAF generally contains fewer aromatic and sulphur-containing compounds than conventional jet fuel. This can help reduce particulate matter emissions during combustion, improving air quality around airports and reducing the climate impact of aviation-related pollutants.



3. Support for Circular Economy
The use of waste materials such as WCO in SAF production supports circular economy principles. Instead of treating used cooking oil as waste, it can be collected, processed, and upgraded into high-value renewable fuel. This approach reduces environmental pollution while creating economic value from discarded resources.

Waste Cooking Oil as a Sustainable Feedstock
Waste cooking oil is generated when edible oils are repeatedly heated during food preparation. Common sources include restaurants, food courts, hotels, households, and food processing industries. During frying, vegetable oils are exposed to high temperatures, moisture, oxygen, and food residues, leading to physical and chemical degradation.

Globally, WCO generation is estimated at approximately 41–52 million tonnes annually, with Asia contributing nearly half of the total supply (Mannu et al., 2024). This large availability makes WCO a strategic feedstock for renewable fuel production, especially in regions with high cooking oil consumption.

WCO is considered more sustainable than virgin vegetable oils because it does not directly compete with food supply. It is also generally cheaper than fresh vegetable oil. According to Suzihaque et al. (2022), WCO is typically two to three times less expensive than virgin vegetable oil, which can reduce overall biofuel production costs.

Composition and Degradation of Cooking Oil
Vegetable oils primarily consist of triacylglycerols, which usually account for around 88–98% of their composition. These oils are widely used in food preparation and contribute significantly to dietary energy intake in many countries. Palm oil is one of the most commonly used cooking oils globally, followed by soybean oil, rapeseed oil, sunflower oil, peanut oil, corn oil, coconut oil, olive oil, and sesame oil (Kumar et al., 2025). The composition of vegetable oils commonly used for cooking is illustrated in Figure 1.

During frying, cooking oils are usually exposed to temperatures between 150°C and 200°C. Under these conditions, several degradation reactions occur, including oxidation, hydrolysis, polymerisation, and thermal cracking. These reactions cause changes in oil colour, viscosity, density, acid value, fatty acid composition, and total polar compounds. Repeated heating also increases the content of free fatty acids and other degradation products. Although this reduces the quality of the oil for food use, it does not eliminate its value as a renewable fuel feedstock. Instead, proper collection and pre-treatment of WCO can enable its conversion into useful hydrocarbon fuels.

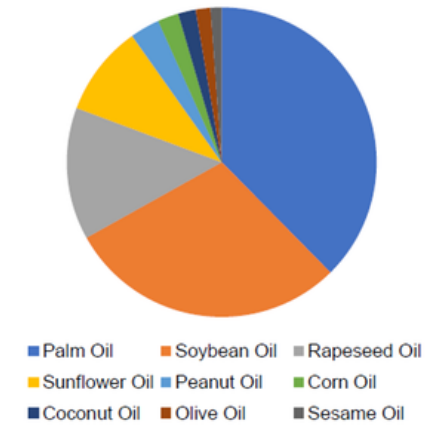


Figure 1. Composition of vegetable oils commonly used for cooking

Environmental and Economic Benefits of WCO Utilisation

The utilisation of WCO for renewable fuel production provides several environmental and economic benefits.

1. Waste Reduction and Pollution Prevention

Improper disposal of WCO can cause serious environmental problems. When discharged into drains or water bodies, WCO can block drainage systems, increase wastewater treatment loads, and affect aquatic ecosystems. Collecting WCO for fuel production helps reduce these environmental risks.

2. Lower Feedstock Cost

Feedstock cost is one of the major factors influencing the economic feasibility of renewable fuel production. Since WCO is cheaper than virgin vegetable oil, its use can improve the cost competitiveness of biodiesel, renewable diesel, and SAF production.

3. Renewable Fuel Production

WCO can be converted into several types of renewable fuels, including biodiesel through transesterification and renewable hydrocarbons through hydroprocessing. Previous studies have shown that WCO-derived biodiesel can improve emission characteristics by reducing particulate matter, carbon monoxide, and hydrocarbon emissions compared with conventional diesel fuel (Awogbemi et al., 2021; Manikandan et al., 2023).

4. Contribution to Low-Carbon Transportation

By transforming WCO into renewable fuel, the transportation sector can reduce its dependence on fossil fuels. In the context of aviation, WCO-derived SAF can contribute to cleaner air travel and support long-term decarbonisation strategies.

Conversion of WCO into Renewable Hydrocarbon Fuels

The conversion of WCO into renewable diesel or SAF commonly involves catalytic hydrodeoxygenation. This process removes oxygen from fatty acids and triglycerides to produce hydrocarbons similar to those found in conventional petroleum-based fuels.

According to Chang et al. (2025), three major deoxygenation pathways are involved in the conversion of fatty acids into hydrocarbons:

1. Hydrodeoxygenation

Hydrodeoxygenation removes oxygen in the form of water using hydrogen. This pathway produces hydrocarbons while preserving more carbon atoms from the original fatty acid structure.

$$R–COOH + 3H_2 \rightarrow R–CH_3 + 2H_2O$$

2. Decarboxylation

Decarboxylation removes oxygen in the form of carbon dioxide. This pathway does not require as much hydrogen as hydrodeoxygenation but results in the loss of one carbon atom.

$$R–COOH \rightarrow R–H + CO_2$$

3. Decarbonylation

Decarbonylation removes oxygen in the form of carbon monoxide and water. Similar to decarboxylation, it also produces hydrocarbons with one fewer carbon atom than the original fatty acid.

$$R–COOH \rightarrow R–H + CO + H_2O$$



These pathways are important because they determine the type, yield, and quality of hydrocarbons produced. For aviation fuel applications, further upgrading such as hydrocracking and isomerisation may be required to obtain hydrocarbons within the jet fuel range.

Catalytic Hydrodeoxygenation for SAF Production

Catalytic hydrodeoxygenation is one of the most promising technologies for converting bio-based feedstocks into hydrocarbon fuels. The process was originally adapted from petroleum refining technology and involves the removal of oxygenated compounds under hydrogen pressure in the presence of a catalyst.

Typical hydrodeoxygenation operating conditions involve elevated temperatures between 250°C and 400°C and hydrogen pressures that may reach approximately 20 MPa, depending on the feedstock and catalyst system used (Galadima et al., 2022). During the process, several reactions may occur, including hydrogenation, hydrogenolysis, hydrocracking, decarboxylation, decarbonylation, and dehydration.

The removal of oxygen is essential because oxygenated compounds can reduce fuel stability, increase acidity, and cause corrosion problems in engines. Through Hydrodeoxygenation, WCO can be converted into hydrocarbons with improved thermal stability, lower oxygen content, and better compatibility with existing fuel infrastructure.

Role of Catalysts in Hydrodeoxygenation Reactions

Catalysts play a crucial role in determining the efficiency, selectivity, and stability of the hydrodeoxygenation process. A suitable catalyst should promote oxygen removal, enhance hydrocarbon yield, minimise undesirable side reactions, and maintain activity over repeated use. Several catalyst systems have been investigated for hydrodeoxygenation reactions, including:

1. Zeolite-Based Catalysts

Zeolite-based catalysts are widely studied due to their acidity, thermal stability, and shape-selective properties. Their pore structures can influence hydrocarbon distribution and promote cracking reactions needed to produce jet fuel-range molecules.

2. Metal Oxide Catalysts

Metal oxides can provide active sites for deoxygenation and hydrogenation reactions. Their surface acidity, redox properties, and oxygen vacancy characteristics may influence catalytic performance.

3. Activated Carbon-Supported Catalysts

Activated carbon is commonly used as a catalyst support because of its high surface area, porosity, and chemical stability. Metal particles supported on activated carbon can enhance hydrogenation and deoxygenation performance.

4. Nickel-Based Catalysts

Nickel-based catalysts have attracted attention as lower-cost alternatives to noble metal catalysts. Nickel can promote hydrogenation and C–O bond cleavage, making it suitable for HDO reactions involving fatty acids and triglycerides.

5. MOF-Based Catalysts

Metal–Organic Frameworks have recently emerged as advanced porous materials with strong potential for catalytic applications. Their high surface area, tunable pore structure, and adjustable active sites make them attractive for biomass upgrading and renewable fuel production.



Metal–Organic Frameworks as Advanced Catalysts

Metal–Organic Frameworks are porous crystalline materials composed of metal ions or clusters connected by organic linkers. Their structural flexibility allows researchers to design catalysts with specific pore sizes, active sites, and chemical functionalities.
MOFs offer several advantages in catalytic applications:

1. High Surface Area
MOFs typically possess exceptionally high surface areas, allowing better dispersion of active metal species and improved contact between reactants and catalytic sites.

2. Tunable Pore Structure
The pore size and shape of MOFs can be modified through the selection of metal centres and organic linkers. This tunability is useful for controlling reactant diffusion and product selectivity.

3. Adjustable Chemical Functionality
MOFs can be functionalised with acidic, basic, or redox-active groups. This allows the catalyst properties to be tailored for specific reactions such as hydrogenation, esterification, transesterification, and hydrodeoxygenation.

4. Metal-Support Interaction
MOFs can stabilise metal nanoparticles within their porous frameworks. This can improve catalyst stability and reduce particle aggregation during high-temperature reactions.

5. Defect Engineering
Defect engineering has been reported as an effective strategy to improve catalytic performance. Defective MOFs may provide additional active sites and enhance catalytic activity in hydrogenation and deoxygenation reactions (Shan et al., 2023).

MIL-101(Cr) for Biomass Upgrading and SAF Production

Among the many MOF materials reported, MIL-101(Cr) (Figure 2) is one of the most extensively studied chromium-based MOFs. It consists of chromium metal centres connected by terephthalic acid linkers to form a highly porous structure.

MIL-101(Cr) has attracted significant attention because of its high surface area, large pore volume, and excellent stability. Upon activation, it can generate coordinatively unsaturated chromium sites that act as Lewis acid sites. These sites are important for catalytic reactions involving oxygenated compounds.

