New Techniques and Applications of Bioprocess inspired Manufacturing and Synthesis

[1]Iheanyi Emeka Ukamaka and [2]Agada Martina
[1,2]University of Nigeria, Nsukka, Nigeria.
[1]ukamaka3221@hotmail.com

Correspondence should be addressed to Iheanyi Emeka Ukamaka : ukamaka3221@hotmail.com.

Article Info
Journal of Computational Intelligence in Materials Science (https://anapub.co.ke/journals/jcims/jcims.html)
Doi: https://doi.org/10.53759/832X/JCIMS202301009.
Received 10 January 2023; Revised from 06 May 2023; Accepted 25 July 2023.
Available online 02 August 2023.

Abstract – Manufacturing and designing bio-inspired materials has been successful in the past two decades due to the techniques, which focus on emulating well-defined geometries or specific functionalities of real biological materials. Additionally, in contrast to our human technologies, which often need severe circumstances, biological structure-forming techniques in natural frameworks may produce biomaterials effectively and correctly in ecologically benign conditions. Thus, bioprocess-inspired fabrication has been suggested as a new research area in recent years to explore natural structure-forming processes in order to develop unique approaches for manufacturing sophisticated materials with different morphologies and functionalities. In this paper, we focus on reviewing the principles, techniques, and applications of bioprocess-inspired manufacturing and synthesis. This paper also reviews the process of biomineralization, which is an application of bioprocess-inspired fabrication used by living organisms in establishing biominerals such as shells, bones, diatoms, and teeth. This survey has aim to critically discuss bio-process-inspired to cover the dearth of literature in this area of research.

Keywords – Bioprocess Inspired Manufacturing, Bio-Inspired Materials, Bioprocess-Inspired Fabrication, Biomineralization Inspired Synthesis.

I. INTRODUCTION

Natural selection and evolution over billions of years have produced biological systems that are both incredibly clever and inventive. When it comes to improving human productivity and igniting new innovations, nature provides immense potentials. New procedures, algorithms, and manufacturing techniques were developed after being inspired by the structures, laws, ideas, and operations of biological systems. The concepts of biological construction, regulation, and control may teach us a lot about creating a society that is both progressive and long-lasting. Hence, this has given rise to the study of bio-inspired engineering, often known as naturally-oriented engineering. Other famous cases of bio-inspired systems and engineering aspects integrate the formulation of aircraft wings based on the biomechanics of eagle wings, the design of swimwear based on the texture of hydrophobic coating, and the design of buildings based on the structure of birds' nests.

There is a strong emphasis in bio-inspired technology on the use of bio-inspired materials. Biosystems' unique capabilities to endure and adapt to their surroundings are in part due to their incredible micro/macro architecture. Thus, these functions and structures have served as a tremendous source of inspiration for the creation of biomaterials with novel functionalities and structures, giving rise to the fascinating study area of bio-inspired materials during the last two decades. Even more impressively, the structure-forming activities of bio-systems can often be established at a normal temperature, unlike the high pressure or temperatures required for artificial synthetic processing. A new field of study, called bioprocess-inspired fabrication, has emerged as a result of scientists drawing inspiration from the processes by which biosystems generate their structures and applying those lessons to the manufacture of man-made materials. Others have proposed that we may use what we discover about bioprocesses in nature as inspiration for creating cutting-edge fabrication tools for brand-new forms of functionality.

There are two primary categories of bio-inspired materials, namely bioplastics and biocomposites. Materials that are bio-inspired either (1) exhibit thermal activities or (2) exhibit load-bearing activities, both of which are similar to the macro/microstructure or patterns seen in living creatures. Materials with (1) a waterproofing or water harvesting system, often referred to as smart materials have been inspired by the function of organisms. These materials are mostly utilized to enable movement or heat control, self-cleaning, vibration resistance, and self-healing. There are two broad classes of bio-inspired materials that mimic biological processes, both of which are closely connected to one another: (1) materials that promote growth and (2) materials that aid in reproduction. A scale-based method is used by biomaterials researchers in their studies of nature. The energy efficiency of buildings may benefit from imitation at any size, whether it macro, micro, or nano. Green and efficient buildings may be built using these methods. The micro- and macro-scale levels of imitation are primarily focused on in the field of biomimicry (the study of emulating the functions, processes and structures of living creatures). The microscopic level of imitation is the primary emphasis of nanotechnology, which may also be thought of as a kind of biomimetic design.

The basis of bio-inspired nanoscale materials may be traced back to either nanocomposites (a blend of traditional nano-materials and bio-materials) or nano-structured materials, both of which include structural modifications at the nanoscale. Chu, Khan, Deng, and Unluer [1] have produced bio-inspired concrete, for instance, that optimizes the chemical and physical characterization of concrete structures by mimicking the precipitation of organic fibers such mineralization skeleton. Dirt-repellent coatings, UV-resistant frames of woods, and self-cleansing windows are just a few examples of how nanotechnology has improved the efficiency of traditional building materials.

The vast majority of macroscale bio-inspired materials are biodegradable. Both the "biological" and "technological" cycles are categorized by Kim, Lee, Kim, Kang, and Kim [2], and both may be comprehended or enhanced to aid in the reduction of waste. The former stands to gain from incorporating biological fibers into the combination of materials (bio-inspired nanomaterials), whereas the latter focuses on guaranteeing the eternal form of durability of metal and mineral elements once they penetrate the process of production. Bio-aggregates are a kind of man-made plant material utilized in construction recently. These materials get their name since they are made from a synthetic plant material whose basic components are plants. Ecomaterials are a subset of the materials mentioned here; this is because the whole manufacturing and disposal cycles of goods are taken into account during the design phase.

Over the course millions of years of natural selection and the evolution process, nature has developed a wide variety of highly efficient bioprocesses (including detoxification, biomineralization, photosynthesis, self-assembly, molting, cellular absorption, and several physiological processes). Photosynthesis and Biomineralization are two examples of colorful bioprocesses that are widely used because they achieve synthesis and manufacturing with high precision and efficiency while having little impact on the surrounding ecosystem. The organic-inorganic nanocomposite (shells, bones, and teeth) formed by the biological process of biomineralization generally outperform their synthetic analogs. Man-made technological progress relies on our capacity to systematically design and fabricate inorganic materials with desired properties such as crystallographic, dimension, structure orientation, and defect number, and then combine these designs in a highly ordered fashion.

