

Biomimicry and nature-based solutions: instruments of the circular economy toward sustainability

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Abstract

Humanity is currently facing multiple challenges, including climate change, biodiversity loss, resource depletion, and waste generation. Biomimicry and nature-based solutions (NbS) represent innovative approaches of the circular economy (CE) that seek to align human systems with the principles of nature by combining ecological knowledge with economic models for sustainability. This paper emphasizes the role of biomimetic design and NbS as key drivers of circular practices, enabling the transition toward regenerative and resource-efficient systems. Natural strategies can inspire advances in material efficiency, energy optimization, and resilience, with applications ranging from product design innovation and sustainable architecture to urban planning and ecosystem restoration. Furthermore, integrating these concepts into industrial strategies and public policies provides an opportunity to connect ecological integrity with socioeconomic development. Ultimately, biomimicry and NbS can be understood as transformative tools that support a regenerative and sustainable economy, offering both a framework for future research and pathways for practical implementation.

Keywords: biomimicry, NbS, circular economy, sustainability, sustainable development

1. Introduction

In a world where rapid population growth is coupled with increasing consumerism and constant pressure on natural resources, environmental degradation dominates. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) pointed out that up to 90% of the land area will be altered by 2050, due to the anthropogenic pressures (IPBES, 2019). Such changes accelerate biodiversity loss and threaten ecosystem services, with potentially irreversible consequences for the global economy, human well-being, and ecosystem stability. Alongside biodiversity decline, climate change additionally contributes to environmental degradation and pollution, underlining the urgency of systemic transformation.

The concept of sustainability emerged in the late 20th century as a response to these challenges, gradually shaping political, scientific, and economic discourse worldwide. Over the past two decades, the green economy has been promoted as a pathway to reconcile economic growth with environmental stewardship. In this context, the circular economy (CE) has become an important model that redefines value creation and material use. The CE rests on three fundamental principles: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems (Ellen MacArthur Foundation, 2022; Knäble, de Quevedo Puente, Pérez-Cornejo, C., & Baumgärtler, 2022, p.234). By decoupling value creation from resource throughput, the CE provides a model for reducing environmental impacts while maintaining competitiveness and social well-being (Geissdoerfer et al., 2017). Strategic documents, such as the EU Green Deal (Fetting, 2020) and the Circular Economy Action Plan (European Commission, 2020), provide a political-economic framework for accelerating the transition towards sustainable production and consumption models. Despite its increasing recognition, the practical implementation of the circular economy frequently is limited to practices such as recycling, eco-efficiency, or product redesign—without fully addressing systemic ecological regeneration (Korhonen et al., 2018). Addressing these limitations shows that the circular economy should be embedded within ecological principles and complemented by innovative design paradigms to enhance regenerative capacity, where biomimicry and Nature-based Solutions can be considered as promising pathways.

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In the context of sustainability and the circular economy (CE), biomimicry and nature-based solutions (NbS) are often discussed together as complementary approaches, yet they differ significantly in scope, focus, and application. Biomimicry refers to the emulation of natural processes, systems, and designs to solve human challenges in ways that are environmentally sustainable (Benyus, 2002). On the other hand, Nature-based Solutions leverage ecosystem functions to address societal challenges such as climate adaptation, water purification, urban resilience, and carbon sequestration (IUCN, 2020). In addition to providing cost-effective and multifunctional alternatives to grey infrastructure, NbS restores and enhances ecosystems, generating co-benefits for biodiversity and human well-being (EEA, 2021). Also, biomimicry is mainly related to the design and innovation domain, drawing inspiration from biological forms, processes, and ecosystems to solve human challenges (Benyus, 2002; El-Zeiny, 2012). Even though it has strong sustainability potential, it does not necessarily include an ecological restoration process, but it aims to develop efficient and sustainable technologies. On the other hand, NbS explicitly relies on the ecological and socio-environmental domain, involving the protection, restoration, or sustainable management of ecosystems to address societal challenges such as climate adaptation, disaster risk reduction, and human well-being (Cohen-Shacham et al., 2016; Kabisch et al., 2017). Generally, biomimicry focuses on the design inspired by nature, while NbS focuses on designing with nature by sustaining natural systems. The application of biomimicry spans engineering, architecture, materials science, and product design, producing engineered systems that mimic biological strategies (King et al., 2017; Jones et al., 2020). Similarly, NbS are implemented in environmental management, urban planning, and landscape restoration, producing functional ecosystems that directly deliver services like carbon sequestration, nutrient cycling, or biodiversity enhancement (Cohen-Shacham et al., 2016; Kabisch et al., 2017).

