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Impact of Ecological Restoration on Biodiversity Conservation: A Systematic Literature Review

Sandra Elizabeth Campuzano-Vera[1], Huber Gregorio Echeverría Vásquez[2], Juan Mauricio Guaman-Quispillo[3], Dennis Alfredo Peralta Gamboa[4]

Abstract

Ecological restoration is a key strategy to reverse biodiversity loss and mitigate the impacts of environmental degradation, especially in Neotropical regions. This study reviews 29 recent investigations on restoration techniques and their implications for biodiversity conservation. The most effective strategies include applied nucleation, reforestation with native species, and understory light management, complemented by technologies such as drones and image analysis for monitoring. While active restoration accelerates ecosystem recovery, it faces high initial costs. Though more cost-effective, passive restoration proves less efficient in severely degraded areas. Innovative models, such as using Amazonian dark earth and agroforestry systems, have demonstrated dual ecological and economic benefits by fostering community participation and attracting private investments. Restored ecosystem services include pollination, water regulation, and carbon sequestration. However, challenges like lack of funding, limited training, and technical barriers restrict large-scale implementation. Climate change adds complexity by affecting the resilience of restored ecosystems. This analysis underscores the importance of robust public policies, financial incentives, and multisectoral collaboration to ensure the sustainability of these initiatives. In conclusion, ecological restoration is a comprehensive tool to address environmental and socioeconomic challenges, with a significant positive impact on biodiversity and ecosystem services. Innovation and an adaptive approach are needed to maximize its benefits.

Keywords: Ecological Restoration; Biodiversity; Neotropics; Ecosystem Resilience; Ecosystem Services.

Introduction

Biodiversity loss and ecosystem degradation have reached critical levels, jeopardizing the stability of ecosystem services essential for human life. Neotropical regions, known for their high biodiversity and ecosystem richness, face significant threats due to human activities such as deforestation, intensive agriculture, and climate change (Kumar et al., 2024; E & A, 2024). In this context, ecological restoration has emerged as an essential strategy to reverse damage, restore biodiversity, and recover critical ecosystem functions (Edwards & Cerullo, 2024).

Ecological restoration is defined as the process of assisting the recovery of ecosystems that have been degraded, damaged, or destroyed. Its primary goal is to reestablish an ecosystem's composition, structure, and function to a state as close as possible to its original condition. This approach not only seeks to recover lost biodiversity but also aims to enhance ecosystems' resilience to future impacts.

[1] Universidad Estatal De Milagro, Email: scampuzanov@unemi.edu.ec
[2] Universidad Estatal De Milagro, Email: hecheverriav@unemi.edu.ec
[3] Universidad César Vallejo, Perú, Email: jguamanq@ucvvirtual.edu.pe
[4] Universidad Estatal De Milagro, Email: dperaltag2@unemi.edu.ec

In recent years, there has been a surge in research on restoration techniques, including reforestation, wetland restoration, and the introduction of keystone species. However, despite scientific advancements, restoration projects face significant challenges. These include inadequate funding (Bayraktarov et al., 2020), insufficient long-term monitoring, and limited local community participation in initiatives (Toledo-Aceves et al., 2022).

This study aims to synthesize current knowledge on the impact of ecological restoration on biodiversity conservation, focusing on Neotropical regions. The systematic review seeks to identify trends, advancements, and gaps in the literature, providing a solid foundation for future research and restoration projects. Additionally, the study explores how public policies and collaboration among stakeholders can enhance the effectiveness of these initiatives.

Through this analysis, we aim to contribute to a deeper understanding of best practices and strategies for ecological restoration, highlighting its role as an essential tool to address the conservation challenges of the 21st century.

Methodology

To conduct this systematic review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was followed, recognized as a standard for systematic reviews (Urrútia & Bonfill, 2010). This approach ensures transparency and reproducibility in the review process.

The steps involved in conducting the systematic review were as follows:

1. **Database Selection**

   The Scopus database was chosen due to its extensive coverage of relevant scientific literature in the fields of ecology and conservation.

2. **Search Strategy and Equation**

   Keywords related to ecological restoration and biodiversity conservation were used, combined with specific terms for the Neotropical region. The terms included: "ecological restoration," "biodiversity conservation," "neotropics," "ecosystem recovery," and "species reintroduction."

