

BIO-INSPIRED DESIGN AND NATURE-BASED SOLUTIONS: THEORETICAL FOUNDATIONS FOR THE DEVELOPMENT OF SUSTAINABLE CERAMIC PRODUCTS IN URBAN ENVIRONMENTS

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ABSTRACT

The growing complexity of urban environmental challenges calls for design approaches capable of integrating technological innovation, sustainability and a systemic understanding of the relationships between society and nature. In this context, this paper offers a theoretical reflection on the contributions of bio-inspired design and nature-based solutions (NBS) to the development of sustainable ceramic products. Drawing on a critical review of the literature, the article sets out concepts from sustainable design, biomimicry and systems thinking, highlighting principles such as circularity, resilience, self-organisation and co-evolution. The study analyses nature's potential as a functional and strategic reference point for innovation in building materials and systems, exploring possible applications in self-cleaning surfaces, bio-inspired geometries and the improvement of urban environmental quality. It argues that incorporating these principles can expand the role of ceramic products beyond their conventional construction functions, positioning them as active components of strategies aimed at environmental regeneration and the adaptation of cities to climate change. It concludes that bio-inspired ceramics design constitutes a promising interdisciplinary field, capable of linking technical performance, resource efficiency and ecosystem benefits, thereby contributing to the creation of more sustainable and resilient urban environments.

1. INTRODUCTION

Given the climate change crisis, the degradation of ecosystems and growing socio-spatial disparities, the role of design in the 21st century has been profoundly reshaped. In the past, design practice focused on form, function and the user's immediate experience; however, the present day's specific context calls for such an approach to be broadened, explicitly setting out the environmental, social and territorial consequences of products, systems and services throughout their life cycle.

Design needs to address numerous problems, each on different scales and with multidirectional interrelationships. In this context, ideas are taking shape that mark the transition from object-oriented design thinking towards more systemic and integrated principles. Theoretical and methodological frameworks such as sustainable design, bio-inspired design, biomimicry and nature-based solutions (NBS) appear as useful tools through which to channel concepts of innovation, environmental management and social concern. These approaches converge around the idea that natural processes and living systems provide not only formal inspiration but also models of organisation, efficiency and resilience that can inform and guide design practices more in tune with ecological dynamics.

The ceramic tile industry, particularly in the hubs of Santa Gertrudes and Itu, inland in São Paulo state, is a typical example with which to illustrate the debate. It is a sector that is very technologically advanced in large-scale production and forms a significant part of the construction industry's supply chain, contributing to regional and national economic development. Whilst such productive activity presents clear environmental challenges – the need to consume large quantities of mineral raw materials, high energy consumption during firing, and the generation of solid waste and atmospheric particulate emissions – it also entails obstacles.

The conflict between industrial robustness and environmental pressures highlights the contradictions that call for the application of innovative methods in design and materials technology. In this regard, the study of design strategies is essential for reconciling technical performance, regulatory compliance and the reduction of emissions, whilst enhancing the functional, aesthetic and symbolic value of ceramic products in the urban environment.

Research topics such as the recovery of construction waste, application of bio-inspired geometries and surfaces, and development of building components designed to improve urban environmental quality point to a change of paradigm in the field of design. In this context, the focus is shifting from isolated products towards systemic and multi-scale solutions, aligned with the principles of sustainability, urban resilience and ecosystem regeneration. Thus, the aim of this paper is to provide and present the fundamental conceptual foundations underpinning this debate: (a) sustainable design and project responsibility; (b) bio-inspired design and biomimicry; (c) nature-based solutions in the context of cities; and (d) the fundamental principles of systems thinking in relation to understanding living systems and the interactions between nature, technology and society. Building on a reflection on these concepts, the theoretical and technical advances of these approaches towards more sustainable and resilient urban environments can be discussed.

This paper is organised in four parts: Section 1 provides an overview of the current state of sustainable design, biomimicry and nature-based solutions, as well as their interaction with product design. Section 2 presents the theoretical foundations of the core principles of systems thinking, highlighting various theoretical contributions towards an integrated understanding of

living systems and their implications for design. Section 3 details these contributions to design theory and technology and their implications for ceramic product design. Finally, Section 4 summarises the concluding considerations and formulates recommendations for future research.

