**Animals-based biotemplates for catalyst synthesis**

### Mahboubeh Houshiara, Zoheir Salemia, Masoud Mofarahia,b,[[1]](#footnote-1),

*a* *Department of Chemical Engineering, Faculty of Petroleum, Gas and Petrochemical Engineering, Persian Gulf University, Bushehr, 75169, Iran*

*b* *Department of Chemical and Biomolecular Engineering,* *Yonsei University,* *50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea*

**Abstract**

Biotemplating has surfaced as an innovative and sustainable approach to designing and synthesizing high-end catalysts by mimicking nature's intricate hierarchical architectures. Employing biological templates such as chitin, collagen, and viral morphologies, the process allows for materials to be synthesized with improved surface area, porosity, and catalytic activity. Both soft- and hard-template strategies enable exquisite morphological control, enabling energy conversion, environmental cleanup, and catalysis. Hierarchical, hollow, periodic, and nanostructured, one of the most important structures achieved by biotemplating, is improving reaction selectivity and efficiency. Challenges notwithstanding, its full potential can be achieved through scale-up manufacture, material stability, and resolution of ethical concerns in using animal templates. There is future potential in integrating biotemplates with genetic engineering and synthetic materials in a bid to overcome the constraints. The heightened international interest, as indicated by a rise in research production, marks the untapped potential of biotemplate catalysts. Elimination of the gap between laboratory research and industrial practice is the most significant factor for making the technique a mainstream standard material science methodology. Lastly, biotemplating can reverse the game in the area of catalyst design by allowing the worldwide agenda for sustainability through cleaner energy and greener chemical production.

**Keywords:** Biotemplating, Catalysis, Sustainability, Nanostructures, Energy Conversion, Animals.

1. **Introduction**

In biotemplating, researchers have turned to nature for inspiration on how to synthesize highly complex inorganic materials using natural templates to produce hierarchical and complex structures. Biotemplating is a process that entails the incorporation of inorganic compounds with organic templates, mineralization or fossilization, where the organic components are broken down and their inorganic counterparts produced. This process provides a method for the fabrication of highly complex structures that replicate the nanoscale patterns of natural templates (1)(4).  
Nature's evolutionary process has provided the development of materials and biological systems with remarkable properties such as toughness, resilience, and complexity. These materials are extremely optimized to function well in their environments, and they are valuable lessons for modern science. Scientists can replicate and engineer these natural materials by studying the structures and mechanisms that have evolved in nature over millions of years. Through this, scientists can create new functional materials with more capability, particularly in catalysis and energy conversion (1-3).

In biotemplating, researchers have turned to nature for inspiration on how to synthesize very complex inorganic materials with the assistance of natural templates to create hierarchical and intricate structures. Though plants and microbes are extensively researched as potential templates, animal-based templates are under investigation as an excellent alternative due to their unique attributes (1). Insect wings, exoskeletons, or even animal proteins are some of the templates that offer other advantages during catalytic material synthesis. For instance, butterfly wings have been researched due to their complex microstructures and photonic resonances and are excellent candidates for catalysis and electrochemical applications (2). Shells of aquatic animals or animal proteins have also been discovered to be effective in guiding the synthesis of nanoparticles or nanostructured catalysts (1).  
  
Future of biotemplates from animals in catalyst preparation is promising since they can govern the preparation of catalysts with certain characteristics for catalysis. This review considers the use of animal biotemplates in the production of catalysts, benefits, demerits, and prospects of this novel method. Using this bioinspired method, researchers not only can mimic the effectiveness of living systems, but also push the boundaries of catalyst design with potential applications as diverse as energy conversion and clean-up of the environment as well as industrial catalysis (5). The increasing number of papers on biotemplating, as evident in Figure 1, indicates the increasing interest in the use of animal-based templates for catalytic preparation. While microbes and plants have been far the targets of most research efforts, animal templates like aquatic animal shells and insect wings are increasingly being looked at owing to their properties like photonic resonances and nanostructured ability (5). These templates enable the synthesis of hierarchical catalysts with tailored properties for energy conversion, environmental remediation, and industrial catalysis. Bioresearch still makes biotemplating an eco-friendly and bio-inspired solution to the catalyst design, with a promising future ahead.

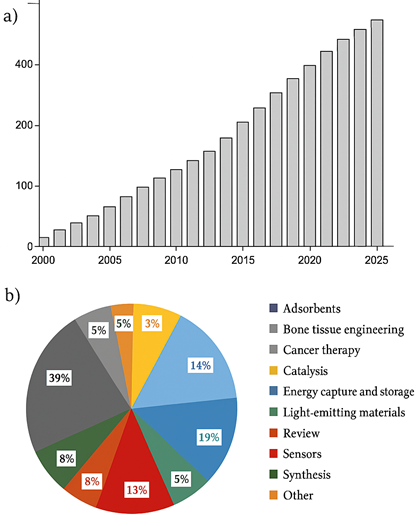


Figure 1. (a) The total accumulated number of publications indexed in the Scopus database from 2000 to June 2025, based on keyword searches for "biotemplating" and "bio-templating," with duplicates removed. (b) The thematic scope of publications on biotemplating indexed in Scopus from 2000 to June 2025

As mentioned above, bioinspired materials have many potential uses (Figure 1b). Early articles on biotemplating described only the process by which the material was synthesized. They were not aimed at any specific application field. These papers were limited to describing the synthetic route and account for about 39% of those published in Scopus. Catalysis (14%) and energy storage and capture (19%) are the main applications of these bioinspired materials in the papers. Among the reviews (13% of all the papers), there were some that were biotemplating specific, i.e., addressing certain templates such as diatoms, polysaccharides, DNA, proteins, fluorescent modified amino acids, or butterfly wings. Sotiropoulou et al. (1) have outlined all the biological templates which had been explored until 2008, while many other publications were interested in the application of this method towards the synthesis of metal oxides (8), ceramics (6), inorganic compounds (6), organic semiconductors (7), optical functional materials (9), and noble metal nanoparticles (10) by other methods and templates.

**1-1. Introduction to Biotemplating in Catalysis**

### 1-1-1. Definition and Importance of Biotemplate Catalysts

Biotemplate Catalysts are those that utilize biological templates or architectures to guide the synthesis of metal-based catalysts, often resulting in novel and highly active materials. The catalysts are extremely valuable in energy and environmental technologies such as photocatalysis, fuel cells, and lithium batteries. Use of biotemplates provides numerous advantages such as improved control of the catalyst structure, increased surface area, and improved performance for a variety of catalytic reactions (11).

Biotemplate-based catalysts are very promising due to the inherent functionality and complexity of biological structures. Plant tissues, microorganisms, and other natural systems possess hierarchical complex structures that can be imitated to design high-performance catalysts (11). Utilization of these natural templates facilitates the production of materials with highly defined structure that are not readily available from conventional synthetic approaches (12). By combining biological scaffolds with inorganic compounds, biotemplating combines the design properties of nature's architecture with the tailored properties of synthetic materials (13).

This review accentuates the importance of biotemplating methods in synthesizing metal-based catalysts and their applications in energy and the environment. Biotemplate catalyst synthesis is divided into types based on template structure: hierarchical, hollow, periodic, and nanostructures. All these structures have distinct advantages for specific applications, including greater stability, reactivity, and efficiency in catalytic reactions (13).

Biotemplate Catalysts also find various applications in contemporary technologies due to their desirable structural and functional features. In photocatalysis, they enable increased solar energy conversion and hydrogen evolution through improved light harvesting and charge carrier separation (11). In fuel cells, biotemplate-templated metal catalysts provide optimally structured surfaces and porosity control, which maximize electrochemical reaction kinetics on the electrodes (15). These catalysts are also used in lithium-ion and lithium-sulfur batteries for energy density and cycling stability improvement by enhancing efficient charge/discharge reactions (16). They also play a critical role in environmental remediation by destroying pollutants through high surface area and active sites (16). Biotemplate Catalysts in chemical synthesis allow for selective and efficient transformations by offering well-defined nano-architectures.

**1-1-2. Recent Progress on Biotemplate Catalyst Preparation**

Recent advancements in the preparation of biotemplate Catalysts have led to a deeper understanding of the relationship between the template structure and the final performance of the metal-based catalysts. Biotemplating allows for precise control over the morphology and particle size of the catalysts, which directly influences their efficiency and application in energy conversion and storage technologies (11).