   The search equation was defined as: TITLE-ABS-KEY ("ecological restoration" OR "ecosystem restoration" OR "habitat restoration") AND TITLE-ABS-KEY ("biodiversity" OR "species diversity" OR "ecosystem diversity" OR "conservation") AND TITLE-ABS-KEY ("neotropics" OR "tropical forest" OR "tropical ecosystem" OR "Amazon" OR "Latin America").

3. **Inclusion and Exclusion Criteria**

   The following criteria were defined:

   - Documents published within the last five years (2020–2024).
   - Only articles were considered as document types.
   - All subject areas were included.
   - Studies published in English and Spanish.

- Full-text studies were included.

4. **Document Selection**

Titles and abstracts were reviewed to assess relevance. Subsequently, the full texts of selected articles were reviewed to confirm their inclusion in the analysis.

5. **Data Extraction and Analysis**

Data extraction and analysis in this systematic review focused on identifying key aspects of the selected studies to provide a comprehensive overview of advancements in ecological restoration.

- **General Data:** Information on authors, year of publication, and geographic location of each study was collected. This analysis highlighted temporal and spatial patterns in the distribution of studies, emphasizing regions and periods with the most research activity in ecological restoration.
- **Ecosystem Types:** The ecological contexts addressed in the selected articles were classified, including tropical rainforests, savannas, wetlands, and mountainous areas. This approach facilitated understanding the specificities of each ecosystem and how restoration techniques adapt to different natural environments.
- **Restoration Techniques:** Methods such as applied nucleation, reforestation with native species, passive restoration, and understory light management were identified. These approaches were compared in terms of their effectiveness in promoting natural regeneration, ecological connectivity, and ecosystem function recovery.
- **Biodiversity Outcomes:** The analysis focused on indicators such as species richness changes, increased vegetation cover, and improved ecosystem functionality. These data provided evidence of the positive impacts of restoration interventions on biodiversity and ecosystem services.
- **Limitations and Challenges:** Economic barriers, lack of funding, technical and climatic limitations, and scalability issues were identified as common challenges across studies. This information is critical for prioritizing attention and designing strategies to overcome these obstacles, ensuring the success of future ecological restoration initiatives.

6. **Synthesis of Results**

Results were synthesized into thematic categories, highlighting the most effective restoration techniques, biodiversity impacts, and primary challenges.

This systematic approach not only allows for an evaluation of the current state of knowledge but also identifies priority areas for future research, contributing to the development of more effective and sustainable restoration strategies.

RESULTS

The initial search yielded 389 documents. After applying the inclusion and exclusion criteria, 60 studies were shortlisted. These were evaluated based on their titles and abstracts, reducing the count to 50 documents. Subsequently, the full texts of the selected articles were reviewed, and 29 studies were ultimately included in this systematic review (Figure 1).