The properties of MIL-101(Cr) make it suitable for various applications, including catalysis, gas storage, environmental remediation, adsorption, separation, and membrane development (Zou et al., 2022). In biofuel production, MIL-101(Cr)-based materials can function either as catalyst supports or active catalytic materials.

MOF-derived catalysts based on MIL-101 structures have been reported to enhance deoxygenation reactions for green diesel production (Chang et al., 2025). Their large surface area allows effective dispersion of active metals, while their adjustable pore system can improve selectivity towards desired hydrocarbon products.



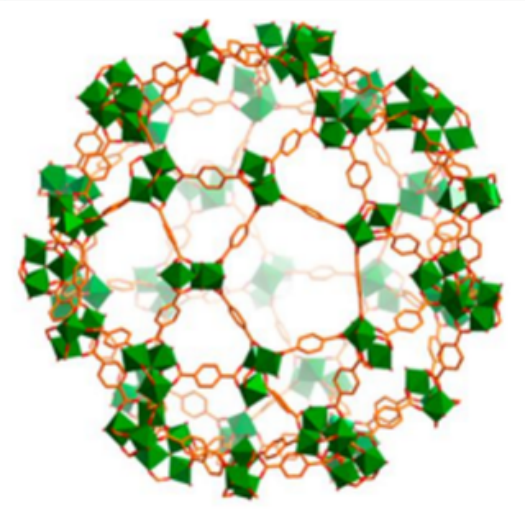


Figure 2. The structure of MIL-101-Cr

Future Opportunities for WCO-Derived SAF

The development of WCO-derived SAF offers strong opportunities for sustainable aviation and waste valorisation.

1. Waste-to-Fuel Industries

The collection and conversion of WCO into SAF can create new waste-to-fuel industries. This may involve partnerships among restaurants, municipalities, fuel producers, aviation companies, and research institutions.

2. Low-Carbon Aviation Development

WCO-derived SAF can help reduce the carbon footprint of aviation, particularly when integrated with renewable hydrogen and efficient catalytic technologies.

3. Advanced Catalyst Research

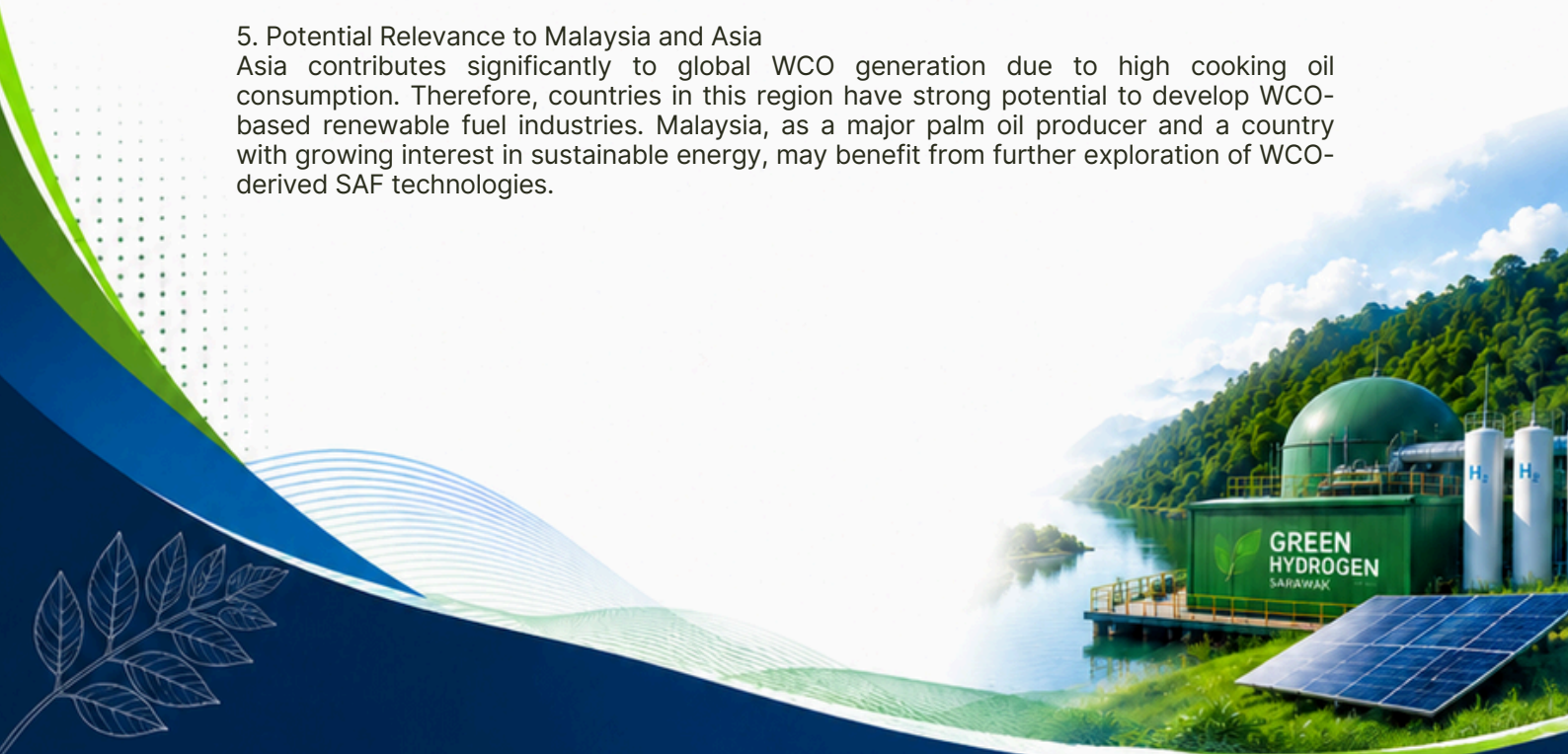
Further research on MOFs, MOF-derived catalysts, and bifunctional catalytic systems may improve hydrodeoxygenation efficiency, hydrocarbon selectivity, catalyst stability, and reusability.

4. Circular Economy Implementation

Using WCO as a feedstock supports circular economy practices by transforming a waste material into a high-value energy product. This approach aligns with sustainability goals related to waste reduction, resource recovery, and low-carbon development.

5. Potential Relevance to Malaysia and Asia

Asia contributes significantly to global WCO generation due to high cooking oil consumption. Therefore, countries in this region have strong potential to develop WCO-based renewable fuel industries. Malaysia, as a major palm oil producer and a country with growing interest in sustainable energy, may benefit from further exploration of WCO-derived SAF technologies.



Challenges and Limitations

Although WCO-derived SAF has promising potential, several challenges need to be addressed before large-scale implementation.

1. Feedstock Collection and Quality Control

WCO is generated from many small and scattered sources. Efficient collection systems are required to ensure consistent supply. In addition, WCO quality can vary depending on the type of oil, frying conditions, contamination level, and storage method.

2. Pre-Treatment Requirements

WCO may contain water, food particles, free fatty acids, and degradation products. These impurities can affect catalyst performance and fuel quality. Proper filtration, drying, and pre-treatment are necessary before catalytic conversion.

3. Hydrogen Demand

Hydrodeoxygenation requires hydrogen, and the sustainability of the process depends strongly on the source of hydrogen. If fossil-derived hydrogen is used, the overall carbon reduction benefit may be reduced. Therefore, renewable or low-carbon hydrogen is important for improving the sustainability of SAF production.

4. Catalyst Stability and Cost

Catalysts used in HDO reactions must remain stable under high temperature and pressure. Catalyst deactivation due to coke formation, poisoning, sintering, or structural collapse remains a major challenge. Advanced catalysts such as MOFs also require further assessment in terms of cost, scalability, and long-term durability.

5. Fuel Upgrading and Certification

Producing hydrocarbons from WCO is only one part of the SAF production process. The final fuel must meet strict aviation fuel standards and certification requirements. Additional upgrading steps may be necessary to achieve the required composition, freezing point, energy density, and combustion properties.

Conclusion

Waste cooking oil is no longer merely a discarded by-product of food preparation. With proper collection, pre-treatment, and catalytic upgrading, it can become a valuable feedstock for producing renewable diesel and sustainable aviation fuel. Its low cost, wide availability, and waste-based origin make it an attractive resource for supporting circular economy and low-carbon transportation.

The conversion of WCO into SAF through catalytic hydrodeoxygenation offers a promising pathway for producing renewable hydrocarbon fuels compatible with aviation applications. Catalysts play a central role in improving the efficiency and selectivity of this process. In particular, Metal–Organic Frameworks such as MIL-101(Cr) provide exciting opportunities due to their high surface area, tunable pore structure, Lewis acid sites, and potential for advanced catalyst design.

Although several challenges remain, including feedstock variability, hydrogen demand, catalyst stability, and fuel certification, WCO-derived SAF represents an important step towards cleaner aviation. By combining waste valorisation with advanced catalytic technology, this approach can contribute meaningfully to greenhouse gas reduction, sustainable fuel production, and future low-carbon aviation development.



