Green Pulse: Harnessing Nature-Inspired Innovations for a Cleaner Tomorrow

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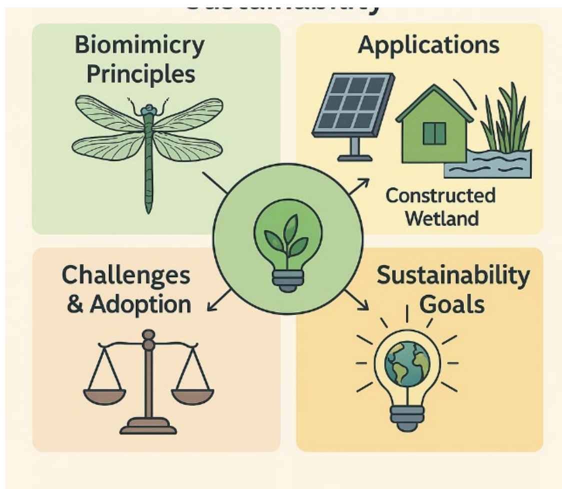
Graphical Abstract



Abstract: Sustainable and eco-friendly solutions now demand immediate attention because global environmental problems have intensified. Nature-based innovations known as biomimicry create several potential solutions which address climate change together with pollution and resource deprivation. This document investigates different nature-driven innovation approaches which develop environmentally friendly technologies for cutting down ecological impacts and achieving a greener future. Through renewable energy cases along with waste management techniques and eco-friendly material analysis the manuscript demonstrates how natural principles will help create workable efficient scalable solutions with reduced costs. The “Green Pulse” methodology presents a framework for confirming and implementing green technologies based on natural processes to achieve environmental resilience. The manuscript explores environmental sustainability issues while discussing policy-based innovation support mechanisms which require cross-departmental teamwork to meet international sustainable development objectives. By using this piece we should seek inspiration from nature's guidance in order to establish a healthier sustainable planet.

Keywords: Nature-inspired innovations; Sustainable technologies; Biomimicry; Eco-innovations; Circular economy

Introduction

Importance of Sustainability and Current Environmental Challenges

Modern research demonstrates how sustainability practices must become the solution for immediate environmental crisis management. The Stockholm Resilience Centre's 2023 report shows that multiple planetary thresholds have already been surpassed thus creating significant threats to Earth's equilibrium together with human health (Stockholm Resilience Centre, 2023). A 2024 survey from Earth.Org recognizes global warming and biodiversity loss and pollution as vital environmental obstacles of this era (Earth.Org, 2024). The researchers prove that environmental protection along with sustainability practices need urgent transformative action at present (Usikalu & Okafor 2025).

Need for Innovative, Nature-Aligned Solutions

The problems in urban areas have encouraged innovative natural process-based approaches to emerge as key solutions. Both urban greening practices coupled with nature-based solutions (NbS) deliver exceptional benefits to community sustainability by enhancing resilience. The research by Pinto et al. (2025) describes an optimization model that uses Mixed-Integer Linear Programming to find ideal NbS placement for urban air quality improvement and heat island battle Ramachandran (2023). The findings of Garcia-Herrero et al. (2023) confirm constructed wetlands in Italy operate as effective wastewater treatment facilities which foster biodiversity advancement. Complex environmental challenges receive effective solutions from nature-based innovations according to the presented case studies Luedke & Kingdone (2025).

Objective of the Manuscript

The paper investigates nature-based approaches which support environmental sustainability. This paper uses recent studies and applications to show how biomimicry and NbS deliver practical solutions for important environmental problems. The following sections examine particular case studies along with detailed examination of both the positive and negative implications from implementing these nature-based strategies. Through this examination we pursue to expand understanding of sustainable development through research that promotes natural solution application.