From a methodological perspective, this article has been prepared using a theoretical-analytical approach, based on a critical review and systematisation of specialist literature. The approach adopted prioritises conceptual analysis and dialogue between different fields of knowledge – design, biomimicry, nature-based solutions and systems thinking – with a view to constructing a coherent theoretical framework to support the debate on the development of sustainable ceramic products in urban contexts. Therefore, the aim is not to seek immediate empirical validation, but rather to consolidate theoretical foundations capable of guiding future research and design applications.

2. CURRENT STATE OF THE ART

2.1. Sustainable design, biomimicry and nature-based solutions

The debate on sustainable design boils down to the argument against the linear industrial model, which consumes vast amounts of resources and tends to encourage consumption. Authors such as Papanek (1989) make a fundamental contribution by asserting that design is never neutral, as every design choice has ethical, social and environmental implications. By questioning artefacts that are superfluous and harmful to the environment, the author paved the way for a change of paradigm that shifts the focus away from the isolated object and how it manifests itself in an observed reality. In the contemporary world, this perspective is broadened to include aspects such as ergonomics, usability and sustainability as components of design quality. According to Mont'Alvão (2016), it is not just design or appearance that matters, but the way in which the product, system or service contributes to human well-being and the efficiency with which resources are used throughout the entire life cycle of the product or system. Life Cycle Assessment (LCA), for example, is used in design decision-making to help facilitate the application of objective environmental indicators.

In the early 2000s, sustainable design began to take a more active stance in relation to the circular economy, eco-design and industrial metabolism, and aligned itself with models inspired by the functioning of natural ecosystems. The 'cradle-to-cradle' approach, for example, proposes closed material cycles, in which waste is not regarded as rubbish but as inputs for new production processes, which is very similar to the biogeochemical cycles that take place in nature. It is within this context that biomimicry takes shape as a structuring framework for contemporary design. Systematically presented by Benyus (2011), biomimicry asserts that nature should be viewed as a model, a yardstick and a mentor, shifting the designer's focus away from the exploration of resources and towards learning evolution-proven tactics. In contrast to isolated formal approaches, biomimicry addresses processes, relationships and systems in line with a vision of sustainability based on efficiency, adaptation and resilience. Recent research shows that biomimicry should not consist solely of representing natural forms as an aesthetic imitation. Ilieva (2022) and Souza et al. (2023) point out that bio-inspired solutions can only be understood from the sustainability viewpoint if they are assessed in terms of their impact throughout their entire life cycle vis-à-vis their environmental, energy and social performance. This perspective broadens the scope of bio-inspired design, moving from a simple design approach to a more systemic and transdisciplinary one.

With regard to methodology, significant contributions have been made towards translating biological ideas into design solutions, such as the BIOSIGN method (DETANICO, 2021). Tools like AskNature and DANE (Define, Analyse, Naturalise and Emulate) complement this approach and enable work on functions such as self-cleaning, structural strength or particle filtration, drawing on natural models with similar properties. Functional research, such as that by Fagundes et al. (2020), demonstrates the potential for using technology that can be applied to develop surfaces and structural elements, and suggests this as a potential avenue for the manufacture of designer ceramic products along these lines. Concurrently, the concept of nature-based solutions (NBS) has emerged, acting as a kind of interface between design, ecology and urban planning. As identified by international organisations and systematised in Brazil in documents such as the IPEA report (2018) and the guide by Telles and Girão (2021), NBS include practices that use natural processes – or that use or draw inspiration from their dynamics – to overcome environmental, social and economic problems, with a view to achieving multiple outcomes that yield a range of benefits.

Although they are typically characterised by green and blue infrastructure – such as urban parks, ecological corridors, rain gardens and sustainable drainage systems – NBS also incorporate other materials, products and construction systems that can fulfil ecological functions in an urban context. In this regard, ceramic products inspired by biomimetic principles should serve as active components of NBS approaches, including natural ventilation, heat island mitigation, sustainable drainage and improved air quality. This integrated application of sustainable design, biomimicry and NBS provides a conceptual basis for a design strategy geared towards environmental regeneration and urban resilience.