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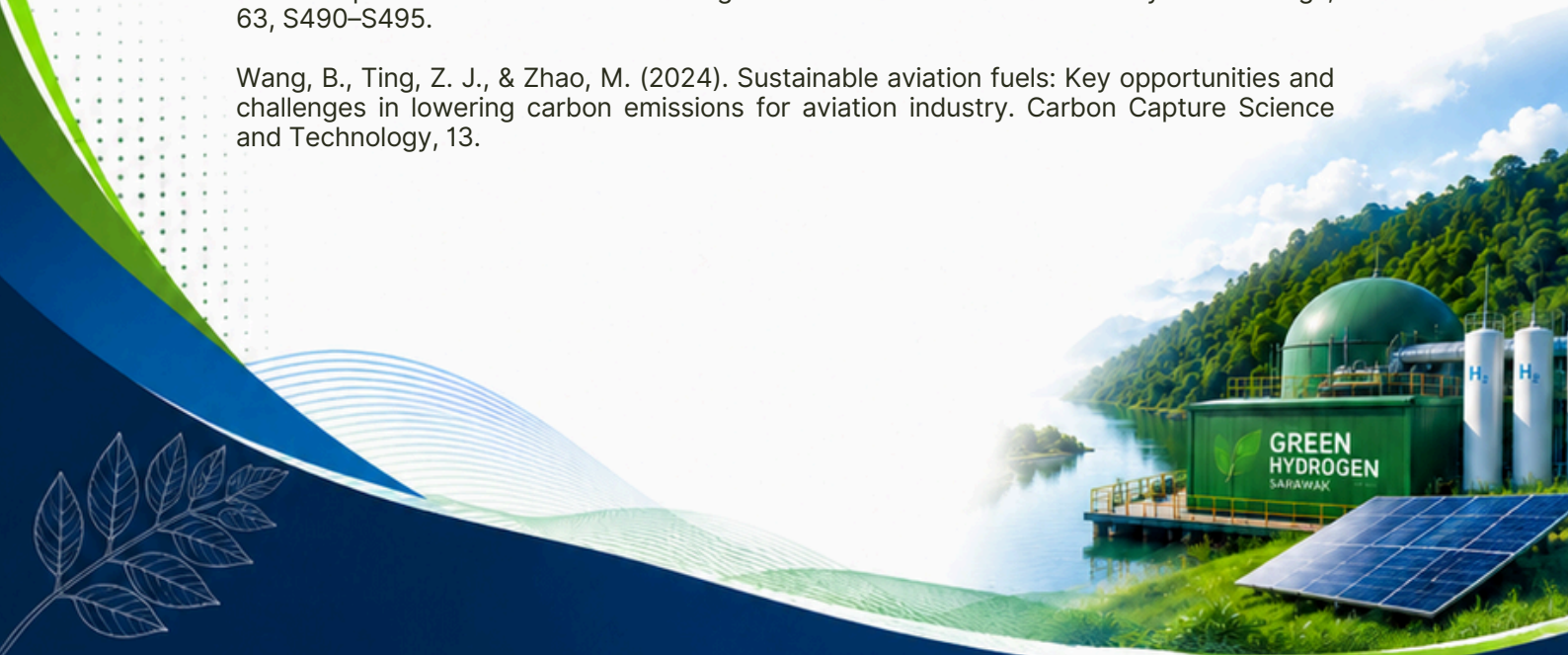

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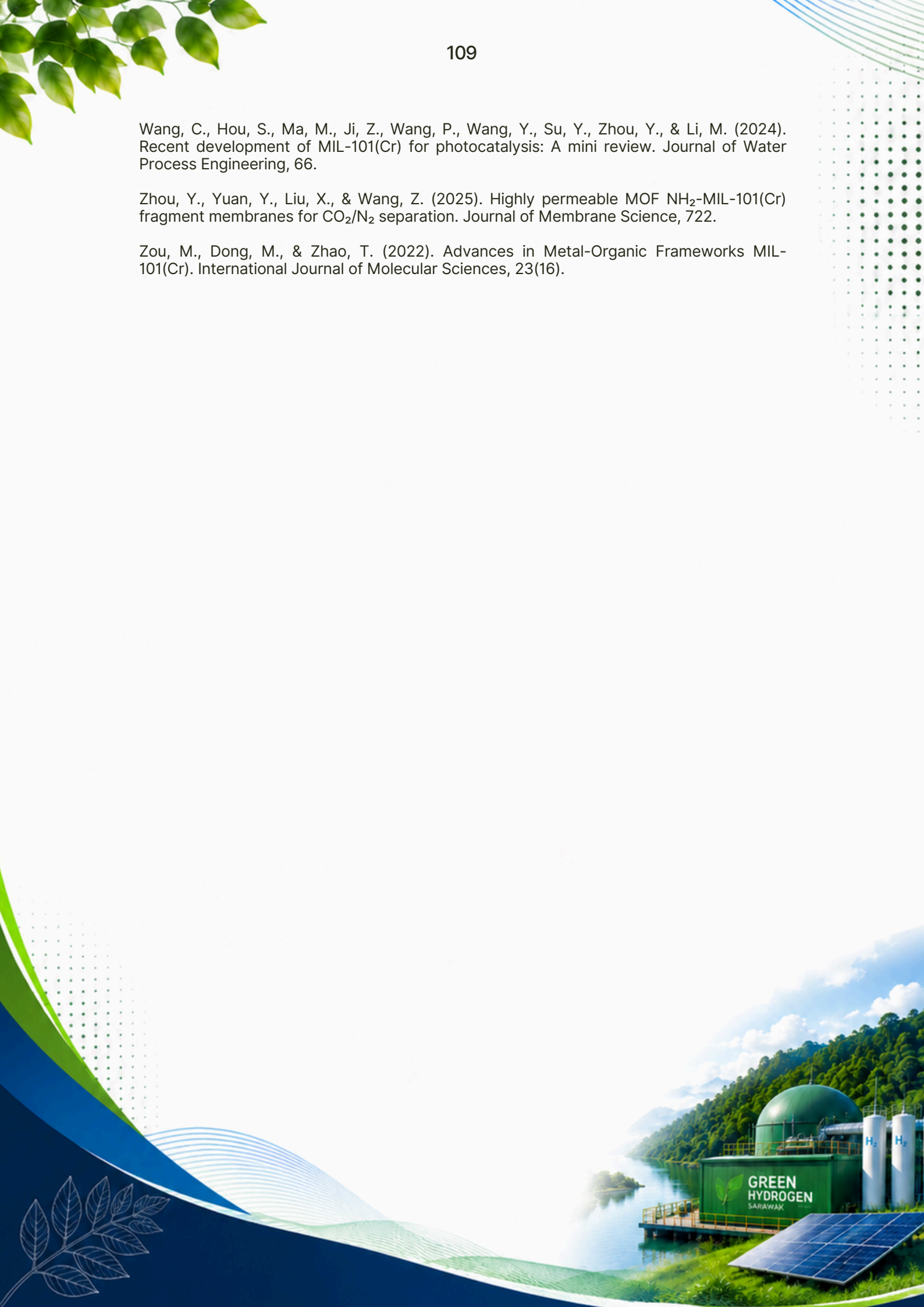

The Indirect Role of Green Leadership in Promoting Low-Carbon and Eco-Friendly Operations Through Green Innovation and Supply Chain Practices

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Introduction

The global food and beverage industry is currently facing an unprecedented sustainability crisis, accounting for approximately one-third of total anthropogenic greenhouse gas (GHG) emissions worldwide (Yang & Wang, 2025). Within this sector, global beverage production alone generated an estimated 1.5 billion tonnes of CO_2-equivalent in a single year, reflecting the substantial energy intensity of modern food processing and operational systems (Lu et al., 2026). Moreover, when food waste from these operations is disposed of in landfills, it decomposes and releases methane, a greenhouse gas with 28 times the heat-trapping potential of carbon dioxide (US EPA, 2023). Wasted food is also responsible for approximately 58% of all landfill methane emissions, underscoring the urgent need for zero-waste and low-carbon operational transitions (US EPA, 2023). In Indonesia, the food and beverage sector contributes substantially to environmental degradation and national waste generation . According to the Ministry of Environment and Forestry (KLHK), approximately 18.9 million tonnes of food waste are generated annually across the country, while more than 60% of landfill waste consists of organic matter originating primarily from restaurants and catering businesses. In West Java, particularly within Bandung Raya as a dynamic culinary hub, small and medium-sized enterprises (SMEs) face increasing pressure from consumers and regulators to adopt low-carbon and zero-waste operations. However, many culinary SMEs continue to struggle to embed low-carbon sustainability into daily operations due to resource constraints, limited technological capability, and insufficient strategic environmental leadership.



As decarbonization becomes increasingly urgent, environmental issues have become a central managerial concern, encouraging businesses to prioritize initiatives such as resource reduction policies and energy efficiency policies (Gallego-Álvarez et al., 2025). In this context, Green Leadership (GL) emerges as a important organizational driver. Green leaders can strengthen organizational commitment toward sustainability by promoting environmentally oriented strategies, operational discipline, and energy efficiency practices. Nevertheless, leadership alone does not automatically translate into measurable reductions in carbon footprints. The mechanisms through which GL fosters Eco-Friendly Operations (EFO) remain insufficiently examined, particularly the indirect pathways mediated by Green Innovation (GI) and Green Supply Chain Management (GCM). Green innovation in the food industry increasingly involves the transition toward renewable energy and electrified, non-thermal processes to replace conventional fossil-fuel-dependent thermal methods (Yang & Wang, 2025). At the same time, green supply chain practices are essential because logistics facilities and warehousing operations are highly energy-intensive, accounting for approximately 11% of total emissions in the global logistics industry (Cannava et al., 2025). Therefore, this study examines how green leadership indirectly promotes low-carbon eco-friendly operations through the mediating roles of green innovation and green supply chain management among culinary SMEs in Bandung Raya.

Theoretical Background and Literature Review

This study is theoretically grounded in Transformational Leadership Theory and the Natural Resource-Based View (NRBV) of the firm. Transformational Leadership Theory explains how leaders shape organizational values, motivate employees, and influence behavioural change through idealized influence, inspirational motivation, intellectual stimulation, and individualized consideration (Bass, 1985). In the context of environmental management, green leadership extends this logic by emphasizing a leader's role in embedding environmental values, low-carbon awareness, and sustainability-oriented behaviour into daily business practices. Therefore, green leadership is expected to encourage culinary SMEs to pursue environmentally responsible actions, particularly through green innovation and green supply chain management. The Natural Resource-Based View provides a complementary theoretical lens. NRBV argues that firms can build competitive and operational advantages by developing capabilities related to pollution prevention, product stewardship, and sustainable development (Hart, 1995). In this study, green innovation and green supply chain management represent two key environmental capabilities through which green leadership can be transformed into low-carbon eco-friendly operations. Green innovation enables firms to redesign products, processes, and energy-use systems, while green supply chain management allows firms to manage sourcing, logistics, storage, and supplier relationships in a more sustainable manner.

