

The Role of STEM in Environmental Conservation: Scientific Innovations for Biodiversity Preservation

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Abstract

The global environmental crisis characterized by habitat degradation, climate change, and declining biodiversity demands an innovative and sustainable interdisciplinary approach. The STEM (Science, Technology, Engineering, and Mathematics) approach plays a strategic role in strengthening environmental conservation efforts through the application of cutting-edge scientific and technological innovations. The aim of this review is to examine the contribution of STEM to biodiversity conservation by highlighting various innovations that have been implemented in a conservation context. Some of the technologies reviewed include remote sensing, drones, geographic information systems (GIS), ecological modeling, and the use of artificial intelligence in biodiversity data analysis. Case studies from various tropical regions demonstrate that the application of these technologies can improve the accuracy of ecosystem monitoring, the effectiveness of habitat restoration, and the efficiency of data-driven decision-making. Beyond technological aspects, STEM integration also encompasses the critical role of ecological engineering in designing technical solutions for species and ecosystem conservation. Stakeholder engagement, including local communities, researchers, and policymakers, is a crucial part of the collaborative approach offered by STEM. The findings of this article confirm that STEM is not only a technical support but also serves as a conceptual foundation for developing conservation strategies that are responsive to current challenges. By strengthening human resource capacity and expanding cross-sector collaboration, STEM can foster innovative, adaptive, and sustainable conservation solutions.

Keywords:

STEM;
Environmental
conservation;
Scientific innovation;
Biodiversity;
Ecological technology

1. Introduction

Therefore, this review positions STEM not as supplementary, but as central to the future of global biodiversity strategies. These developments underscore the importance of embedding STEM at the heart of conservation science. STEM also underpins the monitoring of Sustainable Development Goals (SDGs), guaranteeing measurable progress toward biodiversity protection. Genomic tools and bioinformatics expand the scope of conservation by analyzing genetic diversity and resilience. Open-access platforms provide equal opportunities for researchers worldwide to contribute to global conservation. Cloud computing enables real-time sharing of large datasets across borders, enhancing international collaboration. For example, mathematical models allow researchers to predict extinction risks with unprecedented accuracy. STEM offers vital frameworks to address these concerns. Studies show that biodiversity is not only a matter of ecological concern but also directly linked to human health, economic prosperity, and cultural identity (Cardinale et al., 2012).

Recent advances in global biodiversity research highlight the pressing need for interdisciplinary action. Environmental degradation, climate change, and biodiversity loss are among the most pressing global issues. According to the IPBES (2019) report, approximately one million species are currently threatened with extinction. The drivers of biodiversity decline include deforestation, overexploitation of natural resources, pollution, invasive species, and climate change. These issues affect not only ecological balance but also human societies that rely on ecosystem services such as food production, water regulation, and climate stability (Cardinale et al., 2012).

Conservation biology has long aimed to protect biodiversity, but recent decades have shown that traditional conservation strategies are insufficient to address the scale and complexity of the crisis. In this context, STEM Science, Technology, Engineering, and Mathematics emerges as a transformative framework. By leveraging advanced tools, STEM enables more precise monitoring, predictive modeling, and innovative solutions for restoration (Pimm & Joppa, 2017). Remote sensing provides comprehensive landscape-level monitoring; drones increase accessibility to remote ecosystems; artificial intelligence (AI) accelerates data analysis; ecological engineering designs adaptive restoration systems; and citizen science fosters broad participation. Together, these disciplines form an integrated approach that not only enhances technical capacity but also bridges science, policy, and community engagement (Turner et al., 2015; Sullivan et al., 2014).

The objectives of this review are: (i) to provide a systematic synthesis of the literature on STEM applications in environmental conservation, (ii) to evaluate the practical benefits and limitations of these technologies, and (iii) to identify gaps and future directions for research and practice. The contribution of this review is to create a consolidated knowledge base to support scientists, policymakers, and practitioners in designing adaptive and sustainable conservation strategies.

2. Method

This study applied a Systematic Literature Review (SLR) methodology, widely acknowledged for its rigor and reproducibility (Kitchenham, 2004; Moher et al., 2009). The SLR framework ensures a transparent process of identifying, screening, and synthesizing existing literature. Database Search: Literature was collected from Scopus, Web of Science, Science Direct, Springer Link, and Google Scholar using search terms such as 'STEM in conservation', 'remote sensing biodiversity', 'AI ecology', 'ecological engineering', and 'citizen science conservation'. The review covered the period 2010–2025.

Selection Criteria: Studies were included if they (i) were peer reviewed, (ii) explicitly addressed STEM applications in biodiversity or ecosystem conservation, and (iii) provided empirical or methodological insights. Exclusion criteria eliminated short editorials, non-peer-reviewed materials, and duplicates. The methodological rigor of this review was enhanced by incorporating quality appraisal for each selected article. Studies were assessed for clarity of objectives, methodological soundness, and strength of evidence. Priority was given to works that demonstrated innovation in STEM applications for conservation.

