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Integrated Approaches to Sustainable Resource and Environmental Management

*Edited by Ling Zhang, Mohd Nazip Suratman,
Rahmawaty, Seca Gandaseca,
Mohd Hasmadi Ismail, Shuli Wang and Jinfeng Rao*



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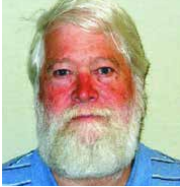
Volume 45

Aims and Scope of the Series

Scientists have long researched to understand the environment and man's place in it. The search for this knowledge grows in importance as rapid increases in population and economic development intensify humans' stresses on ecosystems. Fortunately, rapid increases in multiple scientific areas are advancing our understanding of environmental sciences. Breakthroughs in computing, molecular biology, ecology, and sustainability science are enhancing our ability to utilize environmental sciences to address real-world problems.

The four topics of this book series - Pollution; Environmental Resilience and Management; Ecosystems and Biodiversity; and Water Science - will address important areas of advancement in the environmental sciences. They will represent an excellent initial grouping of published works on these critical topics.

Meet the Series Editor



J. Kevin Summers has been working as a Senior Research Ecologist at the Environmental Protection Agency's (EPA) Gulf Ecosystem Measurement and Modeling Division. He worked with colleagues in the Sustainable and Healthy Communities Program to develop an index of community resilience to natural hazards, an index of human well-being that can be linked to changes in the ecosystem, social and economic services, and a community sustainability tool for communities with populations under 40,000. He led research efforts for indicator and indices development. Dr. Summers is a systems ecologist and began his career at the EPA in 1989 and has worked in various programs and capacities. This includes leading the National Coastal Assessment in collaboration with the Office of Water, which culminated in the award-winning National Coastal Condition Report series (four volumes between 2001 and 2012), and which integrates water quality, sediment quality, habitat, and biological data to assess the ecosystem condition of the United States estuaries. He was acting National Program Director for Ecology for the EPA between 2004 and 2006. He has authored approximately 150 peer-reviewed journal articles, book chapters, and reports, and has received many awards for technical accomplishments from the EPA and from outside of the agency. Dr. Summers holds a BA in Zoology and Psychology, an MA in Ecology, and Ph.D. in Systems Ecology/Biology.

Meet the Volume Editors



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Preface

In an era defined by the profound and interconnected crises of climate change, biodiversity loss, and resource scarcity, the quest for sustainable pathways forward has never been more urgent. The prevailing, often fragmented approaches, relying on isolated disciplines, technological silver bullets, or top-down mandates, have repeatedly proven insufficient to address the systemic nature of these challenges. This edited volume emerges from the conviction that our collective future hinges on a fundamental shift: toward integration as a core principle for understanding and action.

This book argues that environmental sustainability cannot be achieved through sectoral thinking alone. It requires weaving together diverse strands of knowledge, from cutting-edge science and engineering to deep cultural wisdom, local ecological understanding, and participatory governance. It demands frameworks that connect local action with global governance and balance immediate needs with long-term stewardship. The chapters herein, contributed by scholars and practitioners across multiple fields, explore what this integrative paradigm means in theory and in practice across a range of critical environmental domains.

The volume opens by establishing the conceptual imperative for holistic approaches. This foundation is built upon in subsequent chapters that delve into specific, intertwined challenges. This volume is intended for a broad readership, including students, researchers, policymakers, and practitioners who seek to navigate the complexity of contemporary environmental issues. We hope it inspires not only reflection but also the courage to bridge disciplinary, sectoral, and temporal divides in pursuit of sustainable and equitable solutions.

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Section 1

Introduction

Introductory Chapter: Rethinking Environmental Challenges through Integrated Approaches

Ling Zhang and Shuli Wang

1. Introduction

The intensification of global change and the increasing frequency of extreme climatic events have become prominent [1]. Environmental challenges are now shaping the trajectory of human development. From the rising frequency of extreme weather events and shifting climate patterns to the relentless loss of biodiversity, the degradation of both natural and cultural heritage, and the pressing imperative for a just energy transition, mounting evidence unequivocally indicates that the planet is under profound and multi-dimensional stress. These are not isolated crises but deeply interconnected phenomena, stemming from the complex interplay between human activities and natural systems. For decades, the dominant paradigm for addressing these issues has often been fragmented, relying on singular disciplines, isolated technological fixes, or top-down policy mandates. While such approaches have yielded important insights and achieved localized successes, they have frequently proven inadequate in delivering systemic, equitable, and sustainable solutions.

A fundamental transformation is therefore imperative, one that must embrace “integration” as its core principle. This necessitates weaving together diverse strands of knowledge, ranging from advanced technology and materials science to profound cultural wisdom, localized ecological understanding, participatory governance models, and lessons from humanity’s historical relationship with the environment. Furthermore, it is essential to establish the frameworks capable of connecting local action with global governance, and of balancing immediate needs with long-term stewardship, thereby fostering resilience and sustainability.

2. Beyond silos: The imperative for holistic understanding

A critical limitation of fragmented approaches is their tendency to overlook the inherent feedback loops, cascading effects, and historical contexts within socio-ecological systems. For instance, deforestation is often quantified in terms of carbon emissions or hectares lost [2]. However, its impacts extend far beyond these metrics, altering local climate, increasing fire risks, and compromising human health and food security. Similarly, the invasion of non-native species into ecosystems reveals the complexity of environmental change [3]. Driven by climate warming and land-use

changes, such invasions involve more than just shifts in vegetation cover, they trigger a cascade of effects, such as altering forest structure and biodiversity, impacting soil microbial communities, and generating complex, intertwined feedbacks on greenhouse gas emissions, potentially increasing CO₂ emissions through root respiration while enhancing CH₄ uptake *via* improved soil aeration [4]. Viewing this phenomenon solely as a threat to biodiversity or an opportunity for carbon sequestration overlooks its nuanced, system-level consequences for biogeochemical cycles and climate feedbacks.

Conversely, the abandonment of historical human infrastructure can also create vulnerabilities. For example, historical water management system designated as a World Heritage site represents a model of past integrated engineering that holistically addressed water, energy, and mining needs. Its current state of disrepair is not only a loss of cultural heritage but also a missed opportunity for climate adaptation. Such a system, which once captured surface water to power mines and manage landscapes, could be revitalized to mitigate contemporary challenges such as summer droughts, flash floods, and ecological water shortages [5]. Neglecting such historical solutions in favor of exclusively novel technologies reflects a failure to integrate knowledge across time.

This need for integration is equally critical in addressing the global energy transition, particularly in bridging development gaps. The issue of community energy access serves as a case in point. Providing affordable, reliable, and clean energy to remote communities is not merely a technical problem of installing solar panels or wind turbines, which is a complex socio-technical challenge. Success depends on integrating appropriate technologies with a deep understanding of local socioeconomic factors and aligning these efforts with broader sustainable development goals. Top-down, purely technical solutions may fail if they disregard local maintenance capacity, cultural acceptability, or economic viability. Genuine solutions require a fusion of engineering, social sciences, economics, and participatory planning.

On a macro-scale, managing the global supply of critical raw materials essential for this energy transition demands a different form of integration. Frameworks such as the United Nations Framework Classification for Resources (UNFC) and the United Nations Resource Management System (UNRMS) exemplify the necessity for integrated global governance. They provide a common language and set of principles to bridge the often-disconnected domains of geology, economics, social impact assessment, and environmental governance. These frameworks enable governments, investors, and communities to make comparable, transparent decisions that balance short-term resource extraction with long-term intergenerational equity, ensuring that present-day development does not compromise the well-being and resource base of future generations. This represents an integration of data, ethics, and multi-stakeholder decision-making on a global scale.

3. Integration in practice: Synergies from local to global

The principle of integration is powerfully demonstrated in the convergence of modern science with enduring cultural and ethical value systems, historical wisdom, and place-based management frameworks. In many communities worldwide, environmental stewardship forms a foundational element of cultural identity. This integrated ethos is also embodied in context-specific solutions such as smart rural energy communities [6]. Here, digital technologies are deployed not as ends in themselves,

but as tools to optimize local renewable resources, enhance energy efficiency, and empower communities within a “Smart Rural” framework. This requires the integration of hardware with software, and the fusion of technological applications with user behavior and local governance.

Furthermore, this integrated approach must inform global environmental mechanisms and standards. Success, whether in designing carbon markets that account for complex forest dynamics in invasive ecosystems, creating funding streams for heritage-based climate adaptation, or developing global critical raw material strategies using frameworks like the United Nations Framework Classification for Resources (UNFC), hinges on integrity and equity. Robust monitoring, reporting, and verification frameworks, supported by the technology and standardized data classification, are essential. Concurrently, the design must prioritize the rights, knowledge, and livelihoods of local communities and heritage custodians. Benefits must be shared equitably, aligning global incentives for mitigation, adaptation, and resource security with local development and cultural continuity.

Ultimately, navigating the Anthropocene demands a literacy that is comfortable with complexity, embraces interdisciplinary and transhistorical dialog, and values multiple ways of knowing. It demands policymakers who can formulate regulations informed by climate models, ecological feedbacks, community heritage, and global resource inventories, engineers and entrepreneurs who design energy systems with historical precedent, social context, and future resilience in mind, and resource managers capable of implementing plans that are scientifically sound, socially supported, economically viable, and ethically grounded in intergenerational justice. Cases such as invasive ecosystem management, the conservation of natural and cultural heritage, the pursuit of sustainable rural energy, and the global governance of raw materials, though geographically and topically diverse, all reveal that our most pressing environmental challenges are, at their core, integrative puzzles. They compel us to deliberately bridge divides between disciplines, sectors, knowledge systems, time periods, and scales of governance to cultivate the holistic understanding necessary for a sustainable and equitable future.

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Section 2

Diagnosing Pressures: Environmental Challenges in a Changing World

Forest in Transition: Moso Bamboo Expansion and Its Consequences for Soil-Driven Greenhouse Gas Emissions

Yadi Yu, Qingye Yu, Chen Wu and Ling Zhang

Abstract

Amid intensifying climate change, moso bamboo (*Phyllostachys edulis*), a fast-growing East Asian native invasive species, has rapidly expanded in subtropical and temperate forests of southeastern China, increasing moso bamboo forest area by 85% from 1988 to 2018, primarily invading broadleaf, coniferous, or mixed forests in natural mountainous, altering forest structure while influencing soil greenhouse gas (GHG) emissions. This chapter synthesizes mechanisms by which moso bamboo's natural expansion in non-managed forest ecosystems affects soil fluxes of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Despite its high biomass production (50–100 Mg ha⁻¹) and potential as a carbon sink for climate mitigation, bamboo's dense root systems, high litter inputs (1656–1928 kg ha⁻¹ yr⁻¹), and low C:N ratio litter accelerate root respiration and microbial decomposition, elevating CO₂ emissions (root respiration rates 1.08–7.87 μmol m⁻² s⁻¹). Concurrently, enhanced soil aeration and pH shifts promote methanotrophic bacterial activity, boosting CH₄ uptake (120–180 μg m⁻² h⁻¹). Low C:N litter accelerates N mineralization, stimulating nitrification and denitrification processes, with N₂O emissions modulated by forest composition and reshaped microbial communities (e.g., increased Actinobacteria and Proteobacteria abundance). Overall, bamboo expansion elevates soil organic carbon storage (20–40 Mg ha⁻¹) but yields complex net climate impacts due to intertwined C-N cycles. Management implications include monitoring bamboo encroachment in biodiversity hotspots. Future research should prioritize long-term flux measurements and metagenomic analyses under climate scenarios to guide ecological conservation and GHG mitigation strategies.

Keywords: moso bamboo, expansion, green house gas emission, forest, climate change

1. Introduction

As climate change intensifies, extreme weather events and rising temperatures create more favorable growth conditions for invasive plants. The negative impacts

of invasive plants on forest ecosystems are multifaceted. They not only alter forest structure and vegetation composition but also reduce the diversity of native species [1]. Moso bamboo (*Phyllostachys edulis*), a fast-growing woody grass native to East Asia, plays a significant ecological role in natural forest ecosystems, particularly in subtropical and temperate forests of southeastern China, Japan, and parts of Southeast Asia [2–4]. The moso bamboo expansion phenomenon refers to its rapid spread into adjacent natural forests, often occurring in response to climate warming and altered precipitation patterns since the late twentieth century. Key drivers include its clonal reproduction via extensive rhizomes, high shade tolerance, and competitive resource acquisition, which allow it to outcompete slower-growing native trees. While moso bamboo expansion is a natural ecological succession within its native distribution range, it has been intensified by human activities such as land-use changes and reduced native forest management, making it a semi-natural phenomenon rather than entirely new. Between 1988 and 2018, moso bamboo expanded rapidly, increasing China's bamboo forest area by 85%, with a high proportion of bamboo forest expansion into natural forests, including mountainous. Moso bamboo expansion gradually ascends from low-altitude to high-altitude of mountainous, reducing biodiversity, and the expansion trend is severe [3, 5, 6]. Its natural expansion, driven by clonal reproduction through rhizomes, allows it to invade or coexist with broadleaf, coniferous, or mixed forests, often forming dense bamboo dominated patches [7, 8]. This substitution of native ecosystems—primarily evergreen broadleaf forests, coniferous stands, mixed forests, and upland grasslands—alters soil nutrient cycling and carbon fluxes at regional scales, potentially amplifying GHG emissions in subtropical Asia. Moso bamboo's rapid growth-reaching heights of 10–20 meters in a single season, and high biomass production (50–100 Mg ha⁻¹) make it a potential carbon sink, offering promise for climate change mitigation [9, 10]. However, its expansion in natural forests alters soil ecosystems, influencing the emission of greenhouse gases (GHGs) such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) [11–13]. These gases are critical drivers of global warming, with soils contributing approximately 20% of global CO₂, 60% of CH₄, and 70% of N₂O emissions [14–16]. Ecological processes facilitating this transition include rhizome-mediated resource competition, enhanced litter decomposition via low C:N ratios, and shifts in soil microbial communities, which collectively influence regional C fluxes by increasing soil organic matter inputs but also respiration rates. This chapter examines the mechanisms by which moso bamboo's natural expansion in forest ecosystems affects soil GHG emissions, focusing on non-managed, natural settings. Unlike plantations, where human interventions like fertilization or harvesting shape soil processes, natural forest bamboo ecosystems are governed by intrinsic ecological dynamics, including competition, climate, and soil heterogeneity. High litter inputs, dense root systems, and interactions with soil microbial communities modify C and N cycling, leading to complex GHG dynamics. By synthesizing current research, this chapter aims to elucidate these mechanisms, assess moso bamboo's net climate impact, and provide insights for ecological conservation and climate mitigation strategies. The focus on natural forests - such as evergreen broadleaf forests or mixed coniferous-broadleaf stands - highlights the unique interplay of bamboo with diverse forest ecosystems.

The significance of soil GHG emissions lies in their role in the global C and N cycles. Vegetation influences these fluxes by altering soil organic matter, moisture, and microbial activity. Moso bamboo's unique traits, including low C:N ratio litter and

extensive rhizome networks, distinguish it from coexisting tree species, potentially amplifying or mitigating GHG emissions. Understanding these processes is critical for evaluating bamboo's role in forest C budgets and informing conservation policies in natural ecosystems.

2. Background on moso bamboo and soil GHG emissions in natural forests

2.1 Moso bamboo ecology and natural expansion in forests

Moso bamboo thrives in natural forest ecosystems, particularly in subtropical evergreen broadleaf forests and mixed coniferous-broadleaf forests, where it often invades gaps or edges created by natural disturbances or outcompetes slower-growing species [17, 18]. In China, moso bamboo occupies over four million hectares, with significant natural stands in mountainous regions of Zhejiang, Fujian, and Jiangxi provinces [12, 19, 20]. Its expansion is driven by clonal propagation via rhizomes, which allows rapid colonization of forest understories or open areas [6]. Bamboo's annual litterfall and deep root systems contribute substantial organic matter to soils, typically red or yellow soils with pH 4.5–6.0 [6, 21]. Moso bamboo's shade tolerance and rapid growth enable it to form dense stands, altering forest structure and soil processes [22].

2.2 Key pathways of soil GHG fluxes

Soils are pivotal in global biogeochemical cycles [23]. CO₂ is released through soil respiration, encompassing root respiration and microbial decomposition of organic matter [24, 25]. CH₄ fluxes depend on the balance between methanogenesis (production in anaerobic conditions) and methanotrophy (consumption in aerobic conditions) [26]. N₂O is produced via microbial nitrification (ammonium to nitrate) and denitrification (nitrate to N₂O or N₂), particularly in N-rich soils [27]. In natural forests, these processes are modulated by vegetation type, soil moisture, temperature, and organic matter inputs. Moso bamboo's high litter production and root activity make it a unique driver of GHG dynamics compared to coexisting tree species [28, 29]. Moso bamboo exhibits substantial litter production, which plays a critical role in nutrient return and soil organic matter accumulation. Studies have shown that annual litter production in moso bamboo forests can range from 1656.02 kg·ha⁻² to 1927.92 kg·ha⁻², depending on management practices and environmental conditions [30]. This high litter input contributes to nutrient fluxes, particularly N, phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), which are essential for maintaining soil fertility and ecosystem productivity [31].

2.3 Relevance of moso bamboo to GHG dynamics in natural forests

Moso bamboo's natural expansion in forests enhances soil organic carbon (SOC) storage, with stocks of 20–40 Mg ha⁻¹, surpassing some degraded forest or grassland soils [32]. However, increased organic inputs may elevate CO₂ emissions through enhanced soil respiration. Moso bamboo's root systems improve soil aeration, potentially increasing CH₄ uptake, while its low C:N ratio litter accelerates N cycling, which may boost N₂O emissions [33]. The complexity of these interactions in

diverse forest ecosystems, with varying tree species and soil conditions, necessitates a detailed exploration of moso bamboo's climate impacts, especially in mountainous regions.

3. Mechanisms of moso bamboo's impact on soil GHG emissions

3.1 Root-driven carbon turnover and CO₂ release

Root respiration originates from the metabolic activities of root cells, particularly in rapidly growing rhizomes and fine roots [34]. The expansion of moso bamboo rhizomes disrupts native soil structure, increasing fine root density and turnover, which mechanistically links to elevated C fluxes via enhanced autotrophic respiration and stimulation of heterotrophic microbes through exudates. The rapid expansion of moso bamboo root systems significantly increases root respiration, leading to enhanced CO₂ emissions. In natural forests, the root biomass of moso bamboo can reach 5–8 Mg ha⁻¹, with an annual fine root turnover, which is substantially higher than that of broadleaf [35]. This high turnover rate results in vigorous root respiration and increased CO₂ flux. Studies conducted in the moso bamboo expansion have shown that root respiration rates range from 1.08 to 5.99 $\mu\text{mol m}^{-2} \text{s}^{-1}$ [36]. Root respiration is positively correlated with root biomass, as the rapid expansion of the root system requires more energy and consequently releases more CO₂ [36]. Under high-temperature conditions in summer, the peak root respiration rate can reach 7.87 $\mu\text{mol m}^{-2} \text{s}^{-1}$, significantly enhancing the total CO₂ flux. Root respiration involves the aerobic metabolism of carbohydrates, resulting in CO₂ release. The high metabolic rate of moso bamboo roots, driven by rapid growth and expansion, increases C consumption. Root exudates, which include low-molecular-weight organic compounds such as sugars and organic acids, further stimulate rhizosphere microorganisms, indirectly enhancing the contribution of heterotrophic respiration to CO₂ emissions [37, 38]. Research has indicated that the extensive fine root system of moso bamboo results in exudation rates comparable to those of woody plants, with a positive correlation between exudation and respiration rates, thereby further increasing CO₂ emissions [39].

3.2 Soil aeration and methane uptake

In natural forest ecosystems, moso bamboo soils typically act as CH₄ sinks due to improved soil aeration from dense root systems [40]. Mechanistically, rhizome penetration creates macropores, reducing soil water-filled pore space and O₂ diffusion barriers and thereby favoring aerobic methanotrophy over anaerobic production. Rhizomes enhance soil porosity, fostering methanotrophic bacteria that oxidize CH₄ [41]. Measurements indicate CH₄ uptake fluxes of 120 to 180 $\mu\text{g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ in bamboo-invaded forest soils, higher than in adjacent grasslands or sparse woodlands [42]. This sink effect is attributed to reduced soil moisture and increased oxygen availability, which inhibit methanogenesis [43].

The long-term impact of bamboo expansion on CH₄ fluxes depends on forest composition. In mixed forests, bamboo's interaction with tree roots may enhance soil drainage, amplifying CH₄ uptake [40]. The invasion of moso bamboo reduces soil pH, thereby favoring the oxidation of CH₄ by methanotrophic bacteria and enhancing the CH₄ uptake capacity of soil [42, 44]. The root system of moso bamboo may decrease

soil moisture content and increase soil porosity; under aerobic conditions, this could accelerate the proliferation and enhance the activity of methanotrophic bacteria, thereby increasing soil CH₄ consumption, that is, CH₄ uptake [45, 46].

3.3 Nitrogen cycling shifts and N₂O emissions

N₂O emissions in moso bamboo-invaded forest soils are driven by microbial nitrification and denitrification, influenced by N availability [47]. Moso bamboo expansion accelerates N turnover through litter-mediated mineralization, providing labile N substrates that feedback into denitrifier gene expression, linking invasion to pulsed N₂O releases. Moso bamboo's low C:N ratio litter accelerates N mineralization, providing substrates for N₂O production [48]. In natural forests, N₂O emissions are primarily driven by endogenous N from litter decomposition, as no external fertilizers are applied [33].

The expansion of moso bamboo alters the pH of native forest stands; compared to native pure forests, soil pH in mixed forests increases, attributable to moso bamboo litterfall elevating alkaline cations such as calcium ions in the soil, thereby influencing soil pH dynamics [49]. Moso bamboo expansion enhances the diversity of soil N-fixing bacterial communities [11], which may modulate microbial activity during nitrification and denitrification processes, consequently affecting soil N cycling. Research indicates that bamboo expansion accelerates soil N mineralization and intensifies ammonification, with NH₄⁺ potentially serving as the primary environmental driver of shifts in soil bacterial communities, however, the resultant pH elevation following moso bamboo expansion impacts nitrification-associated microbial communities, suppressing the activity of ammonia-oxidizing bacteria, attenuating nitrification rates, and thereby influencing soil N₂O emissions [50].

The interaction with coexisting trees influences N₂O dynamics. In mixed forests, bamboo's high-quality litter may enhance tree litter decomposition, increasing N availability and N₂O emissions [44].

3.4 Microbial shifts: Mediators of GHG feedbacks

Moso bamboo's expansion reshapes forest soil microbial communities, which mediate GHG production and consumption. The bamboo rhizosphere fosters abundant Actinobacteria and Proteobacteria, promoting organic matter decomposition and N cycling [51, 52]. Microbial biomass C in bamboo soils is 1.32.7 times higher than in adjacent forest soils, driving elevated CO₂ and N₂O emissions [53]. Methanotrophic bacteria, and methylobacterium, are enriched, supporting CH₄ uptake [54].

Root exudates (sugars and organic acids) stimulate heterotrophic bacteria, enhancing soil respiration and N₂O production [55]. However, the diverse microbial communities in natural forests, influenced by mixed tree species, maintain a balance that limits extreme GHG fluxes. Metagenomic analyses reveal higher abundances of denitrification genes in bamboo soils, but their activity is constrained by low N availability [47]. The high fungi-to-bacteria ratio in bamboo forest soils favors SOC stabilization, reducing long-term CO₂ emissions [21].

Long-term bamboo dominance may reduce microbial diversity, stabilizing GHG fluxes at moderate levels. The interaction between bamboo and tree-derived microbial communities adds complexity. In mixed forests, bamboo's influence may enhance microbial diversity, supporting CH₄ uptake but also increasing N₂O production due to synergistic decomposition [21, 56].

4. Conclusion

The natural expansion of moso bamboo in forest ecosystems drives complex shifts in soil-driven GHG emissions. Through rapid clonal growth, high litter inputs, and extensive rhizomes, bamboo enhances root respiration and microbial decomposition, elevating CO₂ emissions while improving soil aeration and pH to boost CH₄ uptake by methanotrophic bacteria. Its low C:N ratio litter accelerates N mineralization and restructures microbial communities, modulating N₂O production in ways that vary with forest composition. These mechanisms are intertwined with ecological processes like rhizome competition and litter quality shifts. For management, monitoring bamboo encroachment in biodiversity hotspots, particularly in mountainous regions, is essential. Future research should focus on long-term flux measurements and metagenomic analyses under climate scenarios to inform sustainable forest stewardship and GHG mitigation. As global change intensifies, such as warming-induced upward migration, population driven land-use intensification, biodiversity loss, and altered precipitation. These trends suggest a potential for amplified GHG feedbacks; thus, research should prioritize long-term in situ flux measurements, metagenomic profiling of microbial responses, and modeling of invasion scenarios to inform adaptive conservation and mitigation strategies.

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Regional Climate Change as a Driver in Forest Fires

Luis Manuel Galván Ortiz and José Antonio Ávalos Lozano

Abstract

Most of the forest fires have an anthropogenic origin. However, meteorological droughts can create conditions for fires to spread in greater numbers and extent. Two cases are presented in southern Mexico and Guatemala, where human activities have generated large forest losses. The aim is to identify regional climate changes resulting from the increase in temperature attributable to deforestation in the last 20 years. Through remote sensing data, the loss of forest cover, the regional climate trend, and the detection of forest fires are identified. Water balances are simulated in the fire season under different scenarios of drought and high temperatures. This generates edaphic droughts that are more intense than meteorological ones. It suggests that under these conditions, the probability of forest fires is considerable, especially near significant forest fragmentation areas. Analyzing forest fire risk necessitates factoring in both climatic elements and nearby human activities to avoid oversimplifying the attribution solely to global climate change.

Keywords: forest fires, deforestation, regional climate change, drought, evapotranspiration

1. Introduction

Forest fires are nonrandom processes [1], therefore, they depend on society-nature interactions. In most cases, they are the result of human activities related to fire management to develop agricultural, forestry, or urban infrastructure construction activities [2, 3]. On the other hand, although less frequently, there are those of natural origin mainly caused by volcanic activity, lightning, or spontaneous combustion due to the concentration of organic activity.

Fire is one of the main driving variables of forest ecosystems [4, 5] mainly when they are crown or aerial, because fire consumes all the vegetation; its impacts can be negative in the short and long term, since they cause the loss of basic ecosystem services such as the capture of carbon dioxide (CO₂), local regulation of the climate, and reduction of the impact of extreme meteorological phenomena, such as floods, aquifer recharge, food production and various products, air quality, housing materials, and soil preservation, among others (e.g., [6, 7]). But they can also have a positive effect; in fact, surface and underground fires are essential for the proper functioning of forest ecosystems ([8, 9], reducing the amount of combustible material and allowing the mineralization of dead matter, which facilitates the release and incorporation of nutrients. In addition to eliminating competition from invasive competing plants, favoring sanitation and/or

disease control among trees, and in some cases, allowing the germination of some seeds, since many species require their propagules to be subjected to fire stimulation. In Mexico, various tree species have thick, insulating bark, which protects them from lethal temperatures caused by fire, and others are induced to quickly recover their foliage when part of their crown has been affected by fire [8], (e.g., [10]).

In Mexico, between 70% and 90% of the fires occur in bushes and grasslands, and only 10–30% of these events affect wooded formations; the grasslands recover in the first days of the rainy season, while the shrublands take a little longer, from weeks to a couple of years. The case of forest areas affected by crown or aerial fires is different since these ecosystems take between 15 and 50 years to recover, depending on the species and other factors [8].

The type of fires that occur in forest ecosystems depends on three main factors according to their composition and structure:

1) Ecosystems sensitive to the fire regime, such as high and medium evergreen and semievergreen forests, low deciduous forests, mangroves, fir-oyamel forests, and some oak forests. In these formations, fires are not common, therefore, the fire regime is not essential to maintain the composition of the vegetation. However, when there is extreme drought, crown fires can cause catastrophic results since the recovery of the vegetation requires succession processes of several centuries [8].

2) Ecosystems dependent on the fire regime, the trees that make up these ecosystems are adapted to surface fires, which are frequent; therefore, it is difficult for enough combustible material to accumulate for crown fires to occur (they occur every two to ten years). These species sprout well on burned sites, where the fire removes competing plants from the soil and the undergrowth and the accumulated organic matter, completing the mineralization process; in this way, the seeds can hatch (they need to submit to fire stimulation) upon contact with mineral soil [8].

3) Ecosystems independent of the fire regime such as desert and tundra ecosystems; very dry areas with little biomass and organic matter or very cold and humid.

The nature of these three types of ecosystems determines the type, fuel quality, and volume of organic matter that will feed the fire and is, therefore, the main element that determines the characteristics of the fire. Other variables that influence fires are topography, terrain roughness and slope, soil moisture, albedo, wind direction and speed, minimum and maximum temperatures, atmospheric humidity, and precipitation.

It is estimated that every year 350 million hectares of natural areas are damaged by fires worldwide [11]. While in Mexico, in the period 1995–2015, there were an average of eight thousand one hundred and forty-one fires with an annual average affectation of almost 302 thousand hectares. Although 99% of the fires were superficial, the lowest record of lost hectares occurred in 2015 with eighty-eight thousand five hundred hectares affected and the worst year was 2017, with more than 726 thousand hectares damaged [12].

The burning of biomass, which includes forest fires and agricultural burning, is a significant source of greenhouse effect compounds since it contributes from 20–50% of their global emissions [13]. The emissions caused by these burns release significant amounts of particles and gases with significant impacts on human health and ecosystems in the environment; they are made up of complex mixtures of gases and particles, mainly carbon dioxide (CO₂), carbon monoxide (CO), and methane (CH₄). In addition to aerosols and black carbon (PM_{2.5} and PM₁₀), the latter are harmful to human health [13]. In the case of Mexico, Bautista [14] has determined that during the 12-year period from 1999 to 2010, Mexico emitted into the atmosphere an approximate amount of 112 Tg of CO₂, 5.8 Tg of CO, and 1.2 Tg of CH₄ [14].

2. Climate and forest fires

Climate and fires have a close relationship every year; the number of fires is greater during the spring because in this season there are warmer and drier conditions in both hemispheres, in the northern hemisphere around the months of April–May and in the south around October–November. This seasonal process regulates the annual climate-wildfire cycle (**Figure 1**). It should be noted that, in places where human economic activities are intensive, forest fires are present at any time of the year, regardless of the season. However, in the Sixth National Communication and Second Biennial Update Report before the United Nations Framework Convention on Climate Change, the government of the republic affirms that the years that presented the highest number of fires in the period 1998 to 2018 were 1998 and 2011, years associated with intense droughts associated with El Niño conditions [12, 15]. Under the above considerations, climate does not cause fires; however, it is an important factor that determines their frequency and extent, while human activities define their location. If methodologies are built that relate both variables, it is possible to determine the spatiotemporal patterns of fires.

Meteorological drought is a natural condition that does not occur every year; it is part of the climatic variability and is considered one of the main precursors of forest fires, due to the decrease in rainfall and high temperatures because of a greater frequency. Of days with cloudless skies, which causes the loss of moisture in the soil and less water available for organisms, high temperatures produce greater evapotranspiration and less rainfall reduces the availability of water for transpiration, therefore, plants suffer water stress and many die as a consequence, increasing the amount of dead and dry biomass that works as fuel [16].

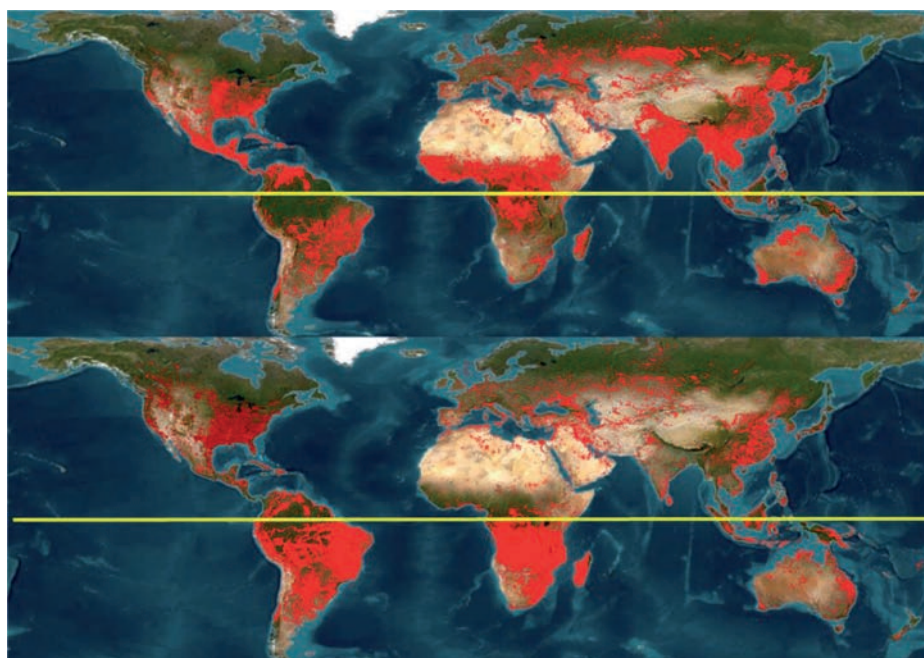


Figure 1.
Global pattern of hot spots during spring 2022, April for the northern hemisphere (top) and October for the southern hemisphere (bottom). Data sources: FIRMS (NASA) data from Landsat sensors, VIIRS and MODIS.

Along with low precipitation and high temperatures, drought additionally generates conditions of low relative humidity [15]. These circumstances caused by natural variability generate an optimal scenario for the spread of fires and risk increases in areas where human activities are intensely present.

3. Regional climate change

The increase in temperature on the planet during the last decades is unequivocal, however, it does not manifest itself in a homogeneous way in all places. Changes in rainfall patterns are less clear-cut, still show multiyear fluctuations, and may be more attributable to ocean surface temperature variations than global warming of the atmosphere. On the other hand, point out a close relationship between vegetation and precipitation, if the vegetation cover is modified, rainfall can be altered and vice versa [17]. Where the change in land use is extensive, it is there where climate change can be attributed to significant changes in the landscape and not to the effect of global warming, this is what in this study is called regional climate change.

These changes in the regional climate are due to the substitution of arboreal vegetation cover by grasslands, agricultural, or urban areas and are basically caused by alterations in the roughness, albedo, and humidity of the regional soil. These three elements are of great importance in the precipitation regime of a site, due to its effect on the dynamics of the atmosphere, basically a decrease in roughness also causes a decrease in friction, which alters the speed of movement of air masses, causing them to move a lot faster, which affects the thermodynamic interactions of air parcels with soil and vegetation. Changes in albedo, in turn, cause changes in the radiative budget of the soil that can go through different paths, increasing soil temperature or decreasing it, which affects evapotranspiration. Finally, the decrease in soil moisture prevents the latent heat transfer between the atmosphere and the ground, decreasing the amount of water that the atmosphere receives by evaporation and convergence; these added effects alter precipitation [18]. Of course, the greater the spatial dimensions of the change in land use, the greater effects on precipitation and regional climate could be expected, causing faster and more intense regional climate changes in its manifestation than global climate change.

4. Methodology and results

Two sites are identified in Guatemala (**Figure 2**) and Mexico (**Figure 3**) where there is a contrast between the permanent loss of trees in the last 20 years and places where the change of arboreal vegetation has not been significant. The behavior of temperature and precipitation is analyzed, in order to determine if there have been changes in the sites, attributable to the change in land use in recent decades, increasing the risk of fire.

Based on observed temperature and precipitation data in deforested sites (90° W, 17° N), a simulated exercise of the water balance shows the availability of water in the spring months (March, April, and May), during a normal year (**Figure 4a**), under conditions of global climate change in the present (+1°C) (**Figure 4b**), regional climate change (+2°C) (4c) and meteorological drought with regional climate change (+4°C and -40% mm) (**Figure 4d**), which would cause, according to the model, a decrease in soil moisture and the possibility of greater dryness in the surrounding vegetation.

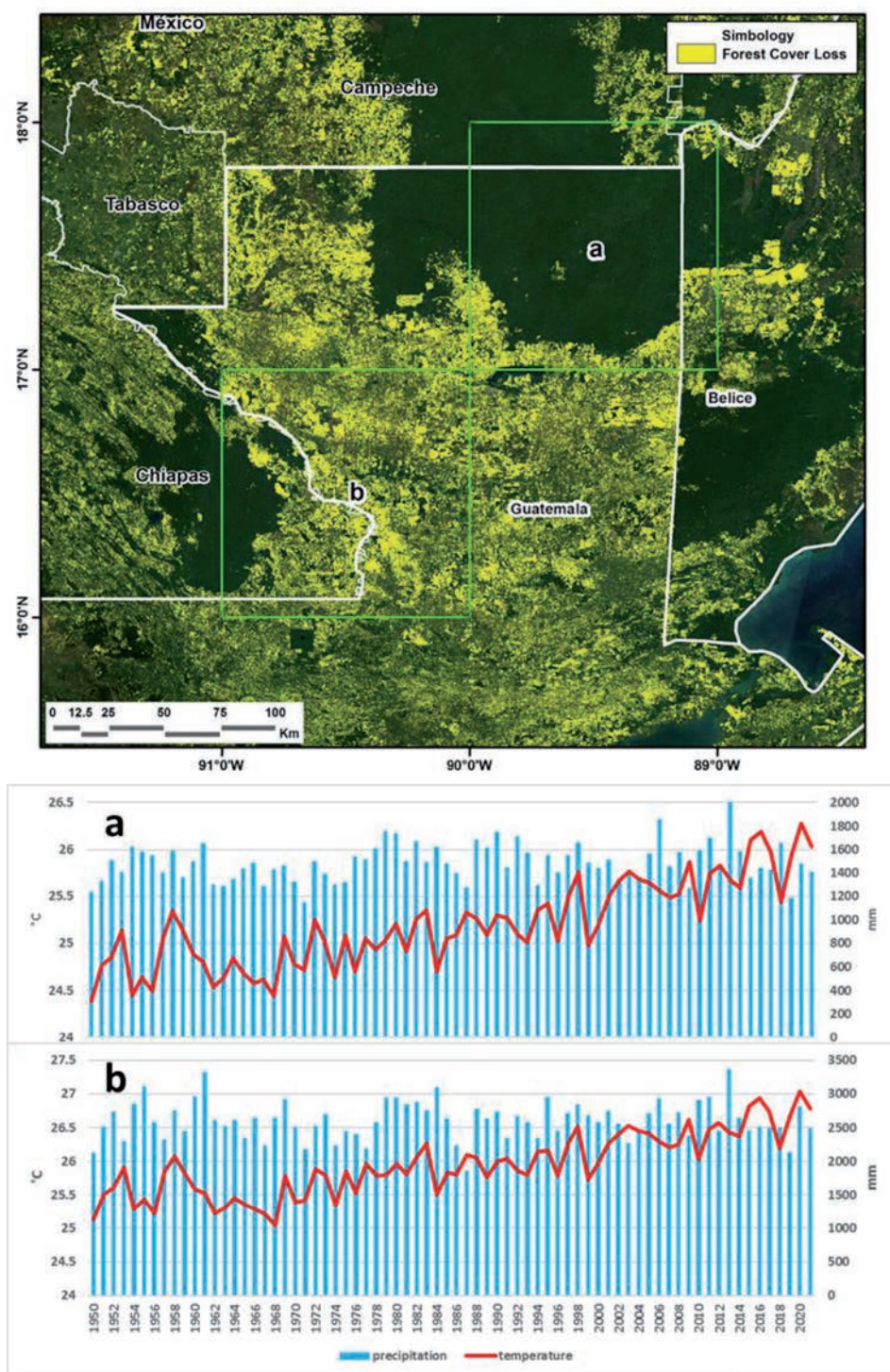


Figure 2.
 Loss of forest cover in 20 years and trends in temperature and precipitation in Guatemala: (a) in a conserved area and (b) area with great loss of forest cover. Data sources: Global Forest Change (2000–2021) [19] and climate data CRU TS 4.06.