Both physical and chemical routes can be utilized for biotemplating. Chemical routes include wet chemical techniques and vapor-phase deposition that are capable of depositing metal or metal oxide precisely onto the biological templates, thus creating catalysts with high surface areas and well-defined structures (14). Evaporation, deposition, and melt infiltration are the physical routes through which biotemplate Catalysts with tailored properties for a particular application can be synthesized. These methods have expanded the range of biotemplate Catalysts that can be synthesized, allowing greater flexibility in terms of material selection and function (14).

**2- Overview of Biotemplating Methods**

Biotemplating techniques using animal waste, such as slaughterhouse bones, is a highly promising technique for the synthesis of green and low-cost catalysts. The richness of bone tissue in hydroxyapatite (HAp) and calcium makes them an ideal source material for catalytic processes. Through treatment processes such as calcination, in which bones are subjected to high-temperature heat to incinerate organic matter but retain inorganic minerals, such substances can be transformed into stable solid catalysts with extensive catalytic ability (6). Bone-based catalysts that result from this are also potentially valuable for processes such as the creation of biodiesel, organic substrate oxidation reactions, and pollution remediation, with a greener catalyst alternative while also being able to address waste disposal issues simultaneously (6).  
  
The catalytic function of bone-derived materials is regulated by a number of parameters, including chemical composition, dependent on environment and species, and bone morphology. With all the advantages accrued from the use of animal bones as catalysts, there are some problems which are encountered with, primarily variation in catalytic activity and need for more sophisticated preparation methods for the enhancement of their performance (7).

**2-1- Methods for Incorporating Animal Templates in Catalyst Formation**

The application of animal templates for the synthesis of catalysts is one of the intriguing approaches in the broader area of templated carbon synthesis. The approach employs templates of organic or biological origin, such as those from animals, to control the morphology of catalyst materials. Naturally occurring animal templates, i.e., chitin, collagen, or keratin, or those processed synthetically from animal-based materials, have been a novel, sustainable alternative to traditional templates. The procedure is typically carried out by replicating the structure of the animal template, then utilizing the replica for synthesizing catalytic materials of well-defined structural and porosity properties.

**2-1-1 Methods of Incorporating Animal Templates during Catalyst Synthesis**

a) Hard-Template Method: During the hard-template method, an animal-derived protein or biopolymer hard template is initially prepared. These templates have some of the structural properties such as pores or shapes which can be emulated. For instance, chitin of the arthropod exoskeleton as a template is used in an attempt to synthesize mesoporous carbon materials. This method typically involves template filling with a carbon precursor (i.e., sucrose or furfuryl alcohol) and its subsequent pyrolysis at high temperatures. The template is dissolved in the course of pyrolysis, typically through chemical etching, to yield a structure of carbon closely mimicking the native animal template. The as-obtained carbon material possesses a porous architecture with tunable pore size and porosity, which is most desirable for energy storage and environmental purification use (8).

b) Soft-Template Method: The soft-template methods depend on the employment of soluble or extractable materials to guide a shape desired. These often utilized animal-derived materials are gelatin or collagen, among the most utilized templates to be used in this method. These templates are prepared either in desired shape or in mesh form and coated over with a precursor material like metal or carbon. When treated with heat or chemicals, the template is dissolved while a structure of the catalyst is left behind. This is a highly appropriate technique for nanostructured catalyst development with shape control, which has a significant impact on the catalytic activity (7).

The process outlined in Figure 2 (a) shows micelle formation and can be referred to as making a soft template. The porous template is produced through the concerted effort of micelles (red and blue structure). When the template is taken away, one obtains a mesoporous product—a catalytic material with a regular porous texture, as it is seen from the final product. This is the same as the soft-template strategy outlined in this chapter, where organic molecules like proteins or surfactants act as templates for the synthesis of structured materials. The second side of the picture (Figure 2(b)) indicates nanocasting, a process extensively used in hard-template synthesis. In this process, a mesoporous template (supposedly derived from some substance like silica or metal oxide) is used, and the precursor material is cast in the pores of the template. After template removal, a mesoporous replica is obtained. This parallels the hard-template method emphasized in the above, where templates are derived from animal or inorganic materials to organize catalytic materials and form well-defined constructs with adjustable porosity for improved catalytic activity.

The hard-template approach, as Figure 2 (b) depicts via nanocasting, uses hard templates like chitin to fabricate porous materials through precursor filling and pyrolysis. The soft-template approach, as figure a depicts via cooperative assembly, uses soluble phases like proteins or surfactants to control material assembly. Both approaches involve dissolution of the template to produce tunable mesoporous structures. These organized materials enhance catalytic activity, a necessity for applications in energy storage and environmental purification. They provide concurrent flexible ways of functional nanostructure design with optimum porosity.

A diagram of a structure

Description automatically generated

Figure 2. Comparison of soft-template and hard-template strategies for mesoporous catalyst synthesis. (a) Cooperative Assembly and Template Removal. (b) Nanocasting

**2-2. Role of Animal-Derived Templates in Catalyst Synthesis**

Utilization of animal template waste, particularly bone waste, for catalyst synthesis is a promising step towards the production of low-cost and eco-friendly catalysts. Slaughterhouse bone waste is abundant in richness and is an environmental issue owing to its lengthy decomposition period (17). However, it can be upcycled to develop catalysts that are eco-friendly and catalytically active for various chemical conversions.

Bone, containing valuable materials like hydroxyapatite (HAp) and calcium, is transformed into active catalysts via simple methods like calcination. High-temperature calcination of bone waste generates a recoverable, stable solid catalyst with less loss of catalytic activity (17). The fact that there are compounds such as hydroxyapatite in bone makes bone a suitable substance for heterogeneous catalysis, wherein it is utilized for reactions such as the production of biodiesel, oxidation of organic compounds, and organic compound synthesis, among others (17).

The catalytic activity of bone catalysts is much sought after in biofuel production, and it is a low-cost and environmentally friendly alternative to traditional catalysts. Bone catalysts have been utilized in biodiesel, oxime, and other bioactive compound synthesis (17-19). The reaction is reconciled with green chemistry protocols through the reduction of the use of expensive and environmentally hazardous catalysts and also providing a solution to the global waste management problem of animal bones.

Animal bones represent an inexpensive, renewable source of hydroxyapatite, which is a calcium-phosphorus compound that suits catalytic uses. Bone morphological features vary with species and are influenced by different inorganic constituents such as zinc, silicon, and magnesium, which vary the catalytic activity. These variations are based on parameters like health status, gender, and age and thus affect the surface area and active site arrangement, thereby having a significant effect on the efficiency of the catalyst. The acid-base nature of the catalyst depends on its calcium-to-phosphorus (Ca:P) ratio, which also affects its activity in catalysis for various reactions (17-18).

Bone-derived catalysts are generally prepared by calcination, hydrothermal synthesis, precipitation, and sol-gel processes, which have their own merits for hydroxyapatite synthesis with specific characteristics such as mesoporosity and narrow pore size distribution (19). Calcination is actually a method wherein the bones are calcined at elevated temperatures, organic content is removed, and inorganic minerals like HAp remain behind, which are used for catalytic reactions. Use of animal bones, especially by-products like fish, mollusks, and meat, provides a green alternative to artificial catalysts that are typically costly and less environmentally friendly (20). Bone-derived hydroxyapatite has proved useful in catalytic applications in processes including biodiesel production, oxidation reactions, and the removal of pollutants. Its excellent chemical and heat stability, in addition to enormous surface area, makes it well-suited to such processes (21). The major advantage of using bone waste as a catalyst is that it is cost-saving, reusable, and contributes to the sustainability of industrial processes. However, the problems of the variability of catalyst performance and the need for improved preparation methods still remain to be addressed.

The inorganic nature of animal bones, as presented in the Table 1, extracts major elements like calcium (Ca) and phosphorus (P), playing a major role in preparing bone-derived hydroxyapatite (HAp) for catalyst synthesis. The higher content of calcium in bones makes them suitable for synthesizing environmentally friendly and stable catalysts used in biodiesel and pollutant treatment. The bone composition heterogeneity caused by age and species influences the activity of the catalyst, as well as surface area, catalytic efficiency. Calcination processes transform bones into efficient catalysts with the advantage of low-cost, environmentally safe over man-made catalysts. Hence, bone catalysts offer an environmentally safe solution and waste disposal.