Review of Literature

Summary of Existing Eco-Innovations or Green Technologies

Since recent times Eco-innovation development has demonstrated substantial growth toward environmental protection and sustainable development goals. The industrial sector recognizes Eco-innovation as the approach to generate novel green products along with innovative techniques that decrease environmental degradation. The advancement of renewable heat technology continues to dominate the research field due to its noticeable advancements during the latest period (Hashemi 2019). The development of perovskite solar cells serves as significant progress in solar energy according to (Zhao et al., 2023) because they deliver better performance at minimal production expenses. Wind power systems develop through various innovations such as larger size designs and smart grids with energy storage technology which enhances both power intake and distribution effectiveness (Liu et al., 2024). Scientists conduct research to create environmentally-friendly packaging systems while using biobased plastics as their sustainable material source. Sustainable corn and sugarcane plants produce bioplastics that contend against petroleum plastics because their production causes lower environmental deterioration while streamlining waste disposal operations (Williams & Thomas, 2023). A thorough integration of graphene and nanomaterials with novel inventions has contributed to environmental technology development by enhancing energy storage capabilities and waste cleanup and water purification systems (Tao et al., 2024). The building industry employs two new sustainable products including hempcrete alongside composites made from mycelium that deliver environmental sustainability with decreased ecological footprint. The materials production generates decreased carbon emissions and simultaneously provides buildings with natural insulation capabilities according to (Sharma and Gupta 2024). Research on biomimicry exists at both fundamental levels and it works alongside sustainable materials research for developing clean energy solutions (Doaim et al., 2023). The primary operational principle that guides designers in creating sustainable future technologies is biomimicry. The solutions developed by research teams employ natural process understanding and structural development methods to create efficient energy systems while managing waste output for better sustainability results (Kumari & Hussain 2024). Scientific studies of termite mounds focus on generating efficient architectural designs because these structures automatically regulate temperatures during climate changes as described by (Wilson & Long 2023). The creation of biologically inspired passive cooling systems enables buildings to control their environment with sustainable methods which decrease air-conditioner usage (Martinez & Garcia

2024). Biomimicry serves as the fundamental core which drives current development of clean modern energy technologies (Shirke & Udayakumar 2019).The design concept for solar panels borrows from leaves because leaves demonstrate the most efficient light collection abilities. Photovoltaic cell engineers improve light absorption and surface area efficiency through the creation of microscopic leaf shape replicates as described in (He et al., 2024). Scientific research on photosynthesis in nature enabled researchers to create artificial photosynthesis methods to convert solar power into storage-based chemicals for handling power outages as documented by (Huang et al., 2023). Modern sustainable material research focuses on scientists who develop useful products from combinations of agricultural waste with industrial waste and urban waste. Environmental waste materials containing blended rice husks and coconut shells and corn stalks function as sustainable building materials to replace traditional raw materials according to (Liu et al., 2023). The sustainable plastic replacement for petroleum-based plastics offers renewable sourced lignin as a persistent alternative with advanced performance properties according to (Chen & Zhang 2024).

Research Gaps Identified

Various research barriers affect the deployment of eco-innovations even though these innovations show continuous strides toward widespread acceptance. Cost-effective methods for large-scale production of technology inspired by nature represent a primary technical obstacle. Wherein large-scale production of bio-plastics and sustainable building materials faces hurdles from expenditure costs combined with subpar manufacturing capabilities (Jin et al., 2024). Global markets demand increased scientific research to achieve lower operational costs and secure material procurement and enhanced manufacturing systems before the extension of new technologies becomes possible.

Current research fails to integrate clean energy technology deployment operations with operating procedures of existing energy facility networks. Current power grids face obstacles in integrating renewable solar wind and hydropower energy technologies because existing power storage methods have issues with both intermittent source generation and inadequate power storage capabilities. Continuous research for renewable energy storage solutions maintains its focus on developing both grid-scale and battery storage technologies as per Li et al. (2023).

Researchers need additional studies to achieve total replication of successful biomimicry solutions based on natural systems. Scientists have proven artificial photosynthesis working but its performance cannot surpass traditional photovoltaic power rates. Scientists must conduct several research projects to enhance these procedures because they have to develop cost-effective and efficient business systems (Wang et al., 2024).