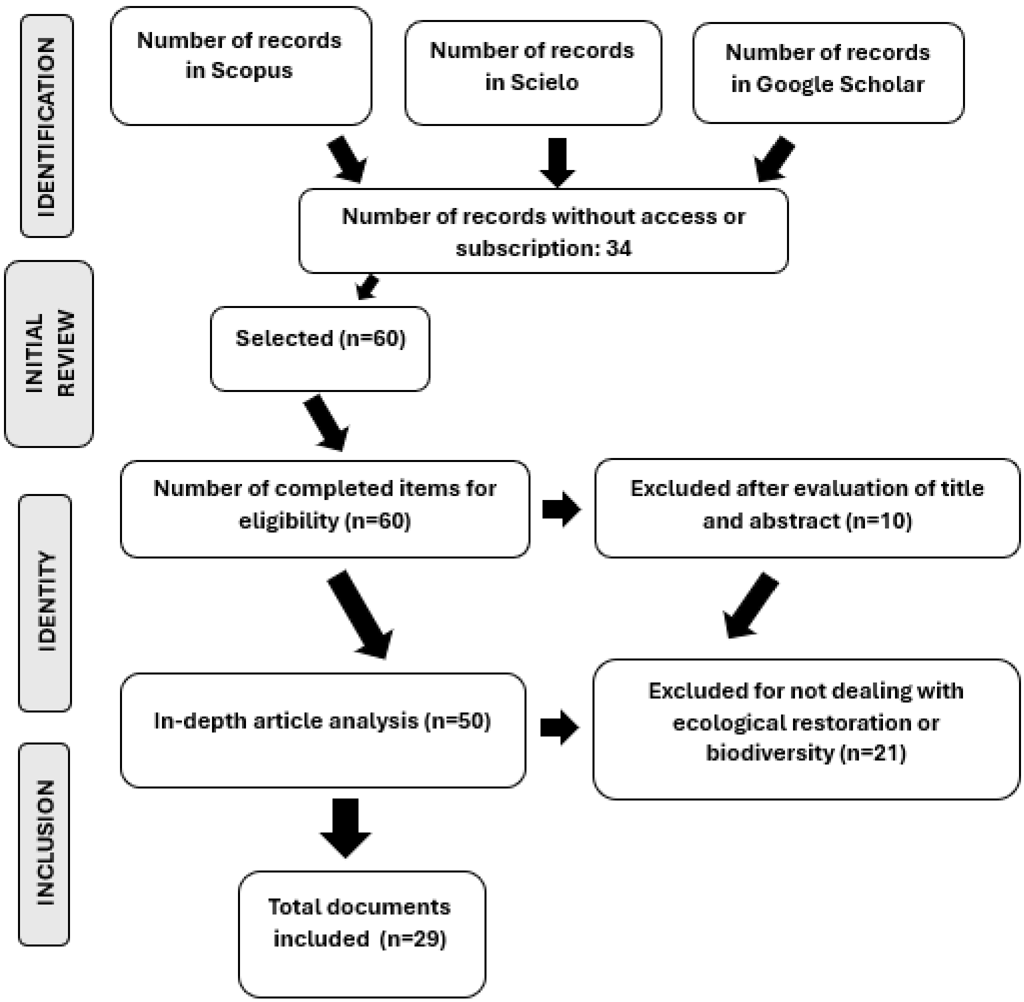

Figure 1: PRISMA selection flow diagram

Restoration Techniques and Effectiveness

Ecological restoration in the Neotropics has advanced significantly through innovative techniques and interdisciplinary approaches. Carbon payment schemes and co-financing models have proven to be viable tools to overcome economic barriers, promoting the planting of native trees and the enrichment of secondary plantations. These approaches have shown promising cost-effectiveness benefits in low-fertility soils (Sinacore et al., 2023). Similarly, applied nucleation has emerged as a key technique, creating microhabitats that foster natural regeneration and ecological succession with notable success in moderately degraded areas (Díaz-García et al., 2020).

In addition, managing understory light through chemical thinning and the use of hemispheric imaging has improved the productivity of timber species and natural regeneration in tropical areas (Barros et al., 2023). Emerging technologies, such as drones equipped with RGB cameras for monitoring and restoration, have enabled precise assessment of degradation and recovery indicators, optimizing strategic planning (Lee et al., 2023).

The application of Amazonian dark earths (ADE) has significantly improved soil structure and microbiota, facilitating the growth of native tree species in degraded soils (Freitas et al., 2023). Agroforestry models that integrate non-timber forest products have demonstrated economic sustainability, attracting private investment and generating financial returns in several tropical countries (Gasparinetti et al., 2022). Ecohydrological strategies implemented in Colombia's tropical watersheds have shown significant improvements in water recharge and flow regulation, emphasizing the importance of restoring soil physical properties (Mosquera-Vásquez & Tobón-Marin, 2023).

Involving local communities in restoration projects has proven essential for long-term sustainability. Traditional ecological knowledge complements modern techniques to accelerate secondary succession processes and landscape restoration (Moreno-Casasola, 2022). Moreover, passive restoration and ecological corridors in tropical montane ecosystems have enhanced biodiversity and ecosystem functionality, particularly in areas impacted by agricultural and livestock activities (Christmann & Menor, 2021).

In semi-arid regions of Brazil, species such as *Combretum glaucocarpum* and *Pityrocarpa moniliformis* have demonstrated high survival rates and rapid growth under climatic stress (Ribeiro et al., 2021). In Malaysia, the taungya system has proven effective for rehabilitating degraded forests, ensuring high genetic diversity (Hamid et al., 2021).

In threatened ecosystems, such as Amazonian ferruginous formations, the use of functional seed traits optimizes species selection and restoration techniques, reducing costs and improving seedling establishment (Zanetti et al., 2020). Additionally, Díaz-García et al. (2020) demonstrated that while both active and passive restoration recover biodiversity in tropical cloud forests, active restoration accelerates the recovery of forest specialists, whereas passive approaches are more cost-effective on larger scales.