Table 1. Inorganic composition of animal bones, highlighting major extracted elements involved in the synthesis of bone-derived hydroxyapatite (HAp) for catalytic applications.

|  |  |
| --- | --- |
| Inorganic Element | |
| Calcium (Ca) | 52.5 ± 3.4 |
| Phosphorus (P) | 23.5 ± 2.1 |
| Boron (B) | 7.6 ± 0.4 |
| Silicon (Si) | 5.5 ± 0.4 |
| Sodium (Na) | 3.0 ± 0.2 |
| Chlorine (Cl) | 1.8 ± 0.1 |
| Sulfur (S) | 1.7 ± 0.1 |
| Potassium (K) | 1.6 ± 0.2 |
| Magnesium (Mg) | 1.4 ± 0.3 |
| Aluminum (Al) | 0.4 ± 0.1 |
| Zinc (Zn) | 0.3 ± 0.1 |
| Iron (Fe) | 0.3 ± 0.1 |
| Copper (Cu) | 0.2 ± 0.1 |
| Manganese (Mn) | * 1. ± 0.1 |

**2-3. Types of Animal-Based Templates: Marine and Terrestrial Sources**

Templates of animal origin for the synthesis of catalysts may be obtained from marine or land sources, each of which would impart distinct characteristics to modulate the catalytic activity. Sea-derived sources such as chitin and microalgae are particularly abundant and unexploited. Chitin derived from crustacean shells has a high nitrogen content (approx. 7 wt%) that can be harnessed in the synthesis of nitrogen-doped carbon (N-doped C) materials for catalysis, energy storage, and biomedical applications (22). Microalgae with high proteins, lipids, and carbohydrates are also potential marine biomass due to their high growth rate and low environmental impact. Nitrogen in microalgae, present largely in the form of proteins, has value in the synthesis of nitrogenous chemicals (NCCs) that find broad uses in industries (23).

On the other hand, terrestrial resources like animal bones provide an alternative route to catalyst preparation. The animal bones contain high amounts of phosphorus and calcium and are primarily composed of hydroxyapatite (HAp). These are used in synthesizing good-quality catalysts for various industrial processes. The variability in composition of animal bones depending upon species of animal, age, and diet is responsible for the diversity in catalyst properties, and this helps in tailoring catalytic operations (24). Both marine and terrestrial animal-based templates are useful in the manufacture of environmentally friendly, sustainable catalysts, offering an alternative to more conventional, petroleum-based catalyst materials.

From the perspective of transformation and use, ocean-based biomass, including chitin and microalgae, is very promising in the synthesis of nitrogen-doped carbon materials, which are outstanding candidates for a variety of catalytic processes. The natural nitrogen fixation in these biomass materials reduces the need for energy-demanding synthetic ammonia, thereby rendering the overall process more sustainable. Furthermore, the nitrogen content in such marine templates is highly significant in boosting the catalytic activity of carbon materials, particularly in applications such as bioimaging, energy storage, and environmental remediation (25-27). Table 2 introduce the use of aquatic (microalgae and chitin) and land (bone-derived HAp) animal-based templates for the synthesis of green catalysts. Aquatic sources such as microalgae and chitin, which are nitrogen and protein-rich, help prepare nitrogen-doped carbon materials and nitrogenous chemicals with zero environmental impact. Land sources such as bone-derived HAp, which are phosphorus and calcium-rich, provide catalysts whose properties can be modulated. Both classes offer eco-friendly alternatives for petroleum-based catalysts, leading to more effective catalysis and sustainability in processes.

Table 2**: Animal-based templates for catalyst synthesis: sources, composition, applications, and sustainability**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Animal-Based Template** | **Source** | **Primary Composition** | **Key Applications** | **Sustainability** |
| Chitin | Marine (crustacean shells) | Nitrogen (7 wt%), polysaccharides | Nitrogen-doped carbon materials, catalysts, biomedical | High (utilizes marine waste) |
| Microalgae | Marine | Protein, lipids, carbohydrates | N-containing chemicals, biofuels, energy storage | High (fast growth, low land use) |
| Bone-derived HAp | Terrestrial (animal bones) | Calcium, phosphorus | Catalysts, biofuels, pollutant treatment | Moderate (depends on animal source) |

3. **Animal-Based Biotemplates for the Fabrication of Bioinspired Catalysts**

Bioinorganic chemistry is the field of chemistry concerned with interaction between metal ions and biological systems, but more precisely with how biomolecules that occur naturally—are they plants or animals—act with biomolecules, like biomolecules in animals, to catalyze material (28). One of the more hopeful approaches is the use of animal-derived biotemplates taking advantage of the hierarchical organization and biochemical pathways of animal tissue or biomolecules to direct the formation of bioinspired catalysts.

These nature-occurring biotemplates of metal ion systems—shells, proteins, collagen fibers, or chitinous lattices—are offering a novel template of metal ion assembly that can result in the assembly of bioinorganic supports with programmed catalytic activity. Employing the inherent stability of the transition metals and their naturally occurring ligands, researchers can evolve hybrid catalysts that replicate the coordination architecture of native metalloproteins. These hybrid systems have distinctive oxidation states and molecular geometry, enabling them to optimize the control of catalytic reactivity and selectivity (28).

Synthesis of transition metal complexes with protein-like ligands or structural motifs allows for the creation of biomimetic catalysts with enzyme activity mimicked not only by structure but also with enhanced thermal and chemical stability. These complexes are adjustable by modification of protein-like binding sites to control thermodynamic and kinetic parameters to accomplish redox catalysis, oxygen activation, and small-molecule transformation breakthroughs (28–29).

For therapy and environmental catalysis also promises biotemplates derived from animals. For instance, use of gelatin (protein in gelatin) or egg-shell membrane as supports has enabled one to design catalysts for site-directed drug delivery and pollutant degradation. Also, biologically active metal-based probes synthesized with these templates have been utilized for DNA mismatch detection and for measuring reactive oxygen species (ROS), providing potential for highly sensitive diagnostic and therapeutic applications (30).

In addition to single molecules, whole functional assemblies isolated from animal tissues—such as nacre (mother-of-pearl) or sponge skeletons—have been utilized to create inorganic-organic hybrids with remarkable electrocatalytic and photocatalytic performance. These bioinorganic interfaces enable redox-active metal complexes to become competent to adequately dialogue with solid supports, and this has been associated with developments in energy conversion, microbial fuel cells, and biosensor development (28-34). Being an interdisciplinarity frontier field, the bioinspired catalyst synthesis using animal-derived biotemplates not only highlights nature's design in application but also aligns with sustainable chemistry and material science of biocompatibility aims.

**4. Scaling Strategies in Bio-Templated Catalysts Using Animal-Derived Structures**

Animal templates have emerged as potent scaffolds for the synthesis of bio-templates in catalysts due to their hierarchical structure, intrinsic biocompatibility, and ease of functionalization. In this chapter, the structural and functional features accounting for the applicability of these templates in catalytic functions and dealing with advanced techniques for upscaling them by new methods and modelling approaches are presented.

**4-1. Structural and Functional Properties**

Animal templates have an extremely complicated hierarchical structure that closely resembles biological systems. One of the best examples is skin-derived scaffolds, which are composed of differentiated layers—epidermis, dermis, and hypodermis—and have specialized functions in protection, regulation of nutrients, and structural support (35).  
. These scaffolds are typically collagen-based and other extracellular matrix (ECM) components such as glycosaminoglycans (GAGs) and proteoglycans, which all synergistically enhance mechanical strength, flexibility, and cellular bioactivity (36). Biodegradability is one of their greatest advantages, which enables these scaffolds to degrade with time, making them most suitable for short-term biomedical or catalytic use and minimizing material build-up over time (35). In addition, porosity supports effective diffusion of wastes and nutrients, and in catalytic reactions, optimal mass transfer. Scaffolds derived from bone, for example, provide porosity that is tunable and supports vascularization and reactive species infiltration (37).

Structurally, the animal-derived templates are highly biocompatible due to structural homology with native tissues, which is stem cell adhesion- and growth-friendly as well as directionally differentiated for tissue engineering and bio-catalysis (38).The matrices are capable of adsorption and slow release of growth factors, cytokines, and enzymes and to promote controlled modulation of biological or chemical micro-environments (38). Besides that, some of these biomaterials of animal origin have immunomodulatory activities such as inhibiting inflammation and wound healing—activities that are beneficial in catalytic and regenerative uses (39). In order to boost their performance even further, the scaffolds can be functionalized with synthetic peptides, nanoparticles, or bioactive molecules that enhance their specificity, catalytic activity, and structural stability in industrial and biomedical applications (40).

