Japan Bilingual Publishing Co.

**New Environmentally-Friendly Materials**
https://ojs.bilpub.com/index.php/nefm

**ARTICLE**

# Hybrid Bio-Inorganic Materials for Environmental Remediation

***Sher Wali Khan** [1]**, Rifhat Bibi** [2*]*

[1] *Department of Chemistry, Rawalpindi Women University, Satlite Town, Rawalpindi 46200, Pakistan*

[2] *Department of Chemistry, Fatima Jinnah Women University, The Mall, Rawalpindi 46000, Pakistan*

## ABSTRACT

Environmental pollution from heavy metals, persistent organic compounds, and emerging contaminants poses a growing threat to ecosystems and human health. Remediation processes have typically been associated with high costs, low selectivity, and secondary wastes, prompting a search for greener solutions. Mixed into renewable biopolymers with reactive metal oxides, hybrid bio-inorganic materials have become a promising general choice in pollutant capture and degradation. The basic characteristics of biopolymers and metal oxides, approaches to their synthesis and combination, and the synergistic effects that enhance the performance of the combination by exploiting synergies not present with the separate components are reviewed. The removal of heavy metals, dyes, pesticides, pharmaceuticals, and PFAS is shown as a case study, demonstrating the material's versatility with different classes of pollutants. Important issues regarding stability, scaling up, and ecological security are critically discussed, and newer areas of research, including green synthesis, interface engineering, and the design of multifunctional materials, are growing. Hybrid bio-inorganic materials have the potential to contribute towards high-efficiency, low-impact remediation strategies. These materials can be adapted to a variety of environmental situations as they incorporate chemical diversity, structural stability, and catalytic activity into the same platform.

***Keywords:*** Biopolymers; Metal Oxides; Pollutant Capture; Heavy Metals; Organic Contaminants; Adsorption; Photocatalysis; Green Synthesis

*CORRESPONDING AUTHOR:
Rifhat Bibi, Department of Chemistry, Fatima Jinnah Women University, The Mall, Rawalpindi 46000, Pakistan; Email:rifhat.bibi@fjwu.edu.pk

ARTICLE INFO
Received: 27 September 2023; Revised: 12 November 2023; Accepted:18 November 2023; Published: 27 November 2023
DOI: https://doi.org/10.55121/nefm.v2i1.858

CITATION
Khan, S.W., Bibi, R., 2023. Hybrid Bio-Inorganic Materials for Environmental Remediation. New Environmentally-Friendly Materials. 2(1): 73–88. DOI: https://doi.org/10.55121/nefm.v2i1.858

# 1. Introduction

The rapid rate of industrialization, urbanization, and agricultural intensification has not only solved the economic and technological challenges facing the world but has also led to the persistent emission of dangerous substances into the environment. Synthetic dyes, pesticides, pharmaceuticals, and persistent emerging pollutants like per- and polyfluoroalkyl substances (PFAS), as well as heavy metals (lead, cadmium, arsenic, and mercury), are all now regularly found in environmental soil, water, and sediments. Toxicity, persistence, and bioaccumulation potential are of such concern to these pollutants that they not only pose a threat to aquatic and terrestrial ecosystems, but also to human health due to food and water contamination [1].

The traditional treatment options—chemical precipitation, coagulation-flocculation, activated carbon adsorption, and advanced oxidation processes — have contributed greatly to the reduction of pollution. However, they are usually subjected to important drawbacks: high operating costs, the generation of waste by-products, a lack of selectivity for specific contaminants, and barriers to regeneration and reuse. This has instigated the investigation into alternatives to the material and strategies that are both efficient and sustainable enough to trap a wide range of contaminants with minimal environmental impact [2,3].

Hybrid bio-inorganic composites are a recent emerging group of promisingly developed materials that offer the benefits of bio-polymer but also the unique benefits of inorganic metal oxides. An extra post-publication growth in research interest on hybrid bio-inorganic materials can be seen in **Figure 1** over the previous 10 years, with a 5-fold increase in publications, as indicated by the discrete growth of publication years. These materials are designed to exploit the complementary characteristics of their two components: the renewability, biodegradability, and functional group diversity of biopolymers, and the high surface area, tenable surface chemistry, and catalytic potential of metal oxides. Biopolymers such as chitosan, cellulose, alginate, starch, and various proteins are abundant in nature and possess reactive functional groups—such as amino, hydroxyl, and carboxyl moieties—that readily bind to contaminants through mechanisms including chelation, hydrogen bonding, and electrostatic attraction. Metal oxides such as $Fe_3O_4$, $TiO_2$, ZnO, $MnO_2$, and MgO, in turn, exhibit strong affinities for heavy metals, the ability to photodegrade organic pollutants, and in some cases, redox-active surfaces that can transform harmful compounds into less toxic forms [4].