Findings and Discussions

To test the proposed capability mediation model, a quantitative explanatory research design was applied to culinary SMEs in Bandung Raya, West Java. Primary data were collected via structured questionnaires distributed to 113 owners and managers of culinary businesses between April and June 2025. The sampling specifically targeted firms actively adopting or transitioning toward eco-friendly practices. For these local SMEs, Eco-Friendly Operations (EFO) are visible through daily efforts to lower their carbon footprints, such as implementing localized composting to divert organic waste from methane-producing landfills, utilizing energy-efficient cooking equipment, and swapping single-use plastics for biodegradable alternatives. Green Innovation (GI) is evidenced by recipe reformulations that minimize food scraps and the integration of renewable energy systems.



Crucially, Green Supply Chain Management (GSM) manifests as "low-carbon logistics," where SMEs collaborate with suppliers to source ingredients locally (reducing transportation fuel emissions) and enforce shared environmental standards across their procurement networks. Data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) via SmartPLS 4 to evaluate the measurement and structural models. The empirical results reveal a critical insight into organizational sustainability and decarbonization where leadership acts as a strategic catalyst rather than a direct operational solution. Figure 1. Research Model Path Diagram displaying relationships between Green Leadership, Green Innovation, Green Supply Chain Management, and Eco-Friendly Operations.

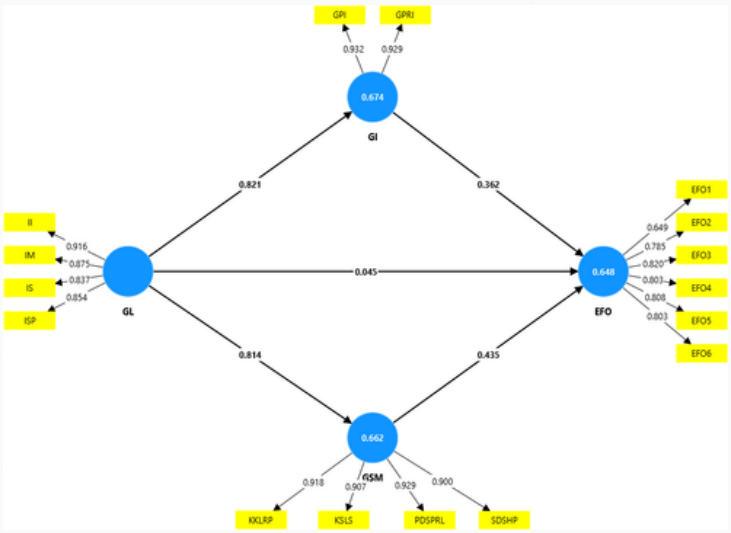

Figure 1. Research Model Path Diagram

The Figure 1. show the analysis demonstrates that Green Leadership (GL) does not have a direct, significant influence on Eco-Friendly Operations (β = 0.045, p = 0.701). Instead, visionary leadership works by actively building organizational systems. GL significantly and substantially enhances both Green Innovation (β = 0.821, p < 0.001) and Green Supply Chain Management (β = 0.814, p < 0.001). Both mediating variables subsequently drive low-carbon operational success. GI positively impacts EFO (β = 0.362, p = 0.005), and GSM similarly impacts EFO (β = 0.435, p = 0.001). The mediation analysis confirms that Green Leadership indirectly influences Eco-Friendly Operations through both GI (β = 0.297, p = 0.010) and GSM (β = 0.354, p = 0.002). Notably, the pathway through Green Supply Chain Management is stronger than the pathway through Green Innovation. This finding is highly consistent with global environmental data, which identifies supply chain logistics and warehousing as massive contributors to industrial energy consumption and greenhouse gas emissions. Because a vast portion of a food business's environmental footprint is embedded in its upstream supply chain which includes ingredient transport, packaging procurement, and cold-chain storage's leaders who successfully broker collaboration and set low-carbon codes of conduct across supply partners achieve the greatest environmental performance. While in-house green innovation refines the firm's internal energy engine, the supply chain determines the overall carbon footprint of the business.

Implications and Recommendations

The findings provide practical implications for culinary businesses, industry practitioners, and policymakers seeking to strengthen eco-friendly operations among SMEs. First, culinary SMEs should develop systems-oriented green leaders who can translate environmental values into daily operational practices. Leadership training may focus on resource efficiency, waste reduction, employee involvement, and the coordination of green innovation and green supply chain practices. Second, SMEs should prioritize Green Supply Chain Management (GCM) as a practical pathway to improve eco-friendly operations. This may include working with local or environmentally responsible suppliers, reducing unnecessary packaging, improving supplier coordination, and encouraging reusable materials where feasible. Third, culinary businesses should adopt manageable green innovation practices, such as improving food preparation processes, reducing food scraps, using energy-efficient equipment, and considering environmentally friendly packaging alternatives. These actions can support gradual operational improvement without requiring large-scale technological investment. Finally, policymakers and industry associations should provide targeted support through training, simple sustainability guidelines, supplier networks, and small-scale incentives. Such support can help SMEs with limited resources translate green leadership into practical green innovation and supply chain practices that support more eco-friendly daily operations.

Conclusion

This study substantiates the argument that green leadership alone is insufficient to directly enhance eco-friendly operations; rather, it operates indirectly by fostering organizational capabilities conducive to sustainability. By testing a capability mediation model, the research demonstrates that green leadership builds the strategic foundation, while green innovation and green supply chain management deliver the actual reductions in energy use and carbon emissions. For the culinary industry in Bandung Raya and beyond, combating climate change and achieving a sustainable, low-carbon future requires integrating visionary leadership with rigorous, capability-driven supply chain and energy-efficient innovation practices.

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Nickel-Embedded Hollow Carbon Spheres for Catalytic Green Diesel Production: A Micro-Review

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Introduction

The industrial transition from petroleum to renewable fuels highlights a critical shift from first-generation fatty acid methyl esters (FAME) to second-generation "green diesel." While FAME is limited by an oxygen content of 10–11 wt%, green diesel consists of straight-chain C15–C18 alkanes that are chemically identical to fossil paraffins (Hongloi et al., 2022).

The conversion of fatty acids to green diesel can be done via three competing deoxygenation pathways:

1. Hydrodeoxygenation (HDO):
$R\text{-}CH_2COOH + 3H_2 \rightarrow R\text{-}CH_2CH_2CH_3 + 2H_2O$

2. Decarboxylation (DCO2):
$R\text{-}CH_2COOH \rightarrow R\text{-}CH_2CH_3 + CO_2$

3. Decarbonylation (DCO):
$R\text{-}CH_2COOH + H_2 \rightarrow R\text{-}CH{=}CH_2 + CO + H_2O$

The HDO pathway preserves carbon but consumes substantial amount of H_2 (three moles per mole of fatty acid) thus needed high pressures (1–10 MPa) reactor setup that will increase the operating costs (Praikaew et al., 2025). On the other hand, DCO_2 is highly exergonic (ΔG = -83.5 kJ/mol) and requires no H_2 for the reaction. Another pathway is DCO where it operates under a moderate hydrogen atmosphere (ΔG = -17.0 kJ/mol) (Peroni et al., 2017).

The catalytic deoxygenation of lipid-derived fatty acids depends heavily on the design of the catalyst and its support. Recently, hollow carbon spheres (HCS) and mesoporous hollow carbon spheres (MHCS) attracted interest to serve as exceptional supports due to a high thermal stability and unique cavity effects (Geng et al., 2024; Wu et al., 2025). These carbon sphere when embedded with active metal such as nickel (Ni), can be applied as nanoreactors providing cost-effective, noble-metal-free alternative for selective deoxygenation. However, performance of this type of catalyst depends strongly on physical dimensions like shell thickness, cavity diameter, and pore size that affected nickel dispersion and mass transport. This mini-review evaluates the core synthesis parameters including dilution ratios, pH, template interactions, and pyrolysis temperatures that critically affect the shape and structural properties of the nickel-embedded carbon sphere. Tuning carbon sphere properties and electronic structure of nickel-embedded hollow carbon spheres offers a powerful strategy for these atom-efficient, low-pressure DCO/DCO_2 pathways for sustainable green diesel production.



Engineering Nickel-Embedded Hollow Carbon Spheres

Traditional green diesel catalysts supported on standard metal oxides like Al_2O_3 and SiO_2 suffer from rapid deactivation due to sintering, leaching, and coke fouling under typical liquid-phase conditions (200–400 °C, 1–10 MPa) (Saraeian et al., 2022; Bilge et al., 2023). Incorporating active transition metals like nickel into hollow (HCS) and mesoporous hollow carbon spheres (MHCS) offers a unique strategy (Geng et al., 2024). Chemically, the adjustable carbon surface can accommodate heteroatom dopants (N, P, S) that generate a strong electronic metal-support interaction (SEMSI). This electronic alteration was reported to help in anchoring the active nickel or nickel phosphide (Ni_2P) phases.

While the fundamental microenvironment engineering of these carbon frameworks has been highly optimized using noble metal variations like palladium (Pd) (Wu et al., 2025), translating these design principles to transition metals like nickel effectively prevents irreversible particle sintering or leaching even within highly corrosive subcritical water environments. Ideally, nickel-embedded HCS structure can function as durable nanoreactors. The inner hollow cavity induces a void-confinement effect that could concentrates H_2 and bulky lipid reactants. This will optimises intermediate adsorption and lowers the activation energy required for C–C and C–O bond cleavage (Guo et al., 2024). Additionally, the highly porous and permeable shell of MHCS help mass-transport limitations commonly happen in bulk microporous carbons. The accelerated molecular transport suppresses intermediate oligomerization, significantly reduces coking, and helps the rapid mass evacuation of long-chain paraffin products to favor atom-efficient deoxygenation pathways (DCO/DCO_2) over the costly hydrodeoxygenation (HDO) (Wu et al., 2025; Praikaew et al., 2025).