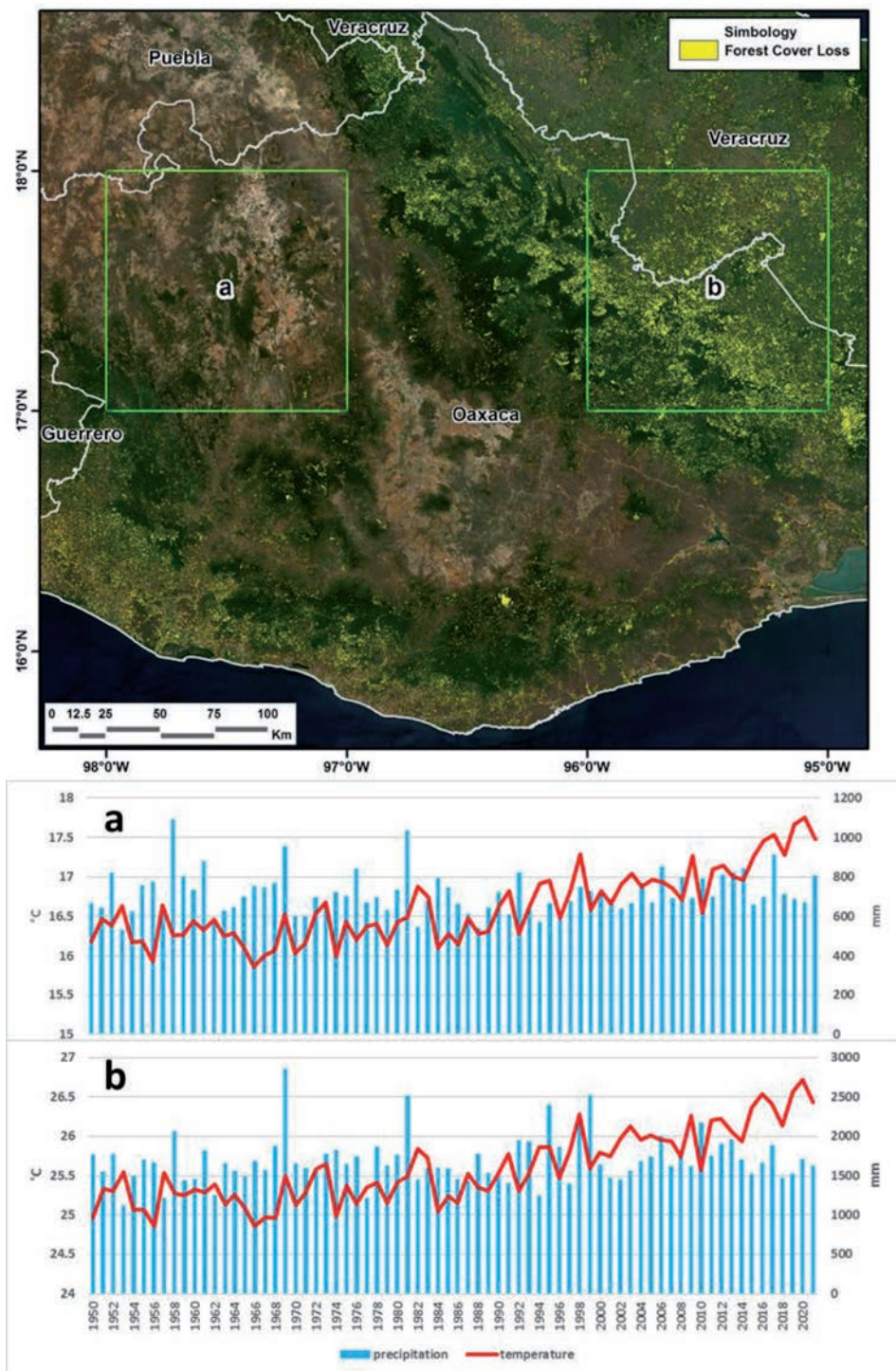


Figure 3. Loss of forest cover in 20 years and trends in temperature and precipitation in Oaxaca, Mexico: (a) in a conserved area and (b) area with great loss of forest cover. Data sources: Global Forest Change (2000–2021) [19] and climate data CRUTS 4.06.

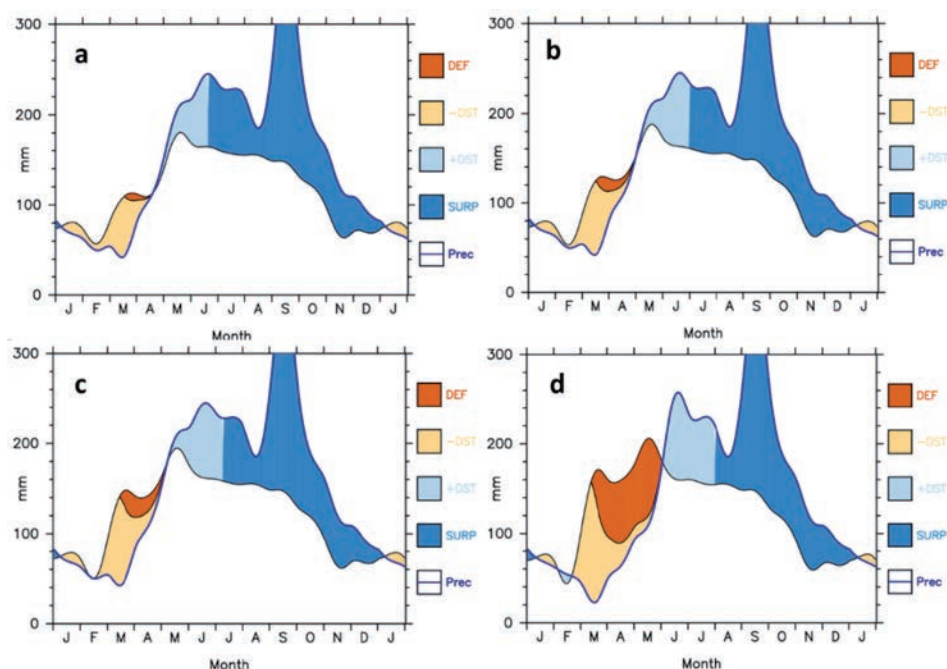


Figure 4.
 Example of a water balance simulation during the months with the highest number of fires (March–May). Example of a water balance simulation during the months with the highest number of fires (March–May): (a) during a normal year; (b) under conditions of global climate change in the present ($+1^{\circ}\text{C}$), (c) regional climate change ($+2^{\circ}\text{C}$), and (d) meteorological drought with regional climate change ($+4^{\circ}\text{C}$ and -40% mm). Data sources: [20].

The simulation of the water balance shows the effect of regional climate change caused by deforestation, which results in a constant increase in air temperature, which grows every year in deforested sites; this phenomenon can induce warmer and drier springs. When, additionally, meteorological drought occurs due to low rainfall and high temperatures, an intense moisture deficit in the soil is caused in deforested areas, which does not occur as intensely in non-deforested areas, which leads to a greater probability of fires in the nearby forests. In other words, without considering global climate change, regional climate change induced by deforestation and added to the appearance of hot and dry years, attributable to climate variability, can generate a favorable scenario for fires to occur in greater numbers and extension, especially in areas where human activities occur with greater density.

In agreement with Breshears et al. [21], regional vegetation presents greater stress in various parts of the world due to increased warming processes during drought events. The author proposes the term “global-change-type drought” to refer to drought under global warming conditions.

An evapotranspiration index is used, which relates at a regional scale the effect of temperature on precipitation at different time scales, called the standardized precipitation-evapotranspiration index (SPEI) developed [22], which shows the relationship between the evapotranspiration potential (PET determined by temperature) and the availability of water (determined by precipitation); therefore, it is useful to estimate possible desertification processes and additionally the impacts of the drought, especially under conditions of regional warming caused by large losses of tree vegetation.

The index was applied in the selected analysis sites, analyzing through SPEI-12 (months) time series, the contrasting behaviors, between deforested sites and those that conserve their wooded area, for the two study cases (Mexico and Guatemala). In the case of northern Guatemala, for the area conserved throughout the period, a characteristic oscillation is maintained, attributable to natural variability, even from 2005 humid conditions are observed, only interrupted by two periods of drought in the years 2010 and 2020. (**Figure 5a**). In the deforested region, on the other hand, there has been a drop in the SPEI values since the 1990s, which has caused an intense moisture deficit in the soil for the last 10 years, evidencing a regional climate change (**Figure 5b**).

In the selected site in the Northwest of Oaxaca, Mexico, due to the altitude and configuration of the terrain, the vegetation has not undergone great changes, only in some lower parts of the valleys are isolated agricultural areas. In this area, the temporal pattern of the SPEI maintains a typical behavior attributable to natural climatic variability; it presents variations but without a clear trend from 1950 to 2000, to later present a period of greater humidity on the surface (**Figure 6a**). On the other hand, in the Northeast of Oaxaca Mexico, in the area that has presented deforestation in the last 20 years, a constant process of low values in SPEI is identified, that is, increasing evapotranspiration permanently, especially in the last 10 years (**Figure 6b**).

When the presence of a climatic hazard, such as meteorological drought, manifests itself in forests, especially in the most vulnerable ones near human activities, it results in the climatic risk of forest fires, and under conditions of global and regional climate change, the risk condition is almost permanent every year [23].

Under these conditions, it is important to establish procedures for monitoring, forecasting, and early warning of forest fires to reduce their impacts. In a context in

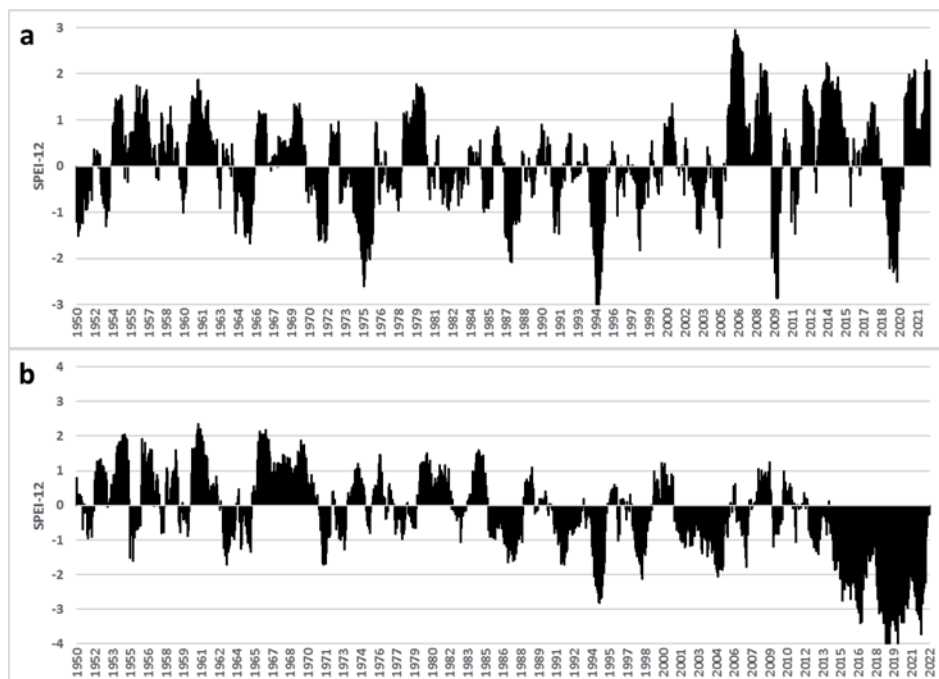


Figure 5. SPEI-12 time series for the sites analyzed in Guatemala: (a) conserved area and (b) deforested area. Data sources: SPEI global drought monitor.

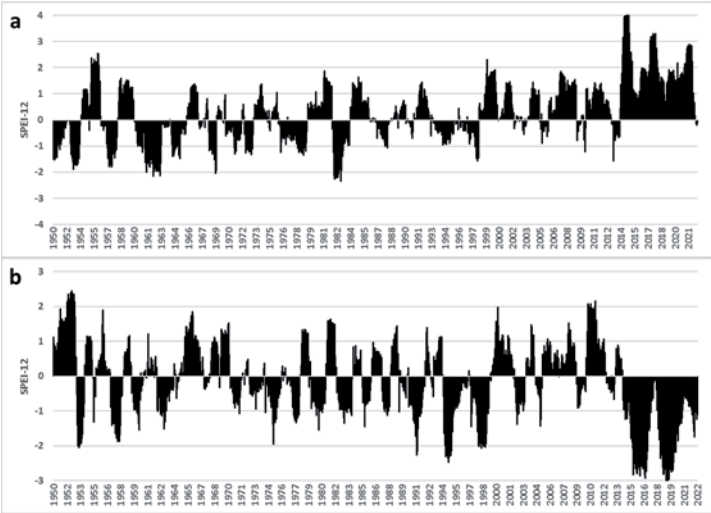


Figure 6.
SPEI-12 time series for the sites analyzed in Oaxaca, Mexico: (a) conserved area and (b) deforested area. Data sources: SPEI Global Drought Monitor.

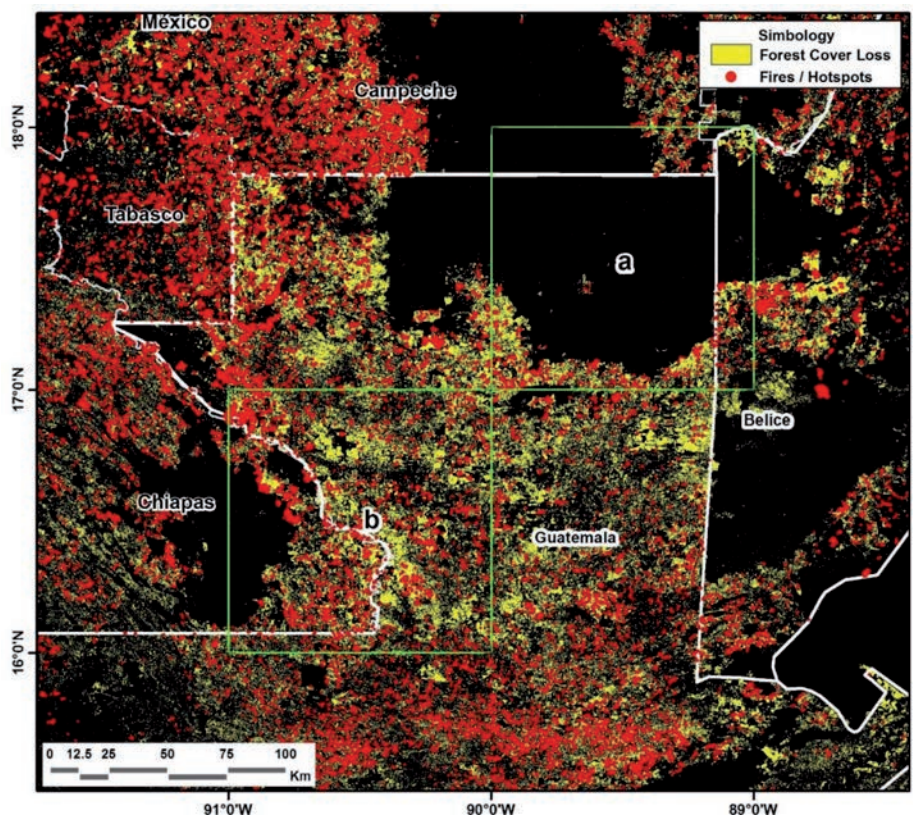


Figure 7.
Distribution of hotspots in the Guatemalan region (May 2019). Data sources: FIRMS (NASA) data from Landsat sensors, VIIRS and MODIS, and global forest change (2000–2021).

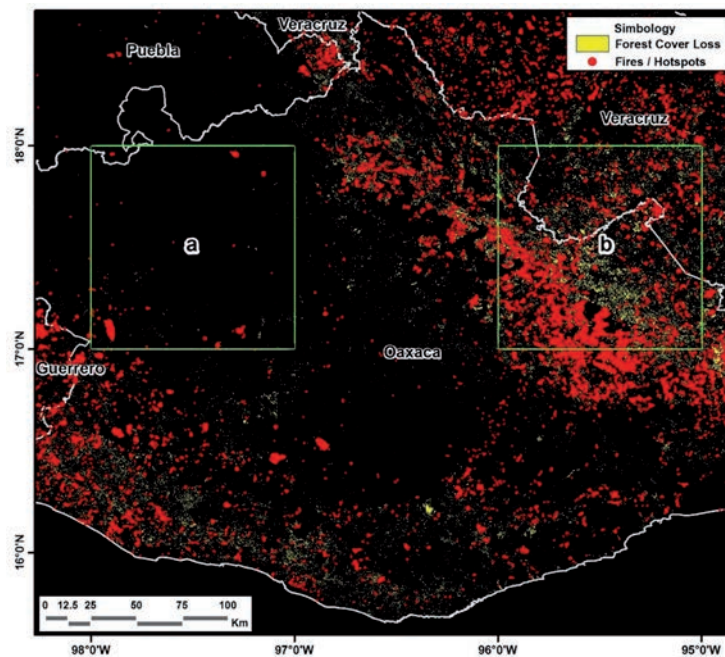


Figure 8.

Distribution of hotspots in the Oaxaca, Mexico region (May 2019). Data sources: FIRMS (NASA) data from Landsat sensors, VIIRS and MODIS, and global forest change (2000–2021).

which their frequency and magnitude are increasing, today it is possible to use many tools, such as those derived from various satellite platforms with great coverage in time and space.

For a period with a meteorological drought like May 2019 with satellite data, hotspots (possible fire) are identified; their distribution is mainly conditioned where agricultural activities use fire, near roads, or where there are deforested areas; however, the atmosphere-soil conditions due to the effect of regional climate change, can induce in greater plant stress, especially in more deteriorated ecosystems, the perfect scenario for the use of fire by some human activity to cause more and larger forest fires. The hotspots occur mainly in deforested areas (mainly agricultural activity) and nearby forests, and the conserved areas only show some isolated fires (**Figures 7 and 8**).

5. Conclusions

It is common to use a naturalistic approach, in which phenomena such as fires are completely attributed to climatic conditions, without considering the profound influence of human activities as the first cause of fires; this continues to be a problem of approach at a global level, under these conditions make it necessary to promote a paradigm shift in the management and protection of forests on the planet. Another problem is that forest fires are arbitrarily linked to global climate change without a true attribution exercise, assuming that the increase in temperatures and the presence of droughts directly induced the fires. It is also necessary to differentiate it from regional climate changes caused by changes in land use and are strongly associated with desertification, which could produce a process of ecological succession, loss

of the productive potential of ecosystems, inducing an increase in the frequency and intensity of fires and magnifying the effect of droughts. Decision makers must address the issue of forest fires from an integrating perspective, where human activities and the effects of adverse weather explain the increase in fires in recent decades from a risk perspective (society-nature).

Additionally, it is necessary to increase the efforts and resources allocated to the analysis of climate information and its use in fire risk management systems, considering the regional vulnerability to define preventive actions, particularly during dry and hot years [24].

Global climate change, especially regional climate change, can generate favorable conditions for the spread of forest fires, but adaptation and risk management strategies are essential and of greater weight in order to curb this environmental problem. Different proposals for adaptation can be derived from these studies, including landscape reengineering processes to reverse and mitigate some effects of climate change. This path makes it possible to adequately face the risks caused by the socio-environmental crisis and those that depend on the natural variability of the climate; it also guarantees the conservation of essential environmental services provided by forests, such as carbon capture and climate and water regulation. The study of forest fires constitutes a fundamental section in the effort to build policies to deal with climate change [25–28].

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Chapter 4

Historical Water Management in the Vicinity of Banská Štiavnica under Changing Climatic Conditions

Michal Červeň

Abstract

From the sixteenth to nineteenth century, a unique and significant water management system was built in Banská Štiavnica and its vicinity, which served the local mines. The water management system consisted of water canals (collecting and transporting) and water tunnels, which concentrated on surface water from rain and snow from Štiavnica Mountains and brought it to the reservoirs of tajchy (the historical water structures). Water from tajchy was drained into transporting water canals that brought water to the mines. Here, water was used as energy power for huge pumping machines that started to pump groundwater from flooded mines. The whole water management system included 170 km collecting and transporting water canals with water tunnels and from 60 water structures. The water management system was one of the largest and the most unique systems in the world. About 32 years back it was listed on the list of world heritage UNESCO with the town of Banská Štiavnica but the system is not used right now and it is in danger. Is it possible to preserve the water management system and use it for citizens and nature during climate change?

Keywords: water management system, tajchy, water canal, climate change, volunteering

1. Introduction

Banská Štiavnica is a historical town located in the central part of Slovakia, in Europe. The town is famous for mining gold and silver in history. First inhabitants started to mine gold and silver more than 800 years ago in the area. The issues with groundwater which had started to flood mines were solved by building the large water management system in the eighteenth century. The progressive water management system in the vicinity of Banská Štiavnica Town worked more than 200 years. The last 100 years it has not been used and its parts are in danger. The historical water management system is the best practice how collecting surface water, how protecting citizens against flash floods, and how to use accumulated surface water from reservoirs of dams during climate change, during dry summers seasons for ecology of streams

and citizens downstream dams. But this topic—how to save and to use the historical water management system is not dealt with in Banská Štiavnica and in Slovakia, that is why the whole system is in danger.

Banská Štiavnica was inscribed on the UNESCO World Heritage List in December 1993, representing the most extensive designation in Slovakia. The site was included on the list due to its Outstanding Universal Value and in accordance with criteria IV and V. The Outstanding Universal Value is described as follows: “The Historic Town of Banská Štiavnica and the Technical Monuments in its Vicinity is an outstanding example of an important mining settlement that has developed since the Middle Ages. The property’s distinct form was created by the symbiosis of the industrial landscape and the urban environment resulting from its mineral wealth and consequent prosperity.”

There, in the vicinity of Banská Štiavnica, was built one of the largest and one of the most unique water management system in the whole world [1]. The whole water management system included 170 km collecting and transporting water canals with water tunnels and 60 water structures, called “tajchy.” This name is from German and means a historical name of a water structure. Tajchy are historical water structures that were built to accumulate surface water from the collecting water canals from slopes of Štiavnica Mountains. Accumulated water was used mainly to pump groundwater from flooded mines. Once the groundwater was drained, the miners could have continued to mine gold and silver. For centuries, the Banská Štiavnica water management system set in motion more than a hundred mining water-powered devices. Currently, there are 26 historical water structures in the vicinity of Banská Štiavnica and the last 1.5 km collecting water canals. More than 168 km water canals are in danger without adequate maintenance. The civil association “Štiavnický tajch” with the help of 1000 volunteers saved and fixed further 6.5 km water canals in this area.

The historical water management system is not only a legacy of the past and a testament to the advancement of Banská Štiavnica, but also a functional model of water retention in the landscape during climate change. It could once again operate in this region and serve as an example for water retention in other parts of the world (Figure 1).



Figure 1.
Štiavnické Mines—Great Windsächta tajch, Evička tajch (Photo: Slavomír Červený).

2. Tajchy: Historical water structures

Tajchy in the vicinity of Banská Štiavnica Town was built from sixteenth to nineteenth century. They are created by earth-filled dams. The body of dams was built of the materials from the nearby area, mainly their upstreams and downstreams spoles. The material of the central sealing cores (mainly clay or loam) was brought from long distances. From the point of view of the construction of dams, we can divide tajchy into homogeneous and heterogeneous. Homogeneous tajchy are older, lower, and more massive. The body of such a dam consists of one or more types of soil materials with similar properties. These kinds of dams were built between the sixteenth and eighteenth century. These dams are the oldest and were mostly built before the arrival of Samuel Mikovíny to Banská Štiavnica—the main project engineer of tajchy in first part of eighteenth century.

The second type are heterogeneous dams, which consist of stabilizing parts and a central sealing core created from clay in thin layers. These types of dams were slimmer, higher with better stability of upstream and downstream slopes. These types of dams were without considerable seepages in downstream slopes. In the stabilization parts of these dams, there are mostly construction pieces of stones mixed with loam or clay with sand and in the sealing core is only pure clay. These types of materials are impervious.

The height of the historical water structures varies from 3.3 m to the highest Great Richňava (32.0 m). Usually, tajchy have only one dam—a dam over the valley. However, there are also tajchy with two or more dams. For example, Počúvadlianský tajch has six dams and this tajch was built on the main ridge of Štiavnica Mountains. Other examples are Great and Small Richňava with three dams. The same numerous of dams has Great Kolpašský—three dams [2].

In the times when Samuel Mikovíny built Great Richňava tajch, its dam body was the third highest earth-filled dam in the world. One of the highest earth-filled dams in the world was built in the vicinity of Banská Štiavnica from the eighteenth to nineteenth century. For example, there were three tajchy in the first 10 of the highest dams in the whole world until the beginning of nineteenth century. Interesting is a construction of the dam because the dams of tajchy, their upstream slope, and downstream slope are too steep. It means, twice as steep as the modern dams in the whole world. Their constructions are breathtaking for plenty of civil engineers. For example, Rozgrund Tajch, its body of dam is one of the steepest earth-filled dam and one of the slimmest earth-filled dams in the world. The list of the highest dams around the world is the significant water management system example, according to the International Commission on large dams [3].

The World Register of Dams has been developed by ICOLD since 1958 and has been updated since then through the work of the Technical Committee of the World Register of Dams and Documentation. The World Register of Dams is the best database of dams of any importance in the world and ICOLD is constantly working to improve it. For the most part, it is based on information provided by ICOLD National Committees [3].

The ranking of the highest dams according to the World Register of Dams until the nineteenth century is below (**Figures 2 and 3**).

1. *Tibi*, Spain, PG = 46.0 m
2. *Jai Samand*, India, TE/PG = 41.0 m
3. *Rajsamand*, India, TE = 39.0 m
4. *Saint Ferrol*, France, TE = 35.0 m



Figure 2.
Great Richňava, an example of eighteenth century earth-filled structure with a height of 32 m, one of the highest of its kind in Europe (Photo: Slavomír Červený).



Figure 3.
Počúvadlianský tajch, an example for historical earth-filled dam with six dams (Photo: Slavomír Červený).

5. Almonacid de la Cuba, Spain, PG = 34.0 m (It is not on the list of ICOLD)

6. Great Richňava, Slovakia, TE = 32.0 m

7. Rozgrund, Slovakia, TE = 30.0 m

8. Počúvadliansky, Slovakia, TE = 29.6 m

9. Ishitaniokuike, Japan, TE = 28.0 m

10. Suwadaniike, Japan, TE = 28.0 m

PG—the wall body of dam, TE—the earth-filled dam, PG/TE—the combined dam, from The World Register of Dams (ICOLD) [3].

3. Collecting and transporting water canals and water tunnels

Collecting and transporting water canals were open canals that were laid out along contours with a minimum slope. The slope of the collecting water canals was around 0.66%. These types of water canals captured surface water. The transporting water canals had a gentler slope than the collecting water canals—about 0.16%. These types of water canals transported accumulated water from reservoirs to mines. The width of the both water canals was from 0.6 to 1.0 m, while their depth varied from 0.5 to 1.5 m [4]. The water canals consisted of a trough and a dyke. In order to avoid major losses and to speed up the transfer of water, water tunnels replaced some long arched parts of the water canals. Water tunnels were also dug along the water canals routes that transferred water from one basin to another basin. This water management system was one of the most complicated ones in the world because the whole system captured only surface water from rain and snow, because there were not any springs, streams, or rivers in these parts of Štiavnica Mountains. The whole water management system was built too high above the natural sources of water. The water canals were built only few meters under the main ridge of Štiavnica Mountains, even some of them that lead through saddles of the main ridge. The unique water management system was built in places where there were/are not any water sources, but it worked for more than 200 years [2].

During research between 2012 and 2019, we identified 170 km water canals in the terrain and in the historical maps in the archives. The historical maps from the archives were from the seventeenth to twentieth century. The total number of identified water canals was 73 in Štiavnica Mountains. For example, Great and Small Richňava had nine water canals with a total length more than 43 km. Some water structures with better hydrologic conditions have not had any water canals.

The longest water canal was Upper Hodrušský 9160 m long and it belongs to Great and Small Richňava Dams. The shortest water canals were only a few hundred meters long [5].

The historical water canals accumulated only the rain water and springs from Štiavnica Mountains. The water canals had the trapezoidal shape with steep parts of trough. These parts were built by the block of stones without using any conjunctive material. The bottom of water canals were made with a tiny layer of clay without used stones. The water in the water canals flowed very slowly.

There was no erosion in water canals, but on the contrary there was a process of sedimentation. Therefore, miners had to do maintenance of water canals annually. Water flowed in water canals only during rains or during snow melting. During seasons without rain, they were dry (**Figure 4**).



Figure 4.
Water tunnel, the shortcut on the line of water canals (Photo: Slavomír Červeň).

4. Current state of the technical monument of UNESCO

In 1993, the town of Banská Štiavnica and its technical monuments in the vicinity were listed on the UNESCO World Cultural Heritage List, becoming the first Slovak town to achieve this status. For registering the town and its vicinity on the UNESCO list includes a unique water management system built since the sixteenth century, which saw its greatest growth in the eighteenth century, made the maximum use of the hydro-energy potential of the surrounding hills, and remained the most advanced water management system until the nineteenth century [6].

There are only three similar water management systems. One of them is in the vicinity of Banská Štiavnica and two of them are in Germany, in Freiberg and in Upper Harz. The oldest water management system is in Upper Harz. This system is from the fifteenth century. All of these water management systems have been built for the mining industry. All of these consisted of water structures, water canals, and water tunnels. The most kilometers of water canals and water tunnels had the water management system in Upper Harz, less than 500 km. The highest dams were built in the vicinity of Banská Štiavnica. We mentioned significant dams in the vicinity of Banská Štiavnica in the previous part of the chapter. The morphology was the most complicated in Štiavnica Mountains because there are steep slopes of mountains and difficult conditions. The engineers had to build high dams with difficult constructions. The last important part for successfully building the water management system is the hydrology. There are good conditions for building the water management system in Freiberg and in Upper Harz. In both areas, they have streams, even rivers. Water from these streams or rivers was captured into water canals or water tunnels and to fill in reservoirs of water structures. The most difficult situation was in Banská Štiavnica when they did not have streams,= or rivers. Collecting water was from rain or snow from slopes of Štiavnica Mountains. It is the best type of water management system for the current situation during climate change (**Figure 5**) [2].



Figure 5.
The collecting water canal (Photo: Slavomír Červeň).

There are 32 and more years since the listing of the historical town of Banská Štiavnica and the technical monuments of its vicinity on the UNESCO list. We would like to present a brief recapitulation of what could and could not be saved in those 32 years. We will focus on one of criterions—namely a unique water management system and a description of its current state.

In total, there are currently 26 registered historical water structures in Štiavnica Mountains, but from 170 km of water canals is still working and it is in good condition and only 1.5 km of water canals have been preserved in good condition. More than 120 km water canals were destroyed but there are only 50 km water canals that are visible in the terrain. The world heritage is in danger.

The main reason for maintaining the water management system is to preserve the important monuments and to reuse this system during climate change. Today, the water from reservoirs of these historical water structures is no longer used, while climate change is an issue in the world and in the surroundings of Banská Štiavnica. The summers are warmer and drier and the local streams dry up, the level of underground water is lower, and the forests get dry too. During the warm summers, the citizens are without groundwater. Autumns are also dry and warm. Yes, we can use water from the reservoirs of water structures against climate change. We are able to drain water to help trees, streams, stream ecology, fishes, and even the citizens who

live under the water structures. In addition, we can collect surface water from rain or snow through the fixed water canals and return water to the reservoirs when it rains or snows. This is a very important aspect of water management in a changing climate. We can manage to capture flash floods through the water canals and save citizens living near local streams in the valleys below the collecting water canals. This is the vision of Štiavnický tajch CA for a better future for the historical water management system on the UNESCO list. We believe that the water management system in the Banská Štiavnica will work again, because it worked more than 200 years.

5. Štiavnický tajch Civil Association

In 2019, the Štiavnický tajch Civil Association (hereinafter CA) was founded, thanks to which 73 collecting and transporting water canals and 15 water tunnels



Figure 6.
Collecting water canal after restoration by CA (Photo: S. Červený).

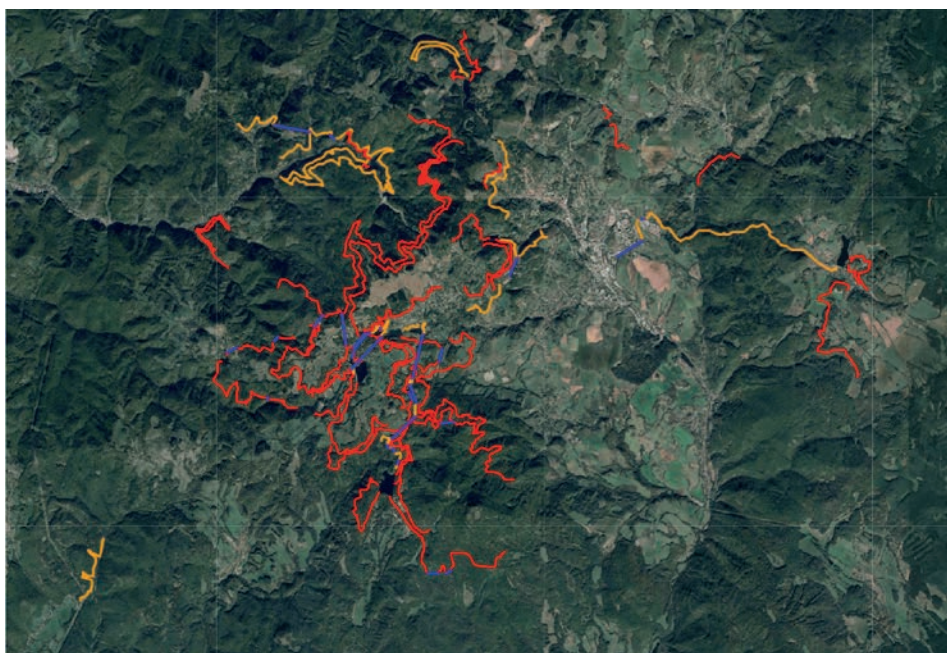


Figure 7.
The historical water management system in the vicinity of Banská Štiavnica, created by Michal Červený [2, 7].

were identified in the field over the course of 8 years before, with the help of historical maps from the eighteenth to twentieth centuries (**Figures 6 and 7**).

Of the total number of water canals, only 1.5 km are functional and maintained by the state. However, it is still possible to save and restore another approximately 50 km. The goal of the Štiavnický tajch CA is to protect, save, and educate the public about the unique water management system in the vicinity of Banská Štiavnica. In the field, the Civil association organizes volunteer days, where selected sections of collecting water canals are saved and restored with the help of volunteers. In total, 6.5 km of the collecting water canals were saved and maintained within 4 years (2021–2024) by the more than 1000 volunteers. As part of public education, the civil association published two publications about the historical water management system in the vicinity of Banská Štiavnica, to organize guided tours around parts of the water management system and historical water structures [5].

The ultimate goal of Štiavnický tajch CA is to restore the last renewable 50 km of water canals and provide them with an administrator who will care about this extremely important world technical monument. We are still without helping state institutes, organizations, and local stakeholders. At present, CA relies primarily on donations from citizens and small grants from individual foundations. Unfortunately, state enterprises, the Monuments Board, and the government of city Banská Štiavnica have not yet become directly involved in supporting the protection and preservation of the historic water management system. Even basic safeguarding to ensure its endurance for future generations is not currently covered by these institutions. This highlights the need for stronger institutional engagement in protecting technical heritage and addressing the challenges of climate change. We believe that the activities of CA could greatly benefit from closer cooperation and support from these organizations.

6. Conclusion

The historical water management system in the vicinity of Banská Štiavnica was listed on the list of world heritage UNESCO. It is one of the most significant historical monuments in Slovakia. The water management system has not been working since beginning of twentieth century. Hundreds meters of water canals and water tunnels were destroyed during the last 100 years. The water from many historical water structures is not used right now even in the time of climate change. The landscape of Štiavnica Mountains, citizens under water structures, streams under water structures, the water organisms, and the whole ecology are without water during warm and dry summers. But the historical water structures have their reservoirs on the maximum water levels but water from reservoirs do not drain to streams under water structures because there is not a change to fill in the reservoirs by water again because of destroyed water canals. The whole areas under water structures are in danger for a drought during the climate change. If some parts of water canals would be fixed again, water will be filled in reservoirs of water structures. CA is currently working on a project that will model the use of restored water canals, their potential to supply water to the reservoirs, and the subsequent utilization of the stored water. If it turns out that the water management system brings significant benefits to both the population and the landscape, the state should adopt these findings and begin to take an active interest in maintaining the system. This should be followed by the state assuming full responsibility for the system, appointing its administrator, and carrying out regular operation and maintenance. The role of CA will be to initiate these steps with the state and its responsible institutions.

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Section 3

Designing Solutions: Technological and Spatial Innovations

Rural Energy for Sustainable Development

Elsayed Ali E. Ali, Chen Hong and Mariam A. Amer

Abstract

This study investigates the potential of rural energy systems to contribute to sustainable development, focusing on integrating renewable energy technologies and smart infrastructure in decentralized energy frameworks. A detailed analysis of energy systems—including off-grid, on-grid, and hybrid configurations—demonstrates their role in overcoming energy poverty and environmental challenges. The performance of key energy sources such as biomass gasification, solar photovoltaics, and wind turbines is assessed alongside advanced storage systems like lithium-ion and lead-acid batteries. Engineering and socio-economic factors affecting rural energy consumption are analyzed, emphasizing temperature, building efficiency, geographic conditions, income levels, and education. Optimization approaches, including Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are highlighted for system sizing. The study concludes that deploying context-specific smart energy technologies and integrated systems can significantly reduce dependency on central grids while ensuring reliability, cost-effectiveness, and scalability in rural electrification.

Keywords: rural energy, sustainable development, energy sources, smart rural, energy access

1. Introduction

The global oil supply system is facing severe disruptions due to factors like the COVID-19 pandemic, the Russia-Ukraine conflict, and Middle Eastern conflicts. These disruptions, coupled with rapidly increasing energy demand, have led to unprecedented oil shortages and pushed prices above acceptable levels. In light of these rising oil prices, there's an urgent need to develop alternative energy sources. Rural regions worldwide, which constitute the majority of available land for development, hold significant promise for this. Despite often being overlooked in innovative development processes, these areas are crucial for achieving persistent and sustainable development.

Thus far, empirical studies on sustainable growth have identified numerous elements that impact the effective application of sustainable development in rural regions [1]. Categorized several factors that contribute to the sustainable growth of rural areas. These include the use of new agricultural production technologies that provide renewable energy and new avenues for the bioeconomy, as well as the

emergence of new, non-agricultural industries, such as bioenergy. In addition, using ICT to create a network of links is a novel approach in this sector [2]. So, the United Nations (UN) has expectations for 2030, which include 17 different Sustainable Development Goals (SDGs) for countries worldwide, one of which is to account for a renewable, affordable, and eco-friendly energy future [3].

The rural energy transition represents a substantial move in the direction of a sustainable, economical, and clean energy system. The expansion of high-quality energy, the variety of service offerings, and user-friendliness are all part of this shift. Regional variations impact the shift, which focuses on boosting renewable energy and enhancing energy infrastructure and efficiency [4].

This review article aims to comprehensively present various frameworks and perspectives on integrated energy adoption based on renewable rural energy systems. It specifically investigates how smart technology models can be effectively adapted and implemented within the rural energy sector, acknowledging significant existing gaps and obstacles. Given the inherent complexities of this field, the article also summarizes the current applications of smart technology in rural energy management, encompassing diverse contexts such as on-farm operations, residential settings, and industrial applications. Furthermore, this review delves into key definitions, explores the pathways to achieving Sustainable Development Goal 7 through rural energy systems, details the main energy sources and grid classifications in rural areas, analyzes the factors impacting rural energy availability and consumption (both engineering and non-engineering), examines strategies for decreasing rural dependency on the national grid, and identifies the challenges inherent in energy integration.