Learning about the different bioprocesses of nature, e.g., detoxification, shedding, and intracellular absorption is just as important as understanding about biomieralization and photosynthesis. Thus, it is believed that research into bioprocesses found in nature, such as biomineralization, photosynthesis, and other bioprocesses, may lead to the creation of novel methods for the synthesis and processing of materials at ambient or low temperatures. In recent years, a number of comprehensive studies have been written on bio-inspired elements and their many features, applications and functionalities. Few articles, however, seem to thoroughly detail bioprocess-inspired techniques. Due to the dearth of literature in this area, we have written a review that attempts to fill the void by detailing the principles, techniques, and applications of bioprocess-inspired manufacturing and synthesis.

The rest of the paper is organized as follows: Section II is about a discussion of Bio-inspired structures and materials. In this section, the idea of bio-process-inspired process and synthesis has critically been discussed. Section III focuses on biomineralization-inspired synthesis and process. This section seeks to discuss natural living organisms in directed synthesis, and selected organisms induced synthesis, where concepts of natural biomolecules (proteins, DNA) induced synthesis, and peptide monomers have been discussed in details. Lastly, Section IV draws final remarks to the paper, reinstating the rationale of the research.

II. BIO-INSPIRED STRUCTURES AND MATERIALS

Lightweight structures with a significant energy absorption capacity are in great demand because of their widespread potential applications in engineering sectors including aerospace, mobility, nuclear facilities, and geotechnical works. Hence, several other types of energy absorbers, such as columns, sandwich constructions, plates, combs, and polyurethane foam, have been developed in recent years. Energy absorption capability has been shown in the referenced research, although the architectures have not yet been optimized. Engineers and scientists have sought to take cues from biological structures that have evolved over millennia to optimize their structure for adaptation to a wide range of severe situations, all in an effort to increase their energy absorption capacity.

Several naturally occurring plant and animal structures (bio-structures) are exemplary in their higher tensile strength, lower density, and higher energy absorbing capabilities, as illustrated in **Fig 1**. They may serve as models for the development of innovative structures with exceptional energy absorption. The citrus maxima (pomelo fruit) has a novel porous mesocarp shelling, which has the potential to absorb energy of approximately 80J during the testing of the free fall without leading to damage on the exterior part of the peel. The shells of certain nuts, such the Cocos nucifera and the Macadamia integrifolia, are very resistant to damage from drops and punctures. When durian fruits are thrown to the ground, the unique thorns on their shells effectively absorb the impact. Animals can teach us a lot about how to take in a lot of energy and use it well. The forewing of a beetle is capable of withstanding a penetration force of up to 23 N, which is far more than the beetle's own fighting power. Hence, the beetle's forewing is crucial in preserving the beetle's thorax and hindwing throughout the beetle's existence, a characterization, which could be employed to the establishment of protective nano-structures. Another example is the sheep horn, which is considered a weapon in the struggle for territory, the pursuit of food, and the pursuit of females.

Sheep horns have a maximum impact resistance of 3400 N, which is more than enough to survive a direct head-on collision. Cattle horns are another source of wisdom because of their extraordinary ability to support weight and absorb force. In [3] described in detail the connection between the structural elements and the techniques of absorbing energy of different mammalian structural components as tusks, bones, horns, and teeth. The techniques of bio-inspired design were also presented by Murphy, Müller, and Jung [4] to develop new types of energy-absorbing composite materials. Inspiration may also be found in marine species. The peacock mantis shrimp, for instance, has a dactyl that is thick and herringbone-shaped. The dactyl's design allows it to absorb shocks of up to 1500 N without shattering. Marine creatures' mechanical and structural characteristics, as well as their defense mechanisms, were analyzed by authors in [5]. To sum up, the exceptional energy-absorbing potential of biological structures and materials may inform the development of novel energy absorbers. One potential replacement for current building types is the use of bio-inspired structures modeled after those found in plants and animals.

Insect compound eyes have a one-of-a-kind optical scheme for imaging, butterfly wings have structural coloration, and pearl has exquisite configurations and actual mechanical characteristics; all of these examples show that nature is an ideal developer for developing complex and exquisite well-ordered nanostructures or patriarchal structural elements for myriad operations. Scientists have produced what they term "bio-inspired materials," which are unique functional materials inspired by these structures. Scientists in the bio-inspired composite field have replicated or copied fundamental functionalities, structure and components of natural creatures, resulting in fascinating study issues in materials engineering, chemistry, and biotechnology throughout the last several decades.

Nanostructures resembling hierarchical branches were discovered on the surface of each papilla by Chen, Lan, and Wang [6]. They were motivated to develop a composite film with great hydrophobic characteristics after seeing the lotus leaf's multiscale structure. In most cases, the pigments in butterfly wings are not solely responsible for their stunning hues; rather, the existence of recurring sub-micrometer structures is what causes the colors to appear. Fabrication of optoelectronic materials with the appropriate nanostructures has surged in recent years thanks to these naturally occurring organisms. Khalaf, Abd El-Lateef, Dao, and Mohamed [7] were motivated to perform pioneering work by the high adherence of mussel to surfaces, and their proposal demonstrated that dopaminergic, an adhesive in proteins found in mussel feet, might polymerize by self in a highly alkaline ecosystem, generating films on different varieties of both inorganic and organic nanomaterials.

The chemistry inspired by mussels has now found widespread use in areas as diverse as surface coatings, medicinal adhesives and sealants, and the functionalization of nanoparticle surfaces. Zhang et al. [8], for instance, has accomplished a great deal in the field of inorganic material creation inspired by the chemistry of mussels. With its widespread availability and desirable features as a building material (low weight and great strength), wood has served as a bioinspiration for researchers developing engineered materials. Using the thermocuring and self-assembling process of conventional resins, Karamikamkar, Rezaie, Naguib, and Park [9] have presented a unique technique for the industrial manufacture of a series of bio-inspired thermoplastic woods with comparable wooden cellular structures, polyphenol matrix, and unique complete performances.

It is not only that biological materials have better characteristics than their synthetic analogues; their hierarchical organizational structure and distinctive assembly contribute to this. For instance, the fracture toughness of nacre, which is made up of layers of protein-polysaccharide 30 nm thick interpenetrating between layers of hydroxyapatite tablets 0.5 m thick, is around 3,000 times that of the manufactured counterpart aragonite. Meyers and colleagues conducted extensive research and evaluated existing literature on the crucial linkages between mechanical and structure characteristics, bioinspired architectures, and operational adaptations. For example, they have investigated the structural make-up of feather shafts and provided an explanation for the transition from a circular to a rectangular cross section.