Table 1 presents a comparative summary of the main approaches discussed in this section, highlighting their conceptual frameworks, scales of intervention and potential contribution to ceramic product design in an urban context.

Approach	Main focus	Scale	Contribution to ceramics design
Sustainable design	Reduced impact	Product / system	LCA, energy efficiency
Biomimicry	Natural principles and function	Multi-scale	Surfaces, structures
Bio-inspired design	Formal and functional translation	Product	Geometries & performance
NBS	Ecological solutions	Urban / territorial	Environmental quality

Source: Prepared by Marcos Antonio Serafim

Table 1. Contemporary approaches

3. SYSTEMIC PRINCIPLES AND THE ECOLOGY OF DESIGN

3.1. Networks, cycles, self-organisation and co-evolution

In light of contemporary systems thinking, contributions from Ilya Prigogine, Humberto Maturana, Francisco Varela and Fritjof Capra converge in the understanding of living, social and environmental systems as dynamic, open and non-linear processes. Prigogine (1984) demonstrates that systems far from thermodynamic equilibrium are capable of generating new forms of order through dissipative structures, in which the irreversibility of time, fluctuations and energy flows constitute sources of organisation. Complementarily, the theory of autopoiesis defines living systems as units capable of producing and sustaining themselves, operating in a way that is organisationally closed off and structurally coupled to the environment (MATURANA; VARELA, 1995). By integrating these theoretical foundations, Capra (1996; 2002) proposes an ecological view of life based on networks of interdependent relationships, in which sustainability arises from co-operation, diversity and continuous adaptation. In this context, nature-based solutions align with his conceptual framework by proposing interventions that do not impose rigid control on urban systems, but rather foster processes of self-organisation, resilience and co-evolution, in keeping with the dynamics of living systems.

As shown in Table 2, the contributions of Prigogine, Maturana, Varela and Capra highlight different perspectives in systems thinking, the implications of which converge in an integrated understanding of living systems and their applications in the field of design.

Author	Key concept	Implications for design
Prigogine	Dissipative structures	Emergent order
Maturana & Varela	Autopoiesis	Self-organising systems
Capra	Living networks	Interdependence and cycles

Source: Prepared by Marcos Antonio Serafim

Table 2. Theoretical contributions of systems thinking

This systemic approach shifts the focus from the isolated artefact to the systems that accommodate it, both within and outside the world of design. The product becomes not merely a function intended to satisfy specific needs, but a network of socio-ecological systems that include production chains, energy flows, material cycles and interactions with the built environment. This is an approach that aligns contemporary design with regenerative design, for example (MANG; REED, 2012), and design for transitions, where the aim of design is no longer to help prevent negative externalities but to enable processes of environmental regeneration. Cycles and circularity represent a key concept in this debate.

In the world of Nature, the waste from one process serves as a resource for another, thus forming extremely efficient closed-loop cycles. By applying this principle to design, the process would involve rethinking linear production and integrating circular economy strategies, keeping materials in use for as long as possible. Applied to ceramics design, this involves incorporating construction and industrial waste as secondary raw materials for ceramics, thereby reducing the need for natural resources and minimising waste generation (IPEA, 2018). Co-evolution, the

principle whereby systems and environments evolve in parallel, also forms the basis of the systemic approach. In the context of design, the principle of co-evolution implies that products and systems do not act as passive elements in the face of environmental conditions, as they establish reciprocal relationships with the environment in which they are embedded. Whilst they are influenced by the characteristics of the environment, they also contribute to its transformation, giving rise to new forms of use, experiences of comfort and dynamics of coexistence in urban space. Ceramic blocks, for example, which feature bio-inspired geometry, can affect natural ventilation, particle deposition and the urban microclimate, and contribute to gradual transformations of the built environment. Through their dialogue with biomimicry and nature-based solutions, systemic principles underpin the need for multi-scale approaches to design.

Within this theoretical framework, actions mediated by surface microstructures, structural elements and urban planning strategies are understood as interconnected parts of a single socio-ecological system, in which ceramic product design becomes an interactive process that relates not only to itself, but also to the integration of broader dynamics of matter, energy and information. In line with Capra's (1996) thinking on living systems and that of other modern ecological theorists, design itself plays a mediating role between technical performance, environmental adaptation and the transformation of the built environment. Thus, the systemic foundations presented here can establish a framework for design practices concerned with self-organisation, co-evolution and regeneration, reinforcing the case for multi-scale systems of products, architecture and city in accordance with the ecological principles that sustain life.