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_  
**4-2. Scaling Methods and Modelling Approaches**

It is the integration of sophisticated engineering with complex biological architectures in scaling up animal template-derived bio-templated catalysts. Scalability and economic viability of the material are largely controlled by factors like reproducibility, structural integrity, and their function under industrial process conditions. Sol-gel processing, freeze-drying, and casting are common methods employed to replicate intricate microstructures of animal tissues without disturbing their hierarchical structure (41). Also, 3D bioprinting and additive manufacturing processes provide precise replication of nature geometries and enable uniform and scalable catalyst template fabrication (42). Surface modification processes such as Atomic Layer Deposition (ALD) and Chemical Vapor Deposition (CVD) are used to functionalize in order to coat the catalytic material on animal-derived scaffolds, rendering them stable and consistent for high-performance applications (43).

For successful scale-up and operation, advanced computational tools are increasingly employed. Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) simulations of the process allow one to predict the heat and mass transfer behavior, structural response to stresses, and the activity of the catalyst in the templated materials (44). Kinetic modeling is also employed in optimizing reaction mechanisms and operating conditions for maximum catalytic performance without compromising scale (45). In addition, artificial intelligence (AI) and machine learning (ML) algorithms are being implemented in the design process for the prediction of catalyst behavior and the optimization of fabrication efficiency, based on large datasets from experimental and simulated studies (46). Finally, sustainability is always the foremost concern; scaling strategies must adhere to the principles of green chemistry and undergo strict lifecycle analyses to ensure that the use of animal-derived scaffolds remains ethically and ecologically acceptable (47).

### 5. Challenges in Scaling and Economic Aspects of Animal-Derived Bio-Templated Catalysts

Large-scale production of animal-based bio-templated catalysts is an economically, logistically, and technologically demanding task. Reproducibility of the template structure on an industrial scale is one of the biggest challenges. Biological heterogeneity of animal sources is translated into morphology of structure, biochemical composition, and mechanics variation, which makes standardization for biomedicine or catalysis difficult (48). Hierarchical structure fidelity in porous structures, i.e., bone scaffolds or collagen matrices, becomes more difficult to maintain at scale-up at the expense of deformation on drying, processing, or functionalization (49). Furthermore, conventional manufacturing routes, e.g., freeze-drying, sol-gel processing, or casting, are not directly scalable to large-scale processing without sacrificing accuracy or efficiency (49). Further, use of more sophisticated coating technologies, such as Atomic Layer Deposition (ALD) or Chemical Vapor Deposition (CVD), is often size-limited by equipment cost, batch-size limitation (43). Economically, large-scale production of animal-based bio-templated catalysts depends on various factors like availability of the starting material, processing cost, and means of waste disposal. Procuring animal tissue under ethically controlled and sterilized conditions is very costly, especially if it needs to be of pharmaceutical- or catalyst-grade purity (50). Additional downstream processing—decellularization, sterilization, and chemical functionalization—adds to capital and operating costs. Poor manufacturing channels and demands for specialist equipment or man power further enhance cost of production, thereby rendering economic feasibility uncertain for commercial use. Additionally, lifecycle analysis evermore takes center stage in assessing environmental footprint and to be feasible within the context of sustainability requirements, and in so doing, can introduce additional regulatory barriers and operational constraints (47, 51). Such difficulties would be overcome by the possible future directions: application of hybrid bio-synthetic templates, robotic fabrication methods, and machine learning-optimized methods to reduce variability and production cost and maintain fidelity in performance (46).

**6. Nanostructure and Morphology Control via Biotemplating**

Biotemplating, a biospired technique, is an important strategy to synthesize materials with complicated and well-defined nanostructure and morphology. By mimicking the structural templates in nature, particularly in the organisms that have evolved to withstand extreme environments, biotemplating employs simple biological building blocks to synthesize complex, functional materials under mild temperatures (45). This approach presents an energy-efficient and green alternative to traditional fabrication methods, which are often beset by high expenses, complex processes, and energy inefficiencies (46-47).

In particular, biotemplating has been given consideration because of the special mechanical properties of nature's materials such as nacre (mother of pearl) to obtain excellent mechanical strength through its complex "brick-and-mortar" structure (47). Biomacromolecules such as collagen, cellulose, and viruses are being utilized as templates now to achieve specifically designed nanostructures in end-products since biomolecules themselves have distinctly defined hierarchical structure (48).

In addition to the potential to reproduce the structure and function of biological materials, biotemplating is also employed for the creation of new artificial materials with new or enhanced properties. Biological templates such as collagen fibrils and cellulose fibers exhibit restricted microenvironments that facilitate the deposition of inorganic or organic species, thereby forming new nanostructures with excellent strength, toughness, and functionality.

**6.1 Key Roles of Biotemplating**

1. **Confinement for Crystallization:** Biotemplates provide a confined environment that directs the crystallization of inorganic materials. For example, in the case of collagen, the confined spaces within its fibrils guide the formation of oriented hydroxyapatite (HAP) nanocrystals in bones (49).
2. Functional Surfaces for Nucleation and Growth Control: The surfaces of biotemplates, such as proteins in cellulose or the surface of viruses, offer functional groups that can control nucleation and crystal growth. This interaction leads to precise structural alignment of nanomaterials, allowing for the design of materials with highly organized and specific properties (50).
3. Self-Assembly of Biomacromolecules: Biomacromolecules such as collagen and cellulose have intrinsic self-assembly properties, which contribute to the formation of hierarchically structured materials. These materials can exhibit complex, multiscale organization, such as chiral nematic structures in cellulose or the “brick-and-mortar” structures in nacre (51).

**6.1.1 Examples of Biotemplating Systems**

1. **Collagen: Collagen, the most widespread protein of the animal, is a leading biotemplating agent due to its fibrillar structure and ability to catalyze inorganic compound mineralization. Collagen is a template for hydroxyapatite inorganic compound formation in bones, in which mineralization is achieved through liquid precursors infiltrating into collagen fibrils and their recrystallization into oriented crystals under confinement (51).**
2. **Cellulose:** As a natural polymer with filamentous structures, cellulose is often used as a biotemplate to guide the synthesis of materials with chiral nematic structures, which exhibit unique optical properties (50). The self-assembly of cellulose-based structures has been explored for applications in advanced materials such as nanocomposites and functional films.
3. **Viruses and Bacteria:** Filamentous viruses such as the M13 bacteriophage are increasingly being utilized as biotemplates for the creation of multiscale and multidimensional materials. The ability of the viruses to self-assemble and be genetically modified to facilitate functionalization offers a promising pathway to the creation of new materials with defined properties (51). Even rod-shaped bacteria, with their potential for functional protein display on surfaces, have been used to trigger functional material synthesis.

**7. Properties and Performance of Biotemplated Catalysts**

**7-1. Catalytic Activity of Animal-Based Templates**

Animal-template biotemplate Catalysts are growing in popularity for their potential in augmenting catalytic activity, with specific mention of renewable energy. The templates, which may be viruses, bacteria, or fungi, all have unique structural features, which can be redesigned for specific energy application. The animal templates, such as the Tobacco Mosaic Virus (TMV) and M13 bacteriophage, offer a template for self-assembly under which nanomaterials of desired sizes are created, which are required for the improvement of catalytic activity (52). The nanomaterials have the potential to be used in a variety of catalytic reactions, such as water splitting to form hydrogen or in fuel cells, for the development of improved and sustainable energy technologies (52).

One of the greatest advantages of animal-based templates is that it is possible to design and control the structures at the molecular level to enhance their catalytic activities. TMV nanorods, for example, have been gold-nanoparticle-functionalized in order to increase their compatibility with metal electrodes in energy storage devices, i.e., batteries (52). This modification increases the surface area and stability of nanorods, which are accountable for greater electrochemical properties, and they are thus highly promising for application in battery electrodes and other energy conversion devices. Structural homogeneity and self-assembly of viral templates also allow one to replicate nanomaterial synthesis, a parameter of utmost importance for scaling up their application in industrial processes (53).

Aside from viruses, other bacteria like E. coli and fungi like yeast have been explored for their abilities to produce varied nanostructures, including nanowires and nanospheres. Microorganisms can be genetically engineered to produce nanomaterials that are not only catalytically active but also low in cost. For example, E. coli was used to produce nanomaterials with the prospect of application in enhancing hydrogen production through photocatalysis, an essential process in the creation of hydrogen-based energy devices. Such biological templates are used extensively due to ease of culture and handling, and they provide a scalable and sustainable route for nanomaterial synthesis relative to other routes (54-57).