The capacity to endure flexure is improved by the novel structural design (circular-to-square shape shift), which also reduces weight throughout the shaft's length. Fiber configurations in the walls' heterogeneous composite are tailored to meet the demands of stresses in certain areas. New materials and structures, such those for manned or unmanned autonomous drones, will be developed thanks to the insights acquired from this study. The complex design of biological materials has given architects and engineers ideas about how to make their own buildings stronger. Clegg published ground-breaking research on the manufacturing of bulk composites that resemble nacre in 1990. Graphite was used to cover ceramic sheets of silicon carbide, resulting in surfaces with the strength of a weak adhesive. Poly (methyl methacrylate) (PMMA) or Al2O3 compounds resembling nacre have been developed by Yang and Lee [10] with ceramic concentrations of up to 80% volume.

A thick compound with brick-wall architecture comparable to nacre was created by first creating a permeable, layered Al2O3 ceramics scaffold employing different forms of ice, and them integrating it with the second liquid phase PMMA. Hybrid ceramic-based materials provide a 300-fold increase in toughness over pure phase ceramics or polymers when used in bulk. Since then, Bouville's team has also developed the most rigid ice-templating-made bio-inspired ceramic. While these synthetic materials seem similar to natural nacre, they were created using methods that mimicked the multi-layered structures by anisotropic collections of construction blocks instead of utilizing mineralization technique, which is utilized by living organisms to establish biomaterials. In recent times, Norði, Glud, Simonsen, and Gaard [11] used a sequential "assembly/mineralization" technique, motivated by naturalistic approaches in mollusks, to create millimeter-thick synthesized nacre that closely mimics the elemental analysis and hierarchical system of real nacre.

Well-organized, multi-resolution bio-structures established by different chemical and physical processes are essential for the actualization of complex functionalities within bio-inspired nanomaterials. By analyzing and emulating the distinct structures or one-of-a-kind properties of natural materials, researchers have created bio-inspired components in recent decades.

Idea of Bioprocess-Inspired Processing And Synthesis

Several biological materials, with fine hierarchical structures and particular purposes, have been made by natural creatures via biofabrication processes to help them thrive in their natural habitats. The topic of bioprocess-inspired materials has seen some substantial research due to its inspiration from the world of biology. Biomineralization is a prototypical example of the formation of natural materials. Biomineralized dactyl clubs on the mantis shrimp, for instance, have helicoidal formations that may break the impenetrable shells of their prey; the biotechnological processes routes utilized to form this morphology from bottom to top are similarly crucial. The evolution of coral reef ecosystems is another fascinating and significant instance. A large number of oysters living together in a reef structure may filter water and mitigate the effects of storm surges, two factors essential to the health of coastal ecosystems. Oysters essentially create reefs by sticking uncured glue to one other and creating a barrier that traps sand, germs, and diatoms. Calcium (34 wt%), carbon (10 wt%) and oxygen (43 wt%) make up the bulk of the biomineralized epoxy coating, with cross-linked acidified proteins (11 wt%) and $CaCO3$ (50 wt%) rounding out the composition. As a result, the bioadhesive materials released by oysters provide a wealth of ideas for the creation of high-inorganic-content, multifunctional hydrogels.

Hydrogels are a type of hydrophobic polymer material that may be generated from monomer and/or polymer by building a crosslinking structure through physical and chemical linkages in an aqueous solution. Hydrogels are widely used in disciplines such as biomedicine, robotics, and smart wearable because of their ability to absorb large amounts of water while remaining flexible and resistant to shear deformation. However conventional hydrogels characterized by mechanical crosslinking often have weak tensile and compressive properties. Nevertheless, hydrogels that have had a high concentration of inorganic compounds added to them may not only develop a more intricate network structure, considerably enhancing their mechanical capabilities, but also find more widespread use. One example is the polyacrylic acid (ACC/PAA)/crystalline calcium carbonate mineral plastic hydrogel created by Kimura, Katsuno, and Yamazaki [12], which has found use in ionic skin, synthetic organic and inorganic hybrid adhesives, and lithium-ion batteries.

The use of high temperatures is customary in the processes of material synthesis and sintering; this is true for the creation of ceramic powders and the sintering of ceramics, to name just two examples. Yet, as shown in **Fig 1**, bioprocessing may be done at room temperature. Hence, research into bioprocesses might one day lead to cutting-edge methods of materials processing at ambient or low temperatures.

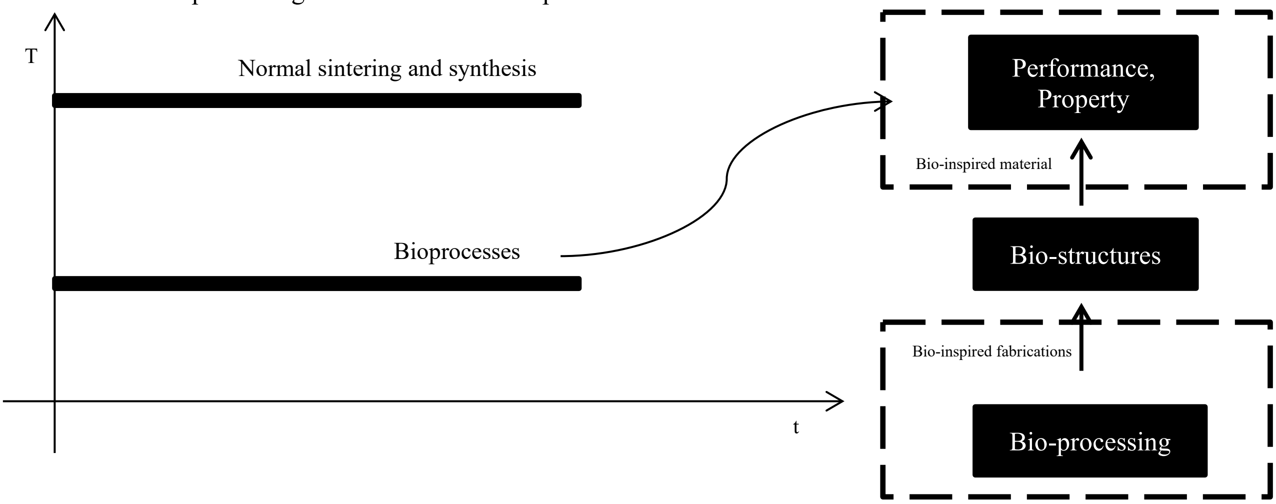

Fig 1. Comparison of bio-inspired materials and bioprocess-inspired fabrication (left) and regular synthesis or sintered in contrast to a natural bioreactor (right).

The four components of materials engineering and science (performance, characteristic, structure, and processing) are widely known. There are four of these components in natural bio-systems as well. Bioprocessing creates bio-structure, which, as seen in **Fig 1**, governs the characteristics and functionality of biosystems. While researching bio-inspired materials, scientists look for typical or fascinating biostructures or biofunctions, and then create artificial formations with corresponding artificial functionalities. The correlation between the bio-structure of nanomaterials and their characteristics has provided researchers with a wealth of knowledge.