2. Key definitions and background

This section provides a foundational understanding of the core concepts essential for analyzing rural energy systems. We delve into the intersection of four key ideas: rural areas, rural energy, Smart Rural communities, and the integration of energy systems, including the concept of the Energy Internet. By providing a more thorough and interconnected overview of these subjects, we aim to establish a cohesive framework for the subsequent analysis.

2.1 Rural areas (RA)

Rural areas are defined as geographic regions with low population density and limited infrastructure, often located far from major metropolitan centers [5]. A common classification, based on the degree of urbanization, identifies rural areas as those with a population density below 300 inhabitants per square kilometer or those that do not meet the criteria for an urban center or cluster [6].

A rural region is any location that is not part of a larger metropolitan center. Compared to cities, rural areas typically have fewer resources and capabilities [7]. Generally speaking, rural areas have a low population density and are located far from major cities [8]. These areas have inherent qualities that make them vulnerable to a number of particular socioeconomic problems, like a lack of employment prospects and a poorer standard of living [9]. According to studies, people and organizations are moving away from rural areas in search of better prospects and lifestyles in cities [10]. At variance with current policies (such as Rural 3.0, which is a framework for

rural development [11] define rural regions as “places of opportunities”, shifting the future prospects to a challenge/opportunity vision.

2.2 Rural energy (RE) and smart rural (SR) communities

The concept of rural energy is evolving beyond simple energy provision to include the social and organizational aspects of energy production and consumption. The European Commission, for example, defines and promotes Rural Energy Communities as a key tool for innovation. These communities are part of a larger hierarchy of energy communities from local to citizen-led and are recognized for their potential to enable Positive Energy Districts (PEDs) [12, 13].

The concentric circle diagram in the **Figure 1** illustrates the hierarchical relationship between different types of energy communities. At the core are Renewable Energy Communities, which are a subset of Rural Energy Communities. These, in turn, are nested within the broader categories of Local Energy Communities and Citizen Energy Communities.

This is directly linked to the idea of Smart Rural Communities, which are rural areas that leverage their inherent strengths and develop new opportunities. They achieve this by enhancing traditional networks and services through digital and telecommunication technologies, knowledge sharing, and innovation. The goal is to benefit both inhabitants and businesses. Within this context, Smart Energy is a core component, defined as the application of smart technology to optimize energy production, distribution, and consumption, thereby creating more sustainable and reliable energy systems [14–16].

2.3 Integrated energy systems (IES) and the energy internet (EI)

A crucial term in the energy sector is Integrated Energy Systems (IES). This concept involves linking various energy sectors such as electricity, heating, cooling, and transport to maximize resource utilization, increase efficiency, and achieve environmental goals. This is a more comprehensive approach than managing each energy carrier in isolation.

Building upon the IES framework, the Energy Internet (EI) is a forward-looking concept that integrates the smart grid with advanced communication technologies.



Figure 1.
Concentric circle diagram local energy.

While smart grids have improved energy management, they can be limited by large demand numbers and a lack of flexibility [17–19]. The Energy Internet addresses these constraints by enhancing interoperability and data management across diverse energy environments. This platform is a vital tool for rural revitalization, as it can address functional requirements in planning, decision-making, agricultural production, and market prosperity [20]. The underlying principle is the use of Smart Technology a system's ability to automatically adapt and modify its behavior by sensing and analyzing data. This is often achieved through the implementation of technologies like the Internet of Things (IoT), Big Data, and Artificial Intelligence (AI) [21, 22].

In summary, the transition to sustainable rural energy systems is a synergistic process. It requires re-evaluating rural areas as hubs of opportunity, fostering organized Rural Energy Communities within a Smart Rural framework, and deploying Integrated Energy Systems that are digitally managed by an Energy Internet platform.

3. Global context and regional challenges

The implementation of rural energy systems is deeply influenced by regional socioeconomic conditions, resource availability, and policy frameworks. While the overarching goal of achieving Sustainable Development Goal (SDG) 7 “Affordable and Clean Energy”—is universal, the pathways to its realization vary significantly across regions due to distinct challenges and opportunities [3]. This section examines the context-specific solutions and challenges in Sub-Saharan Africa, South Asia, and Latin America, drawing on empirical evidence and case studies from the literature.

3.1 Sub-Saharan Africa: Financial and infrastructural barriers

Sub-Saharan Africa faces significant hurdles in rural energy development, primarily due to financial constraints and inadequate infrastructure. Off-grid solutions, such as solar home systems and mini-grids, are often hindered by high capital costs, limited maintenance capacity, and insufficient financing mechanisms [23]. For instance, in Nigeria, hybrid renewable energy systems (HRES) combining solar PV, wind, and battery storage have demonstrated technical feasibility but require substantial upfront investment, with levelized costs of electricity (LCOE) ranging from 0.48 to 1.17 USD/kWh [24].

Despite these challenges, decentralized energy systems offer a viable alternative to grid extension in remote areas. In rural Ghana, the SoAMIRural solar PV mini-grid integrated with advanced metering achieved 95% accuracy in energy management, showcasing the potential of smart technologies to enhance sustainability [23]. However, scaling such solutions demands stronger policy support, international funding, and community capacity building to ensure long-term viability.

3.2 South Asia: Balancing energy access and decarbonization

South Asia grapples with the dual challenge of expanding energy access while transitioning away from carbon-intensive sources. Decentralized renewable energy (DRE) systems, particularly community-owned projects, are gaining traction as a

means to address energy poverty and reduce reliance on fossil fuels [25]. For example, China's rural energy internet platforms integrate solar PV and smart agricultural loads to optimize energy use and reduce emissions [22].

However, the region's energy transition is complicated by policy fragmentation and uneven infrastructure development. In India, for instance, rural electrification programs often prioritize grid extension over decentralized renewables, despite evidence that off-grid systems can be more cost-effective in remote areas [3]. Addressing these issues requires coherent policy frameworks that align renewable energy adoption with broader rural development goals, such as poverty alleviation and agricultural modernization [26].

3.3 Latin America: Hybrid systems and socioeconomic factors

Latin America's diverse landscapes from mountainous regions to dense forests—necessitate hybrid energy systems tailored to local conditions. However, the success of these systems is heavily influenced by socioeconomic factors, including income inequality and community engagement [27]. In Colombia, the Smart Rural Communities (SRC) project combines solar and wind energy with precision farming technologies, demonstrating how integrated approaches can enhance both energy access and agricultural productivity.

Despite these innovations, barriers persist, such as limited policy coordination and financial exclusion of marginalized communities. For example, in rural Mozambique, participatory methods like visual ethnography and Living Labs have been employed to design context-specific energy solutions, yet scalability remains a challenge due to funding gaps [27]. Strengthening public-private partnerships and local governance structures is critical to overcoming these obstacles.

The regional disparities in rural energy implementation underscore the need for tailored solutions that account for local resources, infrastructure, and socioeconomic dynamics. Sub-Saharan Africa requires targeted financial mechanisms to scale off-grid systems, South Asia must balance decarbonization with energy access through decentralized renewables, and Latin America needs hybrid models that integrate community participation. Across all regions, policy coherence, technological innovation, and international cooperation are essential to mainstreaming SDG 7 in rural energy frameworks [3].

4. Achieving sustainable development goal 7 through rural energy systems

The seventh Sustainable Development Goal (SDG 7), as outlined in the United Nations' 2030 Agenda, aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Despite global efforts, several key challenges hinder its realization. According to [3, 28, 29], there are five major obstacles to achieving SDG 7. Rural energy systems offer effective pathways to address each of these challenges:

4.1 Reducing fossil fuel dependence

4.1.1 Challenge

Global reliance on fossil fuels continues to pose a barrier to clean energy transitions.

4.1.2 Rural energy solutions

- Rural areas are ideal for deploying renewable energy sources like solar, wind, biomass, and small-scale hydropower.
- They provide space for piloting carbon capture and storage (CCS) technologies.
- Green hydrogen production can be developed using rural renewable resources.
- Rural settings allow for better integration between energy and other sectors (e.g., agriculture and energy).

4.2 Diversifying the renewable energy mix

4.2.1 Challenge

Lack of diversity in renewable energy portfolios and unequal distribution of resources.

4.2.2 Rural energy solutions

- Rural communities can integrate multiple renewable sources, such as solar-wind or biogas-solar hybrids.
- They serve as testing grounds for decentralized and hybrid systems.
- International cooperation and financial support from the Global North can facilitate the adoption of diverse technologies in rural areas.
- Implementation of global energy frameworks at local levels encourages sustainability.

4.3 Decentralizing energy production and use

4.3.1 Challenge

Centralized energy systems often fail to reach remote and underserved communities.

4.3.2 Rural energy solutions

- Microgrids and smart grids can be established to enable local control and energy independence.
- Rural energy systems support community-managed energy solutions.
- Technological innovations like AI-based Energy Management Systems (EMS) can be applied effectively in small-scale rural settings.
- Peer-to-peer energy trading models are more feasible in localized contexts.

4.4 Enhancing energy and storage efficiency

4.4.1 Challenge

Inefficiencies in energy use and high costs of energy storage.

4.4.2 Rural energy solutions

- Integration of Internet of Things (IoT) technologies allows for real-time monitoring and energy optimization.
- Rural zones offer an excellent environment for experimenting with innovative storage solutions (thermal, chemical, etc.).
- Use of smart metering and load management systems improves both efficiency and reliability.

4.5 Reducing the energy costs of chemical processes

4.5.1 Challenge

Energy-intensive chemical industries often depend on non-renewable sources.

4.5.2 Rural energy solutions

- Renewable-powered small-scale agro-processing and bio-refineries can be developed in rural areas.
- Focus on bio-based chemicals (e.g., bioethanol, bioplastics) using local agricultural inputs.
- Promote green chemistry education and training in rural technical institutions.

A comprehensive framework for implementing SDG 7 is presented in **Figure 2**, highlighting the tools and strategies necessary to achieve affordable and clean energy. The figure is divided into two main sections:

1. Global Initiatives:

- Represented in blue, these initiatives emphasize the need for international collaboration and policy reforms. They include a global climate agreement, improved fossil fuel conversion technologies, and financial assistance from developed nations. These overarching strategies provide the foundation for sustainable energy development globally, with implications for rural areas.

2. Technological and Strategic Solutions:

- Represented in green, these solutions focus on specific technologies and strategies that can be implemented locally. They are further categorized based on their relevance to rural areas:

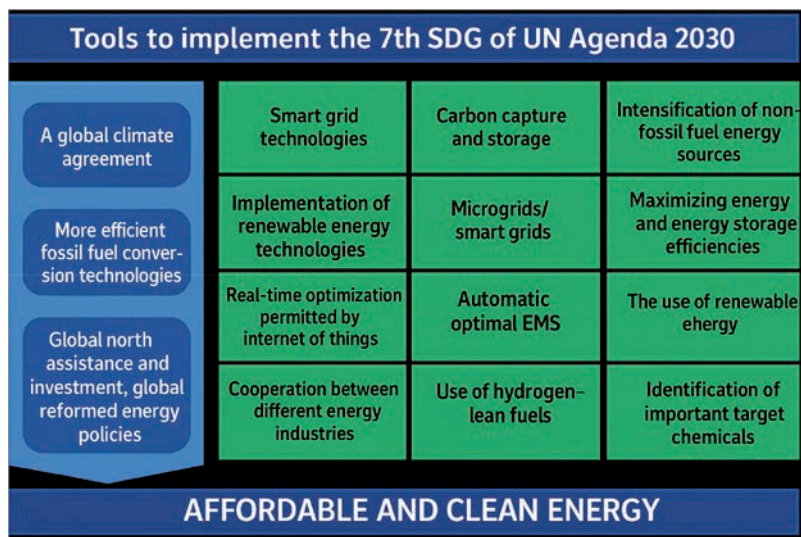


Figure 2.
Tools to implement the 7th SDG of UN Agenda 2030.

- **Highly Relevant to Rural Areas:** Solutions such as microgrids/smart grids, automatic optimal EMS, and the use of renewable energy are particularly suited for rural settings due to their decentralized nature and ability to leverage local resources.
- **Less Directly Applicable:** Solutions like carbon capture and storage, while important, may require significant infrastructure and investment, making them less feasible in many rural contexts without external support.

The figure explicitly notes that the applicability of these solutions depends on the context of rural areas, emphasizing the need for tailored approaches that consider local conditions, resources, and challenges.

5. Energy in rural areas

Rural areas possess distinctive geographical and ecological features that make them especially suitable for the development of integrated energy systems. These regions typically offer vast spatial resources, such as wasteland, rooftops, and other unoccupied land, that are ideal for the installation of solar and wind energy technologies [30, 31]. In addition, the widespread presence of biomass in rural environments provides a valuable and underutilized energy source [32]. Integrated energy systems leverage these diverse resources, enabling the complementary operation of renewable and conventional energy subsystems. This not only addresses the limitations of traditional single-source energy models but also enhances energy efficiency and reduces environmental pollution [33]. Therefore, promoting the development of integrated energy systems in rural regions is essential for sustainable energy transformation and rural economic resilience.

6. The goals of the rural area energy

Some may think that the goal of energy integration depending on rural areas is related to the energy aspect and the returns from it, and the truth is as [3] mentioned that integral energy plays a vital role in alleviating poverty and facilitating socio-economic growth; moreover, it is a prerequisite to achieving sustainable development of rural communities. According to [26], which noted that with the increase in per capita energy consumption, energy poverty alleviation and inequality reduction are simultaneously achieved in rural development. Also, provide a valuable reference for China's rural energy transformation. In addition, [25] noted that developing rural energy is a matter of improving social equity rather than just correcting energy market imperfections in China, which are influenced by urban/rural energy dualism. Therefore, the aims can be classified into main types, the first one is direct aims, and the second is indirect can be summarized in a **Table 1**.

Direct aims	Indirect aims	References
Energy poverty reduction, inequality reduction, increase in per capita energy consumption.	Promoting sustainable development; addressing urban/rural energy dualism; poverty alleviation; social equity; socio-economic growth.	[31]
Meeting basic energy needs (lighting, cooking, productive use); decentralized electrification.	Enhancing rural livelihoods, reducing reliance on traditional fuels, and fostering local employment and entrepreneurship.	[34]
Access to clean and reliable energy, reducing GHG emissions	Improved quality of life (education, safety, health); non-agricultural activities; environmental sustainability	[35]
Energy poverty reduction: correcting energy market imperfections.	Socio-economic development, inclusive growth, and sustainable rural transformation	[3]
Increasing per capita energy consumption.	Alleviating energy poverty, reducing regional disparities, and supporting national energy transition strategies.	[26]
Improving energy infrastructure and accessibility.	Enhancing social equity, bridging urban-rural gaps, and integrating rural development.	[25]
Providing affordable and reliable electricity, heating, and cooling.	Supporting agriculture, promoting climate resilience, and enhancing local economies.	[36]
Cost-effective renewable energy integration.	Reducing carbon footprint, climate targets alignment, and green rural development.	[37]
Efficient use of low-temperature heat for thermal services.	Energy efficiency, fossil fuel reduction, and system sustainability.	[38]
Diversification of rural energy sources and patterns.	Promoting bio-economy, agri-tourism, and smart village support.	[2]

Key Notes:

- *Direct Aims:* These are immediate, measurable outcomes such as increased access to energy, reduced costs, improved reliability, and enhanced efficiency.
- *Indirect Aims:* These reflect broader developmental impacts like poverty alleviation, environmental sustainability, social equity, and long-term economic growth.

Table 1.
The goals of the rural area energy.

7. Classify the rural energy development

7.1 Centralized energy

The primary principle of this strategy is that power outlets are produced at central power plants, conveyed to the locations via high-voltage transmission lines, and transformed into traditional residential or commercial structures. Usually, the final consumer lives far from the main power plants. These transmission lines come with a hefty price tag, from maintenance to power outages, not to mention the land use and space needed to set up such a coordinated generation-distribution operation. In addition, this centralized generation paradigm appears to have numerous environmental impacts, ranging from regional issues to localized concerns about the area surrounding the large-scale power plant [3].

This system's main advantage is its ability to reach a large number of end users over a large area, regardless of how far away they are from the central energy dispatch facility. However, centralized generation schemes rely on a single power supply; they frequently experience power shortages and bottlenecks. This is one of their main shortcomings [39]. Therefore, centralized energy generation technologies cannot ensure that clean, egalitarian, and sustainable energy is available to everybody. "Benefiting the rich and bypassing the poor, centralized energy systems are underpowered, inefficient, and unfair."; [40]. So, the idea that a decentralized generation paradigm should replace the centralized one for energy generation seems highly plausible [41, 42].

7.2 Decentralized energy

With this model, the distribution issue is addressed because any local network or region would be self-sufficient. To ensure that every need is met, local communities, neighborhoods, and homes, as well as industrial agents, should work together and interchange energy within their bounds. When local renewable resource availability is taken into account, this is feasible. The global south perspective is crucial in this regard, and it should be noted that these nations have a wide range and abundance of potential renewable sources that might be incorporated into such decentralized generation networks [3].

The goal of this new strategy for energy distribution is to dispatch power more precisely, particularly by using small-scale conversion units to transmit power to fewer consumers more quickly. The movement of power, responsibility, and authority from higher-level centralized operators to lower-level ones is also referred to as decentralization [43]. Distributed generation offers enhanced energy availability that is more efficient, dependable, and democratic, which is its main advantage. Furthermore, decentralized schemes can support equity, inclusivity, information, transparency, and adaptation within energy systems, which can assist in alleviating climate-related difficulties because security and resilience issues are easier to handle due to the lower size of these schemes [44]. If the cost of producing energy is less than the price of energy in many nations, decentralized infrastructure may be beneficial. Furthermore, decentralization becomes a more appealing choice if the participants in the decentralized energy infrastructure have less influence and a high energy demand. Analyzing the level of decentralization that would optimize the energy policy and solve integration cost issues is crucial. Finally, it is important to analyze the effects of partially or totally decentralized beneficiaries [3]. This could seem to

be at odds with what Marful et al. [23] said. Marful et al. [23] considered Deploying decentralized solar-powered mini-grid systems to supply rural areas with energy is challenging due to the need to support the socio-economic conditions of rural people through automatic monitoring, precise consumption prediction, and sustainable operation. It is permissible [23] considering the absence of communication between dispersed solar-powered mini-grid setups, the primary flaw of decentralized energy systems, which is their small economic scope. Decentralization may be advantageous locally, but it may also have unfavorable macroeconomic effects. In the long run, societies that opt for decentralized energy infrastructure can end up using more energy than they pay for it [3].

7.3 Smart grid

This power grid model depicts hybrid networks, which are built on power plants that are larger than the requirements of the microgrid and that guarantee an economic return, and that preserve centralized energy security while decentralizing power generation and distribution. This according to [3] observed that this tackles the primary flaw of decentralized energy systems.

Multiple renewable carriers can be used for decentralized generation thanks to the idea of smart-grids. Microgrids were first described by [45] and discussed that in other works like as [46, 47], they noted that smart grid are standalone structures equipped with energy production, distribution, and storage systems that adapt to fluctuating demand loads. And this corresponds to what he mentioned [48] that Because renewable resources are erratic and intermittent, sophisticated control systems and power electronics must be integrated to guarantee power quality and system resilience to disruptions.

Demand-side management functions and storage units are two ways that the smart grid may even out variations in power. Through appropriate energy planning, supervisory tools, and enforcement regulations, it is now possible to construct a renewable, economical, and environmentally friendly energy system thanks to recent technological breakthroughs. However, when using standalone producing units, the intermittent nature of the present renewable energy carriers results in variations and variability in the energy outlet quality. The sporadic behavior of various renewable energy sources overlaps when they are connected to a microgrid as the main sources of generation [49].

A smart grid can function in two ways: in linked mode, it exchanges energy with neighboring areas, and in island mode, it supplies electricity to the neighborhood. These microgrids have sensors that detect the flows, inlets, and outputs of power. Building energy units as microgrids has the main goal of utilizing all available renewable generation and storing it for times when demand is lower. When demand exceeds renewable supply, this stored energy can be put to use [3].

8. Classify the rural energy grid

The availability of energy conversion technologies and local load demands has a major impact on the design and functioning of energy systems in rural areas. In order to improve living conditions and boost agricultural output, these systems frequently incorporate provisions for heating, cooling, electricity, and hydrogen supply. For example, hydrogen is essential to decarbonizing the transportation industry [50].

Energy systems are divided into two primary categories: off-grid and grid-connected setups. Each one has distinct developmental trajectories and performance characteristics [50]. On-grid and off-grid electrification choices, as well as a variety of contemporary cooking technologies, are examples of rural energy access techniques that can be broadly categorized according to their connection to the main grid and the technologies used [51]. Several variables, including deployment costs, local context, and sustainability assumptions, affect which of these solutions is best [51].

8.1 Off-grid energy systems

Off-grid energy systems are mostly used in isolated rural locations where traditional grid extension is either financially or geographically impracticable. They function independently from the main electrical grid. To guarantee a steady supply of power, these decentralized systems usually incorporate a wide range of renewable energy sources, frequently augmented by traditional generators (such as diesel) and strong battery storage [31, 35], **Figure 3** illustrate the Key Features, Advantages and Challenges for off-Grid Energy Systems [35].

8.2 On-grid energy systems

On-grid energy systems, sometimes referred to as grid-connected systems, directly connect the nation's electrical grid to local renewable energy sources. Through net metering or feed-in tariffs, this concept allows rural communities to export excess locally generated electricity back to the grid and receive power from the grid during periods of peak demand [31, 52], the mind map **Figure 4** illustrates the key features, advantages, and challenges of grid-connected microgrids [35]. As a key feature, bidirectional power flow enables energy trading and improves overall reliability. This leads to advantages like reduced battery storage requirements and lower costs. However, grid-connected microgrids face challenges such as the need for robust grid infrastructure, vulnerability to main grid outages, and the necessity of supportive regulatory frameworks.

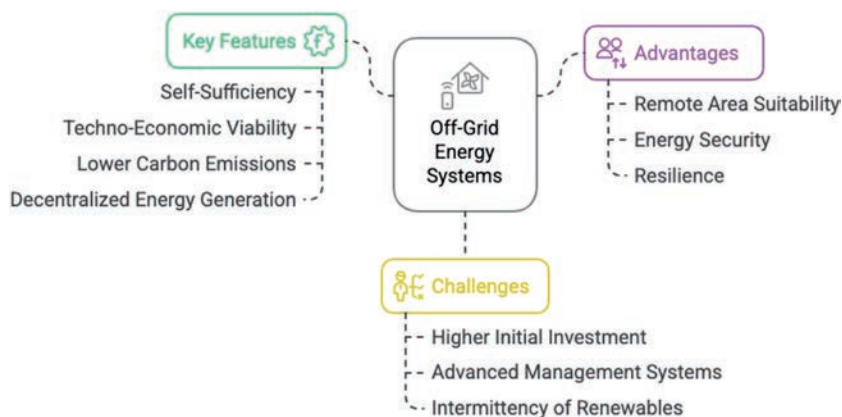


Figure 3.
Off-grid energy systems: key features, advantages, and challenges.

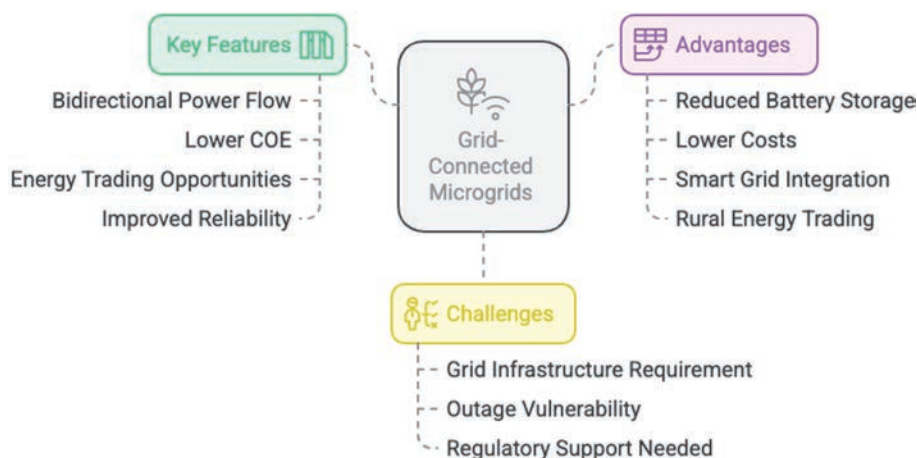


Figure 4.
 On-grid energy systems: key features, advantages, and challenges.

8.3 Grid-connected hybrid systems

Hybrid Renewable Energy Systems (HRES) form the backbone of modern off-grid solutions, combining multiple energy generation technologies such as solar photovoltaic (PV), wind turbines, and biogas, with advanced battery storage systems [53]. This integration effectively mitigates renewable sources' inherent intermittency, thereby enhancing system reliability and reducing reliance on fossil fuels. Battery storage is crucial for managing supply-demand imbalances and ensuring power continuity during periods of low renewable generation or peak load [31, 35]. While energy harvesting from renewable sources offers promising solutions for energy conservation, its opportunistic nature and potential for battery leakage can compromise network availability, necessitating robust power management schemes [52].

Off-grid microgrid design and implementation are complicated by technical, financial, and sociocultural issues, according to [53]. Hybrid designs offer long-term sustainability benefits but demand more upfront planning and expenditure than diesel-only systems. To find the most effective system sizing and dispatch procedures, optimization approaches such as Differential Evolution (DE), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA) are being utilized more and more.

In contrast to purely off-grid solutions, grid-connected hybrid systems offer distinct advantages by integrating local renewable energy generation with existing national grid infrastructure. [31] examined grid-connected hybrid systems, demonstrating a significant reduction in COE. For the same load profile (19 kW peak load and 178 kWh/day energy demand), the COE for a grid-connected hybrid system was reduced to US\$ 0.064/kWh. This substantial cost reduction is primarily due to the ability to purchase electricity from the main grid during periods of high demand and sell excess locally generated electricity back to the grid when local generation surpasses demand. For the specified load profile, the study observed a 9-grid purchase and 23 grid sales relative to the total energy demand or generation. This highlights that grid-connected hybrid systems can offer a lower cost of energy generation compared to stand-alone systems and possess the potential to transform a rural village into an “energy generation hub,” contributing to the broader energy network.

On-grid hybrid systems are becoming more and more popular in developing nations due to their capacity to integrate centralized grid support with distributed renewable generation, providing benefits for the economy and the environment [53]. This concept improves grid stability through bidirectional energy flows and facilitates energy trade between rural and urban areas [53]. In India, where a significant portion of the rural population remains underserved, grid-connected hybrid systems offer a scalable solution. By integrating PV, wind, diesel, and biomass with grid connectivity, these systems provide reliable, sustainable energy while enabling rural communities to contribute surplus electricity back to the grid. Sensitivity analyses show that increasing solar irradiance and wind speed can further reduce NPC and COE, enhancing system feasibility.

The optimization of these hybrid systems combining renewable energy generation with storage is a complex process. It requires balancing multiple variables, including minimizing system cost, maximizing reliability, and ensuring the system meets a specific load profile. Advanced optimization approaches, such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), as mentioned in the paper's abstract, are essential tools for solving these multi-objective problems.

8.4 Modern cooking energy solutions

Modern cooking energy solutions are an essential component of rural energy access, in addition to electricity. Among these are energy-efficient biomass cookstoves, which save a lot of time and money, especially for women, by consuming less wood fuel [51]. Although their adoption may be limited by considerations such as cost, fuel availability, and the requirement for behavioral changes, more sophisticated biomass cookstoves, Liquefied Petroleum Gas (LPG), and biogas digesters also help to promote cleaner cooking [51].

A fundamental framework for tackling the intricate energy problems of rural communities is provided by the deliberate division of rural energy grids into off-grid and on-grid systems. On-grid systems take advantage of economic efficiency and allow for bidirectional energy exchange with the national grid, while off-grid systems provide vital independence and sustainability for geographically remote areas. Context-specific factors such as population density, local resource availability, and the current policy environment all affect which of these models is best. To improve the efficiency and long-term viability of both grid types, smart energy technologies, sophisticated energy management systems (such as those that use PSO, GA, DE, and Lyapunov-based techniques), and reliable renewable energy optimization algorithms must be integrated.

9. The main source of energy in rural areas

9.1 Biomass

Future policy priorities should adopt a more comprehensive perspective on the synergy between biomass's role in the energy transition, climate adaptation and mitigation, improved agriculture, and better land use overall [54]. One of the most important mitigation strategies for reaching the Paris Agreement's 1.5°C GMT target is sustainable biomass. Notwithstanding its unfavorable reputation in the EU, there is compelling evidence that it has the ability to account for 20–30% of future energy

supply in both Europe and the rest of the world, lowering overall mitigation costs and achieving net CO₂ removal through the use of BECCS technologies [54].

Rajbongshi et al. [31] concluded that the “best option scenario for all cases is a biomass gasification system rather than a photovoltaic system” for the hamlet under study. This demonstrates the important role that biomass may play in rural integrated energy systems as a primary energy source. Sensitivity analysis also revealed that a biomass gasifier-battery system is the best setup when the price of biomass is low (less than US\$ 50/t), proving its economic feasibility.

González et al. [36] proposed a Hybrid Renewable Energy System (HRES) that includes a wood chips gasification - Internal Combustion Engine (ICE) Combined Heat and Power (CHP) system. This system is designed to provide both electricity and thermal energy (heating and sanitary hot water) to a rural township. A key aspect of their design is that the biomass subsystem operates at full load to maximize efficiency, especially during winter when there is a continuous thermal demand. The efficiency of the biomass system (gasifier-ICE) is around 75% due to the combined electricity and heat exploitation. This approach leverages indigenously available forest wood biomass, ensuring sustainability by not exceeding the self-growth rate of local tree species and minimizing transportation requirements. The life-cycle equivalent CO₂ emissions for forest wood biomass-based systems are stated as 60 gCO₂/kWh, acknowledging its carbon-neutral balance due to carbon capture during its lifetime.

Li et al. [35] specifically addresses the utilization of biomass in remote rural areas, noting its abundance (e.g., maize straw in their case study, with 3000 tons/year available from 180 ha of maize land). They highlight that biomass is relatively stable and more convenient for storage and transportation compared to solar and wind energy. They propose converting maize straw into biogas for a Fueled Diesel Generator (BDG). The capital cost of a 1 kW BDG is estimated at \$550, with a replacement cost of \$500 and an O&M cost of \$0.05/h. The BDG has a lifetime of 15,000 operating hours and a minimum load ratio of 30%. In their optimal system, the BDG accounts for 34.5% of the total electricity production, operating for 2868 hours/year and starting 782 times a year. This demonstrates the practical application and significant contribution of biomass to integral energy systems in rural settings.

9.2 Solar and wind energy

Because there is so much sunshine in rural sub-Saharan Africa, solar energy is seen as a viable way to generate electricity [42]. Accordingly, there has been a significant rise in the use of free and sustainable renewable energy sources, like solar photovoltaics and wind turbines, to supply electricity [48]. According to [55], there are several benefits to using renewable energy in rural areas, such as an abundance of open space, less wind and solar blockage, lower population density, and a decreased need for electricity.

A type of solar heating system employing phase-change materials (PCMs) for heat storage was presented by [56] for the heating load characteristics of northern rural areas. Moreover, a farmhouse serves as a demonstration of the heating system's useful technical uses. They realized the efficient use of solar energy by using it to power a heating system made up of solar thermal panels, a floor radiant heating terminal, and a phase-change heat storage device (PCHSD). Four possible operating modes of the heating system are defined, taking into account the solar power generation capacity, the heating load characteristics of farm buildings, and the local electricity pricing model.

According to [31], “in a few houses, solar home lighting systems are used for television and lighting” in Jhawani village. This provides a concrete illustration of how solar energy is being used in rural homes. To further promote the importance of solar energy, the study also commonly incorporates photovoltaic (PV) systems as part of their optimized hybrid energy system topologies.

Ramesh and Saini [34] further details on the modeling of solar PV arrays and wind turbines in their HRES. They collected daily average solar radiation data and monthly average wind speed data from NASA, with an annual average wind speed estimated at 3.8 m/s. Their HRES configurations often include both PV and wind components, demonstrating their combined potential. For example, in their optimized results, PV capacities range from 168 to 339 kW, and wind turbine numbers range from 2 to 23, depending on the case and dispatch strategy.

González et al. [36] utilized Up Solar UP265M PV modules (265 Wp nominal power) and SUT200 wind turbines (200 kW) in their HRES design for a rural township. Their multi-objective optimization aimed to find the optimal sizing of these components, considering both life-cycle cost and environmental impact. The life-cycle equivalent CO₂ emissions for PV systems were estimated at 439.9 kgCO₂/kWp (approximately 48 gCO₂/kWh), and for wind turbines at 30 gCO₂/kWh. Their base-case scenario, which balanced cost and environmental impact, resulted in an installation of 8421 square meters of PV panels and 1 SUT200 wind turbine. This study highlights the trade-offs: as the size of solar PV and wind installations increases, environmental impact decreases, but cost increases, as these sources are more environmentally friendly but also more expensive than the current grid mix.

González et al. [37] further reinforce the importance of PV and wind power in HRES, highlighting their role in climate change mitigation. They used monocrystalline PV modules (265 Wp, 1.46 m²) and small-scale SUT200 wind turbines (200 kW nominal power) in their grid-connected HRES optimization. They emphasize that PV and wind power are prioritized over biomass for environmental reasons. The life-cycle CO₂ emissions for PV systems are stated as 439.9 kgCO₂/kWp (around 48 gCO₂/kWh), and for wind turbines as 30 gCO₂/kWh.

Li et al. [35] provided a detailed resource assessment for solar and wind in their case study village. The annual average solar radiation was approximately 4.66 kWh/m²/day, with a clearness index of 0.580. They used a Generic 1 kW flat plate PV with a capital cost of \$1000 and a lifetime of 25 years, and a derating factor of 80%. For wind, the annual average wind speed was 6.02 m/s at an altitude of 1272 m and anemometer height of 50 m. They used a Generic 10 kW horizontal-axis wind turbine with a capital cost of \$11,000 per unit and a lifetime of 20 years. In their optimal system, PV panels accounted for 51.3% of the total electricity production (165,327 kWh/yr), and wind turbines accounted for 14.2% (45,823 kWh/yr). The study also performed a sensitivity analysis on solar radiation and wind speed, finding that increases in both resources decreased the COE and NPC of the hybrid system, emphasizing their positive impact on affordability and economic feasibility.

9.3 Storage systems

Particularly in rural regions, thermal energy storage technology may successfully support northern China's clean heating program [56]. In addition, [31] consistently included “Battery (Surrette 6CS25P)” as an energy storage component in their off-grid and grid-connected hybrid system designs. They state that “in this hybrid system, apart from renewable sources of energy, the battery is used for energy storage,

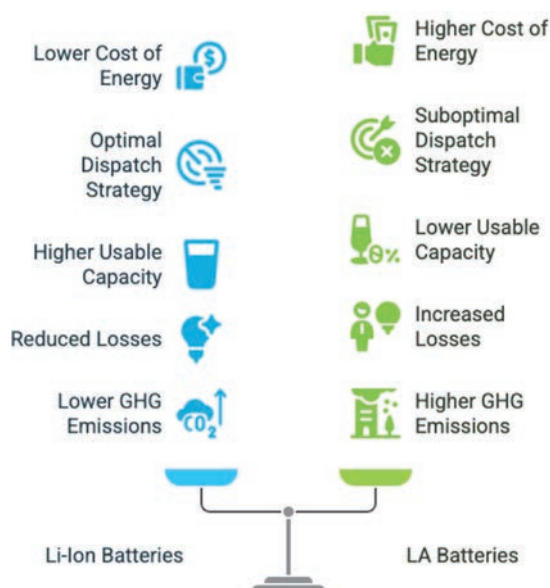


Figure 5.
Li-Ion batteries offer superior performance over LA batteries.

a converter for conversion purposes (DC-AC), and a diesel generator as a backup power.” This directly supports the importance and inclusion of storage systems in integral energy solutions for rural areas.

In their HRES, they compared lithium-ion (Li-Ion) and lead acid (LA) batteries in great depth regarding battery storage. Their conclusions are noteworthy as **Figure 5**.

The figure’s presentation emphasizes how crucial cutting-edge battery technology and efficient dispatch techniques are to improving the integrated energy systems’ environmental and economic sustainability in rural regions.

On the other hand, [35] included Generic 1 kWh lead-acid batteries in their optimal system design. They specify a nominal voltage of 12 V and a lifetime throughput of 800 kWh, with a round-trip efficiency of 80%. The capital and replacement cost for one battery unit is \$300. In their optimal PV/Wind/BDG/Battery system, 331 batteries were included. They also discuss the operational role of batteries, noting that they are used as a “supplement back-up facility” to maintain constant voltage during peak loads or capacity shortfalls, and are charged by excess energy from renewable sources or the BDG. Battery discharge occurs during evening peak loads and midnight to enhance cost-effectiveness and system stability. The cash flow analysis indicates that batteries are replaced twice during the 25-year project lifetime (in the 10th and 20th years).

10. Main factors impacting energy availability in rural areas

Numerous factors influence energy availability in rural areas, some of which are related to power generation and others to energy consumption. All of these factors need to be considered when considering rural areas as support areas for the centralization of the electrical grid, i.e., reliance on them in integrated grids. We will attempt to address the majority of these factors in the following by splitting them into two groups as follows:

10.1 Factors impacting energy generation

The rural energy transition represents a substantial move in the direction of a sustainable, economical, and clean energy system. The expansion of high-quality energy, the variety of service offerings, and user-friendliness are all part of this shift. Regional variations impact the shift, which focuses on boosting renewable energy and enhancing energy infrastructure and efficiency [4].

10.2 Factors impacting energy consumption

Energy consumption in rural areas is affected by a set of factors. This section will be divided into two groups, namely the group of engineering factors and non-engineering factors, as in **Figure 6** and **Table 2**.

10.2.1 Engineering factors

Factors such as annual average temperature, physical geographical characteristics, and tree density play a significant role in influencing energy consumption in rural areas. Rural houses have a lower energy efficiency compared to cities, with high total energy consumption, low efficiency, and poor indoor thermal environment. Technological advancements to increase energy efficiency are widely regarded as an effective way to solve climate change challenges. Compared with that in cities, the energy efficiency of rural households is trailing, with high total energy consumption, low efficiency, and a poor indoor thermal environment [58]. To decrease energy consumption, ultra-low-energy rural residential buildings are proposed, with heat transfer coefficients determined by construction cost, energy efficiency, and retrofit feasibility.

The empirical data demonstrate the magnitude of the direct rebound impact on residential energy consumption. The predicted energy savings in residential structures cannot be entirely accomplished in rural regions, and even a large “backfire” impact exists in rural China. More particularly, the magnitudes of the rebound effect for residential structures in urban regions are lower than in rural locations. The fundamental explanation for the rebound effect is that the energy demand for residential structures will increase when energy efficiency improves [59].

Deng et al. [60] proposed reducing rural energy consumption through ultra-low-energy rural dwellings. Their study used optimal design and simulations to determine building envelope heat transfer coefficients based on cost, energy efficiency, and

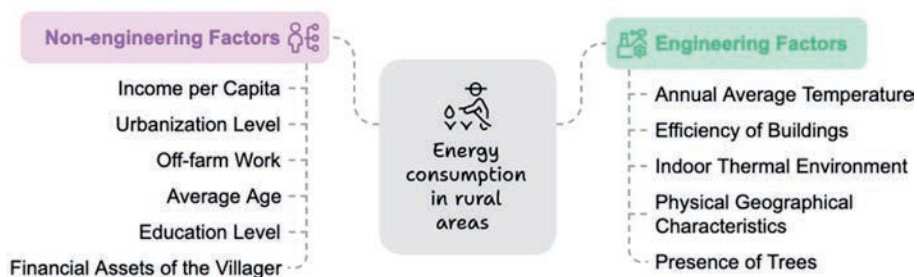


Figure 6.
Factors impacting energy consumption.