Some of the interesting areas of study are uses of biotemplated nanomaterials for renewable energy devices such as solar cells and fuel cells. TiO2 and CuInSe2 nanomaterials using animal templates are being explored for uses in photocatalytic water splitting, which is expected to mitigate the energy crisis for hydrogen production. Though the developments have been achieved, the efficiency of such materials is still an ongoing research field because the majority of such systems are beset by low conversion efficiency and exorbitant production cost currently. However, having the ability to accurately tune the properties of biotemplated nanomaterials offers the prospect of being able to overcome these issues and make renewable energy systems cost-competitive in the future (54-57).

In addition, animal-based template biotemplate Catalysts have proved to be superior in the development of renewable energy technologies. They are scalable, tailor-made, and structurally precise, thus very efficient in catalysis reactions, for example, hydrogen production, fuel cells, and energy storage devices. While ever-evolving research continues to strive to reveal the highest potential of such bio-templated materials, they have the potential to be a key factor in the development of more efficient and sustainable energy systems, leading the way towards a greener, energy-harmonious future. Such developments go a long way in suppressing the environmental footprint of conventional energy sources as well as promoting the ongoing development of renewable energy sources (58).

Animal-template biotemplate Catalysts are being fabricated as a highly viable alternative for conventional catalysts, particularly for use in renewable energy processes. The novel catalysts take advantage of the unique structural properties of biological templates such as viruses, bacteria, and fungi to create nanomaterials that are optimized for topnotch catalytic performance. For instance, biotemplates like Tobacco Mosaic Virus (TMV) and M13 bacteriophage enable nanoscale self-assembly to form materials for use in crucial catalytic reactions like water splitting and fuel cells (59). Biotemplating enables molecular-level control over nanomaterial structure with high accuracy, thereby improving their efficiency in catalytic processes toward sustainable energy technology.

In contrast to traditional catalysts, which are typically founded on costly and ecologically unsuitable materials, biological templates from animals offer scalable and sustainable pathways to the synthesis of nanomaterials. The E. coli and yeast organisms can be biogenetically engineered to produce catalytic and multifunctional nanostructures, such as nanowires and nanospheres, with the potential to deliver enhanced efficiency for photocatalytic hydrogen production (59). While the advances in biotemplate nanomaterials are promising for application in solar cells and fuel cells, conversion efficiency and production cost remain issues. However, the capability to architect the properties of such biotemplate materials makes them serious contenders in seeking economically competitive and environmentally friendly renewable energy systems that ultimately move away from traditional energy sources with less environmental impact.

Biotemplate Catalysts are a new field in green chemistry where natural templates from biological structures are used in the design of high functionality materials for effective energy and green environmental processes. The hierarchical complex structures available in nature, including those encountered in plant tissue and animal tissue, are harnessed through the use of biotemplate Catalysts to produce highly effective properties materials that are applied in various green processes (59). One of the greatest benefits of biotemplate Catalysts is the possibility of replacing toxic synthetic templates so that greener, non-toxic, and sustainable processes can be brought in.  
In green chemistry, biotemplate Catalysts have good prospects in view of enhancing the efficiency of energy conversion and environment remediation. Solar energy harvesting, for example, photocatalytic hydrogen production, and CO2 reduction are being utilized with biotemplated material (59). These materials, which are created from nature-based forms such as plant photosynthetic systems or the optical properties of butterfly wings, contain inherent properties that make them well adapted for energy harvesting and conversion. Through the replication of these structures, biotemplate Catalysts are able to significantly maximize the efficiency of photocatalytic processes, which play a crucial role in renewable energy harvesting and pollution abatement (59).  
  
In particular, biotemplated materials are applied in photocatalytic hydrogen evolution and CO2 reduction, two of the most promising fields to address the energy issue of the world. The ability to transform sunlight into hydrogen or liquid fuel with high efficiency through photocatalysis would be a revolution in clean energy production (59-60). Biotemplated catalysts, through their well-controlled nanostructure, enhance the light harvesting and catalytic activity of materials, which renders them more efficient in these fields. For instance, the unique diatom or other microbial form, evolved naturally for maximum light capture and conversion, can be utilized as templates to produce artificial material, which mimics these properties to generate hydrogen or fight CO2 emissions (60).

Also, biotemplate Catalysts find applications in solar cells, where natural biotemplates could be employed for improving the light-harvesting efficiency of solar cells or photovoltaic devices. Hierarchical structures of biological systems can realize improved energy absorption and charge conduction and thus more efficient solar cells (61). Biotemplate materials have been studied in the case of lithium-ion batteries to enhance the efficiency of the cathode and anode by fabricating nanoscale pores and channels to achieve better surface area for ion storage and increased charge/discharge cycles.

Application of biotemplate Catalysts is also of great importance in the degradation of environmental contaminants. Biotemplates such as proteins or polysaccharides may be used to develop catalysts that degrade organic contaminants such as dyes and other poisonous chemicals in water (60). The fact that high surface area catalysts with suitably tailored pore structure can be created allows for efficient adsorption and degradation of pollutants and hence a clean technology for water purification.

Biotemplate Catalysts stand out in renewable energy technology and environmental remediation, showing the convergence of material science and biology. Through natural templates of biological organisms—plants, animals, and microbes—scientists are able to synthesize highly functional materials with improved performance in green applications (60). One of the most significant advantages of utilizing biotemplating procedures is that they are capable of creating renewable, nontoxic materials as substitutes for their toxic synthetic equivalents. Such a shift is of paramount significance in the realm of renewable energy wherein the process requires highly proficient catalysts to perform efficiently on procedures like photocatalytic hydrogen evolution and CO reduction. The distinctive characteristics of biotemplated catalysts, motivated by nature's extremely efficient energy conversion systems, yield improved light absorption, high surface area, and improved catalytic activity, paving the way for the development of clean energy production.

In the remediation of the environment, biotemplate Catalysts hold the key to solving pollution and water contamination issues (61). The catalysts can be designed to degrade organic pollutants—such as dyes and other toxic chemicals—using enhanced adsorption and destruction mechanisms. Biotemplated materials can tap into higher efficiency in capturing and disintegrating toxic chemicals, thus making bodies of water cleaner and purer (61). As an instance, the use of green templates like proteins or polysaccharides allows the creation of catalysts that are degrading pollutants and also sustainable. Biotemplate Catalysts in general are one very promising field in green chemistry, driving applications in renewable energy as well as pollution control, and leading the world towards an environmentally friendly and sustainable tomorrow.

**8. Challenges and Opportunities in Animal-Based Biotemplating**

Animal biotemplating is faced with a special series of challenges that restrict its general use to catalyst synthesis. The process is narrowly restricted by ethics in the isolation of templates from threatened species or the utilization of unsustainable processes. Additionally, the inherent structural sophistication of animals might cause widespread template variability themselves, which is propagated to product unreliability in the resulting nanomaterials produced from them. These differences can be the cause of problems for reproducibility and scalability of biotemplating processes as a pre-requisite for industrial use (64). Moreover, the organic nature of animal templates implies that they will be unstable under stressful conditions, for instance, high temperature or aggressive chemical environments. This non-durability is undesirable for the long-term and operation of biotemplated materials, particularly in demanding applications for catalysis where durability and reliability are essential.

Despite these challenges, the potential for animal biotemplating toward the synthesis of new catalysts is highly prospective. The nanoscale morphology of animal templates, including the intricate patterns in the wings of butterflies and resilient shells, can be utilized for the synthesis of catalysts that have higher surface areas, active sites, and activity. The secret to the future of biotemplated catalysis is the blend of animal template with high-performance synthetic material, like nanomaterials or metal-organic frameworks. Perhaps this biotic-synthetic hybrid pathway could offer superior catalytic capability through the convergence of the best excellences of nature and synthetic worlds (64). Moreover, advances in synthetic biology and genetic engineering could offer the potential for mass-producing biotemplating processes, such that they could be commercially feasible on a large scale. While material and ethical stability problems continue to dominate, inter-disciplinary advances can contribute to the creation of high-performance, specialist, and sustainable catalysts through global efforts towards green technologies and solutions for energy, pollution, and sustainability challenges.