Additionally, it should be highlighted that, unlike our current synthesis or sintering procedures, which often need severe circumstances, the amazing structure-forming mechanism in living organisms rapidly and correctly fabricates bio-systems under such settings. For instance, the shell structure-forming process is performed at room temperature and results in a well-defined structure with strong mechanical characteristics (particularly good toughness) made up of 5% organic layer and 95% inorganic layer. In the calcification of the shell, certain proteins with a well-organized mix of -chitin, flexible polymer gel and asp-rich proteoglycans play fundamental roles. The mechanism by which shark teeth are formed is the most intriguing example. Shark teeth may alter and develop in many days. Throughout its lifespan, a shark will replace 20,000 teeth.

How come shark teeth come into being so much hard before humans' teeth do? This is due to the factor of development, a distinct biological environment, or just a more straightforward crystallization process? Perhaps there is more to the story, and we can learn more about the structure-to-forming process of sharks' teeth for ceramics manufacturing. It was argued that the remarkable biological structure-to-forming approach of bio-materials is worth learning from to effectively produce unique synthetic approach for more advanced technologies, which would ultimately evolve to bioprocess-inspired industrialization as a further research field. The term "bioprocess-inspired fabrication" has been defined as "developing novel synthesis and processing methods by drawing ideas and inspiration from natural processes that give rise to structure." It is evident from **Fig 1** that bioprocess-inspired manufacturing draws inspiration from biological processes or the relationship between biological processes and biostructures.

Biomineralization, photosynthesis, and other common bioprocesses are worth studying about by chemists and manufacturing engineers. In light of this, we propose that works on bioprocess-inspired manufacturing be organized into three categories: biomineralization-based manufacturing and synthesizing, bioprocess-inspired synthesizing and manufacturing, and photosynthesis-inspired synthesizing and manufacturing. In reality, as shown in **Table 1**, fascinating work has been accomplished over the last several decades in the development and manufacture of sophisticated materials through a comprehension of natural bioprocesses. Different techniques stimulated by biological biomineralization approaches have been evaluated to established materials with sophisticated frameworks or characteristics, starting with the groundbreaking studies on the in vivo productions of gold nano-materials within natural alfalfa seeds, and onto in-vitro SiO2 metamorphism stimulated by the silaffin extracted from diatoms.

Shafirovich, Khannanov, and Shilov [13] have created inorganic compounds with distinctive forms and characteristics as a result of photosynthesis, another significant natural bioprocess. In order to manufacture oxides, dimethyl sulfide, reduced graphene oxide (rGO), sulfides, metal phosphides and metal phosphates, the photosynthesis-inspired method has steadily been used since the authors revealed that photo-inspired holes and electrons could stimulate a redox reaction. Recent research has produced some intriguing findings by taking lessons from other biological bioreactors. To our understanding, no publications has critically addressed "bioprocess-inspired fabrications" of bio-materials, irrespective of the fact that significant development has been attained in the developments and manufacturing of materials stimulated by natural processes. The novel term "bioprocess-inspired manufacturing" is formally suggested and comprehensively discussed for the first time in our study.

The study strategies and directions we recommend in detail are shown in **Table 1**. There has already been a large amount of study done in several areas. Nevertheless, other paths are only hypotheses and recommendations for which little or no study has yet been done. The authors as well as other scientists from across the globe will present their major findings in the subject of bioprocess-inspired manufacturing in this publication, and we will also explain and comment on the recommended future paths. Materials with distinctive structures and/or functionalities have been created using manufacturing techniques inspired by bioprocesses at room temperature. This approach, in our opinion, has the potential to lead to the creation of fresh methods for the manufacture and processing of materials.

Table 1. Overall Techniques Within Bioprocess-Inspired Fabrication

Bioprocess-inspired fabrications	Biomineralization inspired	Bioprocess-inspired additive processing
		Novel design-based mineralization
		Organics simulation natural organism-based synthesis
		Recombinant protein-based synthesis
		Chosen organism-induced synthesis
		Biological organism-indiced synthesis
		Bioprocess-inspired additive processing
	Photosynthesis inspired	Application of biological photo-systems or/and materials simiilating PS and for inorganic synthesization
		Application of single inorganic model for the material fabrications
	Others	Photosynthesis and biomineralization processes
		Application of physiological processes within biological organisms as platforms

III. BIOMINERALIZATION-INSPIRED SYNTHESIS AND PROCESSING

Biomineralization, which is employed by living things to create biominerals (such as shells, teeth, bones, and diatoms) made up of organic and inorganic stages and often displaying extraordinary features. Proteins, peptides, and polysaccharides are examples of organic compounds that often control crystal formation and nucleation, modulating its appearance and characteristics. In comparison to our prevailing technological domain, where more extreme factors are often needed to produce synthetic fibers, these processes take place under ambient circumstances. Using self-assembly and organic-inorganic recognition to assemble multiscale building pieces into precise nanostructures, biosystems create high performance biominerals. Hence, understanding the natural mechanisms involved in the synthesis of biominerals might provide fresh insights required to create novel synthetic techniques. For instance, the delicate and complex design of the nacre's inorganic (hydroxyapatite tablets) and biological (protein-polysaccharide) layers offers hints as to how artificial structures may be enhanced. Similar to this, developing new methods for putting together various nanocomposites and structures would result from studying the crucial elements throughout the structure-forming procedures of these nanocomposites.

The primary biomineralization processes (biomacromolecules within nucleation and crystals development, collections of nano-structured inorganic or artificial element into distinct different hierarchical dimensions, and exquisite natural manufacturing, etc.) have sparked a wave of research into the creation of novel methods for synthesizing sophisticated substances and nanomaterials with the appropriate architectures and characteristics, particularly at room temperature. As a term, "biomineralization-inspired synthesizing and processing" refers to methods and techniques developed with the help of insights gained from studying biomineralization. Our goal in this overview is to provide an advent to the biomineralization-inspired fabrication field, which uses biological systems, microbes, and natural matrices like transgenic proteins or peptides, natural proteins, and polymers as either "process-directional" and "structure-directional" agents to regulate the initiation, development, and final form of inorganic compounds.