Factor category	Specific factor	Impact on energy consumption	References
Engineering factors	Agricultural mechanization	Positive	[57]
	Annual average temperature	Negative	[4]
	Building efficiency	Positive	[58–60]
	Indoor thermal environment quality	Positive	[58]
	Physical geographical characteristics	Positive	[26, 61, 62]
	Distance to county center	Negative	[26]
	Presence of trees	Negative	[63]
Non-engineering factors	Income per capita	Positive	[4, 57]
	Urbanization level	Positive	[4, 57]
	Off-farm work	Positive	[64]
	Average age & population aging	Positive	[26, 65]
	Education level	Positive	[26]
	Financial assets of villagers	Positive	[26]

Table 2.
A summary of factors impacting energy consumption.

retrofit feasibility. They recommended a cost-effective mix of high-performance exterior and interior walls, considering carbon emissions. A technical standard for such housing has been submitted by the China Academy of Building Research, supporting the development of ultra-low-energy rural homes in China and beyond.

The average yearly temperature in rural regions is one of the key factors influencing energy usage. According to [4], a 1°C increase in average temperature may result in a 22.3 kgCE physical energy and 2.8 kgCE effective energy loss. Numerous experiments have shown that trees can reduce the energy consumption of adjacent buildings, but little research has been carried out on how leaf area density (LAD) and the distance between walls and trees (DW-T) in different orientations affect the energy consumption of rural houses [63]. The physical geographical characteristics of rural areas, such as latitude, altitude, and distance from county centers, significantly influence energy consumption. Higher altitudes and latitudes increase heating demand due to lower temperatures, as seen in regions like the Qinghai-Tibet Plateau where energy use is notably higher in pastoral areas compared to agricultural ones. These factors are key determinants in rural energy consumption patterns [26, 61, 62].

10.2.2 Non-engineering factors

The non-engineering elements impacting energy consumption in rural regions can be characterized as income per capita, urbanization level, off-farm work, the average age, education level, and financial assets of the villager.

The two primary factors influencing energy consumption are the degree of urbanization and per capita income. The use of 6 kgCE of physical energy and 4 kgCE of effective energy can lead to a 1000 yuan increase in per capita income, respectively. 4.86 kgCE of physical energy and 1.83 kgCE of effective energy can expand with every 1% increase in the population's rate of urbanization [4]. Energy poverty is a significant obstacle to reducing poverty in rural China [64]. In recent times, off-farm

employment has started to become more crucial to raising rural households' standard of living with considering the cost and accessibility of energy use.

According to [26], the primary variables influencing the energy consumption of rural regions are the villagers' average age, educational attainment, and financial assets. However, [65] mentions that China's energy consumption and population aging highlight the significant impact of renewable energy on agricultural productivity. The findings suggest that both an aging population and renewable energy use contribute to a low-carbon country, with a continuous contribution of 2.23 and 0.56%, respectively.

Beyond the technical considerations of system design, understanding the factors that influence energy consumption is vital for accurate planning and deployment. **Table 2** synthesizes various engineering and non-engineering factors and their documented impact on energy consumption in rural settings.

As shown in **Table 2**, these factors are categorized to highlight their diverse influences. "Engineering Factors" relate to physical and environmental attributes, such as agricultural mechanization and building efficiency, which generally have a positive impact on consumption. Conversely, factors like higher annual average temperatures and the presence of trees can have a negative impact by reducing heating and cooling demands, respectively. "Non-Engineering Factors" encompass socioeconomic and demographic characteristics like income and urbanization, which are often positively correlated with increased energy use. This comprehensive view of influencing factors is crucial for developing accurate energy demand forecasts and designing truly context-specific rural energy solutions.

11. Strategies for decreasing rural dependency on the national grid

The challenge of rural communities' dependency on the national grid can be resolved in a variety of ways, starting with energy saving and progressing to energy autonomy without reaching the level of energy support provided by the national grid.

11.1 Saving energy

Planting trees around rural houses significantly enhances energy savings during summer, particularly as leaf area density increases. According to [63], *Osmanthus fragrans*, *Koelreuteria paniculata*, and pomegranate trees are among the most effective species. The energy-saving rate improves as the distance between the building wall and the tree crown increases. The most efficient orientation for planting is on the west side of houses, achieving energy savings ranging from 2.11 to 14.98%. These findings highlight the vital role of strategic tree planting in promoting energy efficiency in rural areas.

11.2 Autonomy energy

Standalone microgrids constructed of distributed generating systems based on renewable sources are increasingly the best way to meet the needs of dispersed small residential communities [48]. Afolabi and Farzaneh [24] conducted a technical and economic assessment of an off-grid hybrid renewable energy system (HRES) in the rural community of Olooji, Nigeria. They developed a size optimization model using metaheuristic particle swarm optimization to reduce electricity costs and

implemented a fuzzy-logic-controlled energy management system for dynamic power regulation and storage control. The study provides essential insights for decision-making and feasibility analysis in rural energy planning.

Similarly, Alzahrani [48] explored the optimal design and techno-economic performance of a standalone microgrid. Utilizing intelligence-based control strategies, the system achieved a low electricity cost while maintaining resilience against variations in load demand and weather conditions. Khon et al. [66] introduced a comprehensive planning tool for low-voltage microgrids tailored to developing countries. The tool addresses the growing adoption of DC-powered devices and distributed energy sources, enabling optimal electrification through hybrid AC/DC microgrids with minimal upfront investment. Marful et al. [23] evaluated a mini-grid system incorporating advanced metering infrastructure and a sustainable demand capacity of 24 kVA. The system demonstrated 95% accuracy in energy management, highlighting its potential to support energy conservation and long-term sustainability in rural communities.

12. Challenges of integration of energy

Integrating energy systems in developing regions, particularly in the Global South, presents numerous challenges. These challenges are not only technical but also social, economic, and political. Addressing them is essential for ensuring equitable access to energy, promoting sustainability, and supporting national development goals [3]. **Figure 7** shown Below are some of the key challenges.

The transition to integrated energy systems (IES) is a complex process, facing challenges that are both technical and socioeconomic. As illustrated in the **Figure 7** “Challenges in Energy Integration,” these hurdles are multifaceted. Decentralization requires a fundamental shift from a centralized power model to distributed energy

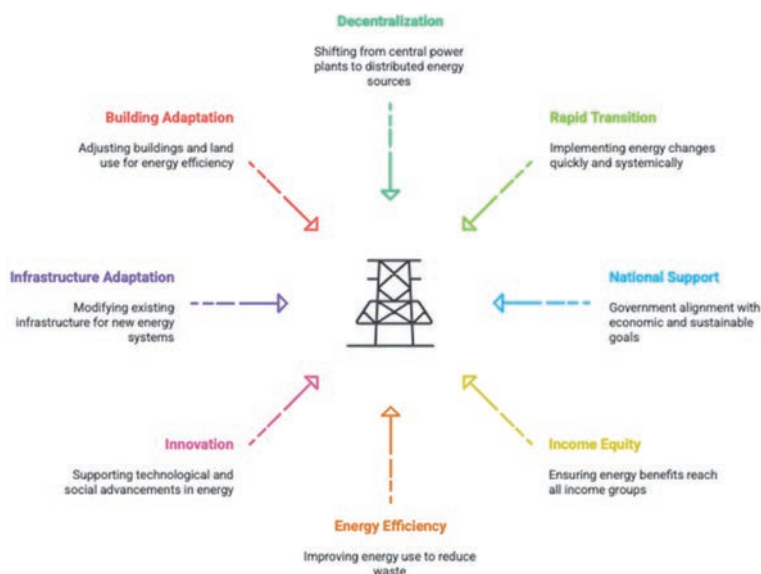


Figure 7.
 Challenges of the integration of energy.

sources, demanding significant changes to existing infrastructure. This infrastructure adaptation is crucial for enabling bidirectional power flow and smart grid functionalities. The process is further complicated by the need for a rapid transition to meet climate goals, while simultaneously ensuring energy equity for all income groups. Ultimately, overcoming these challenges requires sustained national support and a continuous focus on innovation in both technological and social spheres to improve energy efficiency and create resilient systems.

13. Conclusion

This comprehensive review demonstrates that rural energy systems are a cornerstone for achieving SDG 7 and fostering broader sustainable development. The integration of decentralized and smart energy technologies—ranging from solar PV and biomass gasification to intelligent microgrids and modern storage solutions—offers significant opportunities to improve energy access, reduce environmental impact, and stimulate rural socio-economic growth. However, realizing this potential requires a multi-faceted strategy involving technical innovation, robust policy frameworks, and substantial financial investments. Key solutions include adopting hybrid energy systems, promoting smart grid infrastructure, international cooperation, and targeted support for rural innovation. Addressing challenges such as infrastructure limitations, financial constraints, and socio-cultural barriers is essential. Ultimately, the transformation of rural energy landscapes is both a necessity and an opportunity to advance equity, resilience, and sustainability on a global scale.

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Engineering Synthetic Zeolites for Enhanced CO₂ Capture: Strategies, Synthesis, and Applications

Syed Abdul Moiz Hashmi, Waqar Hussain, Hina Moiz and Muhammad Hammad Rasool

Abstract

Synthetic zeolites offer a promising solution for CO₂ capture due to their tunable pore structures, high stability, and selective adsorption properties. This chapter explores advanced synthesis techniques, including hydrothermal, solvothermal, and microwave-assisted methods, alongside post-synthetic modifications such as ion exchange and amine functionalization to enhance CO₂ uptake and selectivity. Computational modeling using Density Functional Theory (DFT) and Grand Canonical Monte Carlo (GCMC) simulations provides molecular-level insights, guiding the optimization of adsorption performance. While zeolites demonstrate strong CO₂ affinity, challenges like moisture sensitivity, regeneration energy, and scalability remain barriers to industrial adoption. Case studies highlight their potential in flue gas treatment and direct air capture, emphasizing the need for improved material stability and integration with hybrid systems. Advancing zeolite design through interdisciplinary research and sustainable process development is key to unlocking their full potential in large-scale carbon capture applications.

Keywords: zeolite-based CO₂ capture, adsorption mechanisms, post-synthetic modifications, hierarchical zeolites, computational modeling, Density Functional Theory, Grand Canonical Monte Carlo Simulations

1. Introduction

Global warming represents one of the most pressing environmental challenges of our time. It is primarily driven by the unprecedented anthropogenic release of greenhouse gases, most notably carbon dioxide (CO₂) [1]. This unprecedented release of CO₂ in the atmosphere disrupts the radiative balance of our planet, which leads to a sustained increase in global temperatures [2]. This warming initiates a wide range of adverse impacts, including accelerated melting of polar ice caps, unpredictable precipitation patterns, and an increase in the frequency and intensity of extreme weather events. Such changes damage ecological stability and have long-lasting implications for biodiversity, agricultural productivity, and water resource management, while also posing significant risks to human health [3]. Addressing

global warming is therefore essential for sustaining life on Earth, and it requires a comprehensive approach that combines technological innovation, rigorous policy frameworks, and international collaboration. Effective CO₂ mitigation strategies must focus on reducing emissions through the widespread adoption of renewable energy, enhancing energy efficiency, and developing carbon capture and storage technologies. In addition, adaptive measures are needed to manage the residual effects of climate change [4, 5].

A wide range of carbon capture, utilization, and storage (CCUS) technologies have been developed to mitigate the increasing emissions of carbon dioxide (CO₂) from industrial sources and the atmosphere [6]. These approaches cover a variety of methods, from post-, pre-, and oxy-combustion capture processes used in power plants and heavy industries to innovative direct air capture (DAC) systems that capture CO₂ directly from ambient air [7]. While absorption processes employing aqueous amine solutions remain the industrial standard for CO₂ removal, alternative methods such as membrane separations, cryogenic distillation, and chemical looping have also been explored on a smaller scale. Despite the promise of these techniques, each faces its own challenges in terms of energy efficiency, cost, and operational complexity. Adsorption-based processes have presented a particularly attractive option due to their lower regeneration energy requirements and the possibility of cyclic operation via pressure or temperature swings [8, 9].

Adsorption utilizes the physical or chemical affinity between CO₂ molecules and porous solid materials. Traditional adsorbents such as activated carbons, metal-organic frameworks (MOFs), zeolites, and silica-based materials have been widely studied [8]. Activated carbons, with their high surface areas and porous structures, offer rapid kinetics but often suffer from limited selectivity for CO₂ over other gases. Metal-organic frameworks (MOFs) provide excellent tunability and exceptionally high surface areas, but their stability under industrial conditions and high production costs remain significant drawbacks [10, 11]. Silica-based adsorbents, although cost-effective, typically lack the requisite adsorption capacity and selectivity. Among these adsorbents, synthetic zeolites have shown great potential as an excellent adsorbent; their crystalline, aluminosilicate frameworks allow for precise tuning of pore sizes and surface chemistry, enabling high selectivity and capacity for CO₂ capture even under challenging conditions [12, 13].

The flexibility in the design of synthetic zeolites allows for the optimization of their performance under various conditions, thus enhancing their applicability in real-world scenarios [14]. The key advantage of synthetic zeolites lies in their ability to selectively capture CO₂ molecules while excluding other gases [15]. Additionally, the surface chemistries of these materials can be modified to increase their affinity for CO₂, thereby improving their adsorption capacity and efficiency. This ability to tailor surface and pore properties makes synthetic zeolites a versatile and powerful tool in the development of effective carbon capture technologies [16]. The growing environmental crisis has urged significant research and development efforts aimed at improving the synthesis, modification, and application of zeolites in CO₂ capture systems.

This chapter presents a thorough examination of the various synthesis methods for zeolites, analyzing how different techniques influence their crystalline structure, porosity, and overall performance in CO₂ adsorption. The discussion will include both traditional and innovative synthesis approaches, highlighting how process parameters such as temperature, pressure, and precursor composition dictate the formation of distinct zeolitic frameworks. Furthermore, post-synthetic modifications such as ion

exchange, amine functionalization, and hierarchical structuring that significantly enhance the CO₂ adsorption capacity and selectivity of these materials will also be assessed.

Furthermore, the chapter also presents an overview of the fundamental adsorption mechanisms with particular emphasis on the role of surface functional groups and pore connectivity in facilitating the interaction with CO₂ molecules. In addition, a review of the real-world applications of modified zeolites through case studies has also been presented, which details their effectiveness in industrial flue gas treatment and direct air capture systems. The chapter concludes with a discussion on the emerging trends and future directions in the field, highlighting the importance of interdisciplinary collaboration to address current challenges and drive forward the development of zeolite-based carbon capture technologies.

2. Synthesis methods for zeolites

Zeolites are crystalline aluminosilicate materials that are known for their uniform, microporous structures and exceptional thermal and chemical stability. The ability to tailor their pore size, composition, and surface properties through controlled synthesis makes zeolites highly attractive for applications such as gas separation and carbon capture. This section introduces the various synthesis methods used to produce synthetic zeolites with a focus on carbon capture as the target application, highlighting the techniques that have become the foundation of zeolite chemistry. By understanding these methods, it is possible to understand how adjustments in synthesis parameters directly influence the structure and performance of the material in practical applications.

2.1 Overview of the traditional and innovative synthesis techniques for tailoring zeolites focused on carbon capture

2.1.1 Hydrothermal crystallization

Hydrothermal crystallization is a well-established method for synthesizing zeolites with tailored properties for CO₂ capture, as illustrated in **Figure 1**. This process involves preparing a precursor gel containing silica, alumina, water, and a

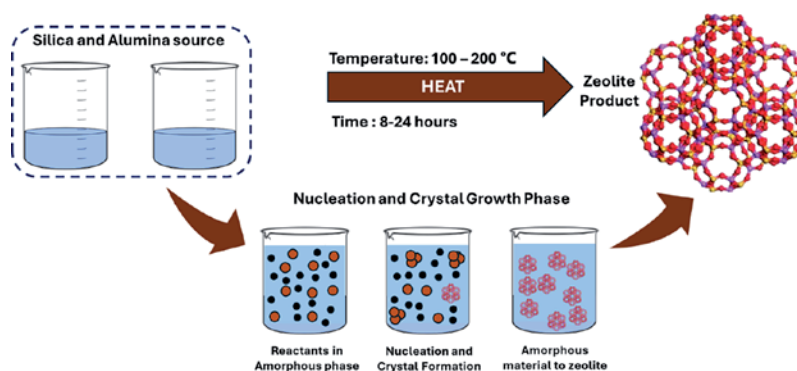


Figure 1.
A visual representation of the hydrothermal process for zeolite synthesis.

structure-directing agent (SDA), which is then sealed in an autoclave and heated at temperatures typically ranging from 100 to 200°C under controlled pressure conditions. During this treatment, the amorphous gel undergoes nucleation and crystal growth, forming a well-defined microporous structure [17].

The hydrothermal conditions play a critical role in determining key adsorption properties. The Si/Al ratio, pore dimensions, and framework topology can be finely tuned to enhance CO₂ affinity and adsorption selectivity [18]. A higher Si/Al ratio, for example, reduces hydrophilicity and improves CO₂ adsorption in humid environments, while pore architecture influences CO₂ diffusion and binding strength [19]. Moreover, the careful selection of SDAs enables the formation of specific zeolite frameworks that optimize CO₂ capture efficiency. By leveraging these parameters, hydrothermal synthesis provides a scalable route for designing zeolites with enhanced CO₂ adsorption performance, making them promising candidates for direct air capture and post-combustion CO₂ removal.

2.1.2 Solvothermal synthesis method

Solvothermal synthesis follows the principles of the hydrothermal crystallization method, but in the solvothermal method, water is replaced with organic solvents, which introduce unique control over reaction conditions [20]. As illustrated in **Figure 2**, this substitution significantly alters the precursor solubility, reaction kinetics, and framework development. Organic solvents enhance the dissolution of silica and alumina, creating a more homogeneous reaction medium, which in turn promotes uniform nucleation [21]. This controlled environment allows the formation of alternative zeolitic frameworks that may not be achievable under purely aqueous conditions.

The choice of solvent plays a vital role in tailoring key adsorption properties of the synthesized zeolite. Solvents with lower dielectric constants slow the condensation of silica and alumina species, resulting in larger crystals with fewer structural defects, while those with higher boiling points sustain high reaction temperatures, accelerating crystal growth and enhancing crystallinity [21]. These factors combined influence the pore structure, which is fundamental for CO₂ adsorption efficiency.

Additionally, the enhanced solubility of precursors under solvothermal conditions facilitates the development of unique structural features, including varied channel dimensions and novel topologies that can improve CO₂ diffusion and adsorption selectivity. The ability to control crystal size and morphology with high precision makes solvothermal synthesis a valuable approach for designing zeolites optimized for carbon capture applications.



Figure 2.
A visual representation of the solvothermal method for zeolite synthesis.

2.1.3 Dry-gel conversion method

The dry-gel conversion method offers an alternative approach to zeolite synthesis by utilizing a preformed dry gel instead of a liquid-phase precursor. As illustrated in **Figure 3**, this method involves preparing a homogeneous precursor mixture, removing most of the solvent, and then exposing the dried gel to a controlled water vapor atmosphere to induce crystallization [22]. Unlike hydrothermal synthesis and solvothermal synthesis, where the precursor is immersed in a liquid medium, dry-gel conversion relies on water vapor diffusion to trigger the reorganization of silica and alumina species, leading to nucleation and crystal growth under relatively mild conditions [23].

This vapor-phase interaction results in several advantages for CO₂ adsorption applications. The absence of a bulk liquid phase minimizes dissolution-precipitation phenomena, which often cause structural inconsistencies in conventional hydrothermal synthesis. On the other hand, dry-gel conversion produces zeolites with a more uniform pore architecture, ensuring consistent adsorption performance [24, 25]. Additionally, the dry-gel procedure is less demanding; it operates at lower temperatures and shorter reaction times, reducing energy consumption while maintaining well-defined microporosity.

The controlled formation of a stable and homogenous pore network is specifically beneficial for CO₂ capture, where adsorption efficiency is closely linked to pore size distribution and framework stability [26]. By enabling precise structural control with improved energy efficiency, the dry-gel conversion method presents a scalable and cost-effective route for developing high-performance zeolites tailored for carbon capture applications.



Figure 3.
A visual representation of the dry-gel method for zeolite synthesis.

2.1.4 Ionothermal synthesis method

Ionothermal synthesis is an innovative approach to zeolite fabrication in which ionic liquids are utilized as both the solvent and the SDA. As illustrated in **Figure 4**, ionic liquid salts that remain in a liquid state at or near room temperature offer unique advantages due to their low volatility, high thermal stability, and tunable solvent properties. Unlike conventional aqueous or organic solvents, they are able to create a highly controlled reaction environment under relatively mild conditions, enabling the formation of zeolitic frameworks with definite structural characteristics [27].

The use of ionic liquids in zeolite synthesis provides several key benefits for CO₂ capture applications. Their low vapor pressure minimizes solvent evaporation and

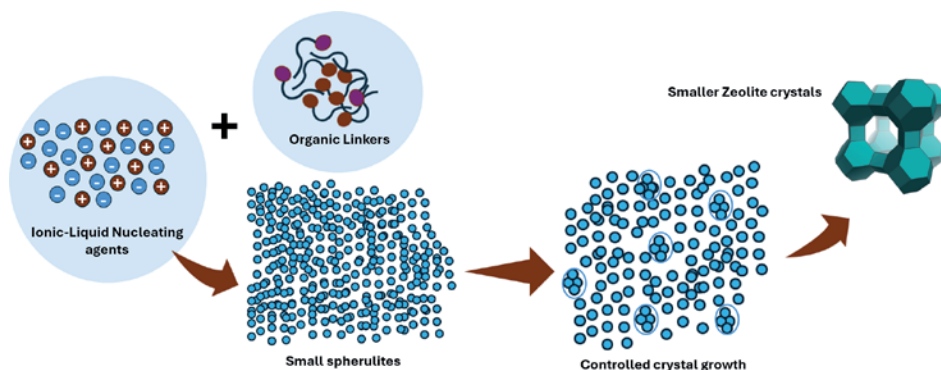


Figure 4.
A schematic representation of the ionothermal method for zeolite synthesis.

pressure build-up, allowing for precise reaction control [28]. Additionally, their high ionic strength enhances the solubility of inorganic precursors like silica and alumina, resulting in a more homogeneous reaction medium. This promotes uniform nucleation and crystal growth, which in turn facilitates the development of zeolite frameworks that may be challenging to achieve through traditional methods [29].

Apart from enhancing precursor solubility, ionic liquids actively participate in the crystallization pathway by coordinating with framework-forming species. This interaction directs the formation of novel topologies, leading to zeolites with unique pore architectures that improve CO₂ diffusion and adsorption selectivity [30]. Moreover, the enhanced thermal and chemical stability of these frameworks makes them particularly suitable for demanding carbon capture applications, including direct air capture and post-combustion carbon capture. Much like the dry-gel synthesis method, the ionothermal method also operates at lower temperatures, reducing energy consumption and preventing the degradation of sensitive framework components. These advantages further increase its viability as a sustainable synthesis approach.

2.1.5 Microwave-assisted synthesis

Another highly efficient technique is the microwave-assisted synthesis. In this technique, microwave irradiation is utilized to heat the reaction mixture rapidly and uniformly, hence offering several advantages over conventional heating methods [31]. As illustrated in **Figure 5**, this process involves the direct absorption of microwave energy by polar molecules present in the precursor mixture, leading to an almost instantaneous and homogeneous temperature rise across the reaction medium. This rapid and uniform heating accelerates nucleation and crystal growth, resulting in smaller, more uniform zeolite crystals with enhanced crystallinity [32].

A key advantage of microwave-assisted synthesis for CO₂ capture applications is the precise control it offers over reaction parameters, including microwave power and irradiation duration. These adjustments allow for the fine-tuning of pore structure and surface characteristics, directly impacting CO₂ adsorption capacity and selectivity [33]. The improved crystallization kinetics provided by microwave-assisted synthesis play a crucial role in optimizing particle size, morphology, and reproducibility, making it a promising approach for large-scale production. By reducing reaction

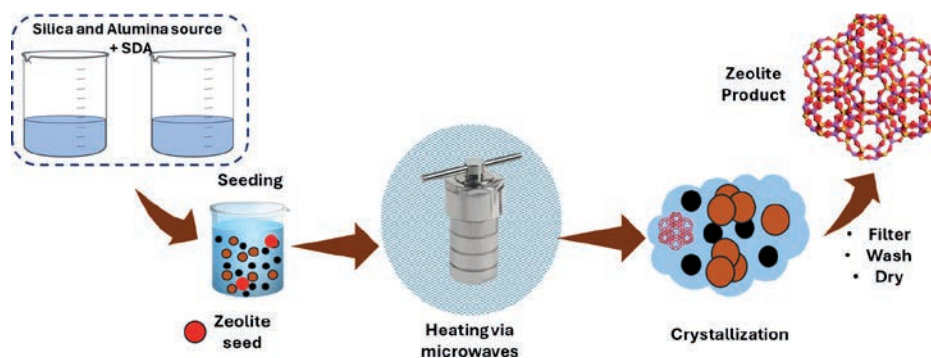


Figure 5.
 A schematic representation of the microwave-assisted method for zeolite synthesis.

times and overall energy consumption, this method significantly enhances energy efficiency, an important factor for sustainable zeolite synthesis [31].

The ability to tailor these properties ensures the development of high-performance zeolites with enhanced adsorption kinetics, making this method an attractive alternative for next-generation carbon capture materials.

2.1.6 Mechanochemical synthesis method

The mechanochemical synthesis method utilizes mechanical force to drive the chemical reactions necessary for zeolite formation, offering a solvent-free or minimal-solvent alternative to traditional synthesis methods. As illustrated in **Figure 6**, this method involves subjecting precursor materials, typically silica, alumina, and structure-directing agents (SDA), to high-energy mechanical milling. Mechanical energy facilitates the breaking of chemical bonds and ensures thorough mixing of reactants, accelerating nucleation and crystal growth without dependence on bulk solvents [34].

By minimizing dissolution-reprecipitation processes, mechanochemical synthesis enhances control over crystal morphology and pore structure, yielding zeolites with smaller, more uniform crystals and a well-distributed microporous architecture

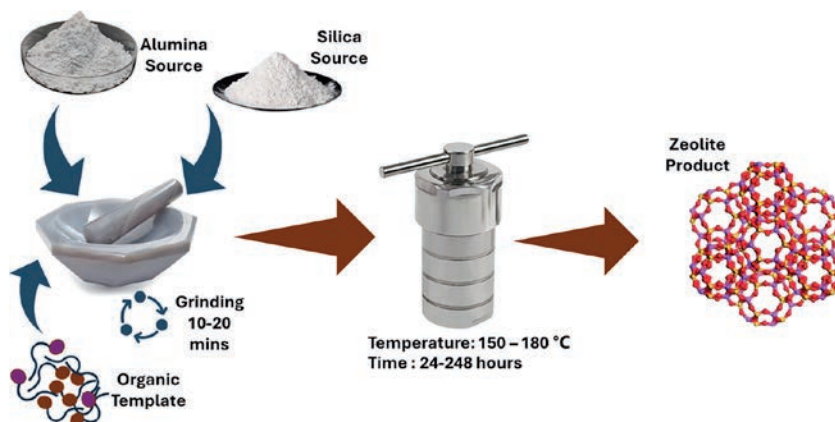


Figure 6.
 A schematic representation of the mechanochemical method for zeolite synthesis.

[35]. These characteristics are particularly beneficial for CO₂ adsorption, where pore uniformity directly influences gas diffusion and selectivity. Additionally, this method significantly reduces solvent waste and energy consumption, making it a more environmentally sustainable alternative.

Despite these advantages, mechanochemical synthesis also faces certain challenges. The intense mechanical forces involved can lead to structural defects or incomplete crystallization, which may impact zeolite adsorption performance. Additionally, maintaining consistent crystallinity and reproducibility during scale-up remains a key hurdle [36]. Optimizing milling parameters, including time, rotational speed, and the type and amount of auxiliary additives, is crucial for ensuring the development of zeolites with tailored adsorption properties. With persisted refinement, mechanochemical synthesis holds promise as a scalable, eco-friendly route for producing zeolites designed for carbon capture applications.

2.1.7 Comparative analysis of zeolite synthesis methods for carbon capture

Having explored the synthesis techniques, it is important to assess their effectiveness in tailoring zeolites for CO₂ adsorption. Each method presents unique advantages in pore structure control, adsorption selectivity, scalability, and energy efficiency. **Table 1** provides a comparative overview, summarizing key attributes relevant to carbon capture applications.

This comparison highlights that hydrothermal and solvothermal synthesis excel in framework control and structural precision, but their extended processing times and higher energy demands can limit scalability. In contrast, microwave-assisted and mechanochemical methods offer faster synthesis, reduced energy consumption, and improved sustainability, making them promising for large-scale applications. Ionothermal synthesis stands out for its ability to fine-tune framework properties and enhance CO₂ selectivity, while dry-gel conversion provides a balanced approach, combining efficiency with structural uniformity. Ultimately, the selection of a synthesis method depends on the specific performance requirements for CO₂ adsorption capacity, selectivity, and large-scale feasibility.

Synthesis technique	CO ₂ uptake	CO ₂ /N ₂ selectivity	Pore control	Surface functionalization	Scalability	Stability
Hydrothermal Crystallization	High	High	High	Medium	Medium	High
Solvothermal Synthesis Method	Medium	Medium	High	High	Low	Medium
Dry-Gel Conversion Method	Medium	High	Medium	Low	Medium	Medium
Ionothermal Synthesis Method	High	Very High	Medium	Medium	Medium	High
Microwave-Assisted Synthesis	High	High	Medium	Medium	High	High
Mechanochemical Synthesis Method	Low	Medium	Low	High	Very High	Medium

Table 1.
Comparative evaluation of zeolite synthesis techniques for CO₂ capture.

2.2 In-situ hierarchical synthesis methods

In-situ hierarchical synthesis methods have emerged as a complex strategy to enhance the performance of zeolites by incorporating multiple levels of porosity within a single material. Traditional zeolites, which are synthesized via conventional hydrothermal crystallization or other traditional synthesis methods, possess well-defined micropores typically ranging from 0.3 to 1.3 nm in diameter. While these micropores provide excellent molecular sieving capabilities and high surface areas, they often cause diffusion limitations that restrict the rapid transport of molecules. To overcome these limitations, researchers have developed in-situ hierarchical synthesis techniques that facilitate the simultaneous formation of micropores and additional mesopores (2–50 nm) or even macropores (>50 nm) [37]. A detailed graphical description of the in-situ hierarchical synthesis process is presented in **Figure 7 (a)**.

This approach is generally based on a dual templating strategy during the crystallization process. In these methods, a conventional SDA is used in combination with a secondary templating agent, which is often a surfactant, block copolymer, or other sacrificial organic template that induces the formation of larger pores alongside the intrinsic microporous framework [38]. During crystallization, the mesoporegen interacts with the precursor gel, guiding the assembly of the zeolitic structure while occupying spaces that, upon removal by calcination or chemical extraction, result in a network of mesopores [39]. The integration of these different pore sizes creates a material with a more open, interconnected structure, which facilitates enhanced mass transport and provides greater accessibility to adsorption sites. This enhancement in diffusion and mass transport is depicted graphically in **Figure 7 (b)**.

The outcome of the hierarchical synthesis process is highly dependent on a range of synthesis conditions, including temperature, pressure, pH, and precursor concentration. Reaction temperature affects not only the rate of nucleation and crystal growth but also the stability of the mesoporegen template; maintaining an optimal temperature is crucial to ensure that the template is neither decomposed prematurely by slow kinetics [40]. In the same manner, the pH of the synthesis medium influences the hydrolysis and condensation rates of silica and alumina species, in this way

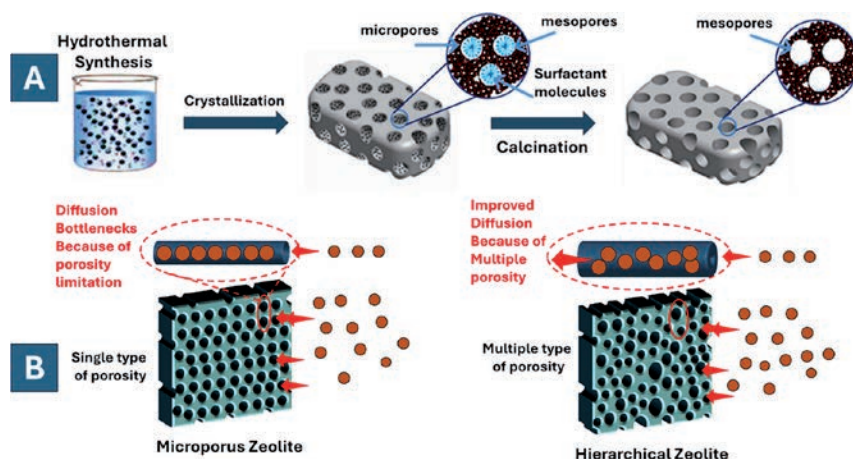


Figure 7.
 (a) A detailed schematic representation of the in-situ hierarchical synthesis process for zeolites and (b) the impact of inducing hierarchy in overcoming the diffusion limitation in zeolites.

dictating the formation of the zeolitic framework and its interaction with both the SDA and the mesopore. The concentration and ratio of the mesopore relative to the traditional SDA are critical as well; an optimal balance is required to achieve a uniform distribution of mesopores throughout the microporous matrix [41]. Excess mesopore can lead to overdevelopment of the mesoporous network, which may compromise the structural integrity of the zeolites. On the other hand, if the amount of mesopore is insufficient, it may fail to provide the desired enhancements in mass transport [42].

The introduction of hierarchical porosity through in-situ synthesis significantly impacts the functional performance of zeolites in applications such as CO₂ capture. The additional mesopores reduce diffusion limitations by providing supplementary channels for gas molecules, thereby increasing the rate at which CO₂ can access the active adsorption sites within the microporous regions. This multi-scale pore architecture also leads to more efficient heat transfer during the cyclic adsorption-desorption processes, which is critical for industrial-scale operations. Although the method offers substantial advantages in terms of improved accessibility and enhanced adsorption kinetics, careful optimization of synthesis parameters remains essential to ensure that the zeolitic framework retains its crystallinity and mechanical robustness while achieving the targeted hierarchical structure [43].

3. Post-synthesis modification techniques to enhance CO₂ affinity

Post-synthetic modifications provide a means of enhancement to tailoring zeolites for increased CO₂ adsorption performance. By altering the surface chemistry and active sites of the zeolitic framework, these modifications improve both the capacity and selectivity of the adsorbent [44, 45]. The preceding section will examine several key modification techniques, namely ion exchange, amine functionalization, mobile cation incorporation, and nitrogen activation, and discuss their influence on the adsorption properties of zeolites. An overview of these modification techniques is illustrated in **Figure 8**.

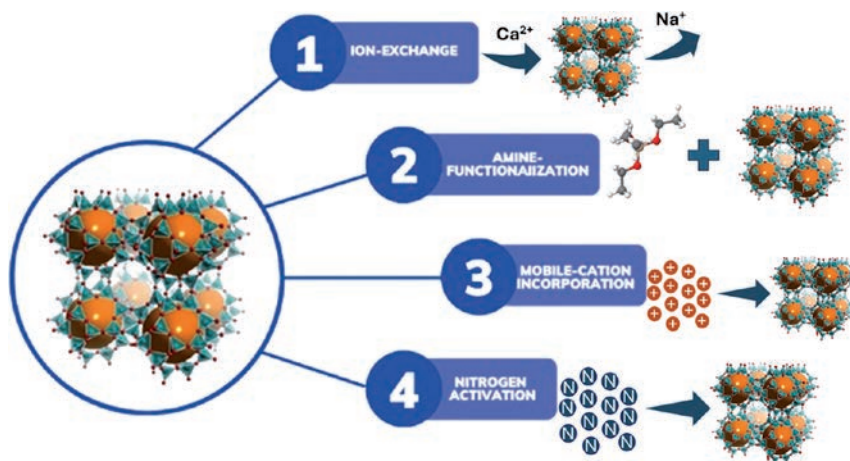


Figure 8.
Overview of post-synthesis modification techniques for enhancing CO₂ affinity in zeolites.

3.1 Ion exchange

Ion exchange is a fundamental post-synthetic modification technique used to tailor the chemical and adsorption properties of zeolites for enhanced CO₂ capture. In this process, the native framework cations, typically sodium (Na⁺) or potassium (K⁺), are replaced with alternative cations such as calcium (Ca²⁺), magnesium (Mg²⁺), or various transition metal ions. This substitution is usually achieved by immersing zeolite in an aqueous solution rich in the desired cation under controlled conditions of temperature, pH, and contact time [46].

The process of ion exchange alters the acidity and basicity of the zeolite surface by changing the charge distribution within the framework. The introduced cations influence the electrostatic interactions between the zeolite and CO₂ molecules, which is critical given that CO₂ holds a significant quadrupole moment. For instance, larger or more polarizable cations tend to create stronger adsorption sites by enhancing these interactions, in this manner increasing the binding energy of CO₂ [47]. This effect is particularly advantageous under the low partial pressure conditions typical of post-combustion gas streams, where the selective capture of CO₂ is crucial.

In addition to modifying the adsorption strength, the nature and size of the exchanged cations also affect the diffusivity of CO₂ within the zeolitic pores. Cations that are appropriately sized and sufficiently mobile can optimize the pore environment, ensuring that CO₂ molecules diffuse effectively throughout the structure. Conversely, if the cations are too large or too rigidly bound, they may obstruct the pore channels, blocking gas transport and constraining the overall adsorption kinetics of the material [48].

A systematic ion exchange process requires optimizing multiple key parameters. The concentration of the exchanging cation in the solution must be high enough to drive the substitution reaction without causing unwanted precipitation or degradation of the framework. Temperature and pH are also critical, as they influence both the ion exchange rate and the stability of the zeolite structure during the process. The duration of the exchange process must be carefully controlled to achieve uniform substitution across the entire material while preserving its structural integrity [49].

3.2 Amine functionalization

Amine functionalization is a widely used post-synthetic modification technique that involves the grafting of organic amine groups onto the internal surfaces of zeolites. This modification strategy is based on the well-established reactivity between amines and carbon dioxide (CO₂), which leads to the reversible formation of carbamate species under appropriate conditions. Typically, primary and secondary amines react with CO₂, often in a 2:1 stoichiometry, in order to form ammonium carbamate species. In the presence of moisture, alternative reaction pathways can result in the formation of bicarbonate species, depending on the specific amine used and the operating conditions [49].

The introduction of amine groups onto the zeolitic framework serves several critical functions. Primarily, it significantly enhances the chemisorptive interactions with CO₂ by creating strong acid-base interactions that increase both the adsorption capacity and selectivity of the material. This is particularly beneficial under low CO₂ partial pressure conditions, such as those found in post-combustion flue gases or in direct air capture scenarios, where the inherent affinity of amines for CO₂ drives adsorption even when concentrations are dilute [50]. The functionalization process

effectively lowers the activation energy for CO₂ binding, in this manner improving the kinetics of the adsorption process and ensuring that the zeolite maintains efficient adsorption performance.

Despite these advantages, amine functionalization also introduces several challenges that must be addressed through careful optimization. One of the primary concerns is the potential degradation of amine groups over multiple adsorption-desorption cycles [51]. Exposure to high temperatures, oxygen, and other reactive species during cyclic operations can lead to the deterioration of the amine functionality, thereby reducing the long-term performance of the adsorbent. Moreover, the strong chemical interactions between amine groups and CO₂, although beneficial for enhancing selectivity and adsorption capacity, can lead to higher energy demands during the regeneration process. This higher regeneration energy input may offset some of the benefits gained during adsorption if it is not addressed properly [52].

3.3 Mobile cation incorporation

Mobile cation incorporation is an advanced modification strategy designed to enhance the dynamic interaction between CO₂ molecules and the zeolitic framework. This approach involves substituting the native, relatively immobile extra-framework cations with alternative cations that exhibit greater mobility within the porous network. The underlying concept is to create transient, adaptable adsorption sites that can readily bind and release CO₂, thereby optimizing both uptake capacity and selectivity [53].