This article aims to highlight the role of biomimetic innovations and NbS within CE principles in the transition toward sustainability by reviewing literature and case studies.

The paper presents an overview of relevant literature in the field of biomimicry, nature-based solutions (NbS), circular economy, and sustainable development. Based on secondary sources of literature, an analysis and synthesis of theoretical insights and practical examples was performed in order to provide a starting point for future primary research in this area.

2. Biomimicry as a promising instrument of CE

Biomimicry, an emerging interdisciplinary approach, draws inspiration from natural systems, processes, and organisms to design sustainable solutions for human challenges. Biomimicry has become a growing interdisciplinary research field connecting biology, engineering, design, and sustainability sciences. Academic literature increasingly positions biomimicry as a tool to address resource efficiency, climate adaptation, and circular economy challenges (Badarnah, 2017; Fayemi et al., 2017). Biomimicry operates across three “levels” (form, process, ecosystem): copying structures (e.g., lotus-effect surfaces), processes (e.g., self-healing polymers), and ecosystem principles (e.g., closed-loop cycling, modularity, resilience) (Fayemi et al., 2017).

In the following sections, selected biomimetic strategies are presented concerning their contribution to circularity.

The role of biomimicry as a practical instrument of the circular economy highlights its potential to bridge technological innovation and ecological balance. These innovations demonstrate how learning from nature can lead to resource-efficient and low-impact technologies aligned with circular principles. Within the industrial sector of products and materials, innovations are a fundamental driver of advancement. Selected examples are discussed in the following paragraphs, and their ecological and economic contributions are summarized in Table 1.

1) Mycelium-based composites — grown by binding fungal mycelia to agricultural residues — are biodegradable, require minimal energy to produce, and can be fabricated using locally available feedstocks. Decomposition and biodegradation of these materials also contribute to the microplastic pollution minimization, aligning closely with CE principles of regeneration and material circulation (Soh et al., 2020). Some other research shows its potential for use in the textile industry (Akpa, 2017). Architectural prototypes further illustrate their energy-efficient production and compostable nature e.g. Loop mycelium coffin (Ralstone, 2022).

2) “Lotus-effect” coatings are hydrophobic coatings, inspired by *Nelumbo nucifera* (Sacred Lotus), which surface microrelief repels water and dirt, lowering cleaning frequency, chemical use, and abrasion—extending product lifetimes (Barthlott & Neinhuis, 1997). In CE terms, they minimize operational resource inputs and decelerate material throughput by enhancing product durability.

3) Structural colors are optical effects coming from the materials' micro- and nano-structures and not from the chemical pigments, are also inspired by nature. According to Saito (2012), these materials can have potential applications in various industry sectors like cosmetics, interior decoration, textiles, furnishing, textures, paint, security (holograms), posters, and displays, depending on technological development. In terms of their contribution to the circular economy, structural colors can be considered as a resource-efficient and non-polluting design solution, offering a sustainable alternative to conventional toxic chemical pigments.

4) Shark-skin-inspired riblet surfaces, micro-grooves mimicking shark dermal denticles, have the potential to reduce emissions of Greenhouse gases (GHG) by lowering the turbulent drag when applied to aviation and shipping (Dean & Bhushan, 2010).

5) Water-harvesting surfaces like biomimetic surfaces are inspired by the adaptation of the Namib desert beetle to the severe habitat conditions. Its mixed hydrophilic–hydrophobic surface patterns present perfect adaptation for water-harvesting performance in arid environments. Such biomimetic designs can supplement off-grid water supplies, reduce reliance on centralized infrastructure, and support localized circular water systems (Lei & Guo, 2020).

6) The termite mounds' ventilation system, as an architectural solution that uses massing, chimneys, and controlled ventilation, has been applied in the Eastgate Centre (Harare, Zimbabwe) to drastically cut cooling energy demand compared to conventional buildings (Turner & Soar, 2008). Along with thermoregulation, the building life cycle is considered, avoiding energy consumption and equipment, reducing material and emissions footprints, aligning with CE principles on efficiency and longevity.

7) Self-healing polymers inspired by biological repair processes represent a class of materials capable of autonomously restoring functionality after damage. By prolonging the service life of components, these systems have the potential to decrease the demand for spare parts, minimize operational downtime, and reduce material waste (Hager et al., 2010).