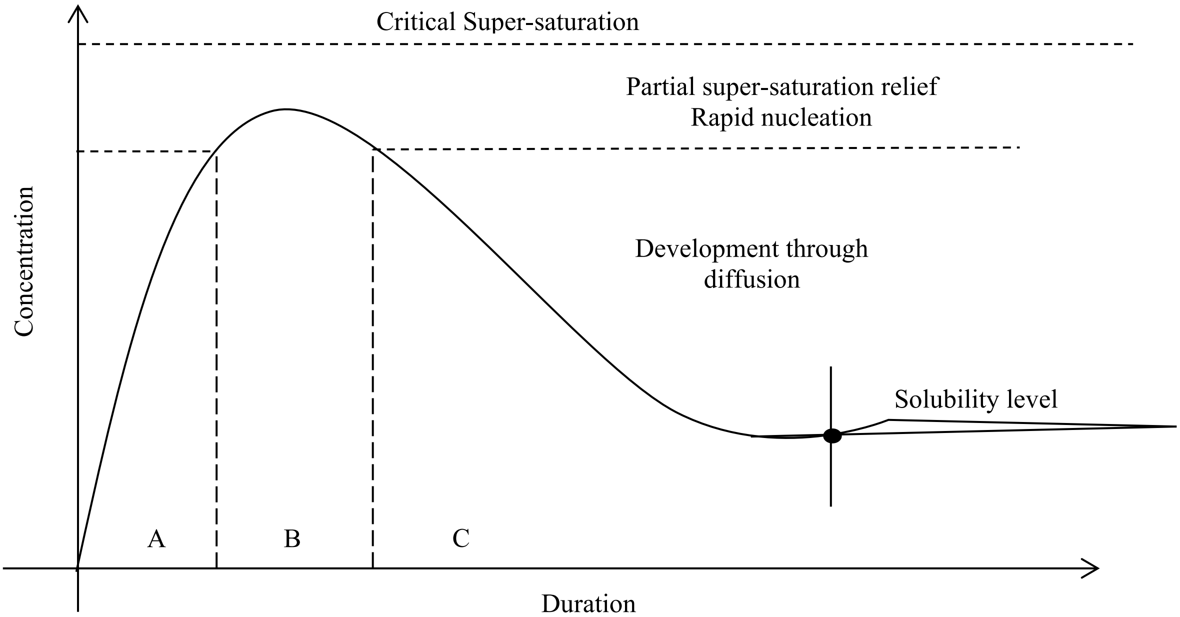

Fig 2. Super-Saturation Process Defining the Development by Diffusion

Biomineralogy is the study of how organic-inorganic materials, such shells, bones, and teeth, are formed by living creatures, with a hierarchical structure. Our capacity to recognize the many macromolecules and their interactions in biomineralization has increased during the last several decades. More recently, attempts have been made to replicate key fabrication processes and structural aspects of biominerals in advanced materials as we gain a better understanding of the processes by which they are generated. Here we provide a high-level overview of the fundamentals underlying the assembly of biominerals, or the guidelines that regulate the accumulation of inorganic solids. Depending on their overall shape, biominerals may be broken down into three distinct categories. (i) Amorphous crystals are the biominerals with the most morphological flexibility, since they may be easily shaped into any desired form. The siliceous diatoms and radiolaria have a wide distribution of them. (ii) Polycrystalline biominerals come in a broad variety of morphologies as well, with complex shapes easily assembled from their tiny crystalline building pieces. A priori, it may be assumed that single crystals are geometric structures with regular, symmetrical faces, where the exterior shape is a mirror of the crystal lattice's interior symmetry. In comparison, single crystals formed during biological calcification may exhibit morphologies that are unrelated to their underlying crystal structures.

Four distinct variables have been identified as critical control points for achieving the desired process output. They are soluble, the degree of condensation, the nucleation process, and the crystal growth. Biominerals always react with biomolecules during their creation, usually proteins and phospholipid-protein complexes found in biological cuticles. Supersaturation of the solutions is the primary driver for the creation of a new stage (the precipitate) during biomineralization, which starts with dispersion of various ions. Typical of every super-saturation process is the curve shown in **Fig 2**, which shows the crystallization of sulfur in ethanol. Precipitation occurs automatically once the sulphur content reaches a threshold supersaturation. The sulphur content returns to its original value over time, allowing the precipitated nanoparticles to expand in the solution if they contain a nucleus. Homogeneous nucleation occurs when a nucleus develops spontaneously from the solution, but heterogeneous nucleation requires an outside source, such a surface (like a protein or membranes), airborne particles, or crystal seeds. Having uniformly sized nucleated nanoparticles before they develop by diffusion is only possible if the germination burst is brief.

Natural Living Organism Directed Synthesis

Biomineralization-inspired fabrication approaches that use biomolecular identification and nucleation characteristics for inorganic synthesizing nanoparticles have made considerable strides in recent years. Biomolecules are used as regulatory agents in many of these procedures, which are carried out in vitro under carefully manipulated settings. Unfortunately, the complexity and inventiveness of natural organisms are beyond the scientific community's ability to replicate with only one or a few proteins used in these procedures. For instance, the production of biominerals often involves fine-tuned biomolecular coordination and cellular functioning inside living systems. What makes living systems special, cellular processing, is not present in in vitro component manufacturing. Moreover, the distribution, mobility, dissolution, hydration, deposition, and development of crystals throughout each step of mineral formation are all controlled and regulated by the complex biological circumstances present in living systems. Using natural living creatures as a console to immediate synthesizing nanoparticles is a good starting point and an effective strategy in this regard because it takes advantage of the characteristics intrinsic in biological systems, e.g., molecular arrangement and identification, a great level of development, organization modulations, easiness in the treatment of chemicals, and cell processing.

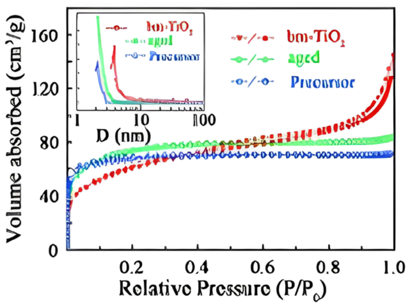

Fig 3. Isotherms of nitrogen gas adsorption and desorption onto TiO_2 samples

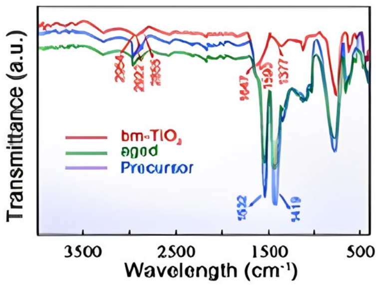

Fig 4. Distributions of relative pore sizes are shown in the inset. Sample spectra of TiO_2 obtained through Fourier Transform Infrared Spectroscopy (FTIR)