In practice, mobile cation incorporation is achieved through controlled ion exchange processes in which the original cations (often sodium or potassium) are partially or wholly replaced by cations known for their higher mobility, such as calcium, magnesium, or certain transition metal ions. The mobility of these cations within the pore channels is critical because it allows them to adjust their positions in response to local variations in CO₂ concentration. When CO₂ molecules enter the pores, the mobile cations can rearrange themselves to form favorable electrostatic interactions, successfully “capturing” the CO₂ molecules [53]. Conversely, during regeneration the cations can easily rearrange, facilitating the release of the adsorbed gas.

This dynamic behavior introduces a degree of flexibility that is not typically present in conventional, static cation environments. The resulting flexible adsorption sites can improve the overall adsorption kinetics, because they reduce the energy barriers for CO₂ diffusion and binding. Additionally, the enhanced mobility may allow for more uniform distribution of adsorption sites throughout the zeolitic structure, leading to higher uptake capacities, particularly under cyclic adsorption-desorption conditions [54].

The effectiveness of mobile cation incorporation relies on several factors. The size, charge, and polarizability of the substituted cations determine the strength of the cation-CO₂ interaction [55]. For instance, cations with moderate ionic radii and higher polarizability can create more effective adsorption sites without obstructing the pore channels [56]. Moreover, the degree of exchange and the distribution of these mobile cations within the framework are critical parameters that need to be optimized. An optimal balance is required between these parameters; if the concentration is too high, it might lead to cation crowding and reduced mobility, whereas

if the concentration is too low, it may not produce the desired enhancement in CO₂ capture.

3.4 Nitrogen activation

Nitrogen activation refers to the process of incorporating or activating nitrogen-containing species within the zeolitic framework to create additional basic sites. This modification is typically achieved through either nitrogen doping or the introduction of nitrogen-rich functional groups during or after the initial synthesis of the zeolite. In nitrogen doping, the zeolite is treated under harsh conditions such as exposure to ammonia or nitrogen plasma at elevated temperatures; these harsh conditions allow nitrogen atoms to substitute for oxygen or become incorporated into the framework [57]. Alternatively, nitrogen-rich organic moieties can also be grafted onto the internal surfaces of the zeolite, thereby directly introducing nitrogen functionalities into the material.

The incorporation of nitrogen into the zeolite structure significantly enhances its ability to interact with CO₂. Given that CO₂ is an acidic gas with a pronounced quadrupole moment, the presence of additional basic sites formed by nitrogen atoms promotes stronger acid-base interactions. This results in an increase in the adsorption strength and selectivity toward CO₂, especially in scenarios where CO₂ concentrations are low. The nitrogen-modified surface not only improves the intrinsic adsorption capacity but also preferentially attracts CO₂ over competing molecules such as water vapor [58]. This preferential adsorption is especially favorable under humid conditions, where conventional zeolites might otherwise suffer from reduced performance due to competitive adsorption of water.

Furthermore, nitrogen activation can contribute to the long-term stability and effective regeneration ability of the adsorbent. By creating robust nitrogen-functionalized sites, the adsorption performance of zeolite is maintained over multiple cycles of adsorption and desorption [59]. However, the process requires careful optimization; parameters such as the concentration of the nitrogen precursor, treatment temperature, and exposure time have to be precisely controlled to maximize the formation of active basic sites without compromising the structural integrity of the zeolitic framework [60].

3.5 Impact of these post-synthesis modifications on selectivity, stability, and regeneration efficiency of zeolites

Post-synthetic modifications of zeolites play a crucial role in enhancing their performance for CO₂ capture by influencing selectivity, stability, and regeneration efficiency. **Table 2** presents an overview of the tradeoff between different performance metrics based on post-synthesis modification techniques.

Amine functionalization, mobile cation incorporation, and nitrogen activation are key post-synthetic modifications that enhance CO₂ adsorption in zeolites. Amine functionalization improves adsorption capacity and selectivity by forming carbamate species, making it highly effective for dilute CO₂ streams, though it increases regeneration energy requirements and may degrade over multiple cycles. Mobile cation incorporation enhances adsorption kinetics by introducing adaptable adsorption sites, allowing cations to reposition in response to CO₂ concentration changes, but requires

Modification method	Selectivity enhancement	Capacity enhancement	Regeneration energy impact	Cycle stability	Key advantages	Key challenges	Refs.
Ion Exchange	Moderate	Moderate	Slight Increase	High	Simple process; cost-effective; maintains structural integrity	Effectiveness depends on optimal cation selection	[15]
Amine Function-alization	High	High	Significant Increase	Moderate	High capacity and selectivity at low CO ₂ concentrations	Higher regeneration energy, potential amine degradation	[49]
Mobile Cation Incorporation	Moderate	Moderate	Slight Increase	High	Dynamic adsorption sites; improved kinetics	Requires precise optimization of cation mobility and distribution	[61]
Nitrogen Activation	Moderate	Moderate	Potential Reduction	High	Effective under humid conditions; enhances both capacity and selectivity	Demands strict control of synthesis parameters	[15]

Table 2.
Comparative performance of post-synthetic modification techniques.

careful optimization to maintain uniformity and cycle stability. Nitrogen activation creates additional basic sites that strengthen acid-base interactions with CO₂, improving selectivity and capacity, particularly under humid conditions, while potentially reducing regeneration energy demands. These modifications, when precisely controlled, significantly enhance the efficiency and durability of zeolite-based CO₂ capture. Each post-synthetic modification technique offers distinct advantages and challenges concerning selectivity, stability, and regeneration efficiency. The choice of modification should be guided by the specific requirements of the intended CO₂ capture application, considering factors such as operating conditions, CO₂ concentration, and the presence of moisture.

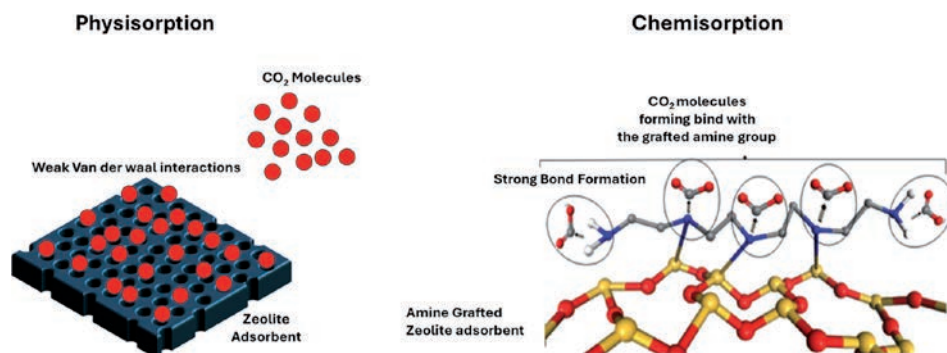


Figure 9.
Graphical representation of the physisorption and chemisorption process in zeolites.

4. Fundamental adsorption mechanism of CO₂ onto zeolites

The adsorption mechanisms in zeolites for CO₂ capture applications are dependent primarily on two distinct processes, physical adsorption (physisorption) and chemical adsorption (chemisorption). A visual representation of the physisorption and chemisorption processes, highlighting their distinct differences, is presented in **Figure 9**.

Physisorption involves the adherence of CO₂ molecules onto the surface of zeolites through weak van der Waals forces. This process is typically characterized by its reversibility and the formation of multilayer adsorption at low temperatures. The efficiency of physisorption in zeolites is influenced by factors such as pore size, surface area, and the presence of exchangeable cations within the zeolite framework. These cations induce basicity and an electric field, which are key parameters for CO₂ adsorption. For instance, the inclusion of exchangeable cations within the cavities of zeolites can significantly enhance CO₂ adsorption capacity [13, 62].

Chemisorption, on the other hand, entails the formation of strong chemical bonds between CO₂ molecules and the active sites on the zeolite surface. This process is usually irreversible and leads to the formation of a monolayer of adsorbed CO₂. Chemisorption is highly dependent on the chemical composition and surface functionalities of the zeolite. Modifications such as amine functionalization can introduce active sites that form carbamate species with CO₂, thereby enhancing adsorption capacity and selectivity. However, this also results in increased regeneration energy requirements due to the strength of the chemical bonds formed [13].

The relationship between physisorption and chemisorption in zeolites is complex and is influenced by factors such as temperature, pressure, and the presence of competing adsorbates like water vapor. Understanding these fundamental adsorption mechanisms is crucial for the design and optimization of zeolite-based materials for efficient CO₂ capture applications.

The interplay between physisorption and chemisorption in zeolites is complex and is influenced by factors such as temperature, pressure, and the presence of competing adsorbates like water vapor [63]. Understanding these fundamental adsorption mechanisms is crucial for the design and optimization of zeolite-based materials for efficient CO₂ capture applications.

4.1 The role of surface functional groups and pore connectivity in facilitating CO₂ interaction

The effectiveness of zeolites in CO₂ capture is deeply linked to their surface functional groups and pore connectivity, which collectively influence adsorption capacity, selectivity, and adsorption kinetics. A detailed understanding of these factors is essential for the rational design and optimization of zeolite-based adsorbents.

4.1.1 Surface functional groups

The chemical nature of the surface of a zeolite significantly impacts its interaction with CO₂ molecules. In their native form, zeolites possess a framework comprising SiO₄ and AlO₄ tetrahedra; this results in a negatively charged lattice balanced by extra-framework cations such as Na⁺, K⁺, or Ca²⁺. These cations serve as primary adsorption sites, attracting CO₂ through electrostatic interactions and van der Waals forces [64]. The type, distribution, and density of these cations are critical

determinants of CO₂ adsorption performance. For instance, zeolites with divalent cations like Ca²⁺ often exhibit higher CO₂ adsorption capacities compared to those with monovalent cations due to stronger electrostatic interactions [65].

Beyond the inherent cationic sites, surface functionalization of zeolites has become an effective strategy to enhance CO₂ affinity. Grafting amine groups onto the zeolite surface introduces basic sites that can form carbamate complexes with CO₂; in this way, it significantly increases adsorption capacity and selectivity [66]. Studies have demonstrated that amine-functionalized zeolites exhibit superior CO₂ uptake, especially under low partial pressure conditions, which are typical conditions for post-combustion carbon capture from flue gases [67].

4.1.2 Pore connectivity

The porous architecture of zeolites, which is defined by pore size, shape, and connectivity, plays a pivotal role in governing CO₂ diffusion and accessibility to active sites. For instance, small-pore zeolites like zeolite A and chabazite have been shown to effectively adsorb CO₂ due to their suitable pore dimensions that facilitate strong interactions with CO₂ molecules. However, while smaller pores can enhance selectivity, they may also slow down diffusion rates, leading to slower adsorption kinetics. On the other hand, zeolites with larger pores or hierarchical pore structures can offer improved diffusion pathways, facilitating faster CO₂ uptake. The introduction of mesoporosity into microporous zeolites has been shown to enhance adsorption kinetics without significantly compromising selectivity [61].

Moreover, the connectivity between pores influences the accessibility of CO₂ molecules to internal adsorption sites. A well-connected pore network ensures that CO₂ can efficiently diffuse throughout the zeolite structure, maximizing the utilization of available adsorption sites. Disruptions in pore connectivity, such as defects or blockages, can hinder diffusion and reduce overall adsorption capacity.

4.1.3 The relationship between surface chemistry and pore architecture

The balance between surface chemistry and pore architecture in zeolites is key for optimizing CO₂ capture performance. A deeper understanding of this relationship enables the design of materials with enhanced adsorption capacities, selectivities, and adsorption kinetics. A detailed insight into the tradeoff between surface chemistry and pore architecture is presented in **Figure 10**.

Surface functionalization, such as the incorporation of amine groups, enhances the chemical affinity of zeolites for CO₂. However, the effectiveness of such modifications is intricately linked to the pore architecture of zeolite. For instance, in materials

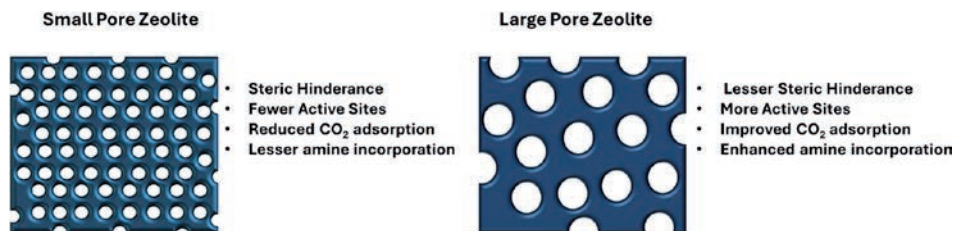


Figure 10.
Graphical representation of the surface chemistry and pore connectivity between small and large pore zeolites.

with small pore sizes, steric hindrance can hinder the incorporation of bulky amine groups, thereby limiting the number of active sites available for CO₂ adsorption. Additionally, narrow pores may restrict the diffusion of CO₂ molecules, reducing the overall adsorption rate. Conversely, zeolites with larger or hierarchically structured pores can accommodate functional groups more readily and facilitate easier access for CO₂ molecules, leading to improved adsorption performance [68]. Therefore, a balanced approach that considers both surface chemistry and pore structure is essential.

Furthermore, the distribution and density of surface functional groups must be optimized in conjunction with pore connectivity. An uneven distribution of functional groups can create localized regions of high adsorption potential, which may not be fully utilized if pore connectivity is poor. This scenario can lead to inefficient CO₂ capture, as some active sites remain inaccessible. Therefore, ensuring a uniform distribution of functional groups and a well-connected pore network is crucial for maximizing the efficiency of CO₂ adsorption. The synergistic effect of surface functional groups and pore architecture dictates the overall performance of zeolites in CO₂ capture applications. A meticulous design that harmonizes surface chemistry with pore structure can lead to zeolite-based adsorbents with superior capacity, selectivity, and kinetics, thereby enhancing the efficacy of CO₂ capture processes [56].

4.2 Insights from theoretical models and experimental observations

Theoretical approaches, particularly molecular simulations, have been instrumental in understanding the interactions between CO₂ molecules and zeolite frameworks. Two prominent computational methods employed in this context are Density Functional Theory (DFT) calculations and Grand Canonical Monte Carlo (GCMC) simulations.

4.2.1 Density Functional Theory (DFT) calculations

Density Functional Theory (DFT) is a powerful quantum mechanical modeling method used to investigate the electronic structure of many-body systems, including atoms, molecules, and condensed phases [69]. In the study of CO₂ adsorption on zeolites, DFT provides detailed atomic-scale insights into the interaction between CO₂ molecules and the adsorption sites within the zeolite framework. By solving the Kohn-Sham equations, DFT determines the electron density distributions, which are crucial for understanding the bonding characteristics, electrostatic potential, and energetic stability of CO₂ within the zeolite structure [70].

One of the primary advantages of DFT is its ability to model the interaction energies between CO₂ and zeolite frameworks, accounting for dispersion forces, electrostatic interactions, and site-specific adsorption behavior [71]. These calculations enable researchers to predict adsorption enthalpies, charge distributions, and preferred binding configurations, which are essential for rationalizing experimental adsorption trends.

For instance, DFT studies have been widely employed to examine the adsorption of CO₂ in different cation-exchanged molecular sieves, where the type of extra-framework cation significantly affects CO₂ binding strength and adsorption capacity [72]. Cations play a key role in modifying the local electric field within the zeolite pores, thereby influencing CO₂ polarization and adsorption energetics. Specifically, in monovalent metal ion-exchanged zeolites, the calculated adsorption capacities follow the order of $\text{Li}^+ > \text{Na}^+ > \text{K}^+ > \text{Cu}^+$. This trend can be attributed to the charge density and ionic radius of the respective cations. Li^+ , having the smallest

ionic radius and highest charge density among the monovalent cations, generates the strongest electrostatic field, enhancing CO₂ adsorption through dipole-induced interactions [73].

DFT calculations further reveal that the electronic properties of zeolites are modulated by cation exchange processes. The partial density of states (PDOS) analysis provides insight into the redistribution of electronic charge upon CO₂ adsorption, highlighting the role of framework oxygen atoms in facilitating binding interactions [74]. In cation-exchanged zeolites, the interaction energy between CO₂ and the framework can be fine-tuned by selecting cations with optimal electronegativity and polarizability. For example, DFT studies on divalent cation-exchanged Y-zeolites (e.g., Be²⁺, Mg²⁺, Ca²⁺, and Zn²⁺) indicate that CO₂ adsorption performance improves in the order of Zn²⁺ < Be²⁺ < Ca²⁺ < Mg²⁺, with Mg²⁺-exchanged zeolites exhibiting the highest CO₂ binding energy [75]. This trend is largely driven by the degree of framework distortion and local charge compensation mechanisms.

Additionally, DFT has been instrumental in exploring the impact of zeolite surface modifications, such as amine functionalization and nitrogen doping. By incorporating nitrogen into the zeolite framework, DFT calculations show enhanced basicity and increased affinity for CO₂ molecules, facilitating stronger acid-base interactions. These computational findings align well with experimental observations, where nitrogen-doped zeolites exhibit superior CO₂ adsorption under humid conditions. Moreover, DFT studies contribute to the understanding of competitive adsorption phenomena, such as CO₂ versus H₂O adsorption in humid environments. CO₂ capture materials often face performance degradation due to preferential water adsorption, which can block active sites. By analyzing adsorption energies and charge transfer mechanisms, DFT allows for the design of hydrophobic zeolites with enhanced CO₂ selectivity over water vapor [73].

4.2.2 Grand canonical Monte Carlo (GCMC) simulations

Grand Canonical Monte Carlo (GCMC) simulations are an important statistical mechanics approach extensively utilized to model adsorption processes in porous materials, notably zeolites [76]. These simulations operate within the grand canonical ensemble, where the system under study can exchange particles and energy with an external reservoir, maintaining constant chemical potential (μ), volume (V), and temperature (T). This framework is particularly suited for adsorption phenomena, as it mirrors the practical conditions where adsorbent materials interact with gas phases at specified temperatures and pressures [77].

In GCMC simulations, the primary objective is to determine the equilibrium distribution of adsorbate molecules within the porous structure of the adsorbent. The simulation employs a series of stochastic moves such as insertion, deletion, translation, and rotation of molecules to explore the configurational space of the system. The acceptance or rejection of these moves is governed by the Metropolis algorithm, which utilizes probability criteria based on the change in the energy and the imposed chemical potential of the system [77]. The key steps in a GCMC simulation include:

4.2.2.1 Initialization

Define the structural model of the adsorbent (e.g., zeolite framework) and set initial conditions, including temperature, chemical potential, and potential parameters for interactions.

4.2.2.2 Monte Carlo moves

Insertion: Attempt to add an adsorbate molecule at a random position within the pore structure. The move is accepted with a probability that depends on the chemical potential and the resulting change in energy.

Deletion: Attempt to remove a randomly selected adsorbate molecule, with acceptance probability determined similarly to insertion.

Translation and Rotation: Propose random displacements and orientations of adsorbate molecules to sample different configurations, accepted based on the resulting energy changes.

Equilibrium and Sampling: Iterate the Monte Carlo moves over numerous cycles to allow the system to reach equilibrium. Once equilibrated, collect data over additional cycles to compute ensemble averages of properties of interest, such as adsorption isotherms and heats of adsorption.

GCMC simulations have been extensively applied to study CO₂ adsorption in various zeolitic frameworks, providing insights into adsorption capacities, selectivities, and the influence of structural modifications. For instance, a study investigated the adsorption of CO₂ molecules inside the pores of faujasite zeolite and evaluated the influence of Ir₄ clusters on the adsorption intensity [78]. The force field designed for CO₂ adsorption in zeolites was extended with parameters for CO₂/Ir₄ interactions, taking Density Functional Theory (DFT) energies as a reference. The findings revealed that despite the fraction of pore volume occupied by the Ir₄ cluster, the adsorption was more intense than that of empty faujasite, highlighting the role of metal clusters in enhancing CO₂ adsorption [78, 79].

In another study, GCMC simulations were employed to predict the adsorption isotherms and isosteric heats of CO₂ and CH₄ on various all-silica zeolites, including BEA, CDO, CHA, DDR, MFI, and STT-type frameworks [80]. The simulations provided detailed insights into the adsorption behaviors of these gases, which are critical for applications in gas separation and storage [81]. GCMC simulations offer several advantages in the study of adsorption phenomena:

Flexibility: They can model a wide range of conditions, including varying temperatures, pressures, and chemical potentials, allowing for comprehensive exploration of adsorption behaviors.

Detailed Insights: By providing molecular-level information, GCMC simulations elucidate the preferred adsorption sites, orientations, and configurations of adsorbate molecules within complex pore structures.

Key differences		
Aspect	Density Functional Theory	Grand Canonical Monte Carlo Simulations
Theory	Quantum mechanics	Classical statistical mechanics
Scale	Atomic/electronic (~0.1–10 nm)	Meso/macrosopic (~nm–μm)
Computational Cost	High (hours/days for small systems)	Low (minutes/hours for large systems)
Output	Electronic structure, binding energy	Adsorption isotherms, loading capacity
Input Parameters	Requires exchange-correlation functional	Requires force fields (e.g., LJ potentials)

Table 3.
Key differences between Density Functional Theory (DFT) and Grand Canonical Monte Carlo (GCMC) simulations.

Predictive Capability: They enable the prediction of adsorption isotherms and thermodynamic properties, guiding the design and optimization of adsorbent materials.

However, the accuracy of GCMC simulations is contingent upon the quality of the force fields and potential parameters used to describe intermolecular interactions. Careful parameterization, often informed by experimental data or higher-level quantum mechanical calculations, is essential to ensure reliable predictions. The key differences between Density Functional theory and Grand Monte Carlo Simulations are presented in **Table 3**.

4.2.3 Assessment of impact of cation exchange using DFT and GCMC simulation approaches

Theoretical models, including Density Functional Theory (DFT) and Grand Canonical Monte Carlo (GCMC) simulations, have been extensively used to study the influence of different cation species on zeolite performance. By substituting native extra-framework cations (such as Na^+ or K^+) with alternative metal ions, researchers can predict changes in the electrostatic potential of the zeolite framework, which in turn affects CO_2 binding strength and adsorption efficiency [82].

DFT calculations have shown that cation exchange significantly alters the local electric field within zeolite pores, thereby modulating the adsorption energy of CO_2 molecules. The extent of improvement in adsorption performance is directly related to the type, charge density, and ionic radius of the exchanged cation [82]. For example, divalent metal cations such as Be^{2+} , Mg^{2+} , Ca^{2+} , and Zn^{2+} have been systematically studied in Y-type zeolites, revealing an increasing trend in CO_2 adsorption performance in the order of $\text{Zn}^{2+} < \text{Be}^{2+} < \text{Ca}^{2+} < \text{Mg}^{2+}$ [83, 84]. This trend can be attributed to differences in the electrostatic potential induced by these cations, where Mg^{2+} -exchanged zeolites generate the highest local field strength, thereby maximizing CO_2 binding affinity. Such findings highlight the importance of selecting optimal cations for tailored CO_2 capture applications.

GCMC simulations complement DFT studies by providing adsorption isotherms and predicting CO_2 uptake across a range of pressures and temperatures. These simulations allow for a more dynamic assessment of cation-exchanged zeolites under realistic operating conditions [85]. For instance, GCMC studies on alkali-metal-exchanged zeolites (Li^+ , Na^+ , K^+ , Cs^+) have shown that Li^+ -exchanged zeolites exhibit the highest CO_2 adsorption capacity due to their strong electrostatic interactions with

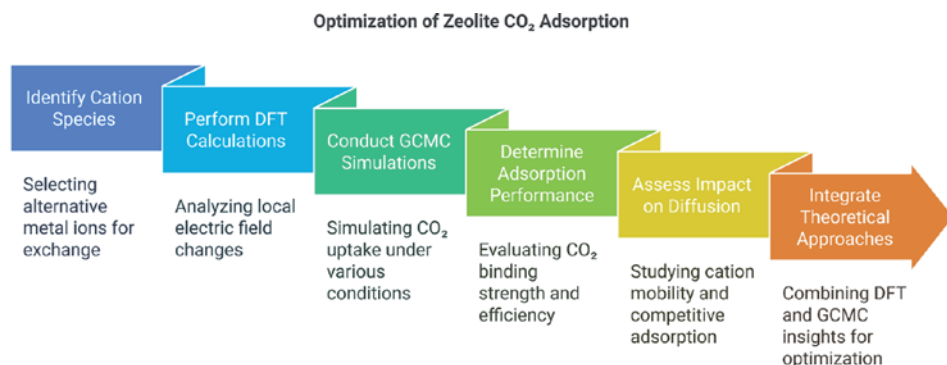


Figure 11. Schematic representation of the optimization process for zeolite-based CO_2 adsorption, integrating Density Functional Theory (DFT) calculations and Grand Canonical Monte Carlo (GCMC) simulations.

the quadrupolar CO₂ molecule. However, while smaller cations such as Li⁺ and Mg²⁺ enhance adsorption, their strong binding may lead to higher regeneration energy requirements, which is a critical factor in practical applications [86].

Beyond the direct impact on adsorption capacity, cation exchange also influences other key properties, such as diffusion kinetics and competitive adsorption behavior. Experimental and computational studies have shown that the mobility of cations within the zeolite framework plays a role in facilitating CO₂ diffusion, particularly in hierarchical and mesoporous zeolites [87]. Furthermore, the presence of competing gas species such as H₂O and N₂ can affect the efficiency of cation-exchanged zeolites, with some cations exhibiting higher selectivity for CO₂ over water vapor [88].

The integration of theoretical and computational approaches enables a deeper understanding of how cation exchange can be leveraged to optimize zeolite-based CO₂ adsorbents. As illustrated in **Figure 11**, this process involves multiple steps, from identifying suitable cation species to assessing their impact on adsorption and diffusion through a combination of DFT and GCMC simulations. By systematically analyzing cation-dependent adsorption trends, researchers can design zeolites with enhanced selectivity, improved capacity, and optimized regeneration energy requirements for large-scale carbon capture applications.

5. Real-world applications of zeolites for carbon capture

5.1 Case studies on using modified zeolites for industrial flue gas treatment

In industrial settings, the application of modified zeolites for flue gas treatment has been explored to enhance the removal of CO₂ and other pollutants. A study by Zewdie et al. [89] investigated the use of zeolite materials for the removal of CO₂, SO₂, and H₂S from flue gases. The research highlighted that CO₂ has a stronger preference for NaA zeolite compared to NaX or NaY variants, indicating the significance of zeolite type in adsorption efficiency. The study also emphasized the need for further modifications to improve the stability and capacity of zeolites under industrial conditions.

Another investigative study by Bahmanzadegan et al. [49] focused on the modification and functionalization of zeolites to enhance their CO₂ adsorption efficiency. The researchers discussed various strategies, including ion exchange and impregnation with amine groups, to improve the performance of zeolites in capturing CO₂ from flue gases. The study concluded that tailored modifications could significantly enhance the adsorption capacity and selectivity of zeolites, making them more suitable for industrial applications.

Furthermore, a comprehensive review by Tao et al. [13] provided an overview of the mechanisms, strategies, and prospects for zeolite development in separating CO₂ from critical scenarios. The authors discussed the potential of modified zeolites in achieving efficient CO₂ separation, highlighting the importance of pore structure optimization and surface functionalization. The review also addressed the challenges associated with the scalability and economic feasibility of using modified zeolites in industrial flue gas treatment.

A detailed summary of the case studies is presented in **Table 4**; these case studies underscore the potential of modified zeolites in industrial flue gas treatment. While challenges related to stability, capacity, and economic viability persist, ongoing research and development efforts continue to enhance the performance of

Study	Zeolite type	Modification	Target pollutants	Key findings
Zewdie et al. [89]	NaA, NaX, NaY	—	CO ₂ , SO ₂ , H ₂ S	CO ₂ shows stronger adsorption on NaA zeolite; further modifications are needed for stability and capacity improvements.
Bahmanzadegan et al. [49]	Various	Ion exchange, amine impregnation	CO ₂	Tailored modifications significantly enhance adsorption capacity and selectivity.
Tao et al. [13]	Various	Pore structure optimization, surface functionalization	CO ₂	Emphasized the importance of pore structure optimization and surface functionalization for efficient CO ₂ separation.

Table 4.

Summary of case studies demonstrating the applicability of modified zeolites for industrial carbon capture applications.

zeolite-based adsorbents. Advancements in modification techniques and a deeper understanding of adsorption mechanisms are paving the way for the practical implementation of modified zeolites in mitigating industrial emissions.

5.2 Applications for direct air capture systems and other practical settings

Direct air capture (DAC) of CO₂ is a critical technology aimed at mitigating climate change by removing CO₂ directly from the atmosphere, where its concentration is approximately 400 ppm. The low concentration of CO₂ in ambient air presents significant challenges for adsorption-based capture methods, necessitating the development of materials with high selectivity and capacity for CO₂ under dilute conditions. Zeolites, crystalline aluminosilicates with well-defined microporous structures, have emerged as promising candidates for DAC applications due to their high surface areas, tunable pore sizes, and the ability to modify their surface properties through post-synthetic modifications.

One effective strategy to enhance the CO₂ adsorption performance of zeolites is amine functionalization. By incorporating amine groups into the zeolite framework, the interaction between CO₂ molecules and the adsorbent is strengthened through the formation of carbamate species, thereby increasing adsorption capacity and selectivity. For instance, a study demonstrated that amine-functionalized zeolites exhibit improved CO₂ adsorption properties, highlighting the potential of this modification for DAC applications [90].

Ion exchange is another modification technique employed to improve the CO₂ adsorption characteristics of zeolites. By substituting the native cations in the zeolite structure with metal cations such as Na⁺, K⁺, Mg²⁺, or Ca²⁺, the electrostatic interactions within the framework are altered, influencing the adsorption behavior. Research has shown that metal cation-exchanged LTA zeolites exhibit varying CO₂ adsorption capacities, with certain cations enhancing the affinity of the zeolite for CO₂, making them suitable for DAC applications [91].

The incorporation of mobile cations into zeolites has also been explored to enhance CO₂ adsorption. These cations can interact with CO₂ molecules, facilitating their capture within the zeolite pores. Studies have indicated that the presence of mobile cations in zeolites can lead to improved CO₂ adsorption performance,

Study	Zeolite type and modification	Application	CO ₂ uptake (mmol/g)	Key observations	Reference
Darunte et al. [92]	Amine-functionalized Zeolite 13X	Direct Air Capture (DAC)	~1.2 at 400 ppm CO ₂	Enhanced uptake and selectivity compared to unmodified zeolite	[92]
Bahmanzadegan and Ghaemi [93]	Mobile cation-incorporated Zeolite Y	DAC and Industrial Separation	~1.0–1.3 at low CO ₂ partial pressures	Improved cyclic performance and faster kinetics	[93]
Lee et al. [94]	Nitrogen-doped Zeolite ZSM-5	Indoor Air Purification and DAC	~0.9–1.1 at ambient conditions	Preferential adsorption of CO ₂ over H ₂ O	[94]
Bahmanzadegan and Ghaemi [49]	Ion-exchanged Zeolite A	Flue Gas Treatment and DAC	~0.8–1.0 at ambient conditions	Tailored cation exchange yields moderate uptake improvements	[49]
Tejavath et al. [90]	Amine-grafted zeolite 13X	Direct Air Capture (DAC)	~1.0–1.6 at ambient conditions	Amine-functionalized domains improve CO ₂ capture	[90]

Table 5.
Summary of recent studies on CO₂ adsorption performance of modified zeolites for direct air capture.

suggesting their potential utility in DAC systems [15]. Nitrogen activation, involving the introduction of nitrogen-containing functional groups into the zeolite structure, is another modification approach that has been investigated. This modification aims to increase the basicity of the zeolite surface, thereby enhancing its interaction with acidic CO₂ molecules. A review highlighted various strategies for zeolite development, including nitrogen activation, to improve CO₂ separation capabilities [13]. A detailed summary of lab-scale studies that explore zeolites for direct air capture applications is presented in **Table 5**.

The robustness and thermal stability of zeolites further contribute to their suitability for DAC applications. Their structural integrity under varying environmental conditions allows for integration into hybrid systems that combine DAC with industrial processes, thereby contributing to overall emissions reduction in both decentralized and large-scale settings. **Table 5** summarizes representative data from these studies on the use of modified zeolites for DAC and other practical applications.

5.3 Evaluation of performance, scalability, and challenges in real-world conditions

Modified zeolites have been extensively investigated for CO₂ capture, and their real-world performance in applications such as direct air capture (DAC) and industrial flue gas treatment has been evaluated through both laboratory experiments and pilot-scale studies. A methodical assessment of performance, scalability, and challenges in real-world conditions is critical for translating promising laboratory results into commercially viable carbon capture solutions.

Laboratory-scale evaluations of modified zeolites have demonstrated CO₂ adsorption capacities on the order of approximately 1.2 mmol/g at ambient CO₂ concentrations (~400 ppm). These studies typically report enhanced selectivity and uptake when zeolites are modified via techniques such as amine functionalization, ion exchange, mobile cation incorporation, or nitrogen activation. However, when these

materials are tested under practical conditions, factors such as the presence of water vapor, competing impurities, and variable operating temperatures tend to lower the effective adsorption capacity. For example, under simulated flue gas conditions, adsorption capacities may decrease to the range of 0.8–1.0 mmol/g, primarily due to competitive adsorption and pore blockage by moisture. In parallel, regeneration studies conducted under laboratory conditions have shown that modified zeolites can typically be regenerated with a modest increase in energy input, often less than a 20% increase compared to unmodified materials. Yet, scaling up these processes poses additional challenges; synthesis reproducibility, material durability, and the efficient integration of the adsorbents into continuous industrial processes are major hurdles.

Several pilot-scale studies have further underscored the challenges in maintaining long-term stability and consistent performance. In industrial environments, modified zeolites must withstand repeated adsorption-desorption cycles under harsh conditions. Laboratory evaluations often report cyclic stability exceeding 90% capacity retention over 10 cycles. However, when implemented in full-scale systems, cyclic performance can be compromised by factors such as fluctuating gas compositions, thermal stresses, and mechanical attrition. Furthermore, economic analyses and life cycle assessments indicate that while modified zeolites offer promising CO₂ capture performance, issues related to the energy penalty during regeneration and the cost of material production remain significant barriers to widespread industrial adoption. **Table 6** summarizes representative trends and observations from various studies evaluating the performance, scalability, and challenges of modified zeolites for CO₂ capture under real-world conditions.

Parameter	Laboratory scale	Pilot/Industrial scale	Remarks	Reference
Adsorption Capacity	0.8–8 mmol/g at different conditions	Modified zeolites exhibited higher uptakes	Ideal lab conditions maximize capacity, but moisture and contaminants in flue gas reduce effectiveness.	[49, 54, 95, 96]
Selectivity	High selectivity with targeted modifications	Lower selectivity in the presence of competing adsorbates (e.g., water vapor)	Surface modifications improve CO ₂ selectivity, but competing gases can reduce performance.	[15, 97]
Regeneration Energy	Moderate energy requirement (typically <20% increase over unmodified materials)	Energy penalty may be higher due to material degradation and non-ideal operating conditions	Lab regeneration is optimized, but scaling up increases energy demands due to variable conditions.	[98–100]
Cycle Stability	>90% capacity retention over 10 cycles	Stability can decline in harsh industrial environments	Lab tests show high stability, but industrial use accelerates degradation due to impurities and stress.	[101–103]
Synthesis Reproducibility	High under controlled laboratory conditions	Variability in quality and uniformity upon scale-up	Consistent synthesis and modification ensure reliable large-scale adsorbent performance.	[104–106]

Table 6.

Comparative performance of zeolites in CO₂ adsorption at laboratory and industrial scales. Adsorption capacity, selectivity, regeneration energy, cycle stability, and synthesis reproducibility are assessed.

While modified zeolites demonstrate promising CO₂ capture performance in laboratory settings, significant challenges remain when scaling these materials for industrial applications. Addressing issues such as reduced adsorption capacity under realistic conditions, increased regeneration energy, and long-term material stability are crucial for advancing the commercial viability of zeolite-based carbon capture systems. Future research must focus on improving synthesis reproducibility, optimizing modification techniques, and integrating these advanced adsorbents into existing industrial infrastructures to achieve effective and economically sustainable CO₂ capture.

6. Emerging trends and future directions

6.1 Recent innovations and interdisciplinary approaches in zeolite synthesis and modification

Recent innovations and interdisciplinary approaches in zeolite synthesis and modification have significantly advanced the development of high-performance adsorbents for CO₂ capture. Researchers have embraced novel synthesis methods, such as in-situ hierarchical synthesis [37], solvothermal synthesis using ionic liquids, microwave-assisted synthesis, and mechanochemical techniques to precisely control pore architecture and surface functionality at the molecular level [27, 107]. These methods enable the creation of zeolitic frameworks with tailored microporous and mesoporous structures, thereby overcoming traditional diffusion limitations and enhancing CO₂ uptake. Moreover, the incorporation of post-synthetic modifications, including amine functionalization, ion exchange, mobile cation incorporation, and nitrogen activation, further refines the adsorption properties, enabling superior selectivity and capacity even under the extremely dilute conditions encountered in direct air capture (DAC) applications [44].

Interdisciplinary collaborations have played a critical role in this advancement by integrating experimental synthesis, state-of-the-art characterization techniques [108] (such as synchrotron X-ray diffraction, solid-state NMR, and high-resolution electron microscopy), and computational modeling approaches like Density Functional Theory (DFT) and Grand Canonical Monte Carlo (GCMC) simulations. For instance, DFT calculations have provided detailed insights into the adsorption energies and electronic interactions between CO₂ molecules and modified zeolite frameworks, elucidating how the incorporation of different extra-framework cations alters the local electric fields and improves CO₂ binding [71, 75]. A seminal review by Nazeri et al. discusses these aspects in detail, highlighting the influence of cation selection on adsorption performance [109]. Similarly, GCMC simulations have been employed to predict adsorption isotherms, assess dynamic behavior, and evaluate the impact of hierarchical pore structures on CO₂ diffusion. For example, a study by Sadeghi et al. demonstrated that GCMC modeling of CH₄, CO₂, and N₂ adsorption in zeolite Y accurately predicts adsorption behavior under varying conditions, guiding the rational design of advanced adsorbents [110]. Furthermore, combining innovative synthesis strategies with targeted post-synthetic modifications has led to the development of hybrid materials that exhibit both enhanced CO₂ capture performance and improved scalability for industrial applications [111].

Collectively, these interdisciplinary strategies not only expand the synthetic toolbox for zeolite production but also enable the development of next-generation CO₂ adsorbents with enhanced efficiency, stability, and economic viability. Such advancements are critical in addressing the challenges of CO₂ capture in both direct

air capture systems and industrial flue gas treatment, ultimately contributing to global efforts in mitigating climate change.

6.2 Potential advancements in hybrid materials and process integration

Emerging trends in hybrid materials and process integration are redefining the landscape of CO₂ capture technologies by combining the unique advantages of different adsorbents and process methodologies to overcome current limitations in capacity, selectivity, and energy efficiency [112].

Recent advancements in hybrid materials focus on integrating zeolites with complementary porous materials such as metal-organic frameworks (MOFs), mesoporous silicas, or carbon-based adsorbents [113]. By combining the high selectivity and robust crystalline structure of zeolites with the exceptionally high surface area and tunable chemistry of these materials, researchers have been able to achieve synergistic effects that enhance overall CO₂ uptake. For instance, composite adsorbents that merge zeolite and MOF domains have been shown to exhibit CO₂ adsorption capacities exceeding 2.0 mmol/g under ambient conditions, along with improved cyclic stability compared to their individual components [113]. These enhancements arise from the optimized pore structure, where micro- and mesoporous regions are seamlessly integrated, and the tailored surface functional groups that favor strong interactions with CO₂ molecules. Such hybrid systems not only leverage the intrinsic advantages of each material class but also facilitate improved processability and mechanical robustness, which are critical for scaling up to industrial applications.