**9. Limitations of Using Animal Templates**

Animal biotemplating has challenges of its own as well, e.g., ethical concerns in utilizing animals for materials synthesis. It might be problematic obtaining animal templates if it involves utilizing endangered species or unsustainable practices. Complexity of animal templates, i.e., highly sophisticated structures, might also cause difficulties in attaining uniformity batch to batch (64). Discrepancies in the characteristics of the templates may result in discrepancies in products, which can affect reproducibility and scalability of biotemplating operations (64). Instability and degradation of templates of animal origin is a disadvantage. Organic templates of animal origin are easily degradable under aggressive conditions such as high temperature under mineralization conditions. This instability can jeopardize the quality and functionality of the end material, especially for applications with high performance such as catalysis (65). Furthermore, biotemplates derived from animals might not be as durable or reproducible as plant-based or synthetic counterparts, which could represent a constraint to industrial adoption at scale.  
In spite of these restrictions, animal biotemplating possesses enormous potential in the design of novel catalysts with improved properties. The nanoscale morphology of the animal template, such as the intricacy of patterns on butterfly wings or the strength of shells, allows for the development of catalysts with improved surface areas, active sites, and reactivity (66). They are potentially more selective, efficient, and sustainable than traditional catalysts, particularly for environmental and energy applications like renewable energy harvesting or pollution cleanup.

**10. Future Directions and Innovations in Biotemplated Catalyst Development**

In the future, there is huge potential for coupling animal templates with other synthetic advanced materials, such as nanomaterials or metal-organic frameworks, to enhance the functionality of catalysts. The hybrid approach is able to combine the biological virtues of animal templates and the exceptional properties of synthetic materials, opening up new opportunities for more effective catalytic reactions (66). Furthermore, the field can see progress in terms of scaling up biotemplating processes, which will enable the synthesis of these bioinspired catalysts at an industrial level, through methods such as genetic engineering or synthetic biology.

Overall, though biotemplating using animals is confronted with limitations such as ethical issues and material instability, its possibility to develop very specialized and efficient catalysts is very promising. Such limitations can be overcome in the future with developments in biotechnology and inter-disciplinary work, resulting in greener and high-performance materials (67). While the world moves towards greener technologies, nature-mimic biotemplate Catalysts may find their niche in the spotlight in solving complex issues that are intertwined with energy, pollution, and sustainability.

**12. Ethical and Environmental Considerations**

**12-1. Ethical Implications of Using Animal Materials**

There are certain ethics issues with the use of animal materials in biotechnological and biomedical applications concerning animal welfare, consent, and methods of animal-based approaches that bring about environmental implications. Of the most critical ethical concerns is the treatment of animals in their harvesting of such materials and inducing injury in their collection of cells or tissues for biotemplating. The ethical concern applies to the larger industrial animal agriculture context as well, where systems of factory-based production, the ethics of animal use, and how animal agriculture helps ecosystems along with diversity are all legitimate questions (67).  
Another serious ethical issue is the use of animals to research and exploit their biological resources for profit. Although the biotechnology industry takes a stance in defending the use of animal tissues on the grounds of their ability to improve human health and wellbeing, the ethical cost of exploiting animals remains something of a contentious debate (67). Also, the exploitation of animals in biotechnology raises the question of whether it is right to subject animals to harm for the sake of technological progress, especially considering that the use of plant or synthetic biotemplating materials can be employed as alternatives (67).  
In that respect, the current controversy within the "clean meat" sector about growing animal cells in a bottle in vitro is an interesting example of how ethics and technology are balanced through consumer demand. For all the merit it has as some kind of ethical alternative to traditional animal farming, it too has such a thing as animal-derived media, which somewhat adds a spin to the ethical issue (68). With the growing demand for cell-based meat, ethical animal cell sourcing and animal growth medium alternatives will be central to resolving the ethical concerns of animal material use in biotechnology**.**

**12-2 Sustainability of Animal-Based Biotemplating**

Animal-based biotemplating, involved the use of animal-derived materials for various biotechnological applications, is riddled with numerous sustainability challenges. Even though animal-derived templates have appealing structural and functional properties for uses in tissue engineering and regenerative medicine, their environmental impact is high. Animal agriculture, particularly livestock farming, is responsible for a significant percentage of global greenhouse gas emissions, resulting in climate change, water depletion, and deforestation (69). The water and land usage in animal agriculture also contribute to sustainability issues.  
  
From a sustainable perspective, increasing demand exists for animal-based material substitutes. Cellular agriculture, culturing animal cells in controlled environments to produce goods such as meat, proteins, or biotemplating materials, is extremely promising. This technology, however, is currently under development and poses significant problems of scaling up and reducing the environmental footprint associated with animal cell culture. The energy-intensive nature of the bioreactor systems and the incorporation of growth mediums of animal origin are the major influencing factors that limit the sustainability of current animal-based biotemplating processes (69).  
  
Making animal-based biotemplating sustainable would require future studies to focus on optimizing cell culture processes, reducing the consumption of animal-derived products, and searching for plant-based or synthetic alternative growth mediums (70). Even further adoption of more sustainable approaches in the supply and processing of animal-derived material, such as utilization of byproducts from other industries or recycling of waste material, can further increase the sustainability of such biotechnological approaches.

**13 . Conclusion and Future Outlook**

In summary, the production of biotemplate Catalysts using animal templates is a viable path toward the material engineering of new catalysts. Through the utilization of the outstanding structural features of biological molecules such as chitin, collagen, and viruses, scientists are capable of creating catalysts not only with enhanced activity but also allowing for the realization of sustainable approaches in material production.  
  
Both soft-template and hard-template methods are valid ways of introducing nature-inspired templates into catalyst design, each having various degrees of control over nanoparticle porosity and morphology. To have the ability to take ideas from nature's very own solution to mechanical issues has enormous application in the field of energy production as well as cleaning the environment. Despite the possible benefits, challenges exist in the area of ethical issues, material stability, and reproducibility of the quality of production. The ability to address issues of animal welfare, environmental sustainability of animal rearing, and reproducibility of biotemplate materials will be important for broader adoption and integration of these techniques into industrial practice.  
  
Future directions in biotemplate catalyst research are to be directed towards new hybrid approaches combining the merits of animal-derived templates and synthetic materials. This can lead to catalysts that are not only highly efficient and specifically tailored towards a particular reaction but also more sustainable in their production. Further, more advanced biotechnology and genetic engineering can help sidestep the ethical dilemmas of obtaining animals.  
  
As the area of biotemplate Catalysts has yet not reached its potential, there remains huge potential to set out creating cleaner technologies in order to realize the world sustainability agenda. With the potential to copy and amplify nature's sophisticated patterns, there is an opportunity into record-breaking materials that have the potential to be a critical factor in alleviating some of the world's most pressing challenges such as harvesting renewable energy and pollution. Lastly, the successful utilization of biotemplate Catalysts to applications will require ongoing commitment to innovation, sustainability, and moral practice.

Biotemplating is a technique whereby biological material or templates are used to produce functional synthetic structures. The strength of biotemplating lies in the fact that it has the ability to utilize nature and technology. Unlike traditional material synthesis techniques, biotemplating need not be done using high-tech equipment, high temperature, or high pressure and therefore it is inexpensive, biocompatible, and scalable. This technique is particularly valuable in the synthesis of materials with intricate, highly organized structures such as mesoporous, hollow, and nanostructured forms, prevalent in nature's biological systems. The structures not only have useful applications in material property enhancement such as surface area and reactivity but are also found to have excellent applications in energy conversion, storage, and catalysis.

The rising level of research in biotemplate materials is a pointer to increased interest and potential in the field. As evidenced by recent works published in countries like China, America, and India, biotemplating is nowadays a highly "hot" topic in the realm of material science. The rate at which scientific articles on biotemplating are published has significantly risen in the recent years, especially as regards its utilization in energy and environmental applications. However, with the large volume of work that has been put into the synthesis and characterization of such materials, most of their potential applications, especially in catalysis, remain to be fully investigated. The gap between laboratory studies and real application therefore highlights the need to further investigate the properties, performance, and scalability of biotemplate materials for catalytic uses.