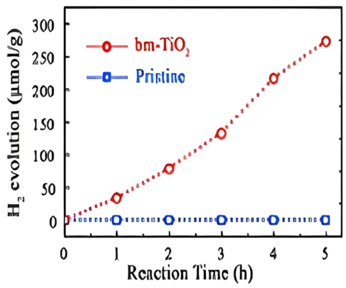

Fig 5. Hydrogen generation after photoelectrochemical water reduction in TiO2 samples exposed to visible light. This is an authorized reprint

The first nanomaterials were created by harnessing the natural physiological processes of living creatures. Research advancements have allowed scientists to forego genetic modification and instead employ live creatures to manufacture compounds incompatible with their physiology. Using live mussels as a direct platform, Fu's team has devised an intriguing approach for the production of nitrogen-doped anatase TiO2. Several researchers have spent time and energy trying to find ways to reduce the huge band gap (3.2 eV) in TiO2 by nonmetallic or metallic doping in order to increase its efficiency as a visible-light converter. In addition, a hierarchically permeability has been incorporated into TiO2 to increase its photocatalytic activity by giving an increased surface area, reduced transport distance, and more active sites. Yet, it is still challenging to develop an optimum synthetic approach that simultaneously introduces a hierarchical highly porous structure and periodic doping, particularly at room temperature. We utilized a method similar to pearl cultivation in which an amorphous precursor was inserted into the Cristaria plicata (water mussel). A hierarchically porous nanocrystal anatase TiO2 formed after 3 months of in vivo condensation (see **Fig 3**). Chemical changes in the bio-mineralized Titanium dioxide (bm-TiO2) sample were discovered throughout the procedure.

The acetic acid-treated precursor has signature stretching oscillations at 1419 and 1532 cm^{-1}. The protein bands in bm-TiO2 are very prominent, especially at 1590, 1647, and 1378 cm^{-1}. These findings show that Ti-acetate chemical within the precursor is currently being substituted by proteins from live mussels (see **Fig 4**). TiO2 nanocrystals also formed nitrogen intercellular spaces at room temperature due to self-doping with nitrogen from protein sources. Visible-light photocatalysts capabilities in waste treatment and hydrogen synthesis (56 mol $h^{-1}g^{-1}$) are shown by the bm-TiO2 nanocrystals, which are difficult to obtain with traditional techniques at cellar temperature (see **Fig 5**). Moreover, this work uncovered the intriguing fact that internal proteins, as opposed to external proteins, serve as protonation catalysts to aid in the crystallization process at room temperature. The researchers also investigated the oxidation of additional inorganic minerals in mussels, including MgO and Fe2O3. With these findings, it may be possible to exploit live creatures for the direct production of elements not essential to their physiological functions. The work has significantly advanced our understanding of biomineralization mechanisms by shedding insight on the structural alteration of these well-studied minerals in natural systems.

In situ synthetic techniques have been used to create metal-organic frameworks (MOFs) by mineralizing around single-celled organisms in moderate aqueous environments. In a groundbreaking study published in 2018, Richardson and coworkers proved for the first time that MOFs may be synthesized in situ, in vivo, within plants. Sufficiently small to be taken up by adhesive and cohesive forces, metal salts and natural connectors were added to plants in this method. These MOF precursors collected around plant biomolecules to promote MOF development. One-phase or two-phase synthesis approaches, might be utilized dependent on the synthesizing rate of MOFs. Even though Zn $(MeIm)_2$ forms so slowly in water, it was just a one-step process when it was exposed to plant trimmings. On the other hand, the inorganic $Tb_2(BDC)_3$) and MOFs ($Eu_2(BDC)_3$ were generated in dual phases, first by hatched with larger precursor, and consequently with a minor one. Plants modified with luminous MOFs may be used as functional materials in the detection of tiny molecules. If the antecedents are tiny enough to travel and the environment are suitable for plants, the discovery suggests that additional useful materials may potentially originate within live plants.

Using living creatures to make valuable materials not necessary in their physiological functions is where the above work's relevance and intriguing qualities really shine. Complementary noble metal oxide nano-elements, such as gold (Au), platinum (Pt), and silver (Ag) have previously been produced by scientists using plant physiology (Pt). Researchers led by Dr. Gardea-Torresdey have made significant strides in understanding the in vivo creation of Ag and Au nanostructures inside of live alfalfa plants. Even though these methods can only produce a limited number of metal nanoparticle kinds, they are nevertheless interesting and worth investigating. There has been some advancement in this area in recent years. When Mukhoro first considered photosynthesis in plants in 2017, it was a major breakthrough. In order to create Au nanostructures in vivo, the green sea algae Ulva armoricana was introduced to diluted standard solutions of Au (III) ions, and then the mixture was subjected to sunlight. Gold nanoparticles founded on the U substrates armoricana, throughout particular cellular membrane, and in the chlorophyll activity shown superior catalytic performance in the degradation of 4-nitrophenols.

Chosen Organism-Based Synthesis

Using natural live creatures as a platform for material synthesis has been shown to provide some very promising outcomes. In order to rationally design materials, however, a thorough comprehension of the bioprocesses used in these in vivo chemistries is required. Exploring the fundamental processes of biomineralization relies heavily on research into the interactions among organic matrix and inorganic nanocrystals. To better understand the connections between supporting microorganisms, reaction circumstances, and resulting materials, many research have been conducted out employing a broad range of isolated biomolecules or/and biological microbes to determine vitro inorganic synthesis, elements with distinctive architectures, for a variety of techniques. Nanostructures with complex, optimized, and productive topologies may be produced by naturally occurring organisms. Comparatively to manmade structural templates like silica nanoparticles or supermolecular microcapsules, these biological resources are frequently low-cost, plentiful, ecologically benign, and inexhaustible. This makes them useful for the fast, efficient production of high-quality biomaterials of specific design.

Natural Biomolecules (DNA), Proteins-Induced Synthesis

At the macro-molecular scale, biomolecular identification and self-assembly play a crucial role in mineralization driven by living systems by precisely assembling molecular components into complex structures. It is hypothesized that the biomolecules play a vital role ("process-directing agent" or structure-directing agent" role) during the process of biomineralization. Extracting them from living creatures is the most efficient way to get hold of natural biomolecules with high levels of decomposition in vitro. Silaffins, a diatom peptide made up of the amino acids arginine and lysine, were initially found by Natarajan, Rajan, and Das [14]. Systematic research revealed that silaffins exhibit two activities, one of which is a calcification function that immediately deposits silica (SiO2), and the other of which just aids other biomolecules in this process. The microstructure, crystallographic behavior, and mechanical characteristics of inorganic materials may be influenced by a broad variety of natural macromolecules, including proteins, catalysts, DNA, phytate, and sodium alginate, as shown by subsequent research. Many thorough assessments have been written to describe these efforts.