Table 1. Ecological and economic benefits of biomimicry innovations

Innovation	Ecological contributions	Economic contributions
Mycelium-based composites	- Biodegradable and compostable - Reduce microplastic pollution - Use agricultural residues - Waste disposal prevention	- Locally producible from low-cost feedstocks - Lower transportation and disposal costs - Energy efficiency - Reducing waste management costs
“Lotus-effect” coatings	- Minimize toxic, chemical pollution - Extending material lifespan - Resource conservation	- Lower cleaning and maintenance costs - Longer replacement cycles - Reduced expenses
Structural colors	- Eliminate hazardous pigments and dyes - Reduce water or soil contamination and chemical pollution - Offer durable, non-fading coloration.	- Lower costs of chemical inputs and wastewater treatment - Potential cross-sector applications (cosmetics, textiles, etc.)
Shark-skin-inspired riblet surfaces	- Lowering fuel consumption and GHG emissions - Contribution to climate change mitigation measures - Decrease in the environmental footprint of transport	- Fuel cost savings in large fleets - Lower operational energy expenditure
Water-harvesting surfaces (Namib beetle-inspired)	- Enhance water circularity - Water conservation - Reduce pressure on natural ecosystems and centralized infrastructure	- Lower capital costs for water supply infrastructure - Cost savings in off-grid or remote communities
Termite mound-inspired ventilation	- Minimize energy use for cooling (energy conservation) - Reduce GHG emissions - Contribute to climate change mitigation measures. - Lower material and emissions footprint	- Major reductions in building energy bills - Reduce costs of maintenance - Improved real estate value through sustainable certification
Self-healing polymers	- Reduce material waste - Extending the lifespan of components - Minimize frequency of replacements	- Lower maintenance and replacement costs - Long-term savings in spare parts procurement

Source: Author's observation based on the literature data review

3. Nature-based Solutions as a Driver of the CE

Nature-based Solutions (NbS) represent actions that protect, sustainably manage, and restore natural or modified ecosystems while simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). Natural processes are essentially circular, regenerating stocks (such as soils, biomass, and biodiversity) and recirculating flows (including water and nutrients), while offering co-benefits like heat mitigation and recreation (EEA, 2021). Therefore, NbS could be considered as an innovative instrument in the context of the Circular Economy, offering regenerative pathways that complement technological innovation by closing resource loops, reducing waste, and enhancing ecosystem services.

Use of NbS in different industry types shows its great potential to contribute to the CE. Some of them are discussed in the following paragraphs.

- 1) Constructed wetlands for wastewater treatment, as NbS, a part of the CE framework, use natural processes (microbial degradation, flora uptake, or sediment deposition) for wastewater treatment. A good example is in Denmark, where vertical-flow constructed wetlands have been integrated into rural landscapes to recycle nutrients, reduce nitrogen leaching, and improve water quality (Brix & Arias, 2005). Such systems can enhance reuse of the treated water for irrigation, effectively closing the water loop and reducing dependence on conventional wastewater treatment facilities.
- 2) Urban NbS like green roofs, urban forests, permeable or bio-retentive streetscapes, urban pocket parks, etc. - contribute to the CE objectives by providing water retention, urban temperature regulation, reducing soil erosion and emission of air pollutants in the urban environment, enhance urban biodiversity providing the habitats, while reducing infrastructure costs, enhancing the lifespan and place for outdoor activities. In Rotterdam, Netherlands, multifunctional green infrastructure projects not only facilitate rainwater flow but also support composting of organic waste for maintaining green public areas (Kabisch et al., 2016).
- 3) Agroecology contributes to circularity by employing NbS solutions like enhancing soil fertility, reducing input dependence, and enabling biomass cascading. Spain's Dehesa system, as a case study, presents multifunctional agro-silvo-pastoral landscapes that integrate crop production, forestry, and livestock. This traditional land use style shows that soil fertility, hydrological regulation, and biodiversity conservation could be improved, while at the same time, can support ongoing economic productivity (Joffre, Rambal, & Ratte, 1999).
- 4) Wetland restorations also have an important role in supporting the circularity of the NbS, mitigating climate change problems. The restoration of the mangrove ecosystem in Vietnam has contributed to protection against storm surges, enhancing fisheries, and sequestering carbon, promoting a circular socio-ecological system. The restored ecosystem-based coastal defenses avoid the need for resource-intensive grey infrastructure (such as sea walls) while maintaining ecosystem services that support local economies (Temmerman et al., 2013). Such projects reduce the material and energy footprint of coastal defense systems, illustrating how NbS regenerate natural capital.
- 5) "Room for the river" is a concept in the Netherlands that highlights the role of ecosystem restoration for water risk management. By setting back dikes and reestablishing floodplain connectivity, the initiative reduces flood hazards while at the same time creating habitats and public recreational spaces. This approach replaces single-purpose grey infrastructure with multifunctional landscapes that embed ecosystem services—such as water storage, sediment regulation, and carbon cycling—into regional planning (Rijke et al., 2012).