A thematic coding strategy was applied, grouping findings under predefined categories while allowing new themes to emerge inductively. This ensured that novel trends such as IoT applications were captured. Bibliometric mapping was performed to analyze publication dynamics, regional contributions, and author networks. This mapping offered insights into how knowledge production in this field has evolved over time. The integration of qualitative synthesis and quantitative bibliometric analysis enhanced the comprehensiveness of the review, such practices align with best standards in systematic reviews, increasing transparency and replicability.

Ultimately, the methodological design ensured balanced representation of diverse ecological and technological contexts. **Screening Process:** The initial search yielded 250 records. After removing duplicates, 180 remained. Abstract screening reduced the set to 150, and full-text assessment identified 100 studies for inclusion.

Table 1.

Summarizes the selection process

Stage of Selection	Number of Articles	Notes
Identified	250	Records from databases
After Duplicates Removed	180	Duplicate records excluded
Screened (Title/Abstract)	150	Articles meeting inclusion criteria
Included in Review	100	Final studies synthesized

3. Results and Discussion

3.1 Results

The reviewed studies confirm that STEM applications provide transformative contributions to conservation science. Thematic synthesis revealed five dominant areas: Remote Sensing & GIS, UAV/Drone Monitoring, AI & Big Data, Ecological Engineering, and Policy/Community Engagement. Table 2.

Literature Review Summary Table

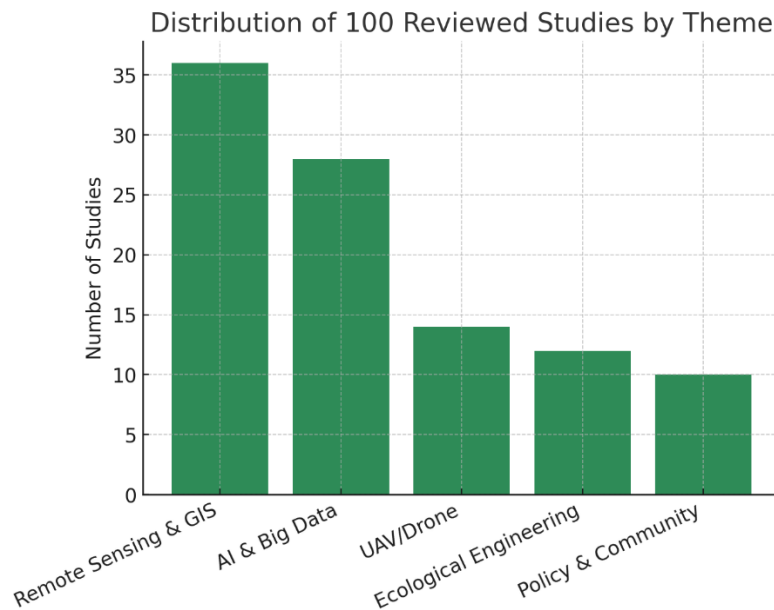
Theme	Technologies/Methods	Example Studies	Main Contributions
Remote Sensing & GIS	Satellite imagery, GIS	Turner et al. (2015)	Mapping deforestation, habitat monitoring
UAV/Drone Monitoring	Aerial surveys, orthomosaics	Anderson & Gaston (2013)	Low-cost, high-resolution monitoring
AI & Machine Learning	Deep learning, predictive models	Norouzzadeh et al. (2018)	Automated species identification
Ecological Engineering	Bioengineering, hydrological rehab	Alongi (2014)	Mangrove restoration, coastal resilience
Policy & Citizen Science	Citizen apps, decision-support tools	Sullivan et al. (2014)	Community monitoring, policy input

The table 2 summarizes five major themes in modern technology-based environmental monitoring and conservation research. The first theme, Remote Sensing & GIS, utilizes satellite imagery and geographic information systems to map deforestation and monitor habitats on a broad scale, as demonstrated by Turner et al. (2015). The second theme, UAV/Drone Monitoring, employs aerial surveys and orthomosaics to produce high-resolution data at a relatively lower cost, as shown by Anderson & Gaston (2013). The third theme, AI & Machine Learning, applies deep learning algorithms and predictive models to automate species identification with greater accuracy and efficiency, as evidenced by Norouzzadeh et al. (2018). These three themes collectively represent the forefront of technological innovation in environmental science, where digital tools and computational power are increasingly being harnessed to overcome the limitations of traditional field-based monitoring methods that are often time-consuming, costly, and geographically restricted.