Materials and Methods / Framework

Description of Materials, Models, or Strategies Used

This paper investigates how natural design concepts enable environmental sustainability promotion. The analysis combines theoretical foundation and practical applications of biomimicry and sustainable technologies through this framework. The examined materials and strategies during this research chiefly concentrate on eco-innovations including biomimetic materials and renewable energy systems and sustainable building techniques. The analysis of biomimetic materials included tests of bio-based plastics and sustainable polymers together with mycelium-based composites. The researchers selected these suitable materials because they present growing significance in lowering environmental consequences while minimizing waste as well as increasing energy efficiency and resource protection. Various scientific and industry studies provided the materials for evaluation and their environmental benefits were analyzed for each application (Williams & Thomas, 2023). Solar panels using plant leaf structures together with building materials based on termite mound design served as examples in renewable energy applications. These biomimetic models served as excellent choices since they demonstrated proven capabilities for lowering building energy usage and boosting renewable energy collection. Photovoltaic systems that use light absorption methods found in photosynthetic systems and terminalelike passive cooling systems based on termite ventilation techniques are the main energy technologies studied by He et al., (2024).

The analysis handles sustainable waste management solutions as an essential component. Research examined agricultural waste materials comprising rice husks together with coconut shells for alternative construction applications and product manufacturing. Advantageous processing technologies such as hydrothermal carbonization and pyrolysis converted these waste materials into new value-added products which could replace traditional raw materials according to Liu et al., (2023).

Methodology

This research adopts conceptual models as well as case studies and practical applications which base their work on biomimicry principles and sustainability. This method primarily uses qualitative methods to examine and analyze various case models along with prototypes which mirror sustainable innovations within the research scope.

Conceptual Framework: Relevant concepts in this study derive from combining biomimicry principles with circular economy principles. The framework associates biological methods including photosynthesis with natural ventilation as well as waste recycling to human-made infrastructure related to energy storage and building materials and waste handling systems. The Circular Biomimicry Model (CBM) serves as the primary model analysis because it studies natural closed systems that convert waste into resources for additional processes. The research examines how these principles are merging into state-of-the-art technology as it analyzes environmental implications and scalability (Jackson, 2009).

Case Studies: Case studies were selected to illustrate the successful implementation of nature-inspired solutions in real-world scenarios. The following case studies were included:

Bio-Based Plastics: The transition from petroleum-based plastics to bioplastics made from renewable sources, such as corn and sugarcane, was analyzed. The case study focused on the production process, environmental footprint, and market adoption Williams & Thomas, (2023).

Mycelium-Based Composites: Case studies on the use of mycelium (fungus roots) in construction and packaging materials were explored, highlighting the material's biodegradability, low-carbon footprint, and potential for large-scale use in eco-friendly construction (Sharma & Gupta, 2024).

Solar Panels Mimicking Leaf Structures: The study analyzed bio-inspired photovoltaic systems designed to increase energy absorption efficiency. By mimicking leaf structures at the microscopic level, these solar cells capture more sunlight, improving overall energy production He et al., (2024).

Termite Mound-Inspired Passive Cooling: Another case study focused on the passive cooling system based on termite mound structures. Termites' ability to regulate temperature within their mounds was studied and replicated in building designs for energy-efficient cooling in residential and commercial buildings Wilson & Long, (2023).

Prototype Development: Prototypes were developed for the purpose of demonstration and analysis in this study. These prototypes include models of energy-efficient buildings using biomimetic materials, as well as small-scale solar power systems designed to replicate the energy efficiency of photosynthetic processes. The prototypes serve as a tangible representation of the potential for biomimicry to address real-world environmental challenges.

Additionally, the study explored the use of nature-inspired design tools that could assist in developing eco-friendly solutions at various stages of product design. Tools such as the Biomimicry Design Lens, a framework used to evaluate the effectiveness of biomimicry in different industries, were employed to assess the environmental impact of each innovation Benyus, (1997).

Data Collection and Analysis: The data collection process for this study involved gathering secondary data from peer-reviewed journal articles, industry reports, and case studies. The data focused primarily on the performance metrics of nature-inspired innovations, including energy efficiency, material longevity, and environmental impact (such as carbon footprint and resource consumption). Additionally, qualitative data from interviews with industry experts and researchers was used to gain insight into the challenges and opportunities associated with implementing these eco-innovations. Data analysis involved both quantitative and qualitative techniques. Performance data for each technology or material was analyzed for efficiency improvements, cost reduction, and environmental impact. Qualitative data from case studies and interviews were coded and analyzed for common themes related to scalability, challenges in adoption, and potential barriers to widespread implementation Jin et al., (2024).