The increased urgency with which we must address our planet's energy and environmental crises has refocused interest on nanostructured materials. There has been a lot of excitement in recent years about the prospect of developing innovative biomaterials with beautiful nanostructures, and novel capacities, which could be tuned at a particular nano-scale. Natural biomolecules such as proteins, polysaccharides, collagen type, and fibers might be utilized as process-orienting reagents to control the production of nanostructured materials (see **Fig 6**) with a wide range of morphologies, including those used as photocatalysts, transistors, and electrodes. Limiting this overview to only the past decade's worth of research on biological protein-directed manufacturing of nanostructured materials employed as photocatalysts and conductors was necessary due to space constraints.

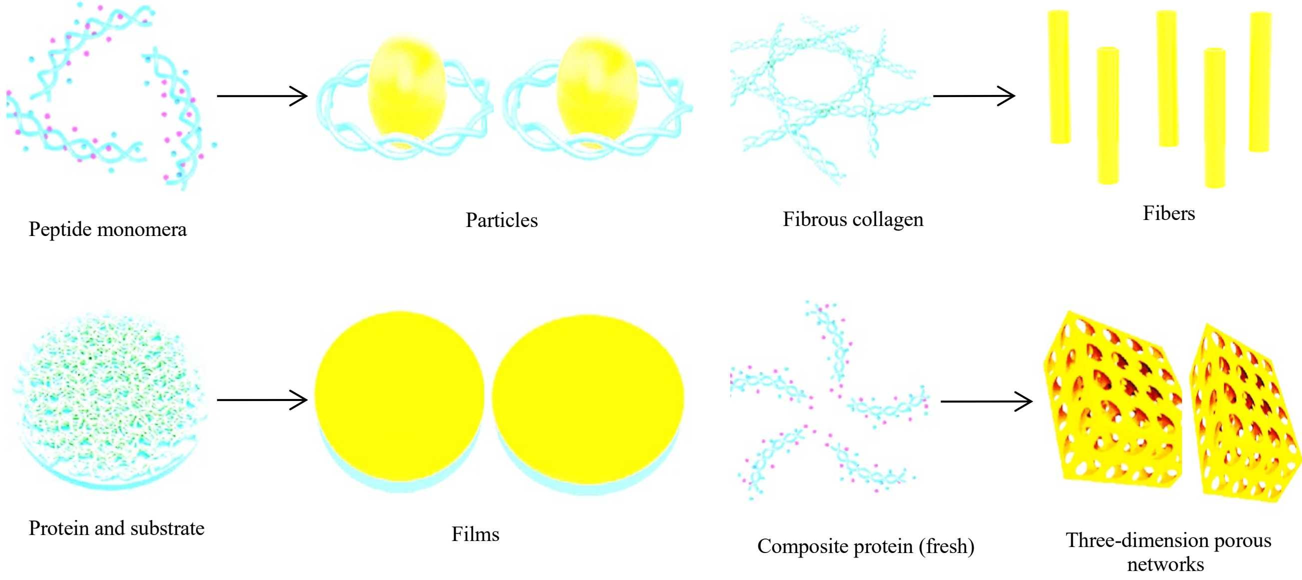

Fig 6. Demonstration of Different Products and Processes Stimulated by Natural Biomolecules

Peptide Monomers

Peptides represent the shorter polypeptide chains constructed with amino acids connected through the peptide bond (the term "peptide" comes from the Ancient Greek meaning "digested," "peptós"). Amino acid chains link together to form proteins, a kind of polymer. Oligopeptides are peptide chains that are fewer than 20 amino acids in length. This includes dipeptides, tetrapeptides and tripeptides. In this context, "polypeptide" is an abnormally lengthy peptide chain without any branch points. Chemically, peptides have characteristics with nucleic acids, polysaccharides, and oligosaccharides all of which are other types of biological oligomers. Proteins are large, complex macromolecular assemblies composed of one or more polypeptides that have been organized in a physiologically useful fashion and are commonly attached to ligands like co-factors and co-enzymes. Amino acids, which have been incorporated into peptides, are known as residues. When an amide bond is formed, one water molecule is sacrificed. Every peptide contains an amine grouping (N-terminus) and the carboxyl grouping (C-terminus), with the exception of cyclic peptides.

Each peptide type has been classified according to its function and source. Peptides found in plants, bacteria, fungi, invertebrates, amphibians, skin, venom, vaccines, immune/inflammatory responses, the endocrine and nervous systems, the digestive system, the cardiovascular system, the kidneys, and the respiratory system. Some ribosomal peptides are processed by proteolysis. In most multicellular organisms, they play a role as a hormone or signaling molecule. Some microorganisms create peptide antibiotics, e.g., antimicrobial and microcins peptides. Typical post-translation changes to peptides include phosphorylation, sulfonation, hydroxylation, palmitoylation, disulfide formation, and glycosylation. Peptides have been found to have the rare yet interesting lariat structure. For example, L-amino acids in platypus venom undergo racemization to become D-amino acids.

When the ribosome is unable to synthesis a peptide, enzymes are responsible for its construction. The non-ribosomal glutathione peptide has a significant role in antioxidant defence of different aerobic organisms. Mostly identified in unicellular plants, animals, and fungi, the non-ribosomal peptides are generated by the modular enzyme complexes known as the non-ribosomal synthetases peptide. The complexes have a similar framework, and they might include several modules, each of which is responsible for a different phase in the creation of the final product. The cyclic structures of the common peptides they form are often exceedingly intricate. The presence of linear nonribosomal peptides, however, is not uncommon. Hybrid molecules are common because this process is linked to the machinery, which constructs polyketides, and fatty acides. The availability of thiozoles or oxazoles in the chemical structure is often used as a marker for molecules made in this manner. Peptones are the byproduct of protein digestion and may be found in dairy and meat products. The byproduct contains a plethora of biological compounds, such as vitamins, minerals, fatty acids, lipids, metals, and more. Peptones are a common supplement to nutritional media used for growing bacteria and fungi. Peptides are tiny fragments of proteins that may be used in place of the full-length protein for analysis or identification. They often occur from laboratory-controlled enzymatic breakdown, although in the case of forensic or paleontological materials, they might potentially have formed naturally.

Sandwich carbon nano-fibers (C@SnO_2@C) were synthesized using collagen, a typical glycoprotein, as both a structure-directing reagent and source of carbon and energy. Ambipolar diffusion is made possible by the C@SnO2@C nanofiber bundle, which has a special hierarchical structure that ensures concordance between electron transportation kinetics and Li+ dissemination kinetics. This volume shift of SnO2 is efficiently accommodated by the peculiar "breathing" behavior brought on by the C@SnO2@C arrangement. As such, the as-synthesized C@SnO2@C nanofibrous bundle offers clear benefits in rate capability and cycle stability in comparison to traditional carbon/SnO2 nanocomposite.