Hydrothermal Carbonization (HTC) has been reported to be a reliable, sustainable thermochemical route to fabricate these carbon sphere as supports from biomass-derived carbohydrate precursors like glucose, sucrose, or starch under mild aqueous conditions (typically 160–250 °C). During HTC, dehydration and polymerization kinetics govern the formation of hydrophilic oxygen-rich shells surrounding a hydrophobic core. Templates such as silica nanoparticles or polymer micelles can be added during the hydrothermal processing to generate uniform hollow or mesoporous cavities. More importantly, the presence of abundance surface oxygen functional group (such as carboxyl and hydroxyl groups) provides highly active coordination sites for coordination of Ni^{2+} ions. This is critical in ensuring good dispersion of the active nickel phase upon subsequent carbonization.

Precise control over synthetic nanoreactor geometries can also be achieved by fine-tuning resorcinol-formaldehyde (RF) sol-gel polycondensation and Stöber parameters. In base-catalyzed assembly, particle dimensions can be regulated by the dilution ratio; decreasing the resorcinol-to-water (R/W) molar ratio from 3.7 down to 0.0037 shifts droplet nucleation kinetics and lead to a systematically increasing average particle diameter from 1.4 up to 27.9 μm (Mahata et al., 2009). Furthermore, adjusting the ethanol-to-water (E/W) volume ratio between 2 and 7 enables simultaneous silica-RF polymerization, increasing the composite sphere diameter from 232 to 489 nm while maintaining high uniformity (Fang et al., 2013). Crucially, increasing the absolute ethanol volume from 19 to 26 mL systematically drives the morphological evolution from solid to hollow cores, allowing researchers to accurately tailor the inner cavity and shell dimensions to optimize nickel dispersion and mass-transport dynamics for high-yield green diesel synthesis.



Future Perspectives

This mini review highlights that the physicochemical and structural properties of hollow carbon spheres (HCS) can be strategically control by delicate balance in synthesis parameter such as dilution ratios, basicity, solvent blends, and template configurations. Precise control over pH and precursor solubility would effect nucleation and polymerization rates, while surfactant and co-solvent ratios drive the morphological preferences from solid spheres to multi-shelled hollow architectures.

When applied to green diesel production, HCS structural parameters offer catalytic efficiency of the embedded active phase. In a nickel-embedded systems, managing the void-confinement environment and shell porosity is expected to be critical to balancing mass transport with optimal intermediate retention for high selectivity reaction toward the atom-efficient DCO/DCO_2 pathways. To transition these nanoreactors from lab-scale curiosities to industrially viable catalysts, future efforts must pivot toward greener, scalable manufacturing. Moving toward solvent-free mechanochemical synthesis or expanding green hydrothermal carbonization (HTC) protocols will significantly lower environmental footprints. Furthermore, leveraging machine learning (ML) algorithms to systematically map the vast, non-linear parameter space of multi-component Stöber and HTC setups represents the most promising path forward to accelerate catalyst optimization.

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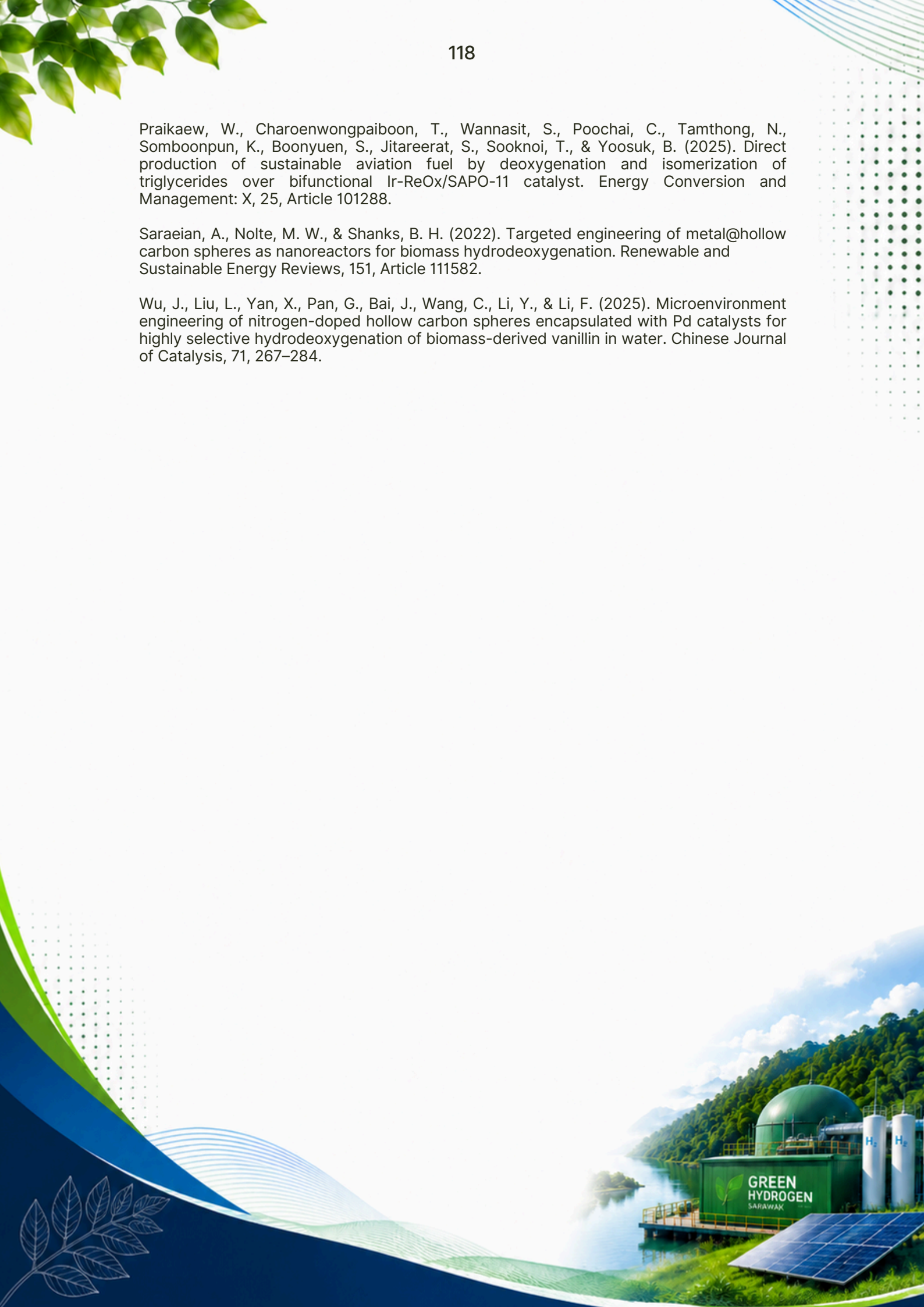

Managing Sarawak's Landscapes for Sustainability: Balancing Agricultural Growth and Biodiversity Conservation

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Introduction

Sarawak is renowned for its rich natural heritage and diverse ecosystems. Located on the island of Borneo, the state is home to some of the world's oldest tropical rainforests, extensive peatlands, freshwater ecosystems and a remarkable variety of flora and fauna. These ecosystems provide invaluable ecological, social and economic benefits, supporting biodiversity conservation, climate regulation, water security, food production and local livelihoods. As Sarawak continues to pursue economic development through agriculture, infrastructure expansion and industrial growth, increasing pressure is being placed on natural landscapes. Consequently, achieving a balance between development and environmental sustainability has become a critical challenge.

Land-use management plays a central role in determining how natural resources are utilized and conserved. Sustainable land-use management refers to the planning and implementation of land-use practices that meet present development needs without compromising ecosystem integrity and the ability of future generations to meet their own needs. In Sarawak, where agriculture remains an important contributor to economic growth, sustainable land-use management is essential to ensure that agricultural expansion does not occur at the expense of biodiversity, ecosystem services and environmental resilience. Figure 1 shows the conceptual framework illustrating the interactions among agricultural development, land-use change, ecosystem services, biodiversity conservation and sustainable development within Sarawak's multifunctional landscapes.





Figure 1: Conceptual framework illustrating the interactions among agricultural development, land-use change, ecosystem services, biodiversity conservation and sustainable development within Sarawak's multifunctional landscapes

The Importance of Sarawak's Ecosystems

Sarawak contains a wide range of ecosystems that contribute significantly to regional and global environmental sustainability. Tropical forests in Sarawak serve as important carbon sinks, helping to mitigate climate change by storing substantial amounts of carbon within vegetation and soils. These forests also regulate hydrological cycles, reduce soil erosion, maintain water quality and provide habitats for countless species.

The state is internationally recognized as part of the Borneo biodiversity hotspot. Many species found in Sarawak are endemic, meaning they occur nowhere else in the world. Iconic wildlife such as orangutans, hornbills, proboscis monkeys, clouded leopards and numerous amphibian and plant species depend on healthy forest ecosystems for survival. The conservation of these habitats is therefore essential not only for biodiversity protection but also for maintaining ecosystem functions that support human well-being.

In addition to ecological benefits, Sarawak's landscapes support the livelihoods of rural and indigenous communities. Forests provide food, medicinal plants, construction materials and cultural values that have been maintained for generations. Rivers and wetlands support fisheries and water resources that are essential for local communities. The sustainable management of these ecosystems is therefore closely linked to both environmental and socio-economic sustainability.

Agricultural Development and Land-Use Change

Agriculture has played an important role in Sarawak's economic development. Over the past several decades, the expansion of commercial agriculture, particularly oil palm cultivation, has transformed many landscapes across the state. Oil palm has become one of Malaysia's most important agricultural commodities, generating employment opportunities, export earnings and rural development.

While agricultural development contributes significantly to economic growth, it also drives land-use change. The conversion of forests into agricultural land can alter ecosystem structure and function, resulting in habitat loss and fragmentation. Fragmented landscapes may reduce the movement of wildlife populations, disrupt ecological processes and increase vulnerability to environmental disturbances.