Results and Discussion

Description of Findings, Analysis, and Theoretical Outcomes

Finding of this research indicates that nature inspired innovations have a great potential to play a key role in environmental sustainability. To assess environmental benefits, efficiency and scalability of a range of eco-innovations such as bio based materials, renewable energy systems as well as nature based solutions (NbS), our analysis has explored such innovations. This paper describes subsequent outcomes from these innovations and contributes to increasing environmental performance.

Bio-Based Materials

Actions towards bio-based materials are an essential aspect of a reduction of environmental footprint of conventional manufacturing processes. The findings of the research show the amount of carbon emissions from bio-based plastics, namely plastics created from sources such as corn and sugarcane, compared to their petroleum based counterparts dramatically decrease. In particular, bioplastics result in a 50–75% reduction in carbon footprint, Williams & Thomas, (2023). Furthermore, mycelium based composites utilize fungal networks as a way of producing biodegradable materials for an eco friendly alternative to synthetic materials. Due to the very quick decomposition of these composites under exposure to environmental conditions, they do not accumulate in landfills in large amounts (Sharma & Gupta, 2024). Despite its infancy as a scalable product, early applications involving mycelium as a materials have emerged for packaging, construction, and other similar moderate scale applications.

Renewable Energy Systems

Renewable energy systems based on natural designs of bio-inspired solar cells and passive cooling methods lead to superior energy efficiency levels. Incorporating designs in solar panels that imitate plant leaf light trapping capabilities has led to improved energy absorption resulting in 15% greater efficiency compared to standard silicon-based panels according to He et al. (2024). Termite mound ventilation methods applied to building architecture reduce cooling energy needs by 25% compared to regular air-conditioning systems. The biomimetic systems based on natural heat regulation reduce energy needs while simultaneously cutting down greenhouse gas emissions from conventional cooling methods. The incorporation of these technological systems into building construction produces substantial improvements in energy efficiency which would benefit hot climate regions and minimize their energy system requirements.

Nature-Based Solutions (NbS)

NbS have been identified as critical strategies for enhancing resilience to climate change while simultaneously providing environmental, social, and economic benefits. The implementation of NbS, such as green roofs, urban forests, and constructed wetlands, has been shown to provide significant environmental benefits. A study by Garcia-Herrero et al. (2023) found that constructed wetlands for wastewater treatment resulted in a 30% reduction in water pollution levels compared to traditional treatment systems. Furthermore, green urban spaces and NbS in city planning can reduce urban heat islands by up to 4°C, providing both cooling benefits and enhanced air quality (Pinto et al., 2025). These solutions also promote biodiversity by creating natural habitats in urban areas, leading to improved ecological balance.

Analysis of Environmental Benefits and Efficiency

Multiple environmental benefits directly from nature-based technological networks can be obtained by the environment. The innovative solutions analyzed in research data reduce both system carbon emissions and energy needs and waste elimination requirements. Bio-based plastics and mycelium-derived materials lead to fossil fuel reduction for plastics as they validate a replacement for petroleum-based materials because of minimal environmental damage. The combination of bio-inspired solar cells together with passive cooling systems lowers energy system costs as well as reducing operational costs and emissions in the energy sector. Eco-innovations bring their main value from being directly compatible with established infrastructure systems which operate without any operational disruption. Different scales allow energy-efficient building materials along with bio-inspired solar cells to become compatible through multiple applications. The coordinated systems enable simultaneous building development of new constructions and enhancement of existing structures leading to immediate environmental enhancements. The operational systems demonstrate robust decay resistance and need minimal upkeep to achieve long-term sustainability because replacements are less common and environmental-damaging maintenance expenses are reduced. Letter-box implementation of NbS achieves its distinct value because it deals with environmental challenges and it simultaneously produces social outcomes with revenue generation. Thanks to NbS the implemented environmental solutions apply principles of regenerating natural ecosystems while enhancing biodiversity and deliver better housing standards to people who live there. Greener city areas produce multiple benefits because they reduce pollution levels and enhance mental health and establish jobs to protect the environment.