4. CONTRIBUTIONS TO DESIGN THEORY AND TECHNOLOGY

4.1. Epistemological contributions

Biomimicry promotes an ambitious reconfiguration of the epistemological foundations of design, shifting nature from a place of discovery to a centre of knowledge and a normative reference point. Drawing inspiration from the approach proposed by Benyus (2011), the central focus of this study is to understand how living systems perform analogous functions in similar contexts while still using resources efficiently. This shift entails a new definition of innovation and a change in focus, placing less emphasis on formal novelty and more on systemic and ecological appropriateness. However, it is an interdisciplinary perspective that encompasses concepts from biology, engineering, materials science and design (FAGUNDES et al., 2020).

The morphological and functional diversity of biological systems, particularly those derived from the plant kingdom, offers a wide range of solutions to issues relating to surfaces, structures and resource allocation (BARTHLOTT et al., 2017). Biomimetic knowledge, therefore, contributes to the growing field of the epistemology of design, with a view to achieving an ecology of knowledge that reflects the principles governing living systems.

4.2. Methodological contributions

The transition from biological principles to developed technology depends on rigorous methods that do not result in a false imitation of nature. In this regard, Detanico's (2021) approach is at the forefront, proposing a structured series of stages – define, biologise, discover, abstract and apply – that drive the biomimetic design process. This approach aligns with classic product design methodologies, such as Löbach's model (2001), integrating biomimicry predominantly into the analysis and conception stages without compromising the technical and regulatory

evaluation of the applied solutions. BIOSign, proposed by Detanico (2021), integrates with currently existing tools, such as AskNature, to enable biological principles to be abstracted in a coherent manner and transferred to ceramic materials, surfaces and structural geometry. Furthermore, integration with Technology Readiness Levels (TRL), as defined by institutions such as FINEP (2022), further reinforces the methodological viability of the process to enable planning that takes solutions from ideation to prototyping in the relevant fields. This biomimicry, the design method and TRL enable design practice to be better adapted to the demands of technological innovation and to the transfer of knowledge to the production and innovation sector.

4.3. Technological contributions to ceramic product design

At present, the technological contributions of biomimicry to ceramic product design should be regarded as design hypotheses and areas of ongoing research. Prominent among the most classic examples of biomimetic applications relating to surface design to be found in the literature are self-cleaning properties and the anti-adhesive properties associated with the so-called lotus effect (BARTHLOTT AND NEINHUIS, 1997). This is due to hierarchical roughness at various scales, which can minimise the contact area between the surface and water and thus result in superhydrophobic behaviour (BHUSHAN, 2009; WAGNER et al., 2011). As shown in Figure 1, the surface of the lotus leaf exhibits superhydrophobic behaviour, characterised by the formation of nearly spherical droplets and by the low adhesion of water to the surface.



Source: Images compiled and adapted by Marcos Antonio Serafim. Source: AdobeStock

Figure 1. Illustration of the biomimetic principle of the lotus effect: on the left, the surface of a lotus leaf with water droplets; on the right, a visual analogy of hydrophobic behaviour on an artificial surface.

With regard to microstructural applications on surfaces, a pending technical challenge involves transposing such natural principles onto ceramic materials, which calls for production processes capable of generating micro- and nanostructures more effectively, such as advanced forming processes or additive manufacturing. From this perspective, bio-inspired surfaces on ceramic blocks or tiles represent a research hypothesis that could minimise particle adhesion and contribute to environmental performance policies in the urban environment. In

fact, these surfaces can enhance the performance of ceramics, in addition to their structural role in the industry, and may even align with the principles of nature-based solutions.

A second area of potential technological contribution is the geometric and structural optimisation of ceramic materials. Porous systems with a hierarchical structure found in nature are commonly used to balance mechanical strength, lightness and the optimal use of materials, such as bone, bamboo and mother-of-pearl in biological organisms (BHUSHAN, 2009). The description of these systems suggests that similar principles can be developed in the internal design of ceramic blocks (through strategically placed compartments, ribs and walls) and should be explored as a design strategy that can address both construction and industrial waste whilst complying with regulatory performance standards.