In parallel, process integration strategies are being developed to lower the overall energy penalty and cost associated with CO₂ capture. One promising approach involves the integration of zeolite-based adsorption units with renewable energy-powered regeneration cycles. By coupling the adsorption process with renewable heat sources or integrating CO₂ capture directly into existing industrial process streams (e.g., in sorption-enhanced water gas shift systems), it is possible to reduce regeneration energy requirements by as much as 25% compared to conventional standalone DAC systems [114, 115]. Moreover, coupling direct air capture (DAC) modules with downstream utilization processes such as the synthesis of value-added chemicals or enhanced oil recovery can create closed-loop systems that maximize CO₂ conversion efficiency and economic viability [116, 117]. Such integrated systems have been critically evaluated in techno-economic studies, which highlight that process integration is essential for achieving commercially scalable and sustainable carbon capture solutions.

Despite these promising advancements, significant challenges remain. The reproducibility of hybrid material synthesis at large scales, long-term stability under industrial cycling conditions, and the efficient integration of these advanced adsorbents into existing process infrastructures are ongoing areas of research. Addressing these challenges requires a concerted interdisciplinary effort that combines innovative material synthesis, advanced process engineering, and comprehensive economic and environmental assessments.

6.3 Current challenges and prospects for next-generation zeolite-based carbon capture technologies

Zeolite-based carbon capture technologies have garnered significant attention due to their high selectivity and thermal stability. However, several challenges impede their widespread industrial application.

Despite the promising potential of zeolite-based hybrid materials for CO₂ capture, several challenges must be addressed to enhance their practical applicability. One of the primary concerns is the limited adsorption capacity of zeolites, particularly under low CO₂ partial pressures, which are characteristic of ambient air conditions. Enhancing adsorption performance through material modifications or hybridization strategies is crucial to making zeolite-based systems more viable for large-scale deployment. Another major issue is moisture sensitivity, as the presence of water vapor in gas streams can significantly reduce CO₂ uptake. Water molecules compete with CO₂ for adsorption sites, decreasing efficiency and stability over multiple adsorption-desorption cycles. To overcome this, researchers are exploring hydrophobic surface modifications and functionalized zeolite structures that can repel moisture while maintaining high CO₂ selectivity. Additionally, regeneration energy requirements pose a substantial challenge, as desorbing captured CO₂ from zeolites often demands significant thermal energy input. Developing low-energy regeneration techniques, such as pressure swing adsorption or renewable-powered thermal desorption, is essential to improving the energy efficiency of these systems. Lastly, scalability and cost remain critical barriers to commercialization. The precise synthesis of zeolites with tailored pore structures and surface functionalities can be complex and expensive, and maintaining consistency at an industrial scale presents economic challenges. Addressing these limitations requires a multidisciplinary approach that integrates advances in material science, process engineering, and economic optimization to develop cost-effective and scalable CO₂ capture solutions. Prospects for next-generation technologies.

Advancements in zeolite-based carbon capture technologies focus on innovative synthesis methods, hybrid material development, process integration, and computational modeling to overcome existing challenges and enhance performance. Employing novel synthesis techniques, such as in-situ hierarchical synthesis and microwave-assisted methods, allows for the precise tailoring of pore structures, leading to enhanced CO₂ adsorption properties. These techniques not only improve the performance of zeolite adsorbents but also aim to reduce production costs, making large-scale implementation more feasible. Another promising approach is the development of hybrid materials, where zeolites are integrated with complementary adsorbents like metal-organic frameworks (MOFs) or carbon-based materials. Such hybrid systems capitalize on the high selectivity and stability of zeolites while benefiting from the exceptional surface area and tunable properties of MOFs and carbonaceous materials, resulting in superior adsorption capacities and improved selectivity. Additionally, process integration plays a critical role in the practicality of zeolite-based carbon capture. Incorporating these materials into existing industrial processes, such as membrane reactors or sorption-enhanced water gas shift systems, can significantly enhance overall efficiency and lower operational costs. Furthermore, advancements in computational modeling and machine learning are accelerating the discovery and optimization of zeolites with superior CO₂ capture properties. By leveraging predictive modeling and data-driven approaches, researchers can efficiently screen potential materials, optimize their structural properties, and guide experimental efforts toward the most promising candidates. These combined strategies are shaping the next generation of zeolite-based carbon capture technologies, paving the way for more efficient, scalable, and cost-effective solutions for reducing atmospheric CO₂ levels.

7. Conclusion

Zeolite-based CO₂ capture has emerged as a promising approach due to its tunable pore structures, high selectivity, and stability under varying conditions. This chapter explored key synthesis techniques, including hydrothermal, solvothermal, and microwave-assisted methods, highlighting their role in tailoring pore architecture for enhanced adsorption. Post-synthetic modifications, such as ion exchange and amine functionalization, have been shown to further improve CO₂ selectivity and uptake, addressing some of the limitations associated with unmodified zeolites. Computational modeling, particularly through DFT and GCMC simulations, has provided valuable insights into adsorption mechanisms, guiding material optimization. However, challenges remain in large-scale implementation, particularly concerning moisture interference, regeneration energy, and long-term stability. Future research should focus on developing scalable and cost-effective synthesis routes, improving material durability under real-world conditions, and reducing energy demands for regeneration. Advancing hybrid material systems and integrating adsorption processes with industrial applications will be crucial in maximizing the efficiency and practicality of zeolite-based CO₂ capture technologies.

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Global Navigation Satellite Systems (GNSS) for Sustainable Tourism: A Review of Applications, Benefits, and Future Directions

Ana Paula Oliveira and Clara Martinez-Perez

Abstract

This chapter explores the role of Global Navigation Satellite Systems in advancing sustainable tourism practices. Originally developed for navigation and geolocation, these satellite-based technologies have evolved into essential tools for managing tourist flows, protecting sensitive ecosystems, and enhancing visitor experiences. The chapter reviews how satellite navigation systems are applied across various domains, including ecological tourism, safety and risk management, environmental monitoring, and participatory destination governance through user-generated geographic data. It highlights the integration of satellite navigation with digital innovations such as geographic information systems, artificial intelligence, and interconnected sensing devices to support adaptive tourism services and data-informed decision-making. Ethical considerations related to personal data protection, digital inclusion, and the accuracy of volunteered information are examined, alongside challenges in infrastructure and technological accessibility. Drawing from current applications and emerging trends, the chapter proposes a conceptual framework for the inclusive and ethical integration of satellite-based navigation systems into tourism strategies. This framework addresses key areas such as collaboration among stakeholders, sustainability metrics, educational initiatives, and open data management. In addition, a forward-looking research agenda is presented, emphasizing the need for interdisciplinary studies, comparative analyses across regions, and the creation of publicly accessible platforms that link geospatial data with indicators of environmental and social performance. The chapter concludes by positioning satellite-based navigation technologies as transformative enablers of smart, inclusive, and environmentally responsible tourism, with strong potential to support global development goals and reshape the future of travel.

Keywords: sustainable tourism, satellite navigation, geospatial technologies, visitor management, environmental monitoring, digital innovation, participatory planning

1. Introduction

In recent years, sustainable tourism has emerged as a strategic framework for achieving a balance between economic development, environmental protection, and sociocultural integrity in travel destinations. As the tourism industry faces growing pressure to reduce its ecological footprint and foster community engagement, digital and geospatial technologies are playing an increasingly important role in enabling smarter, more responsible decision-making. Among these, Global Navigation Satellite Systems (GNSS) stand out as powerful enablers of spatial awareness and real-time data integration across a range of tourism-related activities.

GNSS refers to a constellation of satellite systems that provide continuous, real-time positioning, navigation, and timing (PNT) data worldwide [1], with key systems including the Global Positioning System (GPS, United States), GLONASS (Russia), Galileo (European Union), and BeiDou (China). Originally designed for military and scientific purposes, GNSS has evolved into a cornerstone technology in fields such as transportation, logistics, agriculture, and disaster response. In the tourism sector, however, the potential of GNSS to drive sustainability outcomes—through improved planning, monitoring, and visitor experience—is only beginning to be fully explored.

1.1 Objective and scope

This chapter offers a comprehensive review of how GNSS technologies intersect with the goals and practices of sustainable tourism. It highlights a growing body of literature and case studies demonstrating GNSS applications in eco-tourism, visitor flow optimization in protected areas, safety enhancement in remote travel contexts, and environmental impact assessment. Special attention is given to the role of Volunteered Geographic Information (VGI) and mobile applications that leverage GNSS data for participatory destination management and real-time feedback mechanisms.

In addition to summarizing current practices and innovations, this chapter critically discusses the technical, ethical, and infrastructural challenges associated with GNSS use in tourism, including issues of data privacy, digital accessibility, and connectivity in rural or underserved regions. Finally, it proposes a conceptual framework for the strategic integration of GNSS within sustainable tourism policies and practices, aligned with the United Nations (UN) Sustainable Development Goals (SDGs), especially those related to sustainable cities and communities, climate action, and responsible consumption and production.

1.2 Methodology

To establish a robust conceptual and technological foundation for this chapter, a structured literature review was conducted between April and May 2025. The aim was to identify key applications of GNSS in the context of sustainable tourism and to gather evidence on emerging tools, standards, and performance indicators relevant to this field.

The following academic databases and repositories were used: Scopus, Web of Science, Google Scholar, and arXiv for preprints, complemented by reports from international organizations such as the European GNSS Agency (EUSPA), United Nations World Tourism Organization (UNWTO), European Space Agency (ESA),

and International Civil Aviation Organization (ICAO). Search terms included combinations of the following keywords in English: “GNSS,” “sustainable tourism,” “tourist navigation,” “GNSS-R,” “crowd control,” “eco-routing,” “smart tourism,” “spatial planning,” “performance indicators,” “environmental monitoring,” and “mobility management.”

The inclusion criteria prioritized:

- Peer-reviewed articles or institutional reports published from 2012 to 2025;
- Case studies or frameworks that explicitly applied GNSS or GNSS-Reflectometry (GNSS-R) in tourism or conservation contexts;
- Technical documentation on GNSS accuracy, availability, and integrity for tourism-related tasks;
- Emerging tools or platforms supporting smart, inclusive, and sustainable tourism.

Exclusion criteria included duplicates, sources without full-text access, and publications unrelated to tourism or environmental applications.

A total of over 90 sources were initially screened. After applying the inclusion criteria, 47 publications were selected as core references to support the framework and case examples presented in this chapter. These include journal articles, book chapters, technical manuals, and preprints already integrated into peer-reviewed volumes (e.g., *Lecture Notes in Networks and Systems*).

This mixed-sources approach ensured both scientific rigor and technological applicability, bridging the gap between academic insight and real-world deployment of GNSS solutions in sustainable tourism.

1.3 Structure and organization

This chapter explores the integration of GNSS into sustainable tourism, highlighting technical enablers, practical applications, and emerging challenges. The structure of the chapter is organized to guide readers from foundational concepts to advanced applications and future research directions. Thus, the chapter is organized into the following sections:

1. Introduction—Explains the purpose of the article, what it will cover, the methods used, and how it's organized;
2. GNSS and sustainable tourism—Describes how GNSS helps with positioning, navigation, and alerts in tourism and how it supports smart and flexible tourism services;
3. Key concepts and technologies—Looks at how GNSS works together with other technologies like the Internet of Things (IoT), Geographic Information Systems (GIS), and Artificial Intelligence (AI) to improve tourism;
4. Real-world applications—Gives examples of how GNSS is used in eco-tourism, managing tourist crowds, improving safety, and monitoring the environment;

5. Smart tourism and crowdsourced data—Discusses how tourist data can be collected voluntarily to create smart tourism experiences using big data and AI;
6. Challenges—Highlights important issues such as privacy, access to technology, and making sure the data used are accurate and fair;
7. A framework for GNSS in tourism—Brings the ideas together into a model showing how GNSS can be used effectively in sustainable tourism;
8. Future research—Points out areas where more studies and new ideas are needed;
9. Conclusions—Summarizes the main findings and emphasizes the value of using GNSS in tourism that is smart, safe, and sustainable.

2. Sustainable tourism: GNSS-supported positioning, navigation, and alerts

Sustainable tourism seeks to balance the enjoyment of natural and cultural destinations with the long-term preservation of ecological integrity, social equity, and local economic vitality. Achieving these objectives requires the use of advanced management tools, particularly in destinations impacted by climate change, overtourism, or ecological fragility. Effective tourism management depends on systems that support spatial planning, enable real-time decision-making, and facilitate adaptive visitor behavior [2, 3]. Among these tools, GNSS offer fundamental support. Beyond basic geolocation, GNSS technologies provide a critical backbone for dynamic services that facilitate navigation, monitoring, alerts, and visitor flow management. These functionalities are vital not only for enhancing tourist experiences but also for protecting environmental assets and ensuring safety [4].

2.1 Core spatial functions of GNSS in sustainable tourism

To understand the practical role of GNSS in sustainable tourism, it is essential to outline the main spatial tasks where its contribution is particularly valuable:

- Accurate visitor positioning: Enables real-time tracking of tourists in parks, coastal areas, or mountainous regions—critical for safety, rescue operations, and providing informed routing options [2, 5];
- Protected area enforcement: Helps define and monitor access to ecologically sensitive or restricted zones, reducing habitat disturbance and unauthorized entry [3];
- Visitor flow monitoring and crowd control: Supports the detection of congestion hotspots and helps managers spatially and temporally redistribute visitors to minimize environmental and social impacts [6, 7];
- Context-aware routing and real-time alerts: Delivers personalized navigation, environmental alerts (e.g., floods, fire risk), and adaptive recommendations based on location and real-time conditions [2, 4];

- Infrastructure monitoring and maintenance: Tracks usage and wear on trails, signage, rest areas, and other facilities, especially in remote or high-traffic areas [8];
- Accessible and inclusive navigation: Facilitates the identification of barrier-free routes and services for tourists with mobility, sensory, or cognitive limitations, enhancing inclusivity [3];
- User-contributed data (VGI): Through platforms like hiking apps, tourists contribute geotagged data—photos, routes, and feedback—that improve environmental monitoring and participatory management [9].

2.2 Technical requirements for GNSS in tourism applications

To support the precision and reliability demanded by modern sustainable tourism, advanced GNSS technologies such as Real-Time Kinematic (RTK), Precise Point Positioning (PPP), and European GNSS (e-GNSS) are essential [2, 5] (**Figure 1**). These technologies significantly enhance positioning accuracy and reliability, which are critical for applications like smart mobility, location-based experiences, and real-time environmental or visitor monitoring.

Figure 1 presents a comparison of four GNSS positioning methods: Standalone GNSS, Differential GNSS (DGNSS)/RTK, PPP/e-GNSS, and Wide Area DGNSS. It illustrates how each method processes satellite signals with varying levels of correction support. These range from no corrections in Standalone GNSS to advanced augmentation using reference stations, network databases, or satellite-based systems. The figure also highlights the trade-offs between system complexity and the resulting positioning accuracy.

RTK delivers centimeter-level accuracy using correction data from nearby reference stations via telecom links, ideal for autonomous shuttles and Augmented Reality

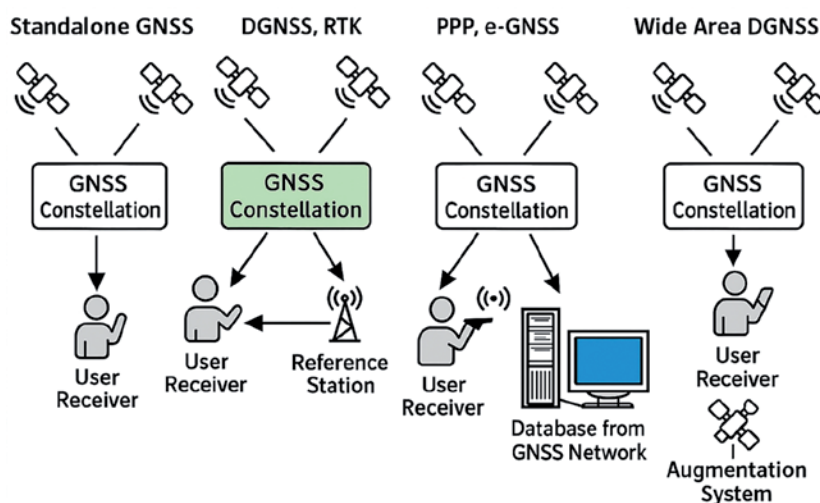


Figure 1.
Comparison of four GNSS positioning techniques: Standalone GNSS, DGNSS/RTK, PPP/e-GNSS, and Wide Area DGNSS. The diagram illustrates how each method processes satellite signals with different levels of correction and augmentation—from no corrections in Standalone GNSS to advanced support through local reference stations, network-based databases, or satellite-delivered enhancements.

(AR) navigation in tourist areas. PPP, while slower to converge, achieves high precision without local base stations, making it suitable for remote or expedition-based tourism. e-GNSS, through systems like Galileo and EGNOS, improves signal reliability and supports safety-critical services, including authenticated positioning and search-and-rescue functions.

The effective use of these GNSS modes relies on a strong supporting infrastructure, including:

- Reference station networks, such as Continuously Operating Reference Stations (CORS);
- Telecom systems, including 4G/5G networks for real-time data transfer;
- Geospatial databases, integrating GIS and VGI;
- Data servers and AI engines for integrating GNSS with IoT, environmental data, and user-generated content.

Together, these elements support the delivery of high-precision, context-aware services that enhance sustainable tourism through low-impact transportation, improved visitor safety, and evidence-based decision-making.

To ensure reliable GNSS deployment in tourism, several key performance parameters must be considered, chief among them: accuracy, availability, and integrity [2, 5, 8]. These must be tailored to the specific operational needs of each use case [2, 5, 8]. A summary of the technical requirements for selected sustainable tourism applications is provided in **Table 1**.

Accuracy is fundamental. While standard GNSS provides location precision within approximately 5 to 10 m, sufficient for general visitor tracking, more demanding tasks such as safety enforcement, ecological zone monitoring, or trail compliance often require higher spatial resolution. In these cases, enhanced positioning methods

Tourism application	Required accuracy	Availability	Integrity requirement	Examples of use
Safety and emergency location in remote areas	1–5 m	High (continuous tracking)	High (life-critical functions)	Tracking hikers in national parks or isolated trails
Visitor flow monitoring in urban heritage sites	<5 m	Very high (dense areas)	Moderate	Monitoring congestion in historic city centers
Ecological alerts and adaptive routing	5–10 m	High (natural environments)	High	Redirecting visitors based on fire risk or habitat alerts
Accessible route navigation	<3 m	Very high (urban/rural mix)	Moderate	Guiding users along wheelchair-friendly or barrier-free paths
VGI collection and participatory mapping	<10 m	Moderate to high	Moderate	Collecting user tracks and points of interest
Mobile infrastructure inspection and planning	1–5 m	High	Low to moderate	Locating signs, facilities, or maintenance points

Table 1.
Technical requirements of GNSS services for sustainable tourism tasks.

like Satellite-Based Augmentation Systems (SBAS) or RTK techniques are essential to achieve sub-meter accuracy [8].

Availability refers to the continuous and dependable reception of GNSS signals. This is particularly important in remote, mountainous, or densely forested areas, where signal obstruction is common. Ensuring uninterrupted service in such challenging environments is vital for applications related to emergency response, navigation, and environmental monitoring.

Integrity concerns the system's ability to detect, assess, and correct errors in the positioning signal. High integrity is crucial in safety-critical applications, where unreliable data could lead to harmful outcomes or misinformed decisions, especially in sensitive ecological zones or during high-risk outdoor activities.

In complex or signal-degraded environments, such as urban canyons or dense forests, hybrid positioning approaches are increasingly employed to enhance performance. These systems combine GNSS with complementary technologies—such as Wi-Fi, Bluetooth Low Energy (BLE) beacons, and inertial sensors—to maintain accurate and consistent location tracking when satellite visibility is limited [2].

Together, these performance parameters ensure that GNSS technologies can reliably support a wide range of sustainable tourism functions, from visitor guidance and safety to conservation and adaptive destination management.

2.3 GNSS as an enabler of smart and adaptive tourism

GNSS technologies are more than a tracking tool; they enable a paradigm shift from static tourism planning to dynamic, data-informed destination management. With real-time spatial intelligence, tourism authorities can implement [4]:

- Adaptive access strategies that respond to real-time congestion or environmental conditions.
- Efficient infrastructure use based on actual visitor flows.
- Tailored experiences aligned with visitor profiles, needs, and behaviors.

Moreover, GNSS integrates seamlessly with other digital technologies such as GIS, smartphone applications, environmental sensors, and AI. Together, these tools form a smart tourism ecosystem that enhances efficiency, safety, visitor satisfaction, and most importantly, sustainability.

By embedding GNSS within this digital infrastructure, destinations can align tourism practices with the UN SDGs, protecting natural and cultural assets while creating meaningful and responsible experiences for visitors [9].

3. GNSS technologies and sustainable tourism

In the tourism industry, GNSS technologies are increasingly recognized as foundational tools for promoting sustainability, enhancing visitor experience, and supporting data-driven planning [10–12].

Figure 2 illustrates the key roles of GNSS in sustainable tourism across four areas: [2]. Positioning, navigation, and alert services for accurate geolocation and safety; [3] Enabling smart and adaptive tourism through dynamic route optimization and



Figure 2.

GNSS technologies support sustainable tourism by enabling navigation, smart visitor management, integration with digital tools, and monitoring of environmental impact.

behavioral mapping; [4] Integration with IoT, GIS, and AI for real-time data collection and predictive analytics; and [5] Managing visitor demand and environmental impact via traffic regulation, resource monitoring, and carrying capacity assessments.

3.1 Positioning, navigation, and alert services for tourism

GNSS is best known for its core function—accurate geolocation and navigation—which offers essential benefits to tourists by improving safety, orientation, and mobility (**Figure 2**) [5, 8]. Tourists rely on GNSS-enabled devices for route planning, wayfinding in unfamiliar environments, and accessing context-sensitive information based on location [4]. These services become especially critical in remote, ecologically fragile, or disaster-prone areas, where GNSS-based alert systems can be integrated with early warning networks to enhance visitor safety and emergency response [8]. Furthermore, GNSS supports real-time tracking of tourist flows, enabling site managers to better coordinate transportation, manage access, and reduce congestion during peak periods [4, 5].

3.2 Enabling smart and adaptive tourism through GNSS

Beyond basic navigation, GNSS plays a transformative role in advancing “smart tourism” (**Figure 2**), a model that integrates digital technologies to create personalized, adaptive, and sustainable visitor experiences. GNSS enables dynamic route optimization, geofencing, and behavioral mapping, which are increasingly used by tourism authorities and businesses to manage visitor movements intelligently. By providing precise spatiotemporal data, GNSS helps balance tourist demand with environmental and social carrying capacities.

Recent studies highlight the growing academic focus on digital innovation in sustainable tourism [6, 13–15]. For instance, Pilelienė et al. conducted a bibliometric

analysis identifying GNSS as a key enabler of responsible tourism strategies [13]. Spatial data derived from GNSS allow stakeholders to monitor visitor distribution patterns, assess the use of natural and cultural resources, and design interventions that align tourism development with environmental protection. As highlighted in the 2023 European Capital of Smart Tourism report [16], cities like San Sebastián and Seville are leveraging sensor-based platforms (e.g., Smart Kalea) and real-time mobility data to optimize crowd management and reduce pressure on sensitive areas. Moreover, Pafos has integrated GNSS data into mobile apps and smart signage (e.g., QR-coded tourism panels and smart mobility systems), enhancing both interpretative experiences and sustainable visitor flows through protected heritage sites. These practices demonstrate how spatial intelligence derived from GNSS and IoT platforms can guide adaptive planning and help balance conservation with tourism development [16].

3.3 Integration with IoT, GIS, and AI technologies

The real power of GNSS for sustainable tourism emerges when it is integrated with complementary technologies such as the IoT, GIS, and AI (**Figure 2**). This convergence enables the creation of interconnected systems capable of real-time data collection, spatial analysis, and predictive modeling.

For example, Barros et al. reviewed applications that combine GNSS with geo-tagged social media and mobile app data for real-time monitoring of visitor behavior in protected areas [14]. These platforms offer critical insights into crowding dynamics, allowing site managers to implement adaptive measures in response to environmental stress.

In urban settings, GNSS-derived data supports spatial modeling of tourist behavior. Neuts and Nijkamp demonstrated this by analyzing crowd perceptions in Bruges, Belgium, showing how locational data can inform the optimization of visitor flows and the mitigation of overcrowding [6]. Similarly, Gutiérrez et al. used GNSS data to map the spatial distribution of Airbnb listings in Barcelona, identifying tourism pressure zones and informing urban planning strategies [15].

Such applications exemplify how GNSS, when embedded within smart city and destination management systems, supports evidence-based policymaking that balances tourism development with environmental sustainability and local quality of life.

4. Applications of GNSS in sustainable tourism

4.1 Eco-tourism and protected natural areas

Eco-tourism promotes responsible travel to natural areas, emphasizing conservation, community engagement, and educational experiences. In this setting, GNSS provide a technological backbone for monitoring ecological impacts and guiding visitors along designated paths to minimize disruption.

For example, in the Bavarian Forest National Park, Germany, researchers assessed GNSS-based VGI collected from outdoor recreation platforms such as Komoot and Outdooractive [17]. These data sources, contributed by tourists themselves, allowed for high-resolution mapping of movement patterns within the park. This enabled managers to distinguish overused trails from underutilized ones, providing a basis for targeted conservation interventions and rerouting efforts to protect fragile habitats [17].

In another case, the municipality of Gelnica in Slovakia used GNSS-integrated GIS to assess visitor flows and underrepresented points of interest. By applying kernel density estimation to location data, planners were able to visualize tourism hot and cold spots. This led to a revision of signage and route planning to support a more balanced spatial distribution of visitors, alleviating pressure on popular sites and stimulating engagement with lesser-known cultural assets [18].

Additionally, GNSS has supported eco-tourism efforts in marine parks and forest reserves in Southeast Asia and South America. In such areas, GNSS is used to track boats and hiking groups, ensuring they remain within permitted zones. Real-time alerts notify guides if sensitive zones or nesting areas are approached, reinforcing conservation measures through behavioral guidance. These approaches contribute to achieving biodiversity conservation targets, as outlined in the UN Sustainable Development Goals.

4.2 Real-time visitor flow and crowd management

Managing the number, timing, and movement of tourists is essential to preserving destination quality and ecological integrity. GNSS data provide an objective and dynamic way to monitor and respond to visitor flows in real time.

In the Forbidden City, Beijing, a site that receives over 15 million annual visitors, researchers combined GNSS, Wi-Fi signals, and Bluetooth beacons to examine movement density, identify spatial congestion points, and adjust visitor flow. The study revealed spatial imbalances, such as bottlenecks around major halls, which were mitigated by reconfiguring signage, redistributing services, and limiting group sizes during peak hours [19]. The GNSS component provided timestamped location data essential for modeling circulation patterns.

GNSS also enables predictive crowd management. Using historical movement data, artificial intelligence models can forecast peak visitation times and recommend preemptive actions. Apps can suggest optimal times to visit specific sites or redirect tourists toward less crowded alternatives, enhancing the overall experience while preserving the site.

Evidence from the Netherlands supports the behavioral effect of such interventions. During a large-scale cultural event, tourists who received personalized recommendations for lesser-visited attractions via a GNSS-based app were more likely to modify their route, reducing crowding in central areas [20]. These digital nudges rely heavily on accurate geolocation data to suggest timely and context-aware alternatives.

Tourist carrying capacity, long treated as a static figure, can be reconceptualized dynamically with GNSS input. Instead of fixed visitor caps, managers can adopt flexible thresholds based on real-time congestion indicators and environmental stress levels. This approach has been piloted in urban parks in Barcelona and natural parks in Costa Rica, where GNSS-informed dashboards guide rangers and urban planners in real-time decision-making [15].

4.3 Tourist safety, risk management, and emergency response

In adventurous or remote travel settings, safety becomes a critical concern. GNSS-based applications are increasingly used to improve risk management and emergency response. For instance, hikers in mountainous terrain or climbers in volcanic areas can be tracked via wearables or mobile apps. If a user deviates from a trail or is immobile for a prolonged period, automated alerts can be sent to park authorities or emergency responders.

In Iceland and Patagonia, where unpredictable weather and terrain pose frequent hazards, GNSS is integrated into emergency systems to monitor the positions of registered hikers. Some national parks require hikers to download GNSS-based safety apps before entering high-risk areas. These apps include geofenced danger zones, route difficulty levels, and emergency beacon functions [4].

The ISO 31030 standard for travel risk management recommends the use of real-time location data to support institutional duty of care. GNSS allows organizations to track their travelers, assess their proximity to crisis events (e.g., natural disasters, civil unrest), and deploy assistance when needed [21]. Platforms developed by companies such as World Travel Protection leverage GNSS to provide 24/7 situational awareness, traveler support, and crisis coordination [22].

At a broader level, aggregated GNSS data can also help detect recurring unsafe behaviors. For example, repeated trail deviation patterns may signal the need for clearer signage or educational outreach. Destinations can thus transition from reactive to preventive safety strategies, supporting both tourist well-being and destination resilience.

4.4 Environmental monitoring and impact assessment

GNSS technologies, particularly GNSS-R, are increasingly integrated into tourism management frameworks as tools for real-time environmental observation and adaptation [10, 23]. Unlike traditional visitor tracking, GNSS-R allows for the continuous and passive monitoring of land surface conditions, such as vegetation moisture, snow cover, soil saturation, and flooding, by measuring the reflection of satellite signals off the Earth's surface. This makes GNSS-R especially suitable for climate-sensitive and ecologically vulnerable tourist destinations, where timely, data-informed decisions are essential to ensure both safety and sustainability [24, 25].

For example, initiatives like the ESA's GREAT and GROOVE projects have demonstrated how GNSS-R can be used to monitor environmental variables that directly affect tourism operations, including trail accessibility, fire risk, or wetland sensitivity [26]. Similarly, the University of Oulu has shown how GNSS-R can identify coastal flood zones in real time, providing critical information for evacuation planning and the dynamic adjustment of tourist routes in low-lying areas [27].

To support operational tourism planning, GNSS-R data can be integrated into digital dashboards and mobile systems that deliver context-aware, real-time recommendations to both managers and visitors. As shown in **Figure 3**, GNSS-R outputs (e.g., vegetation stress, surface moisture, or flooding risk) can feed into sustainable tourism planning tools, which in turn generate updated route suggestions, access warnings, or conservation alerts. For instance, if GNSS-R detects excessive dryness in a nature reserve, authorities may choose to temporarily restrict visitor access to reduce fire risk and protect biodiversity.

This type of integration supports a shift from reactive to anticipatory tourism management, allowing destinations to adapt their offerings based on environmental conditions. The map-based interface shown in **Figure 3** illustrates how environmental zones (e.g., flooding, excessive dryness) can be overlaid with geolocated tourism infrastructure (e.g., trails, viewpoints, visitor centers), enabling intelligent decision-making by both travelers and administrators. This approach is particularly useful in protected areas, mountain parks, and coastal regions that are highly exposed to climatic variability. Furthermore, GNSS-R data complement GNSS-based visitor tracking, enabling correlation between human presence and environmental impact.

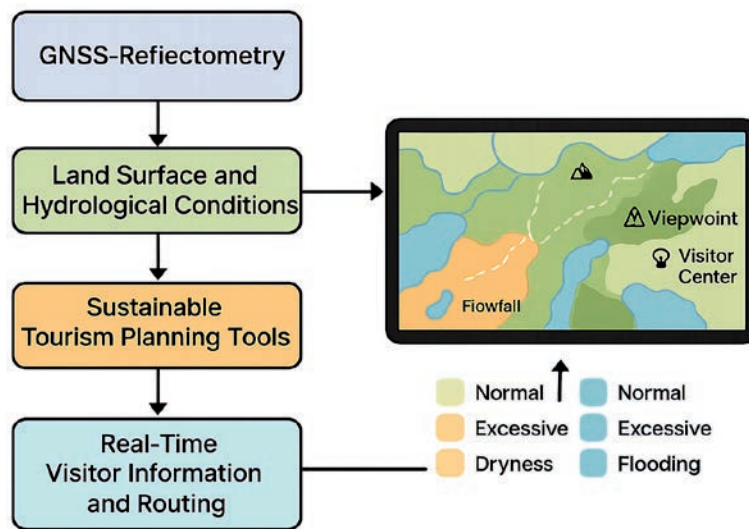


Figure 3.
Conceptual diagram illustrating GNSS-R data integration into sustainable tourism planning tools.

This dual-layer analysis allows managers to detect where foot traffic coincides with ecological degradation (e.g., erosion, habitat disruption), prompting timely interventions such as trail rerouting, seasonal closures, or educational campaigns.

5. Crowdsourced data and smart tourism destinations

5.1 Volunteered geographic information

VGI has emerged as a pivotal tool in sustainable tourism management, enabling tourists to actively contribute geospatial data through applications like Komoot, Strava, and AllTrails [17]. These platforms allow users to record and share their routes, preferences, and experiences, providing valuable insights into visitor behaviors and spatial patterns.

Horst et al. [17] evaluated the utility of GNSS-based VGI for monitoring human spatial behavior in outdoor recreational areas. Their study in the Bavarian Forest National Park, Germany, compared data from platforms such as GPSies, Outdooractive, and Komoot with automated visitor counts obtained from sensor-based monitoring systems. The findings revealed strong correlations between the VGI-derived route data and the actual visitor numbers recorded by the sensors, affirming the effectiveness of VGI in assessing visitor distribution within protected areas.

Similarly, Santos et al. [28] analyzed 22,031 tracks of “on foot” and “on wheels” activities submitted by 3297 users over 12 years in the Lisbon Metropolitan Area and southwest Portugal. Their research demonstrated the applicability of VGI in evaluating recreational uses across metropolitan and rural contexts, highlighting its potential in informing tourism planning and management.

Despite its advantages, VGI is subject to sampling bias, often representing younger, tech-savvy tourists. However, when triangulated with systematic methods, VGI becomes a powerful tool for participatory destination management. Platforms

like Geo-Wiki engage citizens and experts in environmental and socioeconomic monitoring, allowing for the validation and collection of geographical information through crowdsourcing and citizen science [29].

Moreover, the integration of VGI with Geographic Information Systems (GIS) enhances the granularity and accuracy of spatial data, supporting real-time data collection for emergency response, environmental monitoring, urban planning, and cultural heritage preservation [30].

5.2 Smart destinations and adaptive tourism services

The concept of smart tourism destinations (STDs) involves the integration of advanced technologies to enhance the tourist experience and promote sustainable practices. GNSS play a crucial role in this infrastructure, enabling real-time updates, adaptive itineraries, and context-aware recommendations. AI-driven systems analyze GNSS data to suggest less crowded times, highlight sustainable attractions, and optimize public transport options.

El Archi et al. [31] conducted a systematic literature review analyzing smart tourism destinations in the context of sustainable development. Their study identified current applications and future directions, emphasizing the role of digital technologies in enhancing tourism experiences and sustainability.

The European Union's Smart Tourism Destinations initiative provides tailor-made coaching and capacity-building services to help destinations improve data mastery and become or enhance their status as smart tourism destinations. This includes tools setup, self-assessment, priority actions, vision and ambition identification, and roadmap development.

Buhalis and Amaranggana [32] discussed how smart tourism destinations could enhance tourism experiences through the personalization of services. They highlighted the importance of dynamically interconnecting stakeholders through technological platforms, enabling the exchange of information related to tourism activities and the analysis of big data to reveal patterns and trends.

Furthermore, smart tourism destinations must consider the diverse preferences of different generational cohorts. A study by Botezat et al. [33] investigated how managers could arrive at optimized decisions on smart tourism destination attributes for individuals within Baby Boomers, Generation X, Millennials, and Generation Z. The research emphasized the need for a proactive and adaptive approach to cater to the heterogeneous market.

In addition, the integration of smart tourism practices with smart city initiatives can enhance the sustainability and competitiveness of tourism destinations. However, misalignments between smart city projects and tourism strategies can hinder the transformation into smart tourism destinations. Cavalheiro et al. [34] explored this dynamic, highlighting the importance of political continuity, local government tourism strategy, citizen engagement, and consideration of the local context.

5.3 Role of AI and big data analytics in personalized tourism experiences

The integration of AI and big data analytics is reshaping tourism by enabling more personalized, efficient, and sustainable visitor experiences [10, 24]. Leveraging data from VGI, mobile apps, social media, and sensor networks, AI systems can analyze complex datasets to generate real-time insights for both travelers and destination managers [13, 23].

A key application is personalized recommendations, where AI suggests tailored itineraries, attractions, and services based on user preferences, location, and behavior. For example, eco-conscious tourists may receive suggestions for lesser-known nature trails or low-impact transport options, while families might be guided toward age-appropriate activities during less crowded times [10, 24].

AI also powers predictive analytics, allowing managers to forecast demand, anticipate crowding, and adjust services dynamically. These models rely on GNSS data and other inputs to optimize visitor distribution and support sustainable capacity management [4, 25].

In parallel, natural language processing (NLP) tools help analyze tourist feedback from reviews and social media, providing insights into satisfaction and areas for improvement. Combined with sentiment analysis, these tools support continuous service refinement [24].

Big data platforms are central to this ecosystem, integrating data from booking systems, environmental sensors, and IoT infrastructure to enable real-time monitoring and adaptive service delivery, key features of STDs [13].

However, the growing use of AI and big data must be guided by strong ethical practices, including data privacy, transparency, and fairness. Ensuring informed consent and inclusive design is essential to avoid reinforcing biases or compromising user trust [23, 24].

Thus, AI and big data analytics enable a shift from static tourism models to dynamic, visitor-centered systems that enhance both experience and sustainability [10, 24].

6. Challenges and ethical considerations

6.1 Data privacy and informed consent

The widespread use of GNSS and VGI in tourism presents multiple ethical and legal challenges, particularly around data privacy and informed consent. The General Data Protection Regulation (GDPR) of the European Union mandates that user consent for data processing must be freely given, informed, specific, and unambiguous [35]. However, studies have shown that most users do not thoroughly read or understand terms and conditions, leading to questionable validity of consent in digital tourism platforms [36].

To address these concerns, researchers have proposed frameworks for “data protection by design,” which integrate privacy safeguards into system architecture from the outset. Chhetri et al. [37] developed a GDPR compliance tool that uses semantic modeling to ensure that users provide meaningful consent and that data controllers follow lawful data processing protocols.

Another concern relates to the potential future uses of data collected through GNSS-enabled systems. Big data analytics can uncover patterns far beyond the original purpose of data collection, raising concerns about secondary use, profiling, and surveillance. Dynamic consent models, where users can adjust permissions over time, are proposed as a more flexible alternative to static one-time agreements [38].

For platforms leveraging VGI, transparency is essential not only in consent forms but also in explaining how data will be used, stored, and shared. The more aware users are of the value and implications of their data contributions, the more likely they are to participate voluntarily and responsibly.

6.2 Technological barriers and the digital divide

The application of GNSS technologies in sustainable tourism also faces limitations due to the digital divide. In many remote or developing regions, GNSS signal reliability, lack of digital infrastructure, and limited internet access severely restrict the usability of location-based tools [39]. This technological gap often reflects existing socioeconomic inequalities, with marginalized groups, such as rural communities, the elderly, or people with disabilities, being excluded from digital tourism systems.

Digital literacy is another critical factor. Many tourists, especially older individuals or those with limited education, may not be comfortable using GNSS-enabled mobile applications or understanding the implications of data sharing. According to research by Guttentag [40], technology-based tourism services disproportionately benefit younger and wealthier tourists, reinforcing social exclusion.

Solutions must include investments in infrastructure (e.g., 4G/5G networks in rural areas) and digital education programs. Low-tech alternatives—such as printed maps with QR codes, guided tours using analog methods, or offline GPS applications—can help bridge the gap for digitally disadvantaged tourists [41].

Governments and tourism boards must also ensure that smart tourism initiatives are inclusive by design. This includes providing interfaces in multiple languages, designing for accessibility, and ensuring that digital tourism tools do not become gatekeepers to basic tourist services.

6.3 Representativeness and data quality

VGI is an increasingly popular source of spatial data in tourism studies, yet it is not without flaws. One of the major limitations of VGI is its representativeness. Because VGI platforms rely on voluntary contributions, the data often reflects the behavior and preferences of younger, urban, tech-savvy users who are more likely to use mobile tracking apps [42]. This leads to sampling biases and can misrepresent broader tourist demographics.