In marine environments, techniques like coral gardening, larval propagation, and microfragmentation are being applied to restore reefs in Latin America. These practices have proven effective in areas where natural recovery is limited (Bayraktarov et al., 2020).

Impacts on Biodiversity

The impacts of restoration on biodiversity are notable both ecologically and functionally. In subtropical forests of China, the cessation of anthropogenic disturbances has significantly improved vegetation composition and diversity. Shade-tolerant species and those with low nutrient requirements play a crucial role in late ecological succession stages (Ma et al., 2024).

Key species like binturongs act as seed dispersers in degraded forests, facilitating the regeneration of critical species such as figs, essential for restoring ecosystem structural complexity (Honda et al., 2024). In Malaysia, experiments have shown that increased tree diversity enhances vegetation cover and long-term ecosystem functionality. In Costa Rica, nucleation techniques have effectively promoted tree recruitment, supporting the survival of seedlings and saplings in restored areas (Kulikowski et al., 2023).

Ecosystem services associated with agroforestry systems, such as pollination and pest control, have proven essential in regenerating forests, though these benefits may take decades to fully manifest (González-Chaves et al., 2023). Secondary and montane forests have shown multidimensional recovery, including improvements in aboveground biomass, species diversity, and soil functionality, underscoring their potential to mitigate climate change effects (Poorter et al., 2021; Christmann & Menor, 2021).

Experiments in Brazil’s Atlantic Forest indicate that large herbivores mitigate biodiversity loss in tropical forests, slowing compositional changes in species-rich communities. This approach can be integrated into nature-based solutions (Villar & Medici, 2021). Additionally, identifying species with superior germination and survival traits, such as *Cenostigma macrophyllum*, improves restoration outcomes in dry forests, maximizing biodiversity and functionality (Ribeiro et al., 2021).

Monitoring bats in restored sites in Costa Rica revealed that their functional diversity supports key ecosystem services, such as seed dispersal and pest control, demonstrating early restoration success (Haave-Audet et al., 2021). Forest fragments in the Atlantic biome have shown average losses of 25–32% in biomass and 23–31% in species richness, highlighting the importance of restoring degraded areas and improving landscape connectivity (de Lima et al., 2020).

Finally, experiments in Indonesia suggest that sustainable management of underlying vegetation in plantations improves local biodiversity without compromising agricultural productivity (Luke et al., 2020).

Main Challenges

Despite the progress achieved, restoration projects face significant challenges that limit their large-scale implementation. Restoration costs per hectare and a lack of community participation are notable obstacles. For instance, the average annual cost of projects in Latin America is approximately $93,000 USD per hectare, underscoring the need for sustainable investments to expand these initiatives (Bayraktarov et al., 2020). Economic barriers remain one of the primary challenges, with high initial costs restricting the scope of initiatives, although carbon payments and external financial support offer viable alternatives (Sinacore et al., 2023; Díaz-García et al., 2020).

Technical limitations, such as the use of drones and hemispheric imaging, require further refinement to match the precision of traditional methods. The lack of access to low-cost tools remains a significant barrier (Lee et al., 2023; Barros et al., 2023). Another challenge lies in adapting techniques to diverse ecosystems, where issues related to scalability and species selection persist (Díaz-Triana et al., 2023).

Climate change exacerbates challenges by altering precipitation patterns, reducing the resilience of key ecosystem services such as carbon storage and water regulation (Sultana et al., 2023; Christmann & Menor, 2021; de Lima et al., 2020). Landscape fragmentation and the loss of connectivity between restored areas also represent significant challenges. These impacts could be mitigated through the implementation of ecological corridors (Indrajaya et al., 2022; Shestakova et al., 2022).

Although active restoration has proven to be more effective in highly degraded areas, its high initial cost limits its adoption compared to passive approaches. Passive restoration, while more economical, is less effective in severely impacted ecosystems (Gasparinetti et al., 2022; Díaz-García et al., 2020).

These challenges highlight the need for an adaptive and comprehensive approach to maximize the positive impact of ecological restoration in the context of climate change.

Discussion

Ecological restoration in the Neotropics and other tropical ecosystems represents a field of constant evolution, as evidenced by the advancements and challenges highlighted in this review. Restoration techniques have proven effective across various contexts, enhancing biodiversity and ecosystem services while confronting economic, technical, and climatic barriers that require innovative solutions.