Apart from oil palm cultivation, other forms of land-use change include infrastructure development, urban expansion, road construction and hydropower projects. These developments often bring economic benefits but may also create environmental challenges if not properly planned and managed. As a result, integrated land-use planning is increasingly recognized as an important strategy for balancing development objectives with environmental protection.

Environmental Consequences of Unsustainable Land Use

Unsustainable land-use practices can lead to a variety of environmental impacts. One of the most significant consequences is biodiversity loss. When natural habitats are converted or degraded, wildlife populations may decline due to reduced habitat availability, limited food resources and increased human disturbance.

Soil degradation is another major concern. Land clearing activities can expose soil surfaces to rainfall, increasing erosion and nutrient loss. In agricultural landscapes, improper land management practices may contribute to declining soil fertility and reduced productivity over time. Soil erosion can also lead to sedimentation in rivers and streams, affecting aquatic ecosystems and water quality.

Water resources are particularly vulnerable to land-use change. The removal of vegetation can alter water infiltration and runoff patterns, increase the risk of flooding and reduce water quality. Agricultural activities may introduce nutrients, pesticides and sediments into water bodies, potentially affecting aquatic biodiversity and downstream communities.

Land-use changes also contribute to greenhouse gas emissions. Forest conversion releases carbon stored in vegetation and soils, reducing the capacity of ecosystems to regulate climate. Peatland degradation is especially concerning because peat soils contain large amounts of stored carbon that can be released when drained or disturbed.

Biodiversity Conservation Challenges in Sarawak

Despite significant conservation efforts, biodiversity conservation remains a major challenge in Sarawak. Habitat fragmentation is one of the primary threats to wildlife populations. As forests become increasingly divided by roads, plantations and settlements, wildlife movement corridors may be disrupted, leading to isolated populations and reduced genetic diversity.



Human-wildlife conflict has also become more common in certain areas where development activities overlap with wildlife habitats. Animals may enter agricultural lands in search of food, resulting in crop damage and conflicts with local communities. Managing these interactions requires collaborative approaches that consider both conservation goals and community needs.

Climate change presents an additional challenge. Changes in temperature and rainfall patterns may affect species distributions, ecosystem productivity and the resilience of natural systems. Biodiversity conservation strategies must therefore incorporate climate adaptation measures to ensure long-term effectiveness.

Recognizing these challenges, Sarawak has implemented various conservation initiatives, including the establishment of protected areas, Totally Protected Areas (TPAs), wildlife sanctuaries and participation in the Heart of Borneo Initiative. These efforts aim to conserve important habitats while promoting sustainable development across the region.

Sustainable Land-Use Management Strategies

Sustainable land-use management involves adopting practices that maintain ecosystem health while supporting economic development. One important strategy is landscape-level planning, which considers ecological, social and economic factors across entire landscapes rather than individual sites. This approach helps identify areas suitable for development while protecting environmentally sensitive habitats.

The establishment of riparian buffer zones is another effective measure. Vegetated buffer areas along rivers and streams help reduce soil erosion, improve water quality and provide habitat connectivity for wildlife. Maintaining these buffers is particularly important in agricultural landscapes where water resources may be vulnerable to pollution.

Sustainable agricultural practices can also contribute significantly to environmental protection. Good agricultural practices, integrated pest management, soil conservation measures and responsible fertilizer application can improve productivity while minimizing environmental impacts. Certification schemes such as the Malaysian Sustainable Palm Oil (MSPO) and the Roundtable on Sustainable Palm Oil (RSPO) encourage producers to adopt more sustainable management practices.

Agroforestry systems represent another promising approach. By integrating trees with agricultural crops, agroforestry can enhance biodiversity, improve soil fertility, increase carbon sequestration and diversify income sources for farmers. Such systems demonstrate that agricultural production and environmental conservation can be mutually supportive rather than conflicting objectives.

The Role of Communities, Government and Industry

Achieving sustainable land-use management requires collaboration among multiple stakeholders. Government agencies play a crucial role in developing policies, enforcing regulations and promoting sustainable development practices. Effective environmental governance ensures that development activities are conducted responsibly and in accordance with environmental standards.

Local communities and indigenous peoples possess valuable traditional ecological knowledge that can contribute to sustainable resource management. Their participation in decision-making processes helps ensure that development initiatives consider local needs, cultural values and environmental priorities.



The private sector also has an important role to play. Companies involved in agriculture, forestry and infrastructure development can adopt sustainability commitments that minimize environmental impacts and support conservation objectives. Increasingly, businesses recognize that environmental sustainability contributes to long-term economic resilience and social responsibility.

Research institutions and universities further support sustainable land management through scientific research, environmental monitoring and capacity building. Advances in remote sensing, geographic information systems (GIS), drones and environmental modelling provide valuable tools for monitoring land-use change and informing evidence-based decision-making.

Future Directions for Sustainable Landscapes

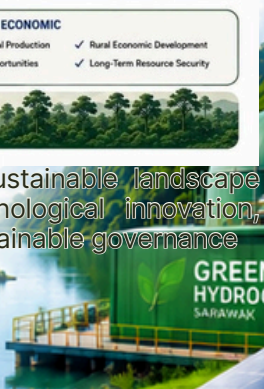
Looking ahead, sustainable land-use management in Sarawak will require continued innovation and collaboration. Nature-based solutions, ecosystem restoration initiatives and climate-resilient land management practices offer significant opportunities to enhance environmental sustainability. Reforestation and rehabilitation of degraded landscapes can restore ecosystem services while supporting biodiversity recovery.

Digital technologies are expected to play an increasingly important role in environmental monitoring and management. Satellite imagery, artificial intelligence and drone-based assessments can improve the detection of land-use changes and support more effective planning and enforcement efforts.

Strengthening environmental education and public awareness is equally important. Greater understanding of the relationship between land use, biodiversity and ecosystem services can encourage more responsible environmental stewardship among individuals, communities and organizations. Figure 2 shows a strategic framework illustrating future directions for sustainable landscape management in Sarawak through nature-based solutions, technological innovation, climate-resilient land management, community participation and sustainable governance.



Figure 2: Strategic framework illustrating future directions for sustainable landscape management in Sarawak through nature-based solutions, technological innovation, climate-resilient land management, community participation and sustainable governance



Conclusion

Sarawak's diverse landscapes provide immense ecological, social and economic value. However, increasing pressures from agricultural expansion, infrastructure development and other forms of land-use change highlight the need for sustainable management approaches. Balancing agricultural growth with biodiversity conservation is essential to ensure long-term environmental sustainability and human well-being.

Sustainable land-use management offers a practical pathway toward achieving this balance. Through integrated planning, sustainable agricultural practices, biodiversity conservation initiatives, community participation and effective environmental governance, Sarawak can continue to pursue economic development while safeguarding its unique natural heritage. The future of Sarawak's landscapes depends on collective efforts to manage natural resources responsibly and ensure that development proceeds in harmony with environmental conservation.

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Webinar Highlights 2026

From January to June 2026, the Institute of Ecosystem Science Borneo (IEB) successfully organised a series of three webinars as part of its strategic commitment to advancing research excellence and strengthening stakeholder engagement.

Each session was thoughtfully curated in line with IEB's mission to promote evidence-based knowledge, support informed decision-making, and enhance community well-being. Featuring distinguished experts from diverse fields, the webinars offered valuable insights into emerging environmental and societal issues while encouraging interdisciplinary dialogue and cross-sector collaboration.

These initiatives reflect IEB's continued dedication to delivering impactful research, fostering knowledge exchange, and contributing to sustainable development at national, regional, and international levels.









Program Highlights 2026





The Program **Towards Zero Food Waste in Bintulu: Youth Environmental Empowerment Programme 2026**, together with the official launch of the **KitarNow Application**, was successfully held on 20 January 2026. The programme gathered a total of 300 participants, comprising youths, students, community representatives, and relevant stakeholders.

This initiative aimed to raise awareness on food waste reduction, promote sustainable consumption practices, and empower young people to take an active role in addressing environmental challenges at the community level. Through this programme, participants were exposed to the importance of responsible food management, waste minimisation, and the adoption of digital solutions to support a more sustainable and environmentally conscious society.

The launch of the KitarNow Application further strengthened the programme's impact by introducing a practical platform to encourage recycling, waste tracking, and community participation in sustainability efforts. Overall, the programme served as an important step towards building stronger environmental awareness among youths in Bintulu while supporting the broader agenda of achieving zero food waste and sustainable community development.

Program Highlights 2026





Kerjasama penyelidikan hadapi cabaran alam sekitar, pertanian

Penyelidik Universiti Pertanian Tokyo, UPMS akan berkongsi ilmu

The Program **International Guest Lecture: Oil Palm Plantation and the Global Environment** was successfully held on 27 February 2026 at the PUTRA Smart Classroom, Universiti Putra Malaysia Sarawak (UPM Sarawak), with a total attendance of 35 participants. The session featured Prof. Dr. Inubushi Kazuyuki from Tokyo University of Agriculture as the invited speaker.

This international guest lecture provided an important platform for knowledge sharing on the relationship between oil palm plantation development and global environmental issues. The session highlighted key topics related to sustainable plantation management, environmental conservation, greenhouse gas emissions, land-use change, and the broader impacts of the oil palm industry on ecosystems and climate resilience.

Through this programme, participants were exposed to international perspectives on agricultural sustainability and environmental management, particularly in relation to oil palm cultivation. The lecture also encouraged academic discussion and exchange of ideas among researchers, students, and stakeholders on how plantation practices can be improved to support environmental protection and sustainable development.

Program Highlights 2026





The Program **Bintulu Zero Waste Schools Challenge 2026** was successfully held from 20 January 2026 to 18 March 2026, with the participation of 20 schools from across Bintulu, Sarawak. This programme was organised as part of an effort to promote environmental awareness, waste reduction, and sustainable practices among school communities.