Horst et al. [17], in their study on VGI in Bavarian Forest National Park, found that while data from Komoot and Outdooractive closely correlated with sensor-based visitor counts, contributions were heavily skewed toward hikers and cyclists, neglecting families, older visitors, or tourists with limited mobility.

To improve representativeness and reliability, researchers recommend combining VGI with traditional data sources, including physical sensors (e.g., trail counters), visitor surveys, and interviews. This mixed-methods approach allows for cross-validation and contextualization of user-generated data [6].

Additionally, territorial unevenness is a recognized issue in VGI-based predictive mapping. High-traffic areas often generate more data, while less-visited but equally important regions remain underrepresented. Zhang et al. [43] proposed a representativeness-directed approach, which adjusts data weighting based on demographic and spatial characteristics to improve the predictive accuracy of geographic models.

Another quality-related challenge lies in the temporal inconsistency of VGI. Contributions may be dense during peak seasons and sparse at other times, leading to distorted impressions of site popularity or usage trends. Regular data audits, normalization techniques, and temporal smoothing methods are useful strategies to account for such fluctuations [44].

Finally, ethical concerns overlap with data quality. Inaccurate or falsified data, whether intentional or accidental, can lead to misguided planning decisions or

ineffective management policies. Therefore, it is vital that platforms using VGI establish clear standards for data accuracy, traceability, and correction protocols [45].

7. Conceptual framework for GNSS integration in sustainable tourism

Building upon the literature and case studies previously discussed, this section presents a conceptual framework to guide the ethical, inclusive, and impactful integration of GNSS into sustainable tourism planning and management. At the center of this framework lies the need for measurable sustainability outcomes, which can be achieved through the definition and use of Key Performance Indicators (KPIs) that connect geospatial data with actionable strategies.

Table 2 outlines examples of KPIs across environmental, social, and economic dimensions, along with their definitions and practical applications:

These indicators can be incorporated into tourism management plans to continuously monitor performance, detect emerging risks, and inform adaptive interventions. For example, when trail overuse is detected through GNSS data, managers can implement rerouting strategies or communicate alternative options via digital platforms. Similarly, biodiversity risk alerts from GNSS-R can trigger proactive protection measures in sensitive ecosystems. In addition to performance monitoring, effective data governance is essential. Any system using GNSS must comply with privacy regulations such as the GDPR, ensuring that tourists' location data are collected with informed consent, processed lawfully, and stored transparently. The adoption of open geospatial standards and interoperable systems facilitates collaboration across regions and platforms, in alignment with the UN initiative on Global Geospatial Information Management (UN-GGIM) recommendations [46]. Projects using VGI must also incorporate ethical safeguards to avoid misuse or unintended surveillance.

Dimension	KPI example	Definition and application
Environmental	CO ₂ emissions avoided	Estimation of emissions saved by promoting walking routes or public transport alternatives, guiding low-carbon travel strategies
Environmental	Trail overuse frequency	Number of days a route exceeds sustainable carrying capacity; used to manage crowding and prevent environmental degradation
Environmental	Biodiversity risk alerts	GNSS-R-derived indicators of stress in protected zones; inform temporary closures or route adjustments
Social	Accessibility rate	Percentage of tourist routes accessible to people with disabilities; supports inclusive infrastructure planning
Social	VGI participation rate	Frequency of user-contributed geodata; measures engagement and supports participatory governance
Economic	Visits to underrepresented areas	GNSS-tracked flows to less-visited points of interest; helps redistribute tourism and support local economies
Economic	Eco-certified route usage	Proportion of tourists choosing certified sustainable paths; indicates adoption of responsible practices

Table 2.
Key Performance Indicators (KPIs) for sustainable tourism enabled by GNSS technologies.

A commitment to inclusive design is also critical. GNSS-enabled tourism tools must be accessible to all, including older adults, individuals with disabilities, and people in areas with limited connectivity. Multilingual interfaces, voice guidance, offline functionality, and compatibility with assistive technologies are essential features. European case studies have shown that thoughtful, low-tech solutions can greatly enhance accessibility in nature-based tourism areas [47]. Collaboration among stakeholders enhances both the legitimacy and adoption of GNSS tools. The development of tourism technologies should involve local communities, government agencies, developers, and non-governmental organizations (NGOs) to ensure contextual relevance and social acceptance. Participatory mapping efforts that combine GIS expertise with community-sourced data foster empowerment and improve decision-making quality [48]. Finally, developing the skills and knowledge of those involved in tourism is essential for the sustainable use of GNSS technologies. Destination managers, tour operators, and local authorities need training to accurately interpret geospatial data, apply sustainability indicators, and incorporate this information into planning and policy decisions. Tourists can also be actively involved through gamified mobile applications that promote eco-friendly behavior—such as selecting environmentally conscious routes, using public transportation, or participating in conservation activities. These applications use rewards and incentives to encourage responsible and sustainable travel choices [49].

In conclusion, this framework supports a structured yet flexible approach to GNSS integration in sustainable tourism. By emphasizing measurable indicators, ethical data use, inclusive design, multi-stakeholder collaboration, and ongoing education, GNSS technologies can help transform tourism into a smarter, more equitable, and environmentally aligned sector, fully supportive of the UN SDGs.

8. Future directions and research agenda

Building upon the findings discussed throughout this chapter, we propose a forward-looking research agenda to support the continued evolution and responsible application of GNSS in sustainable tourism. The integration of digital technologies into tourism is accelerating, and GNSS offers powerful capabilities that are only beginning to be fully utilized. Based on empirical case studies and bibliometric analyses, including the recent review by Pilelienė et al. [13], there is a clear momentum toward digital innovation in sustainability contexts. However, several gaps remain that require systematic investigation.

First, comparative studies of GNSS-based tourism tools across various geographic and socio-cultural contexts are needed. Much of the current research focuses on Europe, East Asia, and North America, but developing regions and the Global South are underrepresented. This imbalance risks limiting the generalizability of existing findings and may obscure valuable local adaptations of GNSS tools. Future studies should evaluate how these systems perform under different environmental conditions, infrastructure availability, and cultural practices. For example, GNSS-based trail guidance in alpine parks may function differently than in coastal ecotourism zones, both technically and in terms of user expectations [50].

Second, the integration of GNSS data with other technological systems, such as satellite remote sensing, AI, and the IoT, presents a compelling frontier for research. The fusion of these technologies could support real-time, climate-resilient tourism planning. For instance, using AI algorithms to predict crowding patterns or climate

risks based on GNSS and meteorological data could help managers adaptively schedule access to fragile areas or inform visitors about safer travel times. Remote sensing could be used to map vegetation health and erosion, while GNSS tracks provide human movement overlays, offering a holistic view of tourism's ecological footprint. This multimodal integration holds promise as well as raises questions about interoperability, data management, and system complexity [51].

Third, there is a pressing need for longitudinal studies that assess behavioral change in tourists who use GNSS-based applications. While many studies report short-term findings on visitor movement and preferences, few have examined the sustained impact of these tools on tourist behavior, awareness, and environmental stewardship. Do tourists who receive GNSS-based recommendations continue to adopt more sustainable practices in future trips? Can location-aware technologies cultivate lasting changes in travel habits? Investigating these questions through long-term mixed-methods research, combining app data, surveys, and interviews, would deepen our understanding of technology's role in behavior change.

Fourth, more research is required to develop ethical frameworks for the use of VGI in tourism, particularly in culturally sensitive or environmentally vulnerable sites. While VGI offers valuable insights, it can also pose risks to privacy, cultural integrity, and ecological balance. For instance, sharing geotagged images or GPS-tracked routes from sacred or culturally sensitive sites may unintentionally attract large numbers of visitors, which can lead to overcrowding, disturbance of local customs, or a lack of respect for spiritual or community values. Ethical guidelines should be developed in consultation with local communities, cultural custodians, and environmental scientists. These frameworks should cover issues such as consent, data anonymization, community participation in data governance, and protocols for managing sensitive geospatial content [14].

Fifth, there is significant potential in developing open-access digital platforms that combine GNSS data with sustainability performance dashboards, such as the Smart City Dashboard of Amsterdam, which integrates mobility and environmental data for urban planning, or the VISIT Greenland Portal, which uses GNSS and sensor data to monitor tourist flows and environmental pressures in protected areas. Such platforms could democratize access to real-time tourism analytics, helping small destinations, local businesses, and NGOs monitor sustainability indicators and make data-informed decisions. These platforms might include visualizations of tourist density, carbon emissions by travel mode, waste management indicators, or biodiversity metrics. Coupling GNSS with tools like Power BI or open-source GIS could make these systems scalable and cost-effective. Research is needed to determine the best design, data pipelines, and user interfaces to maximize usability and stakeholder uptake.

In addition to these specific directions, there is also a broader need for interdisciplinary collaboration in GNSS and tourism research. Engineers, data scientists, environmental researchers, tourism managers, and policymakers must work together to address the complex challenges at the intersection of technology and sustainability. Interdisciplinary research centers or networks dedicated to smart tourism and geospatial sustainability could play a catalytic role in this domain. Funding agencies and academic institutions should prioritize grants that foster collaboration across disciplines and regions.

Lastly, the research agenda should be aligned with global frameworks such as the UN SDGs. GNSS-based tourism technologies can directly support SDG targets related to sustainable cities and communities (SDG 11), climate action (SDG 13), and

responsible consumption and production (SDG 12). However, realizing this potential requires intentional alignment between research questions, technological design, and sustainability metrics [3, 23].

In conclusion, while GNSS is already contributing significantly to tourism innovation, its transformative potential remains only partially realized. The research directions outlined above highlight the need for comparative, integrative, ethical, and participatory approaches. Addressing these priorities will not only improve the effectiveness of GNSS tools but also ensure their alignment with broader societal and environmental goals. As tourism continues to evolve in the face of global challenges—climate change, overtourism, inequality—the role of geospatial technologies must be examined not only for their utility but also for their capacity to foster a more sustainable and inclusive future.

9. Conclusions

The integration of GNSS into sustainable tourism presents transformative opportunities for enhancing destination management, improving visitor experiences, and supporting long-term conservation goals. GNSS technologies have evolved from their traditional navigational functions into powerful tools that enable real-time tracking, spatial analysis, and data-driven decision-making across diverse tourism contexts.

Throughout this chapter, we have explored the multifaceted applications of GNSS in areas such as eco-tourism, visitor flow optimization, safety, environmental monitoring, and participatory governance. These technologies provide precise and actionable data that can inform policies, improve infrastructure planning, and foster responsible travel behaviors. As destinations face increasing challenges related to overtourism, climate change, and environmental degradation, GNSS offers solutions that are both scalable and adaptable.

However, fully realizing the potential of GNSS in tourism requires addressing several critical challenges. These include bridging technological gaps in remote or underserved areas, designing inclusive digital tools that are accessible to diverse user groups, and ensuring that data collection and use are conducted ethically and transparently. Furthermore, integrating GNSS applications with broader sustainability objectives demands interdisciplinary collaboration and proactive policy support.

Looking ahead, aligning GNSS-enabled strategies with international sustainability frameworks can guide the development of tourism models that are not only innovative but also equitable and environmentally conscious. By fostering cooperation among stakeholders—governments, researchers, communities, and the private sector—GNSS can help shape a tourism future that is more resilient, informed, and responsive.

In an era defined by rapid digital transformation and growing environmental urgency, GNSS stands out as a key enabler of smart, sustainable, and inclusive tourism. Its continued development and thoughtful application will be essential for navigating the path toward a more connected and responsible global travel landscape.

Conflict of interest

The authors declare no conflict of interests.

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Section 4

Enabling Governance: Policy Frameworks and Institutional Pathways

Perspective Chapter: UNFC and UNRMS – Global Tools Enabling Sustainable Resource Management for a Better Tomorrow

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Abstract

Making wise decisions about resource development is complex—supply of minerals and other raw materials should be affordable, secure and sustainable. With progressing climate change, digital transformation, and energy transition, certain raw materials are deemed critical to governments and industries. At the same time, society demands resource management at public and private levels, which meets Environmental, Social and Governance (ESG) expectations and complies with the United Nations’ Sustainable Development Goals (SDG). This raises questions, “How can those responsible for resource management deal with multi-faceted societal expectations, yet deliver on economic targets in a competitive market? How can they communicate their decisions, recognizing the legitimate interests and needs of stakeholders?” The United Nations has provided a Resource Management System (UNRMS) aligned with SDGs to address these challenges for the public and private sector. This has been developed by globally-recognized experts and provides principles and requirements for a comprehensive ESG assessment of resource projects, independent of the resource type. UNRMS is supplemented by the UN Framework Classification for Resources (UNFC), which allows users to consistently quantify resource and classify projects by their environmental, socioeconomic viability and technical feasibility and degree of confidence in estimates. UNFC is scalable from projects to portfolios at company, country or inter-governmental level. This capability is in demand; for example, UNFC has been incorporated into the EU’s Critical Raw Materials Act (CRMA) and the Pan-African Resource Reporting Code (PARC). Adoption of UNRMS and UNFC further augments the application of artificial intelligence (AI) for decision support in sustainable resource management.

Keywords: subsurface extraction, minerals, raw materials, inventory, circularity, sustainable resource management, strategic planning, digital solutions, artificial intelligence (AI), intergenerational justice, United Nation Framework Classification For Resources (UNFC), United Nations Resource Management System (UNRMS),

critical raw materials (CRM), strategic raw materials (SRM), Critical Raw Materials Act (CRMA), UN Sustainable Development Goals (SDGs), environmental-social-governance (ESG), corporate social responsibility (CSR), government-industry-capital allocator

1. Introduction

Access to energy and mineral raw materials are necessary enablers of development. Both are vital in everyone's daily life and essential for maintaining and improving the well-being of societies worldwide [1–9]. The future must be more sustainable and requires a speedy energy transition through responsibly sourced secure and affordable access to raw materials. Even with the most careful behavior and efficient operation, employing all available means including recycling and the use of primary geological resources, such as for example minerals, oil, gas, and groundwater, remains a necessity. The growing world population is in itself a driving force for demand, regardless of each individual's right and desire to live a prosperous life. Several authors have described the importance of effective management of natural resources and the impact on sustainable development [10–12]. Advancing toward sustainable resource management as defined by the United Nations (UN)¹ requires the responsible balancing of the use of natural resources to meet current needs with preserving them and the environment for future generations.

Yet several questions remain: How can we ensure that the production, processing, and application are future oriented, balancing efficient and sustainable management? How can we guarantee continued access to these common goods (i.e., minerals and energy) for future use? How do we distinguish between what is essential and what is merely desirable? Who will make these decisions? These are some of the questions that need to be answered in the context of Sustainable Resource Management (SRM).

In today's global context, market dynamics, increasing segmentation, intense global competition, technological change, and shifting customer demands call for innovation, both technical and structural, in how projects and the associated tasks are managed and monitored. A crucial part is the reliable supply of raw materials. They are essential for ensuring energy supply and the technology shift, including the realization of Industry 4.0 [13, 14]. Finding tailored, efficient, and socially acceptable solutions remains a constant challenge for suppliers, users, and governments alike. Mineral raw materials play a key role in this context, particularly those deemed strategic and/or critical due to supply risks, high economic importance, or low substitutability. Their production must be socially and environmentally responsible and at the same time economically competitive. This management task is multifaceted. Communicating all its facets and addressing legitimate interests and needs of key stakeholders equally are demanding. It requires actions by project owners and governmental stewardship to set the right framework for actions, to monitor compliance, and to ensure transparency where the community requires it. Hence, alignment to Sustainable Development Goals (SDGs) and the Environmental, Social, and Governance (ESG) performance of governments, industries, and capital allocators is increasingly subject to guidelines, directives, and regulations within the

¹ Sustainable resource management is defined as the set of policies, strategies, regulations investments, operations and capabilities within the framework of public, public-private and civil society partnerships, and based on environmental-socio-economic viability and technical feasibility, which determine what, when and how resources are developed, produced, consumed, reused and recycled by the society.

European Union (EU) and beyond [15–17]. To generate the information to meet the goals of each of the ESG requirements, an enormous amount of data from various sources need to be compiled, evaluated, sorted, and classified in a coherent, reliable, and transparent way. Until now, this has been done in a fragmented, sector-specific manner, often under overlapping and inconsistent regulations and timelines. This situation is demanding for industry, for authorities, for capital allocators, and for the impacted public at large. Public trust depends on receiving clear, transparent information that respects citizens' concerns and rights. There must be trust in the information at all stages of the public debate, from the discovery phase to the closure and rehabilitation phase of resource projects. These challenges call for tailored services that use the same reliable data, evaluated to provide digestible and understandable information. It is precisely these challenges that the UN has addressed through the development of its sustainable resource management framework standards, built over many years by experts from Member States.

2. A universal framework for classification of resources and their management

In this section we describe the development, concept, and aim of the resource management framework—the United Nations Framework Classification for Resources (UNFC) and the United Nations Resource Management System (UNRMS) and how they are linked. The comprehensive and holistic concept utilizes factors defined by societal and environmental needs, by economic and technical feasibilities, and by facts that establish confidence about the knowledge of a resource. In concert, they support future-oriented and fairer resource management.

2.1 The United Nations Framework Classification for Resources

The United Nations Framework Classification for Resources (UNFC) [18] is an international classification system for resource data, including mineral resources [19]. UNFC was developed over time. What started in the 1990's as a tool to compare quantity and quality information of different origins for fossil carbon-based energy resources (i.e., coal, oil, gas) and mineral resources became a comprehensive project-based system for classifying and managing a range of primary and secondary resources (**Figure 1**), providing consistency and transparency [18, 20–27].

UNFC was created in response to the need for a general tool to compare resource estimates and project maturity from different sources for reporting and national resource production forecasts and has been in use since 1997. Although it began as a tool for the economic development of a country and its industry, social and environmental considerations became a necessity as pressure on spatially tied resource extraction competed with other land-use, growing population, and an increasing demand for resources. It became a tool for also managing these local and global pressures.

The general principles for estimating such resources were presented in 1980 as the Principles of Resource/Reserve Classification for Minerals [28] and further described elsewhere [27, 29–32]. These early principles are still relevant today for international standard reporting systems for resource and reserve estimates, such as those developed by the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) and used in the mining industry. The CRIRSCO template is bridged to UNFC.

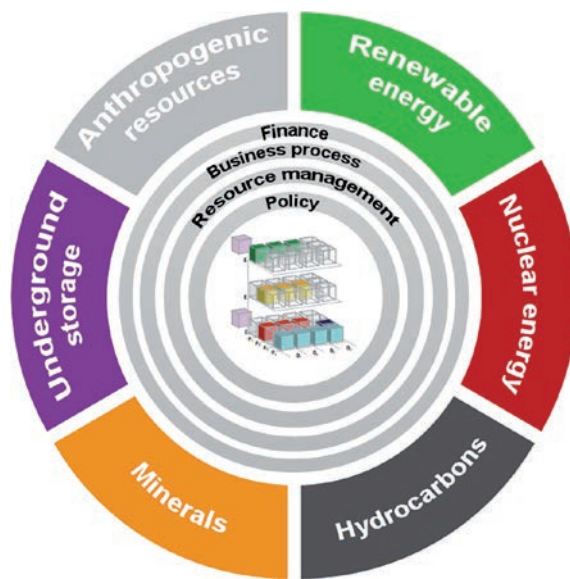


Figure 1.

Range of resource applications covered by the UNFC classification system. Modified from [20].

CRIRSCO-aligned reports, written by certified independent experts, are mandatory for companies listed on many stock exchanges [33]. Environmental, social, and infrastructure aspects are also considered in these reports through assessments of “modifying factors” converting in place estimates to production estimates used in business cases. Such assessments are legal prerequisites for obtaining permits and licenses from the authorities in many countries. Investors today are more focused on environmentally, socially, and economically viable investments and hence need this information to be clearly provided as is the case with UNFC where this is one of the key components of the classification.

The volume and complexity of data required can make resource reports difficult for non-specialists to comprehend and interpret. Under many systems, the classification of opportunities and risks associated with resource extraction and use has to be done elsewhere. This is where UNFC plays a key simplifying role by classifying the information into a clear three-dimensional system (**Figure 2**). This system reflects the knowledge level of the resource, the technical maturity of the development project and the economic, social, and environmental viability of that resource development project.

UNFC enables transparent, consistent assessment of complex information related to the economic, technical, environmental, and social dimensions of resource projects [18]. The system aims to include natural resources such as minerals, anthropogenic (end-of-life) resources, and energy resources, for example, renewables (e.g., bioenergy, geothermal, solar, wind, solar), nuclear energy, fuel, oil and gas, and hydrogen, as well as storage, including carbon sequestration (**Figure 1**). UNFC specifications (rules of application) are regularly updated to reflect society’s changing conditions and needs.

UNFC and United Nations Resource Management System (UNRMS) are already recognized in legislation and/or strategies across many countries and regions. The African Union (AU), in line with the Africa Mining Vision, and the EU acknowledge UNFC in their legal acts, and its application is currently growing toward adoption that is more widespread [17, 34–36]. Countries such as Norway, Ukraine, China, and India are using UNFC for classifying their national mineral resources directly or indirectly [37, 38].

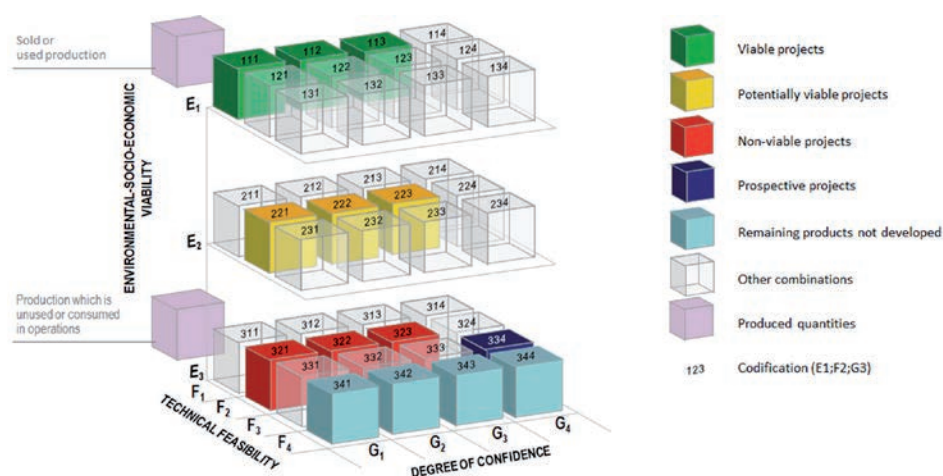


Figure 2.
 The UNFC classification system. From the United Nations Framework Classification for Resources update 2019, UNECE, © (2022) United Nations. Reprinted with the permission of the United Nations [18].

Companies still face requirements under stock exchange regulations, national reporting requirements, and partner demands to report under differing definitions and standards. One of the strengths of UNFC is that it can and has been bridged to a number of such systems, creating comparable information independent of jurisdiction and type of resource. Companies based in, or active in, the EU and listed on stock exchanges must comply with the Corporate Sustainability Reporting Directive (DIRECTIVE (EU) 2022/2464) introduced in 2022 [16]. The EU's Critical Raw Materials Act (CRMA, Regulation (EU) 2024/1252) now also specifies the application of UNFC in the EU under certain additional conditions [17].

In short, UNFC:

- classifies the quantities of a resource in view of the project designed or conceived to recover it;
- allows users to consistently assess the maturity and socioeconomic and environmental viability of resource projects across industry sectors;
- facilitates the consideration of ESG issues;
- enables users to compare and contrast projects, project options, or portfolios of projects;
- carries the ESG-related metrics that projects have, and decision makers need;
- addresses the technical feasibility of projects, uncertainties, and degree of confidence in the estimated volumes of future products;
- bridges to industry sector standards;
- is universally applicable.

2.2 The United Nations Resource Management System

The opportunities and challenges associated with the responsible use of raw materials from various perspectives are discussed in this section. This will help explain the concept of the United Nations Resource Management System (UNRMS) and how it can be utilized by companies, public authorities, capital allocators, policy and decision makers, and the public in the raw materials value chain optimization [39, 40].

UNRMS is a principles-based management framework that addresses the question, “How can resources be used responsibly in line with the SDGs?” It complements UNFC’s quantitative approach to the question, “What is there and how ready is it for development?” [39, 40]. UNRMS aims to be the connector between a project-based classification using UNFC and a holistic management system grounded in the elements of the SDGs. Based on 12 fundamental principles and a set of requirements, UNRMS guides governments, companies, and financiers through the full resource life cycle—exploration, development, production, reuse, and closure—so that every decision can be tested against technical, social, environmental, and economic performance criteria drawn from the 2030 Agenda [41]. Its application guides governments, capital allocators, industries, and project teams to score their plans and performances against each relevant SDG target, document the evidence (policies, permits, stakeholder milestones, circularity metrics, etc.), and publish the results in a consistent, auditable format. The result is presented as UNFC’s numerical codes, supplemented with actionable, SDG-aligned management metrics—turning static resource inventories and assessments of project status into transparent, future-ready development pathways. This compilation is also referred to as a common “strategic dashboard.”

One of the key innovations promoted under the UNRMS framework is “servitization.” The term is used for a transformative business model that redefines how value is created from resources. Instead of selling raw materials or commodities as isolated transactions, servitization enables resource producers to deliver integrated services and outcomes. This includes models such as leasing, pay-per-use, resource performance contracts, or product-as-a-service. Servitization helps extend material life cycles, reduce waste, and align incentives between producers and users toward greater resource efficiency and sustainability. By embedding servitization in resource management strategies, UNRMS supports the transition to a circular and regenerative economy.

Operators and governments could integrate ecosystem conservation measures by applying UNFC to combine life cycle management with decision-making principles. Local communities and non-governmental organizations (NGOs) could gain clearer insight into project stages, impacts, and mitigation measures as an act of stakeholder engagement. Improved transparency with UNFC reporting of project maturity and future production builds trust and allows comparisons of environmental performance across projects and regions. It facilitates transparency with respect to pollution caused by projects.

By embedding UNRMS alongside UNFC at the core of project governance, resource managers in government, industry, and finance can:

- Assess the suitability of alternative framework conditions.
- Self-assess their projects against the broader societal, environmental, and economic goals encapsulated in the 17 SDGs.

- Translate resource inventories into sustainable action plans, linking each project milestone with corresponding SDG and other targets.
- Create a transparent evidence base that enables communication between stakeholders, investors, regulators, and the public, not only showing compliance but also creating proactive contribution to the development agendas.
- Adapt and optimize project pathways over time, using UNRMS as a dynamic management tool to course-correct in response to emerging opportunities, risks, technological advances, or societal expectations.

Critically, while UNFC codifies the future activities based on what we know and how confident we are, UNRMS guides what we should do next and how to do it sustainably.

This strategic integration enables resource projects to shift from isolated technical successes toward becoming multi-dimensional platforms for sustainable development, catalyzing required returns on investment, innovation, and inclusive growth. In a future where access to resources, capital, community trust, and climate-resilient operations will be paramount, UNRMS/UNFC offers the structured intelligence needed to align resource decisions with the evolving demands of a sustainable tomorrow.

UNRMS, thereby, offers a structured approach to integrate sustainable development principles into resource management practices [39]. The combination of UNFC and UNRMS offers crucial tools for achieving global sustainability and other goals. Together, they consider:

- Cradle-to-cradle resource life-cycle stewardship;
- Comprehensive geoscientific and technical applications, economic development, resource recovery, circularity, zero-waste drive;
- Cross-sector energy–minerals–water–climate alignment;
- Value addition through fundamental transformation toward integrated resource (servitization) models;
- Community inclusion and intergenerational equity;
- Digital innovation, transparency, full value-chain traceability.

Therefore, the UNRMS also utilizes the following concepts, as explained below.

2.2.1 Financing the future: UNRMS information as the new language of green capital

Streamlined project financing requires transparent, standardized data on resource projects before committing capital that reflects on ESG for entrepreneurs and for capital lenders. A real-world example of this paradigm shift is the African Mineral Resources Classification and Management System (AMREC), developed in tandem with the Pan-African Resource Reporting Code (PARC). AMREC-PARC, rooted in

and based on UNFC and UNRMS principles, creates a harmonized framework for classifying, reporting, and managing mineral resources across Africa [34]. By embedding environmental and social considerations directly into resource project evaluations, AMREC-PARC enables resource-rich African nations to present projects that incorporate value addition, meet global ESG expectations, attract sustainable finance, control illicit flow of funds, and build public trust. It also facilitates transparent cross-border resource governance and strengthens the credibility of projects in the eyes of both African and international capital allocators [42, 43].

2.2.2 Local acceptance and stakeholder trust

Acceptance for the operation must be achieved in a tetrad of entrepreneurs (operators), authorities, capital allocators, and the civil society. Any project/operation lacking local acceptance risks delays, protests, or outright cancellation by authorities. Local communities and non-governmental organizations want credible data on how resource projects affect people, land, water, and ecosystems. To this end, EU directives such as the Water Framework Directive and other similar regional and national strategies have been adopted. Transparent communication with stakeholders can create the necessary trust. Institutional cooperation between research institutions, universities, and non-governmental organizations serves to enhance capabilities, form a platform on which agreed standards and methods may be prepared, and credibly monitor the ecological and social impacts of resource extraction for stakeholders.

2.2.3 ICE-SRMs as capacity and partnership hubs

An International Centre of Excellence on Sustainable Resource Management (ICE-SRM) is an independent entity in which governments, industry, academia, and civil society collaborate to pilot and implement the UNFC and UNRMS in practice. Each center delivers region-specific case studies, training, and policy advice to accelerate responsible, transparent, and circular resource development. ICE-SRMs can play a significant role as capacity and knowledge hubs, bringing together public authorities, private sector, capital allocators, and the society at large as a focal point to create public-private partnerships.

2.2.4 Strategic resource planning for future generations

Assessing, monitoring, and managing the resources a community has on its territories and forecasting future needs are a government's responsibility. They require coordinated actions by several authorities to ensure that the information and data used for achieving this task are correct, reliable, and up-to-date. What, when, and how to handle the resources for the benefit of today and for the wealth of the future is Strategic Resource Planning. Sustainability means meeting the needs of today without compromising the future [40].

The fundamental shift toward comprehensive and holistic resource management utilizes the factors mentioned above such as financing issues, activities to build and foster trust, stakeholder engagement, and capacity building. In concert with forward-looking strategic planning, this forms the basis for global resource responsibility and intergenerational justice. Intergenerational justice is a general and enduring responsibility of all generations. The concept and principles are described in the following section.

2.3 Intergenerational justice

At the heart of sustainable development lies a profound ethical commitment: the responsibility of stewardship. This concept is tightly linked to intergenerational justice, which refers to the ethical principle that future generations should inherit a world with resources and opportunities at least as abundant and viable as those of the present generation [44]. In the context of sustainability, it encompasses three key dimensions:

1. Distributive fairness in sharing natural resources over time,
2. Restorative responsibility to repair or mitigate environmental harm caused today, and
3. Procedural inclusivity ensuring that decisions about resource use consider the long-term impacts and include the voices of those affected (including future stakeholders) [44].

In practice, intergenerational justice imposes a moral responsibility on the current generation to act as stewards of natural resources, balancing present needs with the rights of future people to a healthy environment and sufficient resources. It calls for limits on over-exploitation, remediation of environmental damage, and precautionary action in the face of uncertainty, so that today's pursuits of economic and social well-being do not impose undue costs or diminished opportunities on tomorrow's world. Ensuring fairness across generations is thus a cornerstone of global sustainability efforts and is explicitly recognized in United Nations frameworks for resource management and development [44]. This imposes strict attention by governments, suppliers, consumers, and capital allocators to efficiency and effectiveness, especially when it comes to non-renewable resource extraction and use. That raises the question, "How UNFC and UNRMS support intergenerational justice?" Key features of UNFC and UNRMS, such as life-cycle planning, transparent and inclusive decision-making, and integration of social and environmental criteria, directly support intergenerational equity in practice. UNFC measures not only how much resource is available and economically extractable but also whether extracting and using it is acceptable in light of social and environmental constraints and the long-term public interest. Thus, a resource deposit that is technically rich but whose exploitation would cause irreparable ecological damage or violate community rights might be categorized less favorably under UNFC, signaling that it cannot be developed until those issues are resolved. The process often referred to as resource categorization—that is, the structured classification of resources based on their readiness for development, technical feasibility, and socio-environmental viability—is formally captured in the UNFC. The UNFC serves as a standardized framework to categorize and communicate resource quantities and project maturity levels, ensuring clarity and comparability for decision support across resource types and jurisdictions. Such an approach embodies intergenerational justice by stressing that present development should not come at the cost of future well-being. Governments and companies using UNFC are urged to plan for responsible use of resources, efficient recovery, and proper closure or reclamation of sites. This life-cycle perspective ensures that the full impacts of resource extraction and use are considered—including post-extraction land use and availability of remaining resources—so that future generations are not left just with abandoned,

degraded sites or a depleted resource base. With that, UNFC provides a structured way to evaluate resource projects with an eye toward sustainability and fairness across generations, making it a tool for implementing the principle of intergenerational justice in resource-rich development decisions. UNRMS calls for a “holistic approach that balances current development needs with preserving resources and environmental health for future generations,” facilitating a fair and just transition to a sustainable economy [40].

3. Data, capacity-building and quality control

Good decision-making depends on data, information, and knowledge of the outputs, outcomes, and impacts of a project [40]. Any model is only as good as the data that feeds it, and since artificial intelligence (AI) increasingly offers opportunities to use data in ways previously not possible, the importance of data quality is growing. It is paramount that the content and reliability of data are quality controlled by experts. This holds also for UNFC and UNRMS, which are evidence-based.

3.1 Data requirements to support UNFC and UNRMS

UNFC structures data and information to classify a resource project according to three main categories: the Environmental-Socio-Economic Viability (E Category), the Technical Feasibility (F Category), and the Degree of Confidence in the estimated quantities of potential production (G Category). These categories can then be visualized in three axes, E – F – G as in the UNFC cube shown (**Figure 2**) [18].

UNFC is intentionally flexible and generic to accommodate multiple user groups. Their needs impact and determine the procedures and ways users approach assessment of the data to classify a project. If there is known information on the G Category, project developers and investors typically look at the status of the F Category, before considering the E Category. Conversely, for regional planning and compiling national inventories, authorities may focus on the G Category first. Yet, none of the categories will be considered in isolation. The factors to be investigated are interdependent, and all influence the final result. For example, the technology that can be used to liberate a target mineral from a mined rock has a direct effect on the costs and is a parameter in the assessment of the environmental risks associated with the project. In mining, factors defining the industrial ESG are commonly considered, and public governance is of overriding importance. It includes Environmental Impact Assessment (EIA), metallurgical recoveries, fiscal measures, exchange rates, energy and water supply, and many more factors that should be disclosed [23, 29, 45]. Here, too, the details are compiled in different data formats for different users and purposes. This requires teamwork and expertise in numerous areas.

Data and information to be considered in the E – F – G Categories are as follows:

The E Category classifies the threefold aspects of the environmental-socioeconomic viability. This category uses data of very different origins, nature, and formats, which, on their own, are complex and heterogeneous. Complexity is further increased because these data are compiled for different target groups and purposes. An example of the environmental evaluation is EIA, which for mining includes forecasts, measurements, and monitoring of dust, water consumption, noise, rehabilitation, biodiversity, and many other indicators. It may include challenges associated with future mine closure and related actions [46, 47]. The corresponding monitoring of

these aspects is a mandatory task for a project owner/operator in most European countries and elsewhere. These data are typically disclosed at the public consultation stage, at least during the application and permitting process. The assessment of social viability is the most difficult to measure. Fact-based information about the workforce, impact on the local prosperity, and the frequency and style of public participation can be measured. However, indicators such as social acceptance and societal license to operate—eventually to be handled through the structure of the state—are snapshots in time that can change at any point, including through measures unrelated to specific performance at the resource site being considered. The third aspect to be assessed on the E Category is economic viability. This involves market analysis, including forecast of demand for the target resource, evaluation of the capital and operational costs to implement the development plan, and expected sales income, together with the time value of money and associated uncertainties. These factors are crucial considerations during the estimation and reporting of a reserve, which is the economically exploitable resource under given conditions [45, 48].

The F Category classifies the technical feasibility of the project, including the maturity of the technologies used to make the resource available for utilization. For example, data on physical infrastructure, rock mass characteristics, technological capacities, processing and beneficiation technologies, as well as the energy requirements are assessed here. Project developers compile these data according to their own needs, since these impact the estimate of future production over time. For competitive and financial reporting reasons, future production is only disclosed as a cumulative quantity, not as a forecast through time, although such a forecast nearly always is critical in decision analyses.

The G Category reflects the degree of confidence in the resource estimates. This improves over time as work to evaluate and assess development potential takes place. Early exploration activity looks to address macro considerations related to, for example, local geology and capture experience from similar resource projects and the associated risks. This reduces uncertainty and improves confidence in resource estimates, providing the basis for informed decision making about progressing to development activities where significant cost is incurred. At every stage of the development lifecycle, information collected is used to further improve understanding of resource estimates and provide the basis for understanding opportunities, risks, and potential value on which investment decisions are based.

At the onset of a mineral resource project, for example, geological mapping (pre-commercial exploration) is undertaken typically by Geological Survey Organizations (GSO) at a regional scale and includes remote sensing, geophysical surveying, geological mapping, and geochemical sampling. The resulting maps and geophysical and geochemical data are usually compiled into the form of national inventories. Prospectivity maps or mineral potential maps may be derived, which show the probability of mineral occurrences. The data is managed by regional and national GSOs, who are responsible for data maintenance and quality. In Europe, the common European Geological Data Infrastructure (EGDI, www.europe-geology.eu) contains a coherent set of the data, following the FAIR principle, that is, the data are findable, accessible, interoperable and reusable, unless strategic or legal constraints prevent their publication.

In prospective areas, data collection may continue with higher spatial resolution and at depth. A variety of exploration technologies such as airborne and ground-based geophysics, heavy mineral sampling, drilling, and trenching are then used to obtain comprehensive petrological, mineralogical, and geochemical information at a local

scale. Data acquisition is usually carried out by exploration companies, although some national GSOs also perform these tasks. For competitive reasons, the data may not be disclosed to the public. Mining authorities are, however, entitled to access the data during the permitting and sometimes during the monitoring and regulating stages.

The majority of the data compilation must be assessed by various authorities in the course of the application and authorization process. The number of authorities involved and the amount of data to be reviewed make the process complex and often lengthy. Pre-sorting into the UNFC categories would simplify the administrative process. The EU CRMA can lead the way for this beneficial use of UNFC. The Act refers to UNFC in the sections on Application of Strategic Projects (i.e., art. 7), National Exploration Program (art. 19), Risk Monitoring and Mitigation (art. 21), and Circularity (art. 27) [17]. For the private sector, owners of Strategic Projects (applicants and operators)—as defined by the EU—are obliged to provide information and to classify the project in accordance with UNFC. The Act obliges the public sector of the 27 EU Member States to provide specific information on inventories and maps and report on stocks of strategic resources using UNFC. Many of the forecasts, targets, and so on implied by the Act can be supported by, or developed from, UNFC. Utilizing UNFC and UNRMS as tools within and beyond single project management, for example, by governments and public authorities for national and regional strategic planning or special planning purposes, the underpinning database may quickly become very large. This is where AI tools may play a valuable role.

3.2 Digital technology and AI promises to revolutionize the preparation, organizing, and consumption of resource management data

AI is transforming every part of society and will contribute to a more efficient and environmentally friendly circular economy through its ability to recognize complex patterns and structures in multi-layered supply chains and the respective process steps [49]. It will allow expert early warning systems to be developed and targeted solutions to be devised that support better resource project management. Identifying and monitoring all complex elements of the supply chain, forecasting the development of all those elements, and assessing all the components needed to ensure environmentally sound processes require quality data as an input and the capability to turn this into information [31, 50–52]. AI will inevitably be a key enabler of this essential shift toward more sustainable development.