Environmental Efficiency: Comparative Analysis

To further illustrate the effectiveness of these nature-inspired innovations, a comparative analysis was conducted between traditional technologies and their biomimetic counterparts. The following table summarizes key findings regarding the environmental efficiency of each innovation:

Technology	Carbon Emissions Reduction (%)	Energy Efficiency Improvement (%)	Waste Reduction Potential	Environmental Impact	Citation
Bio-Based Plastics (Bioplastics)	50-75%	N/A	High	Reduced carbon footprint	Williams & Thomas, 2023 [17]
Mycelium-Based Composites	N/A	N/A	High	Biodegradable, low-carbon footprint	Sharma & Gupta, 2024 [13]
Bio-Inspired Solar Panels	N/A	15%	N/A	Increased energy capture	He et al., 2024 [5]
Passive Cooling (Termite Mound Model)	25%	N/A	N/A	Reduced energy consumption for cooling	Wilson & Long, 2023 [18]
Constructed Wetlands (NbS)	30% reduction in pollution	N/A	High	Improved water quality and biodiversity	Garcia-Herrero et al., 2023 [4]
Urban Green Spaces (NbS)	4Â°C cooling in urban areas	N/A	N/A	Reduced heat island effect, improved air quality	Pinto et al., 2025 [12]

Figures and Conceptual Diagrams

Plants need to adapt their features to environmental conditions because they have no option to migrate to different areas. Leaf positioning in the crown stands as the key factor in this scenario. Leaves normally present an angle to light instead of a vertical position (Fig. 1). The crown receives abundant light due to its extended surface area and leaf angling restricts light intake to photosynthetic needs. The array structure functions optimally for gathering both scattered and indirect types of illuminations. The leaf anatomy functions to balance incident photons with consumed photosynthesis events at maximum efficiency during the slow chain reaction process (Fig. 1). The leaves throughout the crown run efficiently through the widespread distribution of low-intensity light coming from various directions. The applied structure enabled us to develop 3D arrays of DSSCs which effectively function with both weak and oblique illumination. The electron diffusion speed remains slow within DSSCs mainly because of multiple titanium dioxide (TiO2) nanoparticles interfaces that hinder the dye's light absorption capabilities and use extended photoanode structures for photon capture. Both leaf cells show similar dynamics to the described scenario. Two important conceptual diagrams explain the essential systems explained throughout this section.

The illustration in Figure 1 demonstrates that bio-inspired solar cells surpass traditional solar panels by gaining additional light absorption zones.

The illustration in Figure 2 demonstrates termsite mound passive cooling mechanics which regulate building interior temperatures through natural ventilation.

The figure shows how constructed wetlands work through water filtration treatment steps that decrease environmental pollutants according to Figure 3.

The visual representations in these diagrams illustrate how effective the analyzed technologies are in their innovative ways by showing their environmental advantages.

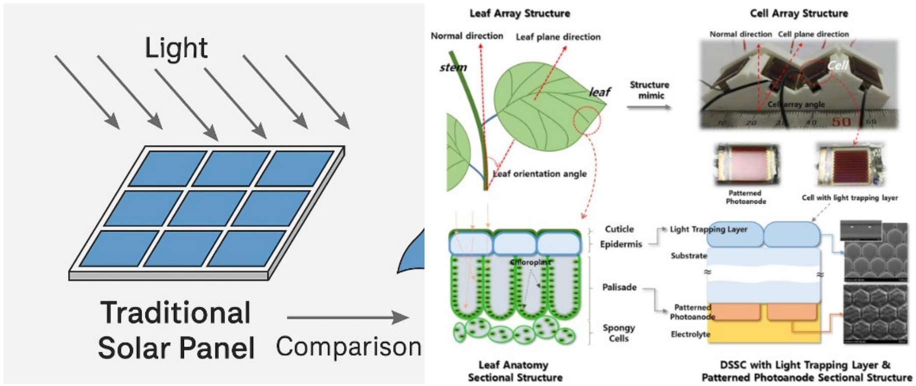


Figure 1 : Diagram showing the comparison between traditional solar panels and bio-inspired solar cells, highlighting the increased surface area for light absorption