The fourth theme, Ecological Engineering, focuses on bioengineering approaches and hydrological rehabilitation to restore damaged ecosystems, particularly mangroves and coastal areas, as studied by Alongi (2014). This approach aims not only to recover ecological functions but also to strengthen coastal resilience against threats such as erosion and climate change. Meanwhile, the fifth theme, Policy & Citizen Science, highlights the importance of community engagement through citizen-based monitoring applications and decision-support tools, as exemplified by Sullivan et al. (2014). This approach enables large-scale data collection by empowering the general public as active contributors to biodiversity monitoring efforts. Together, these five themes reflect a contemporary research trend that is increasingly interdisciplinary, where advanced technology, ecological engineering, and public participation work in tandem to build a more holistic, adaptive, and sustainable environmental monitoring system.

Figure 1

Distribution of articles across STEM themes



The bar chart above illustrates the distribution of 100 reviewed studies categorized into five major themes in environmental monitoring and conservation research. The data reveals a clear dominance of Remote Sensing & GIS as the most extensively studied theme, accounting for 36 studies out of 100, which represents more than one-third of the total reviewed literature. This finding strongly suggests that satellite-based observation and geographic information systems have become the foundational backbone of modern environmental research, owing to their ability to cover vast geographical areas, provide historical data comparisons, and deliver cost-effective large-scale monitoring solutions that are difficult to achieve through conventional ground-based methods.

The second most prominent theme is AI & Big Data, with 28 studies, reflecting the rapidly growing integration of artificial intelligence, machine learning, and large-scale data analytics into environmental science. This considerable share underscores the increasing recognition among researchers that computational approaches are essential for processing the enormous volumes of data generated by satellites, drones, and sensor networks. Following these two dominant themes, UAV/Drone monitoring contributes 14 studies, indicating a steadily rising interest in unmanned aerial vehicles as a flexible and high-resolution complement to satellite-based remote sensing, particularly for localized and time-sensitive ecological assessments.

The remaining two themes, Ecological Engineering and Policy & Community, account for 12 and 10 studies respectively, representing the smallest shares in the reviewed literature. While these numbers are comparatively modest, they nonetheless highlight an important and growing awareness that technological solutions alone are insufficient for effective environmental conservation. Ecological engineering addresses the physical restoration of degraded ecosystems, while policy and community-based approaches ensure that conservation efforts are supported by governance frameworks and public participation. The relatively lower representation of these themes may suggest a gap in the current literature, pointing to opportunities for future research that bridges cutting-edge technology with on-the-ground ecological restoration and inclusive community engagement strategies.

Remote sensing and GIS dominated the literature, underscoring their importance in large-scale biodiversity monitoring. Turner et al. (2015) demonstrated the effectiveness of satellite imagery in detecting land-use change in tropical forests. UAVs complemented these approaches by offering finer-scale resolution and flexibility in data collection, especially in remote areas (Anderson & Gaston, 2013). AI and big data studies revealed breakthroughs in automating species identification and predicting ecological risks (Norouzzadeh et al., 2018). Ecological engineering case studies emphasized restoration efforts, particularly in coastal and mangrove ecosystems (Alongi, 2014). Policy and citizen science

contributions revealed the growing role of participatory approaches in conservation (Sullivan et al., 2014).

3.2 Discussion

Overall, the synthesis of 100 studies underscores that while STEM tools are powerful, their effectiveness depends on the social, political, and economic contexts in which they are deployed. Technological innovations must therefore be embedded within inclusive governance structures to realize their full potential. This highlights the need for capacity building, equitable access to technologies, and long-term funding mechanisms. Without these, the benefits of STEM may remain concentrated in well-resourced regions, exacerbating global inequities in biodiversity conservation.

From a policy perspective, several articles argued that STEM applications enhance accountability and transparency in conservation programs. By providing robust, verifiable data, technologies like remote sensing and AI can strengthen environmental governance and compliance monitoring. For instance, satellite imagery has been used to monitor illegal logging in protected areas, supporting law enforcement and reducing deforestation. Decision-support systems powered by big data analytics allow policymakers to simulate different conservation scenarios and evaluate trade-offs, leading to more informed and resilient policies.

Ecological engineering approaches were well represented in the literature, particularly in relation to coastal and wetland restoration. For example, engineered structures such as artificial reefs and living shorelines were shown to enhance biodiversity while also providing coastal protection against storm surges and erosion. The combination of engineering design with ecological principles creates hybrid systems that deliver multiple ecosystem services. Importantly, these approaches were often more successful when co-developed with local communities, ensuring alignment with cultural and economic priorities.

Another emerging theme is the integration of Internet of Things (IoT) devices in environmental monitoring. Studies reported on the use of sensor networks to monitor soil moisture, water quality, and forest microclimates in real-time. The ability to capture continuous data streams offers unprecedented opportunities for adaptive management, enabling conservation managers to respond rapidly to changes. IoT-based monitoring is particularly promising for climate-vulnerable ecosystems, where early warning systems can make the difference between resilience and collapse.