The challenge provided a platform for schools to actively participate in zero waste initiatives through practical activities such as waste segregation, recycling, food waste reduction, environmental campaigns, and school-based sustainability projects. Through these activities, students and teachers were encouraged to adopt responsible waste management habits and apply sustainable practices within their school environment.

This programme also aimed to empower young people as environmental agents of change by encouraging creativity, teamwork, and leadership in addressing waste-related issues. The involvement of 20 schools reflected strong support from the local education community and demonstrated the potential of schools to play an important role in promoting sustainability at the community level.

Overall, the Bintulu Zero Waste Schools Challenge 2026 contributed to strengthening environmental education and fostering a culture of sustainability among students in Bintulu. The programme also supported broader efforts towards waste minimisation, community engagement, and the development of environmentally responsible future generations.

Newspaper Clipping



Kitar semula berstruktur melalui KitarNow

Komuniti digalak amal kitar semula lebih tersusun, boleh dijejaki, berasaskan data



PERASMIAN: Wan Ibrahim (tengah kiri) dan Dr Shahrul Idza (kiri) melancarkan Program Ke Arah Sifar Sisa di Bintulu: Pemerkasaan Alam Sekitar Bella 2026 sambil disaksikan Dr Kesen (kiri) di Dewan Sri Kenyalang UPMS kelmarin.

"Ia melalui dua jenis akaun utama iaitu Akaun 'Seller' dan Akaun 'Buyer' bagi memudahkan penyelarasan kutipan serta menghasilkan rekod digital yang boleh digunakan untuk pelaporan dan perancangan."

KitarNow app to drive more organised recycling activities



(From left) Kesen, Shahrul, Wan Ibrahim (third left) and other guests pose for a group photo.









Newspaper Clipping

BDA博特拉永續發展
青年環保零廢物計劃

（本報民都魯21日訊）民都魯可持續廢物管理议程，透过民都魯发展局与砂拉越博特拉大学之间的策略性合作，获得进一步深化。

该项合作以青年赋权及社区为本的方法为核心，作为推动社会行为改变与环境永续发展的重要催化剂。

民都魯发展局秘书旺依布拉欣指出，有关合作是通过双方联合举办的“2026年迈向民都魯零废物：青年环保赋权计划”得以落实。

此外，民都魯发展局市与砂博特拉大学共同担任“迈向民都魯零食物垃圾”倡议的领航合作夥伴。

他表示，在全面推动社区层面的实际解决方案之前，教育与公众意识是塑造负责任废物管理文化的重要基础。

“民都魯发展局很荣幸能成为该计划的共同主办单位，并与砂博特拉大学共同担任‘迈向民都魯零食物垃圾’倡议的领航合作夥伴。这项合作反映了双方在强化民都魯废物管理实践方面的共同承诺，我们将从意识培养与教育着手，随後逐步迈向以社区为本的实际解决方案。”

旺依布拉欣昨日在砂博特拉大学民都魯校区举行的“2026年迈向民都魯零废物计划”及“KitarNow”应用程式推介礼上，发表上述谈话。

推介KitarNow應用

该计划亦见证了由砂博特拉大学在民都魯发展局支持下所研发的“KitarNow”应用程式正式推介，进一步彰显科技在促进环境永续实践方面所发挥的关键作用。

旺依布拉欣解释，“KitarNow”不仅是一个数位平台，更是一项实用工具，旨在鼓励社区积极改变行为，并提升公众在回收利用及更系统化废物管理方面的参与度。

另一方面，砂博特拉大学民都魯校区校长亦鲁拉兹教授表示，“KitarNow”应用程式的开发，体现了大学善用科技创新支援可持续实践的承诺。

他相信，该应用程式有助于提升社区对回收实践的理解，支援循环经济理念，并鼓励民众在日常生活中落实更负责任的废物管理方式。



民都魯发展局秘书旺依布拉欣（中）为2026年迈向民都魯零废物计划”及“KitarNow”应用程式推介礼进行开幕仪式。



《KitarNow》應用程式推介

▲砂博特拉大学与民都魯发展局合作落实（KitarNow）推介礼，民理民都魯中小学及私人基公司参与。

推動民建高效回收體系

（民都魯21日讯）民都魯可持续废弃物管理议程获得加强，民都魯发展局与砂拉越博特拉大学展开策略性合作，透过“迈向零废弃的民都魯·2026青年环境赋权计划”，以青年与社区为核心，推动社会行为转变。

砂博大发展局合作落实

由砂拉越博特拉大学开发，并与民都魯发展局合作落实的（KitarNow）应用程式推介礼，昨午在砂拉越博特拉大学民都魯校区举行，活动由民都魯发展局秘书旺依布拉欣阿里主持开幕。

旺依布拉欣在推介礼上表示，该合作是通过联合主办“迈向零废弃的民都魯·2026青年环境赋权计划”加以落实，同时民都魯发展局市与砂拉越博特拉大学携手，成为“迈向民都魯零废弃物”倡议的共同主导单位。

他说，教育与公众意识是塑造负责任废弃物管理文化的重要基础，必须在全面推行社区层面的实际解决方案之前，先行加强相关认知。



强化废弃物管理

“民都魯发展局非常荣幸能成为此计划的联办单位，并与砂拉越博特拉大学共同主导有关倡议，这明合作反映双方在强化民都魯废弃物管理实践方面的共同承诺，从意识与教育着手，逐步迈向以社区为本的实际解决方案。”

该活动也见证由砂拉越博特拉大学在民都魯发展局支持下开发的（KitarNow）应用程式正式推介，进一步强化科技在推动环境永续实践方面的促进角色。

旺依布拉欣指出，（KitarNow）不仅是一个数码平台，更是一项实用工具，有助于鼓励正向行为改变，并提升社区在回收活动及更系统化废弃物管理方面的参与度。



▲在出席者共同为（KitarNow）推介礼进行开幕仪式。

◀砂拉越博特拉大学校长沙鲁拉兹（左）及民都魯发展局秘书旺依布拉欣阿里（右二）分别颁发证书予参与计划的老明小学的代表。

校长：助社区理解回收实践

另一方面，砂拉越博特拉大学校长沙鲁拉兹教授表示，（KitarNow）的开发展现大学善用科技创新，支持永续实践的承诺，并让相关应用更容易为社区所使用。

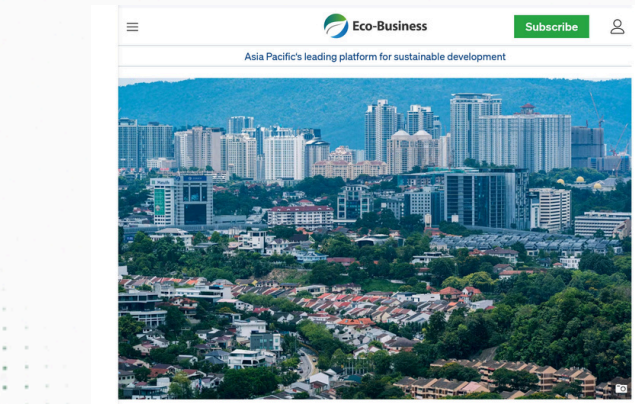
他说，该应用程式旨在协助社区理解回收实践，支持循环经济概念，并在日常生活中推动更负责任的废弃物管理。

民都魯发展局市申，将持续推动民都魯朝向低碳工业和绿色的愿景前进，在各界携手努力下，民都魯正稳步朝向更清洁、更绿色及零废弃的未来。

据了解，我国回收活动长期面对公众环保意识不足、垃圾分类标准不一、以及缺乏系统化追踪机制等问题，导致大量仍具回收价值的资源最终被送往垃圾填埋场，不仅推高处理成本，也加重环境负担。

（KitarNow）应用程式通过提升数据管理、公众参与及跨单位协调，有助于推动民都魯建立更透明、高效的回收体系，该平台旨在协助各机构以更简便、友善的方式记录、管理及监测回收废弃物，学校、企业及各类机构可获奖赏与重量记录回收数据，长期监测回收成效，并直接与回收公司对接安排收集服务，从而促进本地循环经济发展。

出席者包括砂拉越绿计女协会副会长兼常务理事、民都魯教育局副教育官（学生发展组）阿旺古阿里马丁、董事部生态系统科学研究所主任蒂艾德蒂夫阿查里、砂拉越博特拉大学农业与林业科学学院院长诺尔萨斯玛、以及项目主任基伦顺达斯。



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News • Waste Management

Malaysians paying twice for poor waste management, researcher says

Hidden costs and public spending burden households while raising health and environmental risks.

By Nadilla Sakinah — 2 minute read • April 30, 2026

Malaysians are effectively paying twice for poor waste management through taxes and hidden costs such as pollution and health risks, a researcher has said.

Dr Keeren Sundara Rajoo, a researcher and senior lecturer at the Universiti Putra Malaysia, said solid waste management and public cleansing account for between 40 per cent and

https://www.eco-business.com/news/malaysians-paying-twice-for-poor-waste-management-researcher-says/ 1/5



Newspaper Clipping



6/12/26, 3:34 PM Researcher: Waste mismanagement draining public funds, raising health toll | Borneo Post Online

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Researcher: Waste mismanagement draining public funds, raising health toll

BY YUNUS YUSSOF ON APRIL 29, 2026, WEDNESDAY AT 8:00 AM SARAWAK

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(From left) Mami, Osamu and Dr Keeren during a visit to the Ryohshin Co Ltd headquarters in Japan.

BINTULU (April 29): Malaysians are effectively paying twice for poor waste management through public spending and the hidden costs of pollution, health risks and wasted recyclable materials—yet remain unaware of the burden, said Universiti Putra Malaysia Sarawak (UPMS) researcher Dr Keeren Sundara Rajoo.