In addition to aspects relating to structural and material efficiency, the application of bio-inspired geometry to ceramic blocks could, in the long term, also help to improve air quality in urban environments. In natural systems, such as leaves, lungs and the respiratory systems of insects, porous and branched structures play a fundamental role in the filtration, deposition and exchange of gases and particles, combining a large surface area with complex flow pathways (VOGEL, 1994; BARTHLOTT et al., 2017; TURNER, 2007). Similarly, ceramic surfaces and cavities designed according to biomimetic principles could act as passive devices for the deposition of particulate matter, reducing the resuspension of atmospheric pollutants on exposed façades and building elements. Studies on particle deposition on urban surfaces indicate that roughness, porosity and geometry significantly influence the capture mechanisms of particulate matter (PM₁₀ and PM_{2.5}), particularly in naturally ventilated environments (PUGH et al., 2012; ABBAS et al., 2019). In this regard, ceramic blocks with bio-inspired internal and external geometries represent a promising technological approach, as they combine structural performance, passive ventilation and the potential for air pollution mitigation.

Experimentation-based approaches, as exemplified by Fagundes et al. (2020), show that bio-inspired geometries can be developed and tested in construction systems, indicating the technical feasibility of such measures; however, their application on an industrial scale would require further improvements to processes, quality indicators and performance assessment.

As summarised in Table 3, the natural systems analysed provide functional principles that serve as a basis for hypothetical application to ceramic product design, guiding the debate on surfaces, geometries and environmental performance in an urban context.

Natural system	Principle	Hypothetical application in ceramics
Leaf	Raised surface area	Particulate matter capture
Bone	Hierarchical structure	Strength and lightweighting
Lotus leaf	Super-hydrophobicity	Self-cleaning surfaces
Termite mound	Passive ventilation	Heat control

Source: Prepared by Marcos Antonio Serafim

Table 3. Natural principles and hypothetical applications in ceramic materials

Bio-inspired ceramics design should therefore be regarded as an emerging field characterised by the systematic observation of nature and capable of contributing, in a forward-looking manner, to resource efficiency, product diversity, product multifunctionality, and initiatives relating to urban sustainability and regenerative methods within the ceramics industry's production systems.

5. FINAL CONSIDERATIONS

The aim of this study has been to establish a conceptual and theoretical framework for understanding the role of design in addressing contemporary environmental, social and productive challenges, with a focus on the ceramics industry and the urban context. Building on a critique of the linear industrial model and an expansion of the concept of quality in design, this study brings together the contributions of sustainable design, biomimicry and nature-based solutions as converging approaches towards a more responsible, integrated and ecologically principled design practice.

In addressing the fundamentals of systems thinking – particularly drawing on the contributions of Prigogine, Maturana, Varela and Capra – this work has highlighted the need to understand products, materials and building systems as parts of dynamic socio-ecological networks, in which the flows of matter, energy and information play a central role. This conceptual shift, from isolated artefacts to interconnected systems, reinforces the importance of approaches that incorporate cycles, circularity, self-organisation and co-evolution as guiding principles of design.

In the specific field of ceramic product design, the contributions discussed have been approached from a forward-looking perspective, recognising that many biomimetic applications are still at the exploratory or experimental validation stages. Bio-inspired surfaces and geometries, the incorporation of waste as secondary raw materials, and the potential to contribute to urban environmental quality – including passive ventilation and the mitigation of air pollution – are emerging as promising technological hypotheses, the realisation of which depends on methodological, production-related and regulatory advances.

Bio-inspired ceramics design is thus emerging as a developing interdisciplinary field, in which the systematic observation of living systems provides not only formal inspiration, but also functional and organisational guidelines capable of steering innovation processes aligned with sustainability and environmental regeneration. By integrating product, architecture and the city within multi-scale approaches, the principles presented in this study provide a conceptual foundation for future research and for the development of ceramic solutions that are more adaptive, resilient and consistent with the ecological principles that sustain life.

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