**References**

|  |  |
| --- | --- |
| 1. 1. Herrera-Beurnio, M. C., Hidalgo-Carrillo, J., López-Tenllado, F. J., Martin-Gómez, J., Estévez, R. C., Urbano, F. J., & Marinas, A. (2021). Bio-templating: An emerging synthetic technique for catalysts. *A review*. *Catalysts, 11*(11), 1364. https://doi.org/10.3390/catal11111364 2. 2. Hashemizadeh, I., Tsang, D. C. W., Ng, Y. H., Wu, Z., Golovko, V., & Yip, A. C. K. (2017). Bio-mimicking TiO₂ architectures for enhanced photocatalytic activity under UV and visible light. *RSC Advances, 7*, 39098–39108. https://doi.org/10.1039/C7RA05714G 3. 3. Deshpande, A. S., Burgert, I., & Paris, O. (2006). Natural templates. *Small, 2*(8-9), 994–998. https://doi.org/10.1002/smll.200600111 4. 4. Krajina, B. A., Proctor, A. C., Schoen, A. P., Spakowitz, A. J., & Heilshorn, S. C. (2018). Biotemplated synthesis of inorganic materials: An emerging paradigm for nanomaterial synthesis inspired by nature. *Progress in Materials Science, 91*, 1–23. https://doi.org/10.1016/j.pmatsci.2017.08.003 5. 5. Deuerling, S., Kugler, S., Klotz, M., Zollfrank, C., & Van Opdenbosch, D. (2018). A perspective on bio-mediated material structuring. *Advanced Materials, 30*(8), 1703656. https://doi.org/10.1002/adma.201703656 6. 6.Chao, J. T., Biggs, M. J. P., & Pandit, A. S. (2014). Diatoms: A biotemplating approach to fabricating drug delivery reservoirs. *Expert Opinion on Drug Delivery, 11*(10), 1687–1695. https://doi.org/10.1517/17425247.2014.938633 7. 7. Savic, S., Vojisavljevic, K., uč a-Nešić, M. P., Zivojevic, K., Mladenovic, M., & Knezevic, N. (2018). Hard template synthesis of nanomaterials based on mesoporous silica. Metallurgical and Materials Engineering, 24(4). 8. 8. Poolakkandy, R. R., & Menamparambath, M. M. (2020). Soft-template-assisted synthesis: a promising approach for the fabrication of transition metal oxides. Nanoscale Advances, 2(11), 5015-5045. 9. 9. Boury, B., & Plumejeau, S. (2015). Metal oxides and polysaccharides: An efficient hybrid association for materials chemistry. *Green Chemistry, 17*(1), 72–88. https://doi.org/10.1039/C4GC01414A 10. 10. Behrens, S. S. (2008). Synthesis of inorganic nanomaterials mediated by protein assemblies. *Journal of Materials Chemistry, 18*(34), 3788–3798. https://doi.org/10.1039/B804258F 11. 11. Roostaei, T., Rahimpour, M. R., Zhao, H., Eisapour, M., Chen, Z., & Hu, J. (2023). Recent advances and progress in biotemplate catalysts for electrochemical energy storage and conversion. *Advances in Colloid and Interface Science, 316*, 102958. https://doi.org/10.1016/j.cis.2023.102958 12. 12. Pan, Y., Paschoalino, W. J., Szuchmacher Blum, A., & Mauzeroll, J. (2021). Recent advances in bio‐templated metallic nanomaterial synthesis and electrocatalytic applications. *ChemSusChem, 14*(3), 758–791. https://doi.org/10.1002/cssc.202002618 13. 13. Taghvaei, H., et al. (2019). Catalytic hydrodeoxygenation of bio-oil using in situ generated hydrogen in plasma reactor: Effects of alumina-supported catalysts and plasma parameters. *Process Safety and Environmental Protection, 129*, 274-282. <https://doi.org/10.1016/j.psep.2019.06.025> 14. 14. Freeman, A. (2017). Protein-mediated biotemplating on the nanoscale. Biomimetics, 2(3), <https://doi.org/10.3390/biomimetics2030014> 15. 15. Ma, X., Bai, X., Chen, X., Zhang, C., Leng, J., Zhang, A., ... & Wang, J. (2024). Biotemplated heterostructure materials: opportunities for the elaboration of new photocatalysts and selective-oxidation catalysts. Catalysis Science & Technology, 14(1), 10-25.   16 Hussain, F., Alshahrani, S., Abbas, M. M., Khan, H. M., Jamil, A., Yaqoob, H., ... & Munir, M. (2021). Waste animal bones as catalysts for biodiesel production; a mini review. *Catalysts*, *11*(5), 630. |  |