Efficiency and Diversity of Restoration Techniques

The reviewed strategies underscore the importance of combining traditional approaches with technological innovations to meet the specific needs of each ecosystem. Carbon payment schemes and co-financing models, for example, have helped overcome economic barriers by creating sustainable financial incentives for the restoration of degraded forests through the planting of native trees and the enrichment of secondary plantations (Sinacore et al., 2023). These schemes not only promote environmental benefits but also create economic opportunities for local communities. However, their implementation requires robust regulatory frameworks and continuous monitoring to ensure long-term efficacy.

Applied nucleation has emerged as a key technique in moderately degraded areas, creating microhabitats that promote natural regeneration and ecological succession (Díaz-García et al., 2020). This approach not only reduces costs by relying on natural processes but also fosters ecological connectivity, an essential component for restoring functionality to fragmented landscapes. However, its effectiveness could be enhanced by integrating more specific species selection criteria and employing technologies that facilitate monitoring.

Understory light management through chemical thinning, complemented by hemispheric imaging, has demonstrated improvements in timber species productivity in tropical areas (Barros et al., 2023). While this technique is highly replicable in similar regions, it faces challenges related to social acceptance and associated implementation costs. In this context, drones equipped with RGB cameras have revolutionized monitoring strategies, enabling precise evaluation of ecosystem conditions at a low cost (Lee et al., 2023). This technology has optimized planning and facilitated data-driven decision-making, establishing itself as an indispensable tool in restoration projects.

The incorporation of Amazonian dark earths (ADE) in restoring degraded soils has shown promising results, improving soil structure and promoting the growth of native species (Freitas et al., 2023). Similarly, agroforestry models that integrate non-timber forest products not only reinforce the economic sustainability of initiatives but also contribute to biodiversity conservation in areas under high anthropogenic pressure (Gasparinetti et al., 2022). Ecohydrological strategies implemented in Colombia's tropical watersheds have highlighted the importance of restoring soil physical properties to ensure ecosystem functionality (Mosquera-

Vásquez & Tobón-Marin, 2023).

Contributions to Biodiversity

The positive impacts on biodiversity are evident in ecosystems where restoration techniques have been implemented. In subtropical forests of China, the cessation of anthropogenic disturbances has enabled the recovery of shade-tolerant species, emphasizing the potential of natural regeneration strategies (Ma et al., 2024). This underscores the importance of policies limiting destructive human activities, allowing ecosystems to recover autonomously.

In degraded ecosystems, keystone species like binturongs have played a crucial role in regenerating essential species such as figs, which are critical for restoring the structural and functional complexity of forests (Honda et al., 2024). This finding highlights the need to integrate fauna conservation strategies into restoration projects to ensure the continuity of fundamental ecological processes.

In Malaysia, experiments have shown that increasing tree species diversity significantly enhances vegetation cover and ecosystem functionality. Similarly, in Costa Rica, nucleation has been effective in promoting tree recruitment, supporting the survival of seedlings and saplings in restored areas, and reinforcing the value of these techniques for restoring severely degraded ecosystems (Veryard et al., 2023; Kulikowski et al., 2023).

Ecosystem services associated with agroforestry systems, such as pollination and pest control, have proven vital for maintaining ecological balance. However, these benefits often take decades to fully manifest (González-Chaves et al., 2023). Secondary and montane forests have demonstrated multidimensional recovery, including improvements in aboveground biomass, species diversity, and soil functionality, underscoring their potential to mitigate the effects of climate change (Poorter et al., 2021; Christmann & Menor, 2021).

In Brazil's Atlantic Forest, studies have revealed that large herbivores help mitigate biodiversity loss in tropical forests, slowing compositional changes in species-rich communities and promoting ecological resilience. This approach can be integrated into nature-based solutions for biodiversity conservation (Villar & Medici, 2021).

Furthermore, identifying tree species with superior germination and survival traits, such as *Cenostigma macrophyllum*, has improved restoration outcomes in dry forests, maximizing biodiversity and functionality (Ribeiro et al., 2021). In Costa Rica, monitoring bat populations in restored sites has revealed their functional diversity supports key ecosystem services, such as seed dispersal and pest control. This evidence demonstrates the early success of restoration efforts (Haave-Audet et al., 2021).