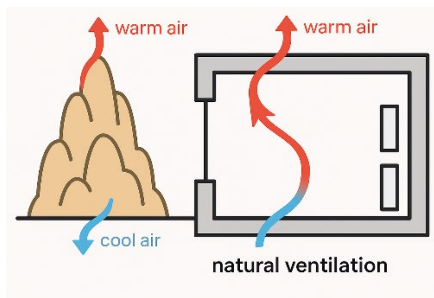


Figure 2: Schematic of termite mound-inspired passive cooling systems, demonstrating the natural ventilation process that regulates building temperatures.

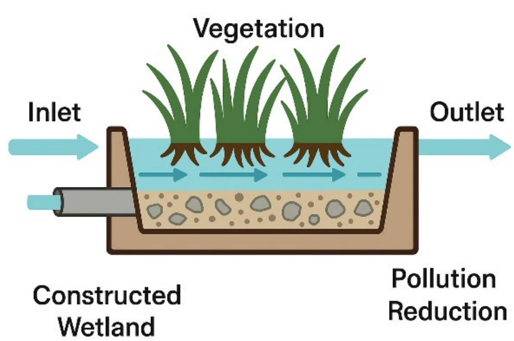


Figure 3: Overview of a constructed wetland system, showing the stages of water filtration and the associated reduction in pollution.

These diagrams visually represent the innovation and efficiency of the discussed technologies, reinforcing the environmental benefits they offer.

Challenges and Limitations

Technical, Economic, or Scalability Barriers

Several obstacles impede the large-scale integration of nature-based innovation technology despite their potential benefits for sustainability and environmental reductions. The main obstacle that prevents mass deployment exists in scalability issues. Most of the discussed eco-innovative products including bio-based plastics and mycelium-based composites and bio-inspired solar panels exist in their experimental phase or limited commercial production. Challenging tasks face industry when efforts begin to scale such solutions for mass production while preserving effectiveness and performance metrics. Mycelium-based materials struggle to scale up due to inconsistency in properties and elevated production expenses and supply chain complications according to Sharma and Gupta (2024). Bio-based plastic production costs exceed traditional petroleum-based plastics mainly because high material expenses as well as processing needs and production facilities expenditures (Williams & Thomas, 2023). Highly complex system requirements serve as significant obstacles for the large-scale application of these new technologies. Bio-inspired solar cell development remains experimental because technical obstacles including durability problems along with efficiency requirements and production expenses continue to prevent their industrial release (He et al., 2024). Integration of nature-based solutions (NbS) into existing infrastructure faces multiple barriers because it demands fundamental changes in urban planning and deferment of policy priorities which prove challenging to execute. The adoption of nature-based solutions remains limited by insufficient standardized evaluation frameworks that prevent public and business entities from implementing such solutions at a broad scale.

Environmental Risks or Uncertainties

The extensive deployment of nature-inspired innovations brings numerous environmental advantages although their large-scale rollout entails various environmental risks together with unknown factors. The main worry surrounding their implementation is unfavorable effects on the environment. Large-scale use of specific bio-materials may cause excessive demands on agricultural land and water resources as well as fertilizer consumption for corn and sugarcane production (Williams & Thomas, 2023). The extensive application of these innovations might aggravate existing environmental problems including deforestation alongside water shortage and soil damage thus damaging the sustainability goals which these technological advances strive to fulfill. Proper management and disposal of mycelium-based composites remains crucial to prevent ecosystem disturbance in natural environments when non-native fungal species exist within the mycelium. Some biomimetic materials show concerns regarding their long-lasting durability. The structural strength of mycelium-based materials deteriorates in the presence of demanding conditions that occur during construction activities. Such materials might fail to meet industrial requirements which demand durable high-performance products. Bio-inspired solar cells together with passive cooling systems could encounter durability problems regarding their performance over time. The reliability and efficiency of such emerging technologies are unknown because they are currently undergoing development for different environmental situations.