1. Zhou, H., Fan, T., & Zhang, D. (2011). Biotemplated materials for sustainable energy and: current status and challenges. *ChemSusChem*, *4*(10), 1344-1387.
2. Ullah, M. W., Manan, S., Khattak, W. A., Shahzad, A., Ul-Islam, M., & Yang, G. (2020). Biotemplate-mediated green synthesis and applications of nanomaterials. *Current Pharmaceutical Design*, *26*(45), 5819-5836.
3. Nasrollahzadeh, M., Soheili Bidgoli, N. S., Shafiei, N., Soleimani, F., Nezafat, Z., Luque, R. (2020). Low-cost and sustainable (nano)catalysts derived from bone waste: Catalytic applications and biofuels production. Biofuels, Bioproducts and Biorefining, 14(5), 1305-1322. <https://doi.org/10.1002/bbb.2138>
4. Perego, C., & Millini, R. (2013). Porous materials in catalysis: Challenges for mesoporous materials. *Chemical Society Reviews, 42*(9), 3956–3976. https://doi.org/10.1039/C2CS35252G
5. Corma, A. (1997). From microporous to mesoporous molecular sieve materials and their use in catalysis. *Chemical Reviews, 97*(6), 2373–2420. https://doi.org/10.1021/cr960406n
6. Mitchell, S., Michels, N. L., & Pérez-Ramírez, J. (2013). From powder to technical body: The undervalued science of catalyst scale-up. *Chemical Society Reviews, 42*(15), 6094–6112. https://doi.org/10.1039/C3CS60033J
7. Zhu, L., Lu, F., Liu, X. D., Liu, X. Q., & Sun, L. B. (2015). A new redox strategy for low-temperature formation of strong basicity on mesoporous silica. *Chemical Communications, 51*(50), 10058–10061. https://doi.org/10.1039/C5CC03348A
8. Shi, X., Ye, X., Zhong, H., Wang, T., & Jin, F. (2021). Sustainable nitrogen-containing chemicals and materials from natural marine resources chitin and microalgae. *Molecular Catalysis, 505*, 111517. https://doi.org/10.1016/j.mcat.2021.111517
9. R.H. Rødde, A. Einbu, K.M. Vårum, A seasonal study of the chemical composition and chitin quality of shrimp shells obtained from northern shrimp (Pandalus borealis), Carbohydr. Polym. 71 (3) (2008) 388–393, https://doi.org/10.1016/j. carbpol.2007.06.006.
10. X. Chen, S.L. Chew, F.M. Kerton, N. Yan, Direct conversion of chitin into a Ncontaining furan derivative, Green Chem. 16 (4) (2014) 2204–2212, https://doi. org/10.1039/c3gc42436g. 25 D. Knorr, Recovery and utilization of chitin and chitosan in food processing waste management, Food Technol. (Chicago) 45 (1) (1991) 114–122.
11. N.K. Mathur, C.K. Narang, Chitin and chitosan, versatile polysaccharides from marine animals, J. Chem. Educ. 67 (11) (1990) 938, https://doi.org/10.1021/ ed067p938.
12. Roostaei, T., Rahimpour, M. R., Zhao, H., Eisapour, M., Chen, Z., & Hu, J. (2023). Recent advances and progress in biotemplate catalysts for electrochemical energy storage and conversion. Advances in Colloid and Interface Science, 318, 102958.
13. Chen, W, Yang, H, Chen, Y, Xia, M, Chen, X, Chen, H (2017). Transformation of nitrogen and evolution of N-containing species during algae pyrolysis, Environ. Sci. Technol. 51 (11) (2017) 6570–6579, https://doi.org/10.1021/acs.est.7b00434.
14. Ngo, F. M., & Tse, E. C. M. (2021). Bioinorganic platforms for sensing, biomimicry, and energy catalysis. Chemistry Letters, 50(5), 974–986. <https://doi.org/10.1246/cl.200875>
15. Schilter, D., Camara, J. M., Huynh, M. T., Hammes-Schiffer, S., & Rauchfuss, T. B. (2016). Hydrogenase enzymes and their synthetic models: The role of metal hydrides. Chemical Reviews, 116(7), 3324-3352. https://doi.org/10.1021/acs.chemrev.6b00180
16. Roat-Malone, R. M. (2007). *Bioinorganic chemistry: a short course*. John Wiley & Sons.
17. Prescher, J. A., & Bertozzi, C. R. (2005). Chemistry in living systems. Nature Chemical Biology, 1(1), 13-21. https://doi.org/10.1038/nchembio714
18. Johnsson, N., & Johnsson, K. (2007). Chemical tools for biomolecular imaging. ACS Chemical Biology, 2(1), 31-38. https://doi.org/10.1021/cb7001688
19. Salic, A., & Mitchison, T. J. (2008). A chemical method for fast and sensitive detection of DNA synthesis in vivo. Proceedings of the National Academy of Sciences of the United States of America, 105(7), 2415-2420. https://doi.org/10.1073/pnas.0712344105
20. Jao, C. Y., & Salic, A. (2008). Exploring RNA transcription and turnover in vivo by using click chemistry. Proceedings of the National Academy of Sciences of the United States of America, 105(41), 15779-15784. https://doi.org/10.1073/pnas.0808720105
21. Kappaun, K., Piovesan, A. R., Carlini, C. R., & Ligabue-Braun, R. (2018). Ureases: Historical aspects, catalytic, and non-catalytic properties–A review. Journal of advanced research, 13, 3-17.
22. Onfray, C., & Thiam, A. (2023). Biomass-derived carbon-based electrodes for electrochemical sensing: a review. Micromachines, 14(9), 1688.
23. Song, G., Qin, F., Yu, J., Tang, L., Pang, Y., Zhang, C., ... & Deng, L. (2022). Tailoring biochar for persulfate-based environmental catalysis: Impact of biomass feedstocks. Journal of Hazardous Materials, 424, 127663.
24. Hutmacher, D. W. (2000). Scaffolds in tissue engineering bone and cartilage. Biomaterials, 21(24), 2529-2543. https://doi.org/10.1016/S0142-9612(00)00121-6
25. Zhang, Y., Yang, G., Wang, J., Zhao, B., He, Y., & Guo, J. (2024). Nanostructured single-atom catalysts derived from natural building blocks. EES Catalysis.
26. Huang, Y., Mosleh, I., & Abbaspourrad, A. (2022). Impact of protein/peptide templates on metallic nanoparticle synthesis and applications. Nano-Structures & Nano-Objects, 30, 100864.
27. Powell, M. D., LaCoste, J. D., Fetrow, C. J., Fei, L., & Wei, S. (2021). Bio‐derived nanomaterials for energy storage and conversion. *Nano Select*, *2*(9), 1682-1706..
28. Ren, S., Xu, X., Hu, K., Tian, W., Duan, X., Yi, J., & Wang, S. (2022). Structure-oriented conversions of plastics to carbon nanomaterials. *Carbon Research*, *1*(1), 15.
29. Liu, Y., Zhu, C., Wan, F., Fang, W., Xue, B., Zheng, Z., ... & Fu, Z. (2022). Biotemplating synthesis of organized structures inspired by biological processes. *Giant*, *11*, 100108.
30. Eder, M., Amini, S., & Fratzl, P. (2018). Biological composites—complex structures for functional diversity. Science, 362(6416), 543-547. <https://doi.org/10.1126/science.aat4985>
31. Wegst, U. G. K., Bai, H., Saiz, E., Tomsia, A. P., & Ritchie, R. O. (2014). Bioinspired structural materials. Nature Materials, 14(1), 23-36. https://doi.org/10.1038/nmat4106
32. Unch, E., et al. (2008). Tough, bio-inspired hybrid materials. Science, 322(5909), 1516-1520. <https://doi.org/10.1126/science.1161379>
33. Mao, L. B., et al. (year). (Title of paper). Journal Name, Volume(Issue), pages. (DOI or URL if available)
34. Lakshmi, K. V. N., S, G., S, N. M., Rajan, R., Pandey, D., & Pandey, B. K. (2024). Circular economy: a catalyst for economic growth-an empirical study. Circular Economy and Sustainability, 1-22.
35. Hart, A. (2023). Circular economy: closing the catalyst loop with metal reclamation from spent catalysts, industrial waste, waste shells and animal bones. Biomass Conversion and Biorefinery, 13(13), 11483-11498.
36. Saleem, H., Khan, S. M., & Rizwan, K. (2024). Nanomaterials derived from animals, plants, and microbes for energy production. In *Nanomaterials in Biomass Conversion* (pp. 117-141). Woodhead Publishing.
37. Ebadian, M.; et al. Biofuels Policies That Have Encouraged Their Production and Use: An International Perspective. Energy Policy 2020, 147, 111906.
38. Callegari, A.; et al. Production Technologies, Current Role, and Future Prospects of Biofuels Feedstocks: A State-of-the-Art Review. Critical Reviews in Environmental Science and Technology 2020, 50 (4), 384e436.
39. Kummamuru, B. WBA Global Bioenergy Statistics 2017; World Bioenergy Association, 2016; p 436. 496 Nanomaterials in Biomass Conversion
40. EPA. Biofuels and the Environment: Second Triennial Report to Congress (Final Report, 2018); US Environmental Protection Agency: Washington, DC, 2018.
41. Popp, J.; et al. The Effect of Bioenergy Expansion: Food, Energy, and Environment. Renewable and Sustainable Energy Reviews 2014, 32, 559e578.
42. Nikolic, S.; Pejin, J.; Mojovic, L. (2016). Challenges in Bioethanol Production: Utilization of Cotton Fabrics as a Feedstock. Chemical Industry and Chemical Engineering Quarterly, 22 (4), 375e390.
43. Thangam, M. A., & Kannan, C. (2024). A green route for sustainable nanoporous solid acid catalyst synthesis using bio-template and analysis of its progressive transformation of CO₂. *ChemSusChem*, *5*(4), 2. https://doi.org/10.1002/cssc.201100048
44. Zhou, H., Fan, T., & Zhang, D. (2024). Biotemplated materials for sustainable energy and environment: Current status and challenges. *Environmental Science & Technology*, *6*(2), 8.
45. Ma, X., Bai, X., Chen, X., Zhang, C., Leng, J., Zhang, A., ... & Wang, J. (2024). Biotemplated heterostructure materials: opportunities for the elaboration of new photocatalysts and selective-oxidation catalysts. *Catalysis Science & Technology*, *14*(1), 10-25.
46. Ullah, M. W., Manan, S., Khattak, W. A., Shahzad, A., Ul-Islam, M., & Yang, G. (2020). Biotemplate-mediated green synthesis and applications of nanomaterials. *Current Pharmaceutical Design*, *26*(45), 5819-5836.
47. TL, S., Rao, K. J., & Korumilli, T. (2025). Natural Biogenic Templates for Nanomaterial Synthesis: Advances, Applications, and Environmental Perspectives. *ACS Biomaterials Science & Engineering*.
48. Williams, D. F. (2017). A paradigm for the evaluation of tissue-engineering biomaterials and templates. Tissue Engineering Part C: Methods, 23(12), 926-937.

65 Hall, S. R. (2009). *Biotemplating: complex structures from natural materials*. World Scientific.

|  |
| --- |
|  |

1. Sung, J. Y., Harris, O. K., Hensley, N. M., Chemero, A. P., & Morehouse, N. I. (2021). Beyond cognitive templates: re-examining template metaphors used for animal recognition and navigation. *Integrative and Comparative Biology*, *61*(3), 825-841.
2. Kaplin, I. Y., Lokteva, E. S., Golubina, E. V., & Lunin, V. V. (2020). Template synthesis of porous ceria-based catalysts for environmental application. Molecules, 25(18), 4242.
3. Rischer, H., Szilvay, G. R., & Oksman-Caldentey, K. M. (2020). Cellular agriculture—industrial biotechnology for food and materials. *Current opinion in biotechnology*, *61*, 128-134.
4. **Saharan, P., Kumar, V., Kaushal, I., Mittal, A., Shukla, S. K., Kumar, D., ... & Om, H. (2023). A comprehensive review on the metal-based green valorized nanocomposite for the remediation of emerging colored organic waste.** Environmental Science and Pollution Research**, 30(16), 45677-45700.**
5. 69 Kaw, A., Jones, D. G., & Zhang, M. (2016). The use of animal tissues alongside human tissue: Cultural and ethical considerations. *Clinical Anatomy*, *29*(1), 19-24.

|  |
| --- |
|  |

1. Corresponding authors E-mail :mofarahi@pgu.ac.ir

   . [↑](#footnote-ref-1)