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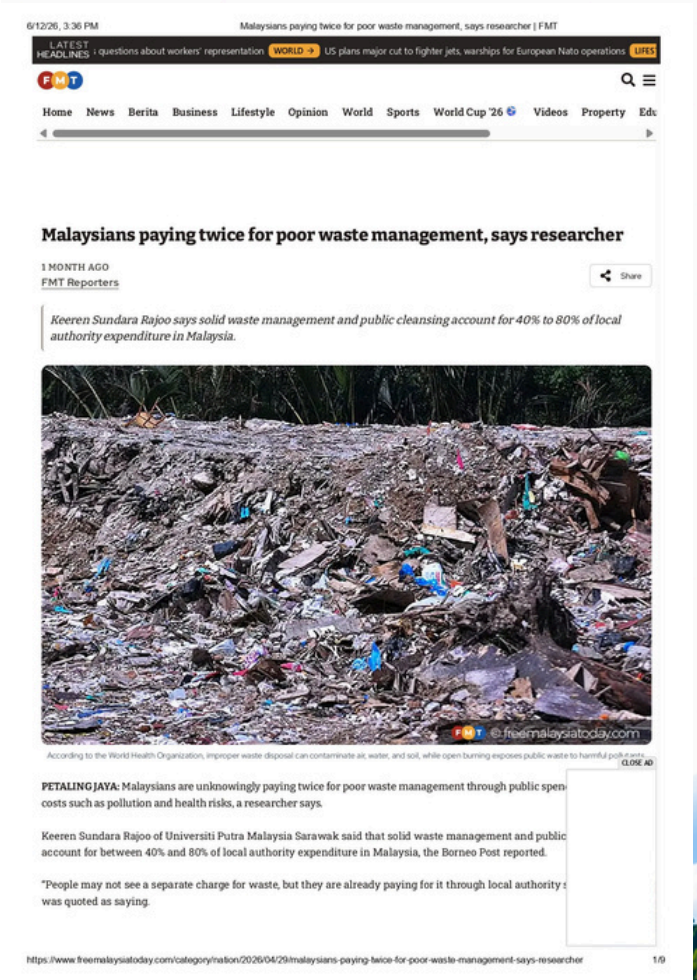

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Malaysians paying twice for poor waste management, says researcher

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Keeren Sundara Rajoo says solid waste management and public cleansing account for 40% to 80% of local authority expenditure in Malaysia.

According to the World Health Organization, improper waste disposal can contaminate air, water, and soil, while open burning exposes public waste to harmful pollutants

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PETALING JAYA: Malaysians are unknowingly paying twice for poor waste management through public spen costs such as pollution and health risks, a researcher says.

Keeren Sundara Rajoo of Universiti Putra Malaysia Sarawak said that solid waste management and public account for between 40% and 80% of local authority expenditure in Malaysia, the Borneo Post reported.

"People may not see a separate charge for waste, but they are already paying for it through local authority was quoted as saying.

https://www.freemalaysiatoday.com/category/nation/2026/04/29/malaysians-paying-twice-for-poor-waste-management-says-researcher 1/9

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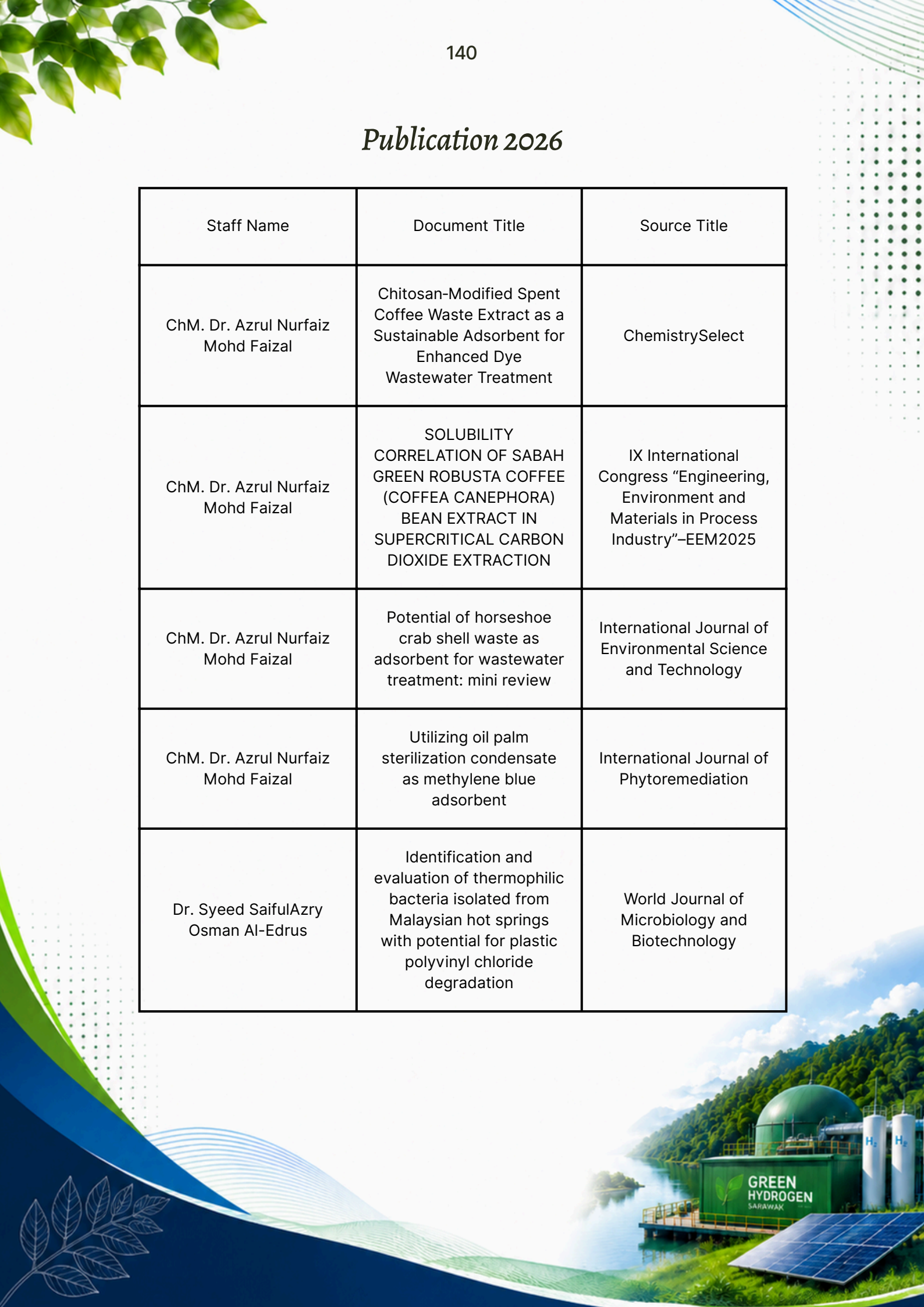

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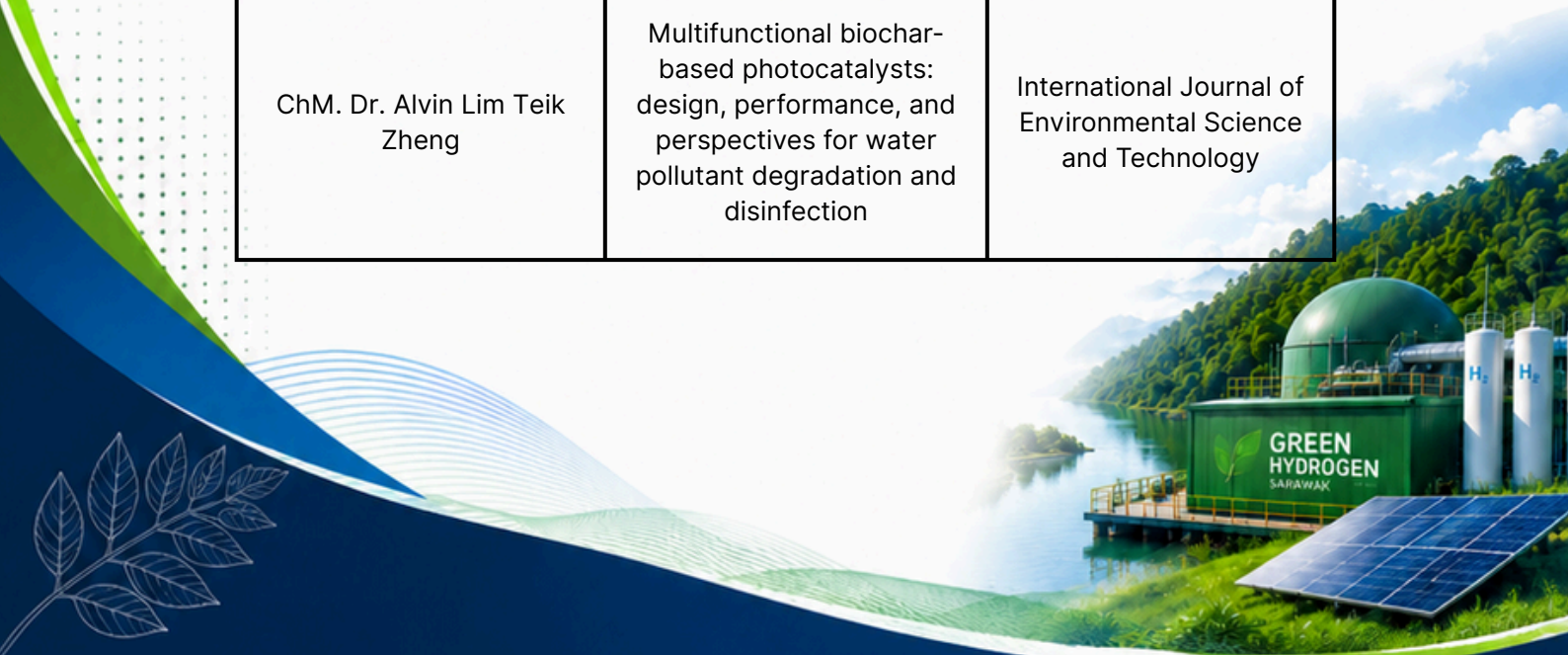

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