There is, however, a Catch-22. AI is extremely energy intensive and is one of the major drivers of increased energy demand over the last decade, a trend that will continue for some time. This energy demand from data centers accounted for 1.5% of the world's electricity consumption in 2024, estimated at 415 terawatt-hours (TWh), of which the United States accounted for 45% and Europe 15% [51]. The IEA forecasts that data centers will consume 945 TWh of electricity by 2030. As a result, the use of AI will increase demand for critical raw materials as defined by the EU [51, 53–55]. The IEA forecasts that demand driven by data centers for critical elements such as gallium will have increased by 10% in 2030 versus today. This demand will be partly offset by technology shifts in semiconductor design that are working toward more efficient and less energy intensive processing power compared to today's silicon-based semiconductors [51]. Increasingly, we see this being reflected in law, for example, through the REGULATION (EU) 2024/1689 known as the EU AI Act, which forces investment in improving the resource performance of AI systems, by reducing energy consumption throughout the lifecycle [53].

There are clear trends emerging around the application of AI in geological resource development. Examples include AI components being used for compiling and interpreting complex geological data and mapping and optimizing operations [56–66]. Statistical techniques enable computers to learn from data through Machine Learning (ML) [64, 67] and Deep Learning (DL) [64, 68] algorithms and to recognize sophisticated patterns by using Layered Neural Networks [67]. There are many examples of resource targets being identified much faster, with better recognition of exploration risks and better mitigation [66] leading to significant cost efficiency. Recent developments show potential to go even further with techniques such as Large Language Models (LLM) [69], Artificial Neural Networks (ANNs) [65], Convolutional Neural Networks (CNNs) [70], Support Vector Machines (SVMs), [71] and market forecasts [72].

Energy companies, particularly in the oil and gas sector, have always been early adopters of advanced information management techniques and have shown great appetite to embrace the use of AI to transform and optimize resource identification, development, and supply, with the objective of providing secure, reliable, and affordable energy supplies while reducing cost, risks, and emissions [73].

The minerals mining sector is seeing ML and AI become a standard part of the toolset for discovery, exploration, and deposit characterization, modeling, and optimizing the operation, production, and rehabilitation of sites. This is lowering the environmental impact of activities and improving safety of operations, as well as better forecasting demand for target resources over the lifetime of operations [74–77]. For mineral exploration tasks that require high accuracy, the use of AI enables a comprehensive understanding of mineral exploration data patterns by learning complex non-linear features, thereby improving the accuracy of prediction results [68].

These applications of AI/ML require sound data foundations to support characterization of resources in the necessary detail but which are very large scale, frequently generated in remote areas, and happen over very large timescales (often decades) [6, 78, 79]. This is because the finding of resources (exploration to discovery), bringing them into operation and the supply chain, and the final decommissioning/closure and rehabilitation process can run over very long timeframes [80].

These challenges go beyond those usually associated with ‘big data’ and require associated solutions to their complexity, need for security, reliable supporting technology, and data management approaches that reflect the timeframes over which the activities happen [81]. With ever increasing use of shared data centers and “cloud computing” [51], the use of AI is supporting unbiased classification of resource management information—greater uptake of standard tools and approaches is needed, both by industry and governments.

To drive this at pace requires the right governance frameworks and effective regulation to facilitate responsible resource development, utilization, and alignment with SDGs. This should be an urgent priority for all governments and is an opportunity to minimize negative impacts on society, the economy, and the environment. The EU has acknowledged the potential and associated risks of AI in its AI Act [53].

There is a general shift in sustainable resource management to move from static reporting, which is insufficient for meeting SDGs, Paris Agreement, and investment demands, to more real-time and predictive systems that can support the required interoperability of data and information for integrated decision making. UNRMS offers a framework that can be effectively supported by technologies like digital twins, AI, and blockchain, as these tools mature. This approach aligns with the wider vision for digital enablers like AI to help structure information about all phases of a project and the associated activity, such that the data collected meet legal

requirements and can be provided to authorities in an orderly manner and readily consumed by users in ways that they find useful. In an increasingly interconnected, digital, and fast paced world, transparency becomes critical—use of standards like UNFC is a prerequisite to delivering the information systems needed to support decision making and informed sustainable development.

Three maturing digital capabilities are combining to transform UNRMS from a static self-assessment system into a dynamic and participatory management platform:

- Digital twins have become default management tools in recent years; they are virtual replicas of physical assets and systems, and in UNRMS they are used to depict a mine or geothermal site by integrating geological models, production data, environmental monitoring, and stakeholder milestones into a cohesive model. This allows dynamic tracking of physical outputs and the project's evolving ESG performance. They can, for example, assess how a project's water use aligns with SDG 6 (Clean Water and Sanitation) or its carbon emissions with SDG 13 (Climate Action). Instead of periodic snapshots, decision-makers and financiers access real-time status dashboards for rapid, evidence-based course corrections.
- AI provides the capability to interpret vast datasets, and ML analyzes interdependencies among operational variables and SDG indicators, detects signs of non-compliance, forecasts ESG risks, and suggests interventions. For example, AI can predict when biodiversity impacts breach thresholds or adjust mining schedules to alleviate water stress. Integrating AI into UNRMS workflows allows resource managers to transition from reactive compliance to proactive stewardship, capturing opportunities and mitigating risks early, promoting continuous alignment with the UNRMS principles of innovation, integrated management, and planetary responsibility.
- Digital ledgers like blockchain provide verifiable transparency and therefore promote trust by recording data related to key project events such as environmental assessments on a tamper-proof distributed ledger, creating an immutable audit trail consistent with UNRMS standards. Smart contracts can automate compliance; for instance, green bond disbursement may depend on real-time validation of water quality metrics. This brings enhanced transparency and information integrity to meet rising expectations from regulators, investors, and communities.

Use of these combined capabilities is driving convergence around (**Figure 3**):

- Continuous SDG performance monitoring: Live dashboards tracking SDG impacts and goal alignment.
- Predictive governance: Anticipating ESG risks before they materialize.
- Smart compliance: Automating reporting, financing, and licensing processes.
- Stakeholder confidence: Providing communities, regulators, and investors with trusted, real-time access to project data.
- Operationalizing UNRMS with these technologies enables future resource projects to demonstrate sustainability in real-time to a global audience demanding measurable impact.



Figure 3.
 UNRMS transformation with technologies.

3.3 Capacity-building and quality control

Gathering the data and ensuring its quality and reliability for the various resources may fall short without quality control or auditing and regular comparison between forecasts and actuals. Internationally recognized standards for the assessment and reporting of resources or even of the definition of a minimum level of user expertise are still largely lacking for applications such as geothermal energy, groundwater, or anthropogenic deposits, including recycled materials.

Hence, quality control protocols or other audits should be in place to ensure that the quality of information fulfills similar standards to those already used for mineral assessments. This is addressed:

- by the UN Economic Commission for Europe (UNECE) Expert Group on Resource Management (EGRM), which has provided guidance on competency requirements as well as on social and environmental considerations, among other supporting documents available online at <https://unece.org/sustainable-energy/expert-group-resource-management-egrm>.
- by the EU CRMA, which requires its Member States to report critical raw materials in their territories, following the UNFC format.
- through ICE-SRMs in various regions to promote and facilitate the use of UNFC and UNRMS in their regions.

The ICE-SRMs provide capacity-building through training and tailor-made workshops. They strengthen the mutual understanding and use of UNFC and promote UNFC and UNRMS. ICE-SRMs located in different countries and regions may focus on different issues and resources covered by UNFC. For example, the ICE-SRM UK focus is on circular economy, critical raw materials, and anthropogenic resources; the ICE-SRM Latin America and Mexico is addressing geothermal and oil and gas issues; and the ICE-SRM Russia has developed a Global Reserves Converter that uses LLM to convert digitally available binding documents on subsurface resource into UNFC information [82]. The ICE-SRM EU is the most recent, launched at the end of May 2025 as a EuroGeoSurveys initiative in view of a Geological Service for Europe (GSEU, www.geologicalservice.eu). The ICE-SRM EU provides a repository of training materials, a network of experts, and national information. It also furthers

capacity building and use through country-specific workshops and promoting UNFC implementation at national levels. While it is beginning with minerals, the ICE-SRM EU will step-by-step provide expertise for all geological themes covered by UNFC, including groundwater and geothermal resources.

To complement the ICE-SRMs, UNECE is building up a centralized knowledge hub that provides compiled information on training material resources and frequently asked questions. It will act as a single-entry point for all stakeholders and for all regions.

4. Conclusions

Energy demand will increase significantly as development continues apace and the need for sustainability makes the energy transition and a shift to a lower greenhouse gas emitting society a necessity. Mineral raw materials are essential for both the current and future energy systems and for almost all aspects of a prospering society. It is a substantial challenge to satisfy the growing demand for energy and mineral resources in ways that meet ESG expectations, address SDGs, and deliver on economic targets in a competitive market. This calls for good communication between all the stakeholders, including the public, and holistic management of resources based on sound principles and reliable and transparent information.

UNRMS principles and requirements for responsible management of resources, coupled with UNFC classifications of actual and potential projects and production, provide a powerful approach to addressing the challenge of sustainable resource management. UNFC addresses “What is there and how ready is it for development?” It enables transparent, consistent assessment of complex information related to the economic, technical, environmental, and social readiness of resource projects and the confidence in the quantities that can be produced. UNRMS addresses the question, “How can resources be used responsibly in line with the SDGs?” It aims to be the connector between a project-based classification using UNFC and a holistic management system with SDGs as fundamental elements. UNRMS guides governments, industry, and capital allocators through the full resource lifecycle. By embedding UNRMS alongside UNFC at the core of project governance, stakeholders can assess potential projects and their impacts via sustainability metrics to facilitate communication and make wise, cooperative decisions. They can also develop and monitor action plans and adapt and optimize project pathways over time.

At the heart of sustainable development lies a profound ethical commitment: the responsibility of stewardship. This concept is tightly linked to intergenerational justice, which refers to the ethical principle that future generations should inherit a world with resources and opportunities at least as abundant and viable as those of the present generation. Key features of UNFC and UNRMS, such as lifecycle planning, transparent and inclusive decision-making, and integration of social and environmental criteria, directly support intergenerational equity in practice. UNFC measures not only how much resource is available and economically extractable but also whether extracting and using it is acceptable in light of social and environmental constraints and the long-term public interest. UNRMS calls for a “holistic approach that balances current development needs with preserving resources and environmental health for future generations,” facilitating a fair and just transition to a sustainable economy.

Reliable and high-quality data and robust analysis are central to good management of resources. Effective use of UNRMS/UNFC depends on robust information

to support dialog between stakeholder groups about portfolio resource management. Clear and transparent information enables the effectiveness of government framework conditions to be measured and alternative projects to be compared and contrasted. This promotes competitiveness, resilience, and trusted communication.

Digital technology and AI will inevitably be a key enabler of the essential shift toward more sustainable development. The use of AI does, in itself, create an additional demand for energy and raw materials. However, emerging digital capabilities like digital twins, AI/ML, and digital ledgers, such as blockchain are transforming how data and information are used in resource development. This brings with it an increasing requirement for quality control of the data and of AI-supported results. These must be reviewed by experts, and quality control protocols or other audits should be in place to ensure that the quality of information fulfills similar standards to those already used for mineral assessments.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 9

Meeting Need for PILI's Field Managers through Islamic Environment Study Program

Kafil Yamin, Asep Saeful Muhtadi and Ahmad Sarbini

Abstract

Being a signatory of the Paris Agreement, a legally binding international treaty on climate change, Indonesia agrees to bring down its national carbon emission to 26% by 2026. This commitment leads to the demand for professional green workers in the field. As the world moves toward carbon trade, the demand for such workers get higher. Among the professionalism aspects is the ability to utilize, develop, and advocate local values for the climate change mitigation. And since more than 80% of Indonesian population is Muslim, Islam has been deeply rooted in the local value and culture. It is not a coincidence that Islam brings strong messages on the importance of safeguarding the nature and repeatedly remind human of their basic responsibility of taking care of the environment. Practicing Islamic teaching on the environment, as it is becoming evident, is far more effective with the help of scientific knowledge. It turns out that green workers in Indonesia should be equipped with decent environmental as well as Islamic knowledge. The most effective way of putting the two types of knowledge together in human is education, particularly higher education integrated curriculum. This paper attempts to seek a possibility of establishing “Islamic Environment” study program with a curriculum that integrates Islamic science and the environmental sciences. The attempt is based on the best practices of implementing Islamic messages in environmental works that has so far been doing by *Pusat Informasi Lingkungan Indonesia* (PILI), or The Center of Indonesia Environmental Information.

Keywords: Islamic environmental study, PILI, carbon trade, Muslim community, green workers

1. Introduction

Global climate change brings nations and countries to work together to bring down the world's level of carbon emission, leading to the Paris Agreement, an international treaty on climate change that was signed in 2016. The treaty was negotiated by 196 parties at the 2015 United Nations Climate Change Conference near Paris, France.

The signatory countries then exploit their natural and human resources to lower their respective carbon emissions to the targeted level. Indonesia agreed to reduce its carbon emissions by 29% unconditionally and up to 41% with international support by 2030, signifying a significant commitment to combat climate change through the agreement. This target was later renewed in 2022 to a 31.89% unconditional reduction and 43.20% conditional reduction [1].

1.1 Carbon emitting sectors

Until 2021, the sector that produced the most carbon emissions in Indonesia was the energy industry, with 679 m of green house gases (GHG) emissions. This figure made up 67% of the total emissions, followed by the forestry and agriculture sectors, which produced around 15% of the total emissions.

After 2021, however, Indonesia cut 10.37 million tons of carbon emissions from power plants, which exceeded the target of 4.92 million tons [2], an achievement of more than 200%. Although the figure remained unverified, particularly on what measures taken, this shows a significant development in energy efficiency.

To keep the carbon emission cut on track, Indonesia imposed a carbon tax through a cap-and-trade scheme on April 1, 2022. The scheme applies to coal-fired power plants with a capacity between 25 megawatts (MW) and 100 MW [3].

The power plants are classified into three categories of greenhouse emissions (BAE): non-mine-mouth coal-fired power plants that produce over 400 MW, non-mine-mouth coal-fired plants with a production capacity between 100 and 400 MW, and mine-mouth coal-fired power plants with a capacity of over 100 MW. The latter is allowed because they play a social function by providing electricity for public and other social purposes.

Indonesia then issued the “Emissions Technical Approval” (PTE), also known as *Persetujuan Teknis Batas Atas Emisi* (PTBAE), which rules a maximum limit on carbon emissions for each coal-fired power plant. This actually defines the allowed emission ceiling that a plant can produce within a specific period.

In 2022, the Ministry of Energy and Mineral Resources (MEMR) set the requirement for businesses organizations participating in carbon trading through an annual GHG emissions monitoring in each power generation unit, which should be later reported to the MEMR no later than 31 December every year. Failure to submit the regular report will have the consequence of being excluded from carbon trading in that particular period.

The second and third-largest emitting sectors were transportation and manufacturing, emitting 141 and 132 m tons of GHG each.

Indonesia's carbon emission from the transportation sector is reported to reach 149,538,000 tons in 2023, accounting for 22% of the country's total emissions. Despite a number of measures to lower the emission rate since the adoption of the Paris Agreement and SDGs, the emission rate remains higher than its neighboring countries [4].

A study by the Institute for Essential Services Reform (IESR) in the Indonesia Energy Transition Outlook (IETO) 2024 shows that passenger vehicles emitted 73.1% of the 150 million tons of carbon dioxide emission from the transportation sector.

Following the transportation sector is Land use change and forestry (LUCF), with deforestation and conversion of natural ecosystems to agricultural or urban areas being the main sources of carbon emissions. How does deforestation become the source of carbon emission? The answers are as follows:

- Trees and other vegetation absorb and store carbon. When they are cut down or burned, however, the stored carbon is released into the air. If the number of trees cut is high, one can easily count how much carbon is released into the atmosphere.
- Deforestation and change in land use disrupt the work of ecosystems in absorbing and storing carbon dioxide. In turn, forest conversion to agricultural and plantation estates releases carbon stored in the soil.

Indonesia's tropical rainforest is the third-largest in the world, with primary forests making up for almost half of it. The rate of primary forest loss is among the highest, with 579 hectares of loss per year during 2015–2020.

1.2 Steps taken toward zero emission

Indonesia is taking numerous measures to deal with climate change. The latest Nationally Determined Contribution (NDC), updated in 2021, sets the target of an unconditional reduction of 29% and a conditional reduction of up to 41% by 2030. However, the NDC has yet to go all the way to net zero emissions. Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience does not specify net zero transport emissions targets.

1.2.1 Transportation

There has been intensive studies and researches by the ministry of transportation that result in a number of documents, which in turn guide transportation policies. The documents outline various targets of carbon emission through gradual shift to biofuels and other renewable energy, improvement of public transports, and improvement of infrastructure. Analysts see, however, these initiatives have yet to be translated into real work program in Nationally Determined Contribution (NDC) and Long-Term Strategy (LTS), except for only 12% of these measures.

Such gap leaves Indonesia vulnerable to adverse impacts of climate change unless better integration and coordination between transport policies and climate change strategies are immediately made.

Opportunities are here for Indonesia to accelerate the adoption of electric vehicles and biofuels and improve public transport and low carbon shipping. Such opportunities need to be secured by comprehensive policies that ensure a sustainable and resilient transport system will be achieved.

1.2.2 Industry

A study by Solikhah et al. [5] on 40 manufacturing companies during 2012–2015 found that the companies' willingness to inform their carbon emission is low—with an average value of 18.79%. It implies, according to the study, the companies' lack of effort to reduce their carbon emissions. The study is made on Climate Change (CC), Greenhouse Gas (GHG), Energy Consumption (EC), Reduction and Cost (RC) of Greenhouse Gas, and Accountability of Emission Carbon (AEC).

It is found that Indonesia's reliance on fossil fuels—accounting for 40.5% of the energy mix in 2023—makes it hard to reach the zero-emission target as planned. A 2050–2060 phase-out is planned for coal. Although blessed with abundant coal and

mineral resources, Indonesia is struggling to achieve the renewable energy target of a 23% share this year (2025) based on its Electricity Supply Business Plan (RUPTL).

As reported to the UNDP, Indonesia's latest NDC commits to a higher GHG reduction target of 31.89% (unconditional) and 43.2% (conditional) that include the target to restore 2 million hectares of peatlands and rehabilitate 12 million hectares of degraded lands by 2030.

Indonesia's biodiversity, rich with large forest coverage, is the rationale behind the industrialized country's willingness to "pay descent compensation" for their carbon emission that contributes a lot to the current global climate change.

1.3 The rising need for green field managers

Indonesia's national plan to reduce carbon emissions has given a boost to the demand for environmental consultants, managers, and project officers who are capable of driving local communities to engage in carbon trade projects by utilizing local rich of values, wisdom, and traditional skill and knowledge.

Huge revenues from the carbon trade require Indonesia to fulfill the demands of green jobs with relevant skill requirements, although the majority of green jobs bear similar tasks to non-green ones. As Halimatussaidah et al. [6] put it, many skills in both types of jobs are rudimentary and generally applicable in different sectors. Therefore, it merely takes short courses or job training to prepare workers for green jobs, which means workers only need additional training instead of an academic qualification. On-the-job training, it turns out, would make Indonesian workers who do not have a high school diploma or higher qualify for green jobs [6].

It is later found, however, that the green workers need knowledge updating, skill renewal, and even specific studies to reach the accomplishment of their projects, particularly when they have to work with the communities and their corporate partners.

2. Indonesia's carbon market potential

Indonesia has the potential to reduce 247 million tons of CO₂-equivalent, and with this, it could bring about up to 1283 million tons of carbon credit each year [7]. This would further result in revenue of about US\$7.3 billion to US\$16.7 billion.

Indonesia will raise the mentioned income on condition that it adopts an internationally recognized monitoring system, Reporting and Verification (MRV) framework, clear regulations of international trading, and carbon taxing.

A carbon credit is basically a tradable certificate that represents the reduction, avoidance, or result of one metric ton of carbon dioxide equivalent (CO₂e) achieved by a certified carbon project. The certificate states the monetary value of carbon emission reduction.

Carbon credit was introduced by the Kyoto Protocol, which established market-based mechanisms to assist countries in meeting their climate commitments. The mechanism includes Emission Trading (ET), Clean Development Mechanism (CDM), and Joint Implementation. The ET enables developed countries to buy and sell Greenhouse Gas (GHG) emissions, while CDM facilitates developed countries to purchase the result of GHG emissions from developing countries. JT, on the other hand, enables several developed countries to jointly develop climate change mitigation projects in developing countries and share the result of the carbon emission reduction.

It is now obvious that carbon emission has become a tradable commodity between developed and developing countries, more specifically, between local communities and international communities. The international carbon trading will be based on such mutual benefits between carbon producing and carbon absorbing parties.

Chances are open for local communities to get benefits from carbon projects even through direct payment. But before coming to this stage, local communities are required to prepare themselves with the knowledge and skills needed for engaging in carbon projects that include standardized administration, reporting, and financial management.

The potential revenue of US\$7.3 billion to US\$16.7 billion definitely covers the values the local communities could earn. However, since the carbon project allows direct payment to the communities, the latter should have been prepared with institutions and financial systems. Most communities do not have these instruments yet.

No less important than the instruments of organization and management are the values the project will be based on. In Muslim communities, any activities beyond the religious ritual are categorized into the so-called *mu'amalah*, or social, economic, and political affairs, that should follow sharia law. Carbon trade, therefore, should have its legal basis on the sharia.

In the *mu'amalah* perspective, the carbon trade is seen as *syaraa'* (buying), *mubi'aat* (selling), and rent *ijarah* (rent) under certain conditions. It is a sale and purchase of a certificate of Greenhouse Gas emission reduction. It is *ijarah* if the act of forest carbon trading is considered to be an activity of hiring services of parties who own the forests because the essence of forest carbon trading contract is the total result of forest carbon sequestration [8].

3. Community at work

On the ground, the community groups work independently to reduce carbon emissions through partnerships with private corporations and local administrations. They have more measurable and real targets with their projects. As described below, some of them are taking place and showing results.

The community environmental awareness, however, needs to be cultivated and grown in the first place before it becomes a strong initiative. In this aspect, non-government organizations (NGOs) come into play. A number of NGOs have shown encouraging results in building people's initiatives to maintain their natural environment. However, their successes should be partly attributed to the private companies that support them with funds.

Yaziji and Doh pointed out in their research, *Corporate-NGO engagements: from conflict to collaboration* [9], that collaborations between corporations and NGOs are now so common. Such a partnership brings benefit to both parties—fund and reputation for NGOs, and access to skills, competencies, and capabilities of outlining corporate social responsibility (CSR) programs.

Yaziji and Doh's elaboration on corporate-NGO engagement, however, lacks discussion on the significance of community groups as unavoidable strategic partners, while the studies on corporate-NGO engagement emerge from social issues such as community business, healthcare, education, and of course, natural environment.

The communities, likewise, have their own knowledge, values, cultures, and traditions that are embedded in how they work, communicate, and collaborate with outside parties. And since the culture and tradition change with times and new realities, the studies on these issues remain needed, and they will continue. The influence of Islamic law or sharia can be found among others on the prohibition of consuming primates and animals with claws or fangs.

Animals that can live in both water and land, such as amphibians and reptiles, are haram or inedible. This particular law prevents Muslims from hunting the two animals in the wild, which functions as a protection. The law also brings a positive impact on the preservation of wildlife, such as tigers, orangutans, and other primate species in Muslim populated areas such as Kalimantan and Sulawesi.

Islam brings both a conceptual and traditional legacy of conservation that are now becoming relevant to the issues of climate change. Among the legacies are *hima* and *harim*.

Hima is a protection zone for preserving forest, plants, wildlife, tree, and animal species. Hima was introduced by Prophet Muhammad in Medina in the seventh century, which was initially established to preserve certain animal species. For this reason, the grazing of domestic animals was prohibited.

Himas in the Middle East have now become Important Bird Areas (IBA) that have been free from hunting and any exploitation for centuries. Himas remains exists in the Middle East and the Arab world for 1500 years ago until today. Environmental experts see Hima as a unique conservation system because it is taken cared and protected by the local community.

Harim, meanwhile, is a system that protects rivers and spring areas. A *harim* zone for a river covers half the river's width on both banks, while the *harim* area for a tree is two-and-a-half to three meters to all directions from the tree [10].

There are numerous prohibitions and commands that show Islam's strong message to care for nature.

4. Indonesia's Islamic tradition of environment

Dewayanti pointed out that there are already several Islamic groups taking climate initiatives at the national and local levels [11].

The Indonesia Ulemas Council (MUI) established a particular institution called LPLH-SDA MUI, Indonesian acronym for the Environmental and Natural Resources Board, to promote environmental sustainability through the publication of Friday sermon books and public education on Islamic environmental messages.

Indonesia's largest Muslim organization, the Nahdhatul Ulama (NU), also created a division called the Nahdlatul Ulama Institution for Disaster Management and Climate Change (LPBI-NU), while the second largest, Muhammadiyah, established the Muhammadiyah Environmental Council (MLH Muhammadiyah), with their respective branches throughout the country. Their down-rooted network enables them to work with the climate-affected communities [11].

Now they feel there is a need for a modern religious approach to equip green activist actions on the fields. Religious leaders, the *da'is* (Islamic preachers), and the imams are challenged to advocate "green Islam", and Muslim environmental activists are expected to build and engage in green network.

For several environmental organizations, however, lack of government support is the reason for not going all out.

5. Pusat Informasi Lingkungan Indonesia (PILI)

PILI, an NGO based in Bogor, West Java, sees the need to help the communities to prepare themselves for such a big and wide-ranging endeavor. Equipped with networks with private companies, the organization builds partnerships with corporations and local communities to work on ecosystem management, tree planting, land rehabilitation, and seashore restoration in an effort to get prepared for the carbon projects.

While bringing a green network to the community, PILI is familiar with Islamic values, which to a certain extent, become both an organizational and personal attitude since it was founded in 2000. The name PILI comes from its Indonesian acronym: *Pusat Informasi Lingkungan Indonesia*, which in English is “The Indonesian Environmental Information Center.” Since the beginning, PILI has worked on data and information collection and network building among stakeholders of biodiversity conservation in Indonesia.

PILI sets its vision as “the realization of just natural resources management in Indonesia,” which guides its missions to encourage and improve the quality of strategic partnership in natural resources management, build stakeholders capacities in natural resources management, and make innovations in community-based products.

PILI has “only” 20 green workers and 40 associates and now is facing huge projects while undergoing an employee shortage. However, for the nature of its work, each PILI field manager leads hundreds of community members, making him/her highly influential to the community concerned. Adding to its significance is that the organization is linked to a number of influential organization such as Forestry and Environmental Ministry, National Development Plan Bodu (Bappenas), Indonesia Climate Change Trust Fund (ITTF), United Nations Environmental Program (Unep), Global Eco Rescue (GER), Goodhope Asia Holding Ltd., PT PAM Mineral, PT Jabar Bersih Lestari (JBL), First Resources Ltd., Astra Argo Lestari, Hexa Consulting, BRI Peduli, Indonesia Social Mangrove Foundation, and Ecolife.

The following projects are parts of PILI's strategy to prepare the local community for carbon trade:

- *Nabire landscape conservation*

Since 2023, PILI engaged in cooperation with Goodhope Asia Ltd., PT Nabire Baru (PT NB), and PT Sariwana Adi Perkasa (PT SAP), the indigenous people of Yeresiam Gua, and Wate Asiaina to implement the Remediation and Compensation Procedure (RaCP)—a scheme that require Roundtable on Sustainable Palm Oil (RSPO) members to make assessment on a High Conservation Value (HCV) of their holdings before conducting new treatment on their concession lands. This will ensure that land areas under the control of RSPO growers are not cleared for new projects [12]. The project sites are in the High Conservation Value (HCP) area of Nabire District, Central Papua.

- *PILI-Jejak.in partnership for tree collective*

In 2023, PILI clinched a peer NGO Jejak.in to restore damaged forests and critical land of water catchment and spring areas in three provinces, eight districts, and ten villages. Some 60,000 trees were planted during the period of November 2021 through February 2024. The tree planting, out of environmental

sustainability, proved to bring higher incomes to the community. Each tree planted absorbed between 6 and 10 mg of carbon dioxide. Incomes for the community come from its fruits and other non-timber yields. The trees planted are *manglid*, coffee, *Nangka*, *jengkol*, *petai*, durian, and avocado.

The project involves 26 community groups, including village administration staffers, farmers, and foresters. In East Lampung, Southern Sumatra, PILI, in cooperation with the local community, planted mangrove along the shore of Labuhan Maringgai sub-district during the period of 2023–2024. At least 26,500 mangrove trees were planted, and the shore now is totally restored with green thick clumps of mangrove.

- *Sekadau landscape conservation*

The carbon absorption capacity of Beganak Forest, Sekadau District, West Kalimantan, significantly increases after PILI, in cooperation with PT Parna Agromas and the local community, intensifies forest protection during 2023. The forest is included in what is called Area Bernilai Konservasi Tinggi (ABKT), the Indonesian acronym for High Conservation Value Area. The area is now well-guarded by the local administration and local community. PILI managed to establish an anti-fire community group in the Beganak and Meragun villages, Sekadau District, to prevent forest fires. The group regularly patrols and monitors the forest on a monthly basis. The groups have legal access to the forest as a source of living under customary rules. Shifting cultivation that has been practiced for generations gives an advantage to safeguarding the forest.

- *PILI-Global Eco Rescue partnership*

PILI and Global Eco Rescue (GER) are now preparing to restore the peatland and mangrove ecosystem in North Kalimantan. The project is aimed at achieving the National Determined Contribution (NED) in North Kalimantan.

- *PILI-KPHP partnership for restoration*

PILI's joint forest restoration project with the South Bukit Barisan National Park (TNBBS) and local environmental group called KPHP is encouraging. The project managed to turn the damaged forest area of Way Nipah into green blocks as wide as 218 hectares, Ulu Belu 77 hectares, and Sekincau 43 hectares. One hundred and thirteen species of animals were saved from the pressure of illegal hunting and forest trespassing. The project also gives a boost to the local rural economy by developing animal husbandry, organic farming, waste processing, and craft business. KPHP is an Indonesian acronym for Kelompok Pelestari Hutan Pesangan, or Pesangan Forest Sustainer Group in English, that was founded in 2012 [13].

5.1 Muslim community's environmental conservation

PILI field workers see Islamic tradition in place. "In villages of Lampung Province people are not allowed to use electric wire for fishing; hunting with rifle; and taking

forest products in the quantity more than one needs,” Evi Indraswati, Field Manager of PILI, said in an interview [14].

Al Hasyim, PILI's project officer at Nabire, Papua, sees that the community knowledge of the environment is derived from Islamic teaching, such as clean and hygienic ways of living, waste treatment, maintenance of water resources, prohibition of hunting, and prevention of hurting animals.

Siti Perhatin, PILI's Reforestation program coordinator, sees higher awareness of taking care of trees, clean environment, and sanitation. The Muslim community is also more prudent of likely floods, landslide, and other nature phenomenon that likely happen around them [15].

Anwar Muzakkir, PILI's botanical and land rehabilitation expert, found more orderly and well-designed kampongs in the upstream of Utara River and Selatan River, South Kalimantan—a Muslim populated province. “There is no big animal keeping near houses. Animals with fangs are *haram* (inedible), so is wild animal hunting,” Anwar said in an interview [16].

5.2 In need for new studies

As PILI field workers said, they always found new things in the community they work with to study further. As Evi Indraswati and colleagues put it, “Each community has its own characteristic, social structure, values and norms and even ways of communication. Our knowledge on the natural environment gives us advantage for our works, but our knowledge on social and cultural environment are always renewed. It's dynamic in nature.”

From her field observation, Siti found that the community has their own knowledge of their natural and social environment. This knowledge becomes a subject to her learning-by-doing process. “The community knowledge complements our knowledge,” she said. To her, among the skills and knowledge that need to be learned is rural communication, social management, endemic tree varieties, animal species, and leadership.

All PILI field officers we interviewed said that communication skill is the top priority of their equipment in accomplishing their missions, followed by knowledge on social and environmental environment, and local biodiversity.

5.3 Rumah Ilmu

In an effort to conceptualize the information, data, and knowledge from the fields, PILI set up a forum called *Rumah Ilmu*, which is English for the House of Science. PILI field workers regularly engage in an exchange of ideas and knowledge in this forum that gradually becomes a hub of intellectual exercise.

After a series of discussions, PILI field workers identify a number of study fields to develop further and dig deeper. According to Zaini Rahman, head of Rumah Ilmu, on top of the study fields are communication, environmental management, applied ecology, and village administration. Applied sociology, rural economy, and religion are followed by supporting study fields that include history, psychology, and energy [17].

“They bring up the information and problems they encounter in the fields to the discussion. Then we engage in intensive intellectual discourses on how to deal with the problems. This activity results in better knowledge and understanding about

the situation we work in. And this is a big help to accomplish our jobs,” said Zaini Rachman in an interview [17].

Zaini said that as the Rumah Ilmu runs more regularly, there is now a need for a syllabus that will guide the study and discussions. The syllabus may have been completed in 2 years of study. This will lead to a more institutionalized learning process. He said there is a possibility and opportunity to go further to become a sort of college or study program in universities.

As Indonesia is becoming known for its big carbon market potential, environmental studies are gaining more popularity in Indonesian universities, with alluring profession and career offer for students. The environmental studies include not only knowledge of the natural environment but also the man-made environment such as cities, constructions, and dams. The fact that it covers not merely pure sciences but also social sciences makes the study field even more interesting.

Environmental studies are now available in Indonesia’s top universities. To name a few: Technology Institute of Bandung (ITB), Technology Institute of Sepuluh November (ITS), University of Indonesia (UI), the Gadjah Mada University, and Diponegoro University. However, the program study that integrate environment and Islam is still in intellectual discourse, and this paper is part of it (Table 1).

No	Subject code	Name of subjects	Credit course
1	234	Islamic conservation history	3
2	222	Islamic conservation	3
3	143	Environmental Fiqh (<i>Fiqh al bi’ah</i>)	2
4	231	Allometry	2
Semester II			
5	234	Environmental modeling	3
6	222	Spatial planning	3
7	143	Environmental valuation	2
8	231	Environmental psychology	2
Semester III			
9	422	Environmental policy analysis	3
10	222	Environmental management	3
11	143	Research methodology	2
12	231	Environmental engineering	2
Semester IV			
13	897	Seminars on assignment	1
14	657	Thesis review	3
Number of credit course			34

Table 1.
The proposed syllabus of Islam and environmental study program.

6. Analysis

The fundamentals of Islam and environmental study is that the environment-related issues are observed with Islamic perspective. As Islam is God's design to be a blessing for the universe, then any harmful deed against nature is a denial of the blessing. Unsustainable and excessive exploitation of natural resources is a defiance against Allah's command to take care of nature.

So is the case with environmental management.

PILI's field managers are equipped with the knowledge they obtained during their university studies as tools to build the community capacity of managing natural resources and the environment. During their field missions they found themselves adjusting their knowledge to the living knowledge, skills, and values of the community they encounter. The adjustment led to "updated knowledges" that need further study.

In general, the PILI fields managers found "local knowledges" that are more relevant to the real situation and so are complementary to their university background. Among the local knowledge is bioecology, which is different in one place than in another. The allometric formula for carbon calculation is another challenge to be developed further. The same goes for habitat characteristics, which are distinct from one another. Knowledge on habitats requires continuous updating.

How the community values the natural resources and how they use them has been another subject of continuous learning and knowledge updating. PILI field managers see how geographical conditions shape the community's way of living, social norms, and cultural values. A combination of geographical conditions, type of local administration, and communication with external parties determine the community character. The studies about this subject may be categorized as "applied sociology".

These are the subjects that come under the Islam and the Environment Study Program. It covers bioecology, allometric calculation, local administration, local geography, culture, and sharia law. The latter can be specified more into sharia law on environment or *fiqh al bi'ah* (Fiqh of environment), which has been initiated by several Muslim scholars in Indonesia. Ali Yafie is the first Indonesian Muslim scholar to write a book on the *fiqh* of environment titled "*Merintis Fiqih Lingkungan Hidup*."

Supporting subjects would be environmental physics, environmental biology, ecology, climate change, environmental biotechnology, environmental sociology, environmental law, entrepreneurship, rural economy, environmental management, the list goes on.

To go further with the study program, PILI built a strategic partnership with the State Islamic University of Sunan Gunung Djati Bandung, paving the way for establishing Islam and Environment at the magister program.

Since 1995, UIN SGD Bandung has provided *Pengembangan Masyarakat Islam* (PMI) or Muslim Community Development study programs that have produced more than 1000 community development officers. The graduates are equipped with social analysis, community building, and development planning capabilities. The PMI curriculum covers human resources building, economic development, and environmental development. However, it has yet to integrate social and Islamic sciences in the study field, which becomes an opportunity for a more integrated study under the Islamic Environmental Study program.

7. Conclusion

Islamic Environmental Studies has what it takes to be a study program of its own. It covers 34 subjects, with likely reduction or addition. The study program is planned to be first introduced by the State Islamic University of Sunan Gunung Djati Bandung, with PILI as a strategic and supporting partner. The university also has what it takes to run the study program for its Islamic science advantage. The new study program will answer the demand for field managers, social workers, and both corporation and community consultants in national efforts to reduce carbon emission to zero level and run carbon trade projects.

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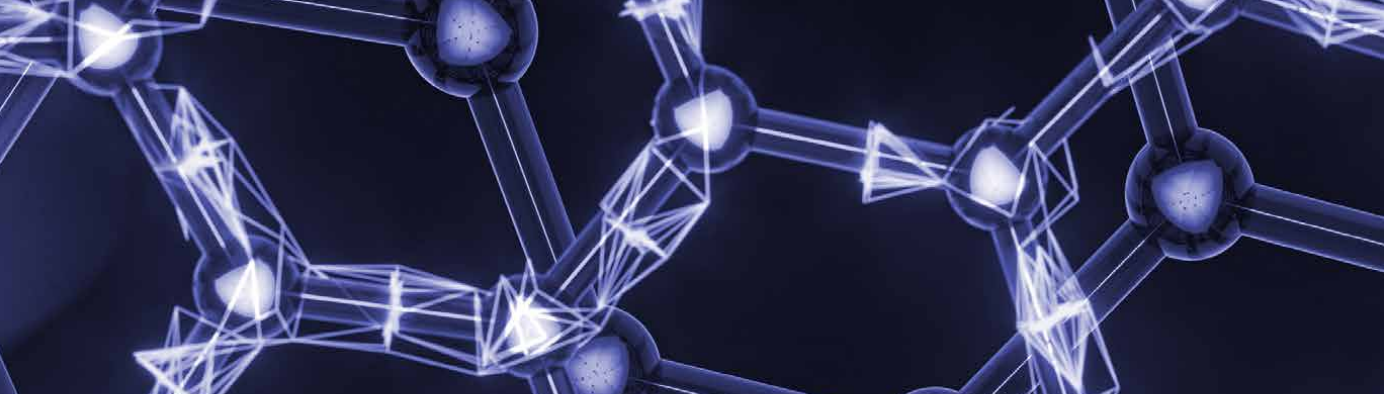
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Our planet faces interconnected crises, climate change, biodiversity loss, and resource scarcity that defy simple, one-dimensional solutions. *Integrated Approaches to Sustainable Resource and Environmental Management* argues that a fundamental paradigm shift is essential: moving from fragmented, sectoral responses to integrated approaches that weave together diverse forms of knowledge. This volume brings together leading scholars to explore what integration means in theory and practice.

From the complex impacts of invasive species on climate feedbacks to reviving ancient water systems for modern adaptation, from designing just community energy solutions to governing global raw material supply chains, the chapters reveal the interconnected nature of our most pressing challenges. The book demonstrates how modern science, cultural wisdom, historical insight, and participatory governance can and must converge to build resilience. A vital resource for students, researchers, policymakers, and practitioners, this book offers a compelling framework and concrete case studies for anyone committed to forging sustainable and equitable pathways in the Anthropocene.

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