Forest fragments in Brazil's Atlantic biome have experienced average losses of 25–32% in biomass and 23–31% in species richness. This highlights the urgent need to restore degraded areas and enhance landscape connectivity (de Lima et al., 2020). Additionally, sustainable vegetation management in Indonesian plantations has been shown to improve local biodiversity without compromising agricultural productivity (Luke et al., 2020).

These findings collectively illustrate how targeted restoration techniques can significantly enhance biodiversity, ensuring long-term ecological and functional recovery across diverse ecosystems.

Persistent Challenges and Future Opportunities

Despite the advancements, restoration projects face significant challenges that hinder their large-scale implementation. High initial costs and the lack of sustainable funding remain critical barriers, particularly in regions with limited resources. For instance, the average annual cost of restoration projects in Latin America is estimated at $93,000 USD per hectare, highlighting the urgent need for innovative and sustainable financial mechanisms such as carbon payment schemes (Bayraktarov et al., 2020; Sinacore et al., 2023).

Technical limitations also present a major obstacle. While drones and advanced technologies have optimized monitoring efforts, these tools require further refinement to ensure the precision of collected data and integration with traditional methods (Lee et al., 2023; Barros et al., 2023). Moreover, the lack of access to affordable tools continues to limit their adoption in large-scale projects.

Another significant challenge is the scalability of restoration techniques. Approaches like nucleation and other strategies require better adaptation to local ecosystems, as well as more precise species selection to maximize their effectiveness (Díaz-Triana et al., 2023). Meanwhile, climate change exacerbates difficulties by altering precipitation patterns and reducing the resilience of restored ecosystems. This impacts critical ecosystem services such as carbon storage and water regulation (Sultana et al., 2023; de Lima et al., 2020).

Landscape fragmentation and the loss of connectivity between restored areas remain significant challenges. Solutions such as ecological corridors could help mitigate these effects, but their implementation demands coordinated efforts among multiple stakeholders (Indrajaya et al., 2022; Shestakova et al., 2022).

Although active restoration has demonstrated greater effectiveness in severely degraded areas, its high initial cost limits its application. On the other hand, passive restoration, while more cost-effective, tends to be less effective under extreme conditions (Gasparinetti et al., 2022; Díaz-García et al., 2020).

Conclusion

Ecological restoration has emerged as an essential tool to counteract biodiversity loss and environmental degradation, particularly in Neotropical regions. This systematic study highlights that restoration techniques not only recover ecosystems but also enhance their functionality and resilience against anthropogenic impacts and climate change. Strategies such as applied nucleation, understory light management, and the integration of advanced technologies like drones for monitoring have proven highly effective in promoting natural regeneration and accelerating the recovery of critical species.

Passive restoration, while more cost-effective, is limited in severely impacted ecosystems, whereas active restoration yields faster results but faces financial challenges. The incorporation of innovative approaches, such as Amazonian dark earths and agroforestry models, has enhanced biodiversity while generating economic benefits, attracting private investment, and encouraging community participation. However, the lack of sustainable funding and insufficient training in restoration techniques remain significant barriers to large-scale implementation.

The benefits of these practices extend beyond ecological recovery, with substantial impacts on ecosystem services such as pollination, water regulation, and carbon sequestration. In this context, agroforestry systems and ecological corridors have proven effective in mitigating landscape fragmentation and fostering ecological connectivity.

Despite these advancements, significant challenges persist. Economic, technical, and social barriers, compounded by the effects of climate change, underscore the need for comprehensive approaches that combine ecological restoration with robust public policies and active community engagement. The development of financial incentives, such as carbon payment schemes, and the implementation of stronger regulatory frameworks are crucial for ensuring the long-term sustainability of these initiatives.

In conclusion, this study demonstrates that ecological restoration is not only a solution for biodiversity conservation but also an integral tool for addressing the environmental and socioeconomic challenges of the 21st century. Success depends on a balanced combination of technological innovation, traditional practices, and effective collaboration among stakeholders. Future research should focus on developing more adaptive techniques, evaluating long-term impacts, and creating financial mechanisms that make these initiatives viable across diverse global contexts.

Conflict of Interest

The authors declare no conflict of interest regarding the publication of this study.

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Author Contributions

Conceptualization: DAPG; Methodology: DAPG, HGEV; Formal Analysis: DAPG; Writing—Original Draft Preparation: DAPG; Writing—Review and Editing: DAPG, HGEV; Visualization: DAPG, HGEV; Supervision: HGEV.

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