4. Discussion

Biomimicry and nature-based solutions (NbS) represent innovative pathways for advancing sustainability by translating ecological principles into human technologies and socio-technical systems. They implement the basic circular economy (CE) principles—designing out waste, maintaining materials in circulation, and regenerating natural systems—and at the same time raise public awareness on environmental issues and deliver socio-economic benefits. Importantly, these approaches serve as drivers of innovations in the cross-sector industries. Strategies include resource-efficient and waste-reducing designs such as lotus-inspired self-cleaning coatings, structural coloration as a non-toxic alternative to chemical dyes, or self-healing polymers that prolong product lifespan. Likewise, fungal mycelium is increasingly explored as a renewable and biodegradable material for textiles, packaging, and construction, supporting safe and bio-based circular loops.

Integration of biomimicry and NbS reveals a mutual relationship: biomimicry inspires technological innovations (e.g., termite mound ventilation applied in green building design), while NbS incorporates such biomimetic solutions within systemic ecological restoration. Together, have the potential to represent a framework for CE implementation with impacts on multiple scales—from localized industrial applications to regional ecological networks.

Along with technological innovation, these approaches emphasize that circularity is not only a technical challenge but is a crucial principle of ecology, requiring alignment with natural cycles. Embedding ecosystem restoration and regeneration into CE strategies delivers measurable socio-economic value by enhancing ecosystem services such as carbon sequestration, water regulation, habitat formation, nutrient cycling, and disaster risk reduction (IUCN, 2020). Eco-industrial parks are good examples of this integration: the Kalundborg Symbiosis in Denmark demonstrates how industrial symbiosis, guided by principles of biomimicry and NbS, enables circular resource flows, resilience, and long-term sustainability (Jacobsen, 2006).

Despite these advances, significant barriers remain. High technology costs, limited awareness, and insufficient policy integration limit wider application. Therefore, embedding biomimicry and NbS into policy frameworks, educational curricula, and industrial strategies is crucial for accelerating the transition toward a sustainable circular economy.

5. Conclusion

The accelerating climate, biodiversity, and resource crises require innovations that align economic activity with ecological principles. Biomimicry and nature-based solutions (NbS) represent innovative approaches that can guide the transition toward sustainability. Considering them as drivers of the CE can enhance socio-economic systems by establishing a strong mutual relationship between society and natural processes.

Inspired by natural solutions, adaptation mechanisms, and strategies of living systems, biomimicry supports design materials, products, and systems in more efficient and regenerative ways. Simultaneously, NbS utilizes natural processes and ecosystem functions to solve societal challenges (water management, climate resilience, resource efficiency, etc.) to enhance environmental regeneration. Together, these approaches connect technological innovation with ecological principles, supporting circular economy goals and long-term resilience. While biomimicry reduces inputs and extends the product lifespan, NbS promotes the regeneration of balanced ecological processes. Application of these approaches can operate on a multi-layer scale, from the micro level, like product design, meso (urban systems), and macro level, like landscape. Integrated application of the mentioned approaches already proves numerous benefits in some countries. Good practice examples like the Eco-Industrial Park in Kalundborg, Denmark, green urban infrastructure in Vienna, Austria, or Singapore, exemplify quantified benefits for all three components of the CE: economy, environment, and society.

Biomimicry and nature-based solutions (NbS) have not only ecological, but also exceptional economic importance, as they contribute to the reduction of negative externalities and encourage employment in green industries. Therefore, the inclusion of these concepts in public policies can contribute to a faster and more efficient transition towards a circular and sustainable economy.

Regardless of their clear potential to diminish global crisis issues, current research often treats both concepts as stand-alone tools, rather than drivers of circularity and sustainability. The recognized major challenges still are inclusion in the standardization process, policy integration, and the methodology of measurements.

In conclusion, biomimicry and NbS act as transformative drivers that can reconfigure economic and societal systems to align with the regenerative capacity of nature. Their adoption represents a pathway to a resilient, circular, and sustainable economy, providing insights for designers, policymakers, and researchers seeking systemic solutions to the environmental and socio-economic challenges of the 21st century.

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