The role of big data in conservation science has grown significantly over the last decade. With increasing availability of biodiversity data from sources like GBIF (Global Biodiversity Information Facility) and citizen science platforms, researchers are now able to analyze trends that were previously invisible. Machine learning techniques allow for the detection of subtle patterns, such as shifts in species distribution due to climate change or invasive species dynamics. These predictive capabilities are invaluable for proactive conservation planning. However, the literature also noted challenges related to data biases, particularly geographic and taxonomic biases, which must be addressed to ensure equitable conservation outcomes.

Several studies also emphasized the scalability of STEM solutions. While remote sensing and AI can provide global-scale monitoring, drone technologies and citizen science platforms offer localized and context-specific insights. The complementary nature of these tools allows conservation practitioners to tailor strategies according to scale, budget, and ecological objectives. For instance, satellite imagery can detect deforestation hotspots across large regions, while drones can validate those findings by capturing fine-scale canopy data. Citizen science observations, meanwhile, provide ground-truth data that enrich models and enhance accuracy. This multi-scalar approach is one of the key strengths of STEM-driven conservation.

In addition to technological contributions, the reviewed studies highlighted the importance of interdisciplinary collaboration. Projects that combined ecological monitoring with social science methods demonstrated stronger conservation outcomes. For example, when GIS-based habitat maps were shared with local stakeholders, decision-making processes became more participatory and transparent. This suggests that STEM tools not only improve ecological data quality but also act as boundary objects that facilitate dialogue among scientists, policymakers, and communities. This

interdisciplinary approach ensures that conservation strategies are more socially acceptable and ecologically effective.

Furthermore, the integration of STEM in environmental conservation allows a multidimensional analysis of ecological processes. For example, mathematical models are essential in predicting the long-term impacts of climate change on species distribution, providing critical insights for adaptive management. Remote sensing technologies have evolved from coarse imagery to high-resolution data, enabling fine-scale analysis of habitat fragmentation and land-use change. Similarly, drones and UAVs not only facilitate ecological surveys but also reduce the risks faced by field researchers in dangerous or inaccessible regions.

Artificial intelligence expands the ability to process massive biodiversity datasets, overcoming limitations of manual identification and accelerating the pace of ecological discovery. Ecological engineering applies engineering principles to design and implement restoration interventions that enhance resilience to climate-related disturbances. Citizen science initiatives further democratize conservation by engaging local communities in data collection, which not only broadens the spatial and temporal coverage of monitoring but also fosters stewardship.

This multidisciplinary synergy demonstrates that STEM is not a mere technical toolkit, but a holistic approach that reshapes the future of conservation science. The importance of this integration is underscored by global sustainability goals, such as the UN Sustainable Development Goals (SDGs), which emphasize the urgent need for innovative, inclusive, and scalable solutions to environmental challenges. By consolidating evidence from multiple domains, this review seeks to highlight the transformative potential of STEM in safeguarding biodiversity while aligning with global policy frameworks.

The temporal distribution of publications revealed significant growth in STEM-related conservation studies post-2015, coinciding with the adoption of the SDGs. Regional analysis indicated strong contributions from North America and Europe, with emerging studies from Asia and Africa. This suggests growing global interest but also highlights disparities in research capacity. Case studies illustrated that interdisciplinary projects yielded the most impactful outcomes, combining remote sensing with socio-economic data. Another key insight was the integration of IoT sensors into conservation monitoring, producing real-time datasets that informed adaptive management. AI-based predictive modeling showed promise in identifying priority conservation areas under climate change scenarios. However, ethical challenges were frequently discussed, particularly concerning data ownership and equitable access to technologies. A recurrent theme was the necessity of involving local communities in the deployment of STEM tools to ensure long-term sustainability. Altogether, the results emphasize that while STEM transforms conservation science, its greatest value is realized when coupled with inclusive governance.

Despite these advances, challenges persist. Many STEM-based solutions require substantial financial investments, limiting accessibility in developing regions. Additionally, capacity gaps exist in terms of trained professionals who can implement and maintain these technologies. Data interoperability and ethical considerations also remain pressing issues (Pimm & Joppa, 2017).

4. Conclusion

The synthesis presented here strengthens the case for STEM as a cornerstone of biodiversity conservation. Future efforts must not only expand technical innovation but also address capacity gaps across regions. Building equitable partnerships will be vital to ensure shared access to technologies and data. Policy integration should emphasize transparency, accountability, and inclusivity in conservation governance. By embracing these principles, STEM-driven strategies can become more adaptive, resilient, and globally relevant. This review highlights the central role of STEM in biodiversity conservation. By synthesizing 100 peer-reviewed articles, the study demonstrates that STEM innovations significantly improve monitoring precision, accelerate restoration practices, and strengthen policy-making. Beyond technical applications, STEM provides a conceptual framework for adaptive and participatory conservation.

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