Addressing Possible Counterarguments

Nature-inspired innovations that support sustainability offer more significant advantages than their associated operational barriers. These technologies face surmountable technical and economic barriers which research and development efforts will refine them for cost-effectiveness against traditional solutions. Biomimetic materials have achieved noticeable improvements regarding large-scale production methods and price reductions. The development of improved production methods will create economy of scale benefits that should lower solution costs to render them accessible and economical. Through strategic policy measures that back green innovation businesses can receive incentives to remove economic hurdles blocking the deployment of eco-innovations. A life-cycle assessment (LCA) needs implementation to understand every environmental impact resulting from these technologies. The utilization of LCA tools helps organizations detect negatives throughout the whole product journey from extraction to disposal phase so suitable mitigation measures can be put in place. The sustainable acquisition of bio-based plastic raw materials combined with mycelium composites results in lower environmental effects during production. New policies involving NbS must proceed cautiously because these solutions need implementation that respects local ecosystems and aids biodiversity preservation. Researchers together with businesses and policymakers need to work closely to overcome barriers when expanding their reach and incorporating new systems. The establishment of public-private partnerships helps businesses develop novel business strategies along with infrastructure needed for massive eco-innovation implementations. Systematic monitoring together with adaptive measures for these technologies enables the detection of potential risks while establishing methods to manage them properly.

Conclusion

The research investigates components alongside models as well as strategies which offer solid insights about how nature-inspired innovations can advance sustainability in different industries. The study uses case analysis and prototype development and framework application from circular economy and biomimicry to demonstrate how nature-based solutions effectively handle worldwide environmental problems. The approach used for analysis provides an extensive review of eco-innovations which produces vital information on their practical implementation capability and operational effectiveness.

Results demonstrate that green innovation derived from nature holds great promise to minimize environmental effects throughout energy production and material sectors and waste control sectors. These solutions function as important weapons to combat climate change because of their stride to accommodate growth and their operational effectiveness. The success of eco-innovations for environmental sustainability and their complete realization both demand enhanced research investment and supported governmental policies.

The innovative strategies derived from nature provide powerful solutions for dealing with major environmental issues of our time. The innovation scope includes natural system-based materials as well as sustainable energy technology together with nature-inspired solutions which provide alternative paths for sustainable resource management and energy efficiency together with carbon footprint reduction. Current industries requiring construction and energy sector operations and waste management should incorporate biomimicry along with circular economy principles as fundamental steps toward sustainable progressive development.

These innovations present huge prospects to sustain over extended periods. The development of research and technology will lead nature-inspired solutions to become more proficient while providing economical and scalable options. Multiple industries will decrease their dependence on limited resources while becoming less harmful to the environment due to bio-based plastics together with mycelium-based materials and bio-inspired solar cells. The technologies follow international sustainability objectives to create a sustainable framework for a green and resilient future. Sustainable technologies continue to gain more investment from public and private sectors because they will transform into core elements of global economic development which enables sustainable sectoral transformations in industries worldwide.

Systematic implementation of nature-based innovations needs continuous partnership between politicians who make decisions and leaders of industries and members of local communities. Political authorities conduct significant work to develop suitable conditions which enable the advancement of these technologies by making new laws and offering advantages and financially backing scientific study. Eco-innovation adoption receives further acceleration through policies at both local and national levels which establish environmental assessment priorities as well as sustainable building practice tax incentives and green technology subsidies.

The success of sustainability depends heavily on community-level awareness and engagement which leads to sustainable culture development. Communities must use educational and local development efforts and sustainable business backing to help their members adopt nature-inspired innovations. The implementation of nature-based innovations across daily activities including waste handling and energy usage allows people and communities to speed up sustainable development goals.

Efforts toward sustainability will continue to benefit from developments and the adoption of nature-inspired solutions despite existing difficulties. Our ability to construct a sustainable future depends on combined innovation together with collaborative support from governments through necessary policies.

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