The established bio-inspired technique has the potential to be used to the synthesis of various high-performance electrochemical devices, in particular for metal oxides with significant volumetric transitions and lower electric conductivity. Moreover, it has been discovered that the naturally generated protein polymers Bombyx mori silk fibroin may guide the regulated mineralization of diverse nanomaterials because of its distinctive self-assembly behavior, high cytocompatibility, and biomechanical capabilities. In order to create more efficient lithium (Li-ion) cells, Martínez-Rodríguez et al. [15] used a biomineralization approach based on the effective framework of silk proteins to create hierarchical olive-like organized magnetite and carbon nanomaterials. Cai and Larese-Casanova [16] also showed that they could use this method to make electrocatalyst for high-performance Li-ion batteries. Rape pollen protein was used to facilitate and control the development of hierarchical meso/macroporous TiO2 systems in three dimensions.

IV. CONCLUSION

The purpose of this paper was to go over the principles, techniques, and applications of bioprocess-inspired manufacturing and synthesis. This paper also discussed the process of biomineralization, which is a bioprocess-inspired fabrication technique used by living organisms to create biominerals such as shells, bones, diatoms, and teeth. This survey aims to critically discuss bio-process-inspired research in order to fill a gap in the literature in this field. The use of bio-inspired materials is heavily emphasized in bio-inspired technology. The incredible micro/macro architecture of biosystems contributes to their remarkable ability to endure and adapt to their surroundings. As a result, these functions and structures have served as a tremendous source of inspiration for the development of biomaterials with novel functionalities and structures, spawning the fascinating study area of bio-inspired materials over the last two decades. Even more impressive, unlike the high pressures or temperatures required for artificial synthetic processing, the structure-forming activities of bio-systems can frequently be established at room temperature. As a result of scientists drawing inspiration from the processes by which biosystems generate their structures and applying those lessons to the manufacture of man-made materials, a new field of study known as bioprocess-inspired fabrication has emerged. Others have proposed that we can use what we learn about bioprocesses in nature to inspire the development of cutting-edge fabrication tools for entirely new forms of functionality.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

Funding

No funding was received to assist with the preparation of this manuscript.

Competing Interests

There are no competing interests.

References

[1]. S. H. Chu, M. Khan, X. Deng, and C. Unluer, "Bio-inspired self-prestressing concrete (SPC) involving basalt fibers and expansive agent," Cem. Concr. Res., vol. 155, no. 106735, p. 106735, 2022.
[2]. C. Kim, Y. Lee, S. Kim, M. Kang, and S. Kim, "Diverse synaptic weight adjustment of bio-inspired ZrOx-based memristors for neuromorphic system," Mater. Sci. Semicond. Process., vol. 157, no. 107314, p. 107314, 2023.
[3]. S. Ganeshkumar, B. K. Singh, R. Suresh Kumar, and A. Haldorai, "Digital Twin Framework for Lathe Tool Condition Monitoring in Machining of Aluminium 5052," Defence Science Journal, vol. 73, no. 3, pp. 341–350, May 2023, doi: 10.14429/dsj.73.18650.
[4]. C. T. Murphy, R. Müller, and S. Jung, "Sample digitization techniques for bio-inspired engineering," in Biomimicry for Materials, Design and Habitats, Elsevier, 2022, pp. 215–246.
[5]. "Marine organisms and adaptations," Science Learning Hub. [Online]. Available: https://www.sciencelearn.org.nz/resources/142-adaptations-of-marine-organisms. [Accessed: 18-Feb-2023].
[6]. Z. Chen, X. Lan, and Q. Wang, "DNA origami directed large-scale fabrication of nanostructures resembling room temperature single-electron transistors," Small, vol. 9, no. 21, pp. 3567–3571, 2013.
[7]. M. M Khalaf, H. M Abd El-Lateef, V.-D. Dao, and I. M. A. Mohamed, "Electrocatalysis of methanol oxidation in alkaline electrolytes over novel amorphous Fe/Ni biphosphate material prepared by different techniques," Nanomaterials (Basel), vol. 12, no. 19, p. 3429, 2022.
[8]. H.-X. Zhang et al., "Fabrication of high-performance PP/graphene nanocomposites via Friedel–crafts," J. Inorg. Organomet. Polym. Mater., 2023.
[9]. S. Karamikamkar, S. Rezaie, H. E. Naguib, and C. B. Park, "Bio-inspired polyethylene-based composite reinforced by thermoplastic polyurethane (TPU) fiber for aerogel production," 2019.
[10]. S.-Y. Yang and M.-J. Lee, "Poly (methyl methacrylate)-containing silver-phosphate glass exhibits potent antimicrobial activity without deteriorating the mechanical and biological properties of dental prostheses," Polymers (Basel), vol. 15, no. 2, p. 297, 2023.
[11]. G. á Norði, R. N. Glud, K. Simonsen, and E. Gaard, "Deposition and benthic mineralization of organic carbon: A seasonal study from Faroe Islands," J. Mar. Syst., vol. 177, pp. 53–61, 2018.
[12]. Y. Kimura, H. Katsuno, and T. Yamazaki, "Possible embryos and precursors of crystalline nuclei of calcium carbonate observed by liquid-cell transmission electron microscopy," Faraday Discuss., vol. 235, no. 0, pp. 81–94, 2022.
[13]. V. Y. Shafirovich, N. K. Khannanov, and A. E. Shilov, "Inorganic models of photosystem II of plant photosynthesis. Catalytic and photocatalytic oxidation of water with participation of manganese compounds," J. Inorg. Biochem., vol. 15, no. 2, pp. 113–129, 1981.

[14]. G. Natarajan, T. P. Rajan, and S. Das, “Application of sustainable textile finishing using natural biomolecules,” J. Nat. Fibers, vol. 19, no. 11, pp. 4350–4367, 2022.
[15]. P. Martínez-Rodríguez, I. Sánchez-Castro, J. J. Ojeda, M. M. Abad, M. Descostes, and M. L. Merroun, “Effect of different phosphate sources on uranium biomineralization by the Microbacterium sp. Be9 strain: A multidisciplinary approach study,” Front. Microbiol., vol. 13, p. 1092184, 2022.
[16]. N. Cai and P. Larese-Casanova, “Facile synthesis and reuse of magnetic black carbon magnetite (BC-Mag) for fast carbamazepine removal from water,” Nanomaterials (Basel), vol. 10, no. 2, p. 213, 2020.