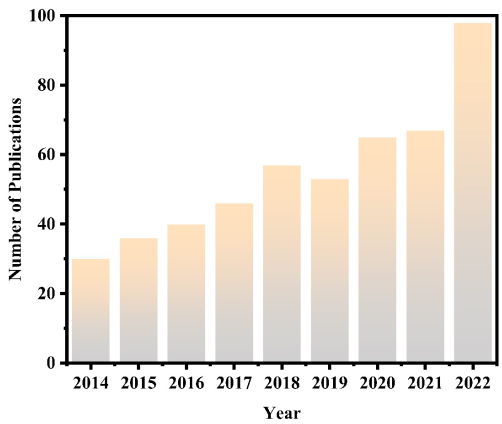


**Figure 1.** Annual number of publications on hybrid bio-inorganic materials (2016–2022), based on Scopus data.

When these two components are integrated, the resulting hybrid materials often display properties that far exceed the sum of their parts. Biopolymers serve as flexible and robust supports that stabilize and disperse metal oxide nanoparticles, preventing their aggregation and thereby maximizing their reactive surface area. This dispersion not only improves the accessibility of active sites but also provides additional binding domains for contaminants. The combination of organic functional groups and inorganic active sites enables multiple modes of pollutant capture, allowing for simultaneous chelation, surface complexation, ion exchange, and photocatalytic degradation within the same material. As an example, a hybrid containing chitosan and FeO sub 3 and sub 4 may be able to bind heavy metal ions via the amino groups of the polymer as well as take advantage of the hydroxylated surfaces of the iron oxide to establish strong surface complexes. Likewise, in hybrids with $TiO_2$, the dyes can be adsorbed, and the $TiO_2$ hybrids can break down the dyes via exposure to light, producing a two-process solution for remediation [5–7].

In addition to chemical performance, the hybrid composite offers improved mechanical durability and high thermal stability, making these materials capable of regeneration through multiple cycles without substantial efficiency decay. Expandability, through the addition of magnetic components like Fe3O4, can enable the rapid and efficient extraction of treated water, providing a solution to one of the main issues of nanoparticle-based remediation systems. Research into these hybrid bio-inorganic materials is a step toward next-generation remediation agents, aimed not only at high efficiency but also at easy deployment and sustainability. Through the integration of the strong sides of natural polymers and advanced inorganic nanomaterials, researchers have managed to develop systems that can solve intricate pollution problems in a fashion that is flexible to practical installations. This paper examines the art of such materials in relation to this premise, particularly focusing on the synergistic effect between biopolymers and metal oxides, which forms the foundation of their ability to capture pollutants. It discusses the character and preparation of each constituent, the mechanism underlying its improved functioning, and various synthetic examples demonstrating its applicability against different grades of contaminants. It is also mindful of the practical obstacles to large-scale expansion of manufacturing, environmental protection, and the transition of these materials into working water treatment platforms. The discussion can provide context for future innovation and the translation of promising laboratory findings into meaningful real-world use. It will summarize what is known to date on this topic and highlight synergistic areas where new knowledge can support ongoing efforts to translate these successful laboratory results into positive real-life applications [8,9].

# 2. Fundamentals of Bio-Inorganic Hybrid Systems

## 2.1. Biopolymers as the Organic Component

Spider silk used to be the most well-known biopolymer. However, now synthetic biopolymers and genetically modified bacteria produce biopolymers that can be harvested, such as those used in water filters. Chitosan, cellulose, alginate, starch, and some protein-based polymers like silk fibroin or casein are also commonly used in the remediation materials. Several biopolymers are interesting in environmental applications due to renewability, biodegradability, and their abundance in waste streams, which are often of agricultural or industrial nature [10].

They have diverse functional groups in their chemical structure, most frequently amino (NH2), hydroxyl (OH), and carboxyl (COOH) groups, and can be relied upon to interact strongly with pollutant molecules or ions. Interactions that result in binding contaminants by coordination to metal ions, hydrogen bonding with polar molecules, or electrostatic attraction with charged species are all possible in these groups. Besides their chemistry, they can be fabricated into other physical formats: films, beads, fibers, and hydrogels. Thus, engineers can control the surface area, porosity, and subsequent mechanical strength to meet a certain treatment need [11].

## 2.2. Metal Oxides as the Inorganic Component

Metal oxides, formed by metal cations and oxygen anions, are inorganic solids whose properties greatly aid in the removal of pollutants. Magnetic minerals like magnetite ($Fe_3O_4$) and maghemite (179\ Gray-$Fe_2O_3$) have a high affinity for arsenic, lead, and other toxic metals. This makes them easy to retrieve from water once treated due to their magnetic properties. Titanium dioxide ($TiO_2$) has long been known to possess photocatalytic properties, allowing it to degrade organic contaminants under ultraviolet or even visible light. Both zinc oxide (ZnO) and manganese dioxide ($MnO_2$) have photocatalytic and oxidative properties, whereas aluminium oxide ($Al_2O_3$) or magnesium oxide (MgO) possess high adsorption capacity and a great stability to the chemicals [12].

These are typically high-surface area materials, and such surfaces can be tailored to ensure that they contain many reactive sites, capable of hosting complexation with the contaminants at the surface. They are equally durable and, therefore, can fit reused cycles of treatment.

## 2.3. Complementary Strengths and Limitations

While biopolymers and metal oxides each have valuable properties, they also have limitations when used individually. Biopolymers may be mechanically weak, prone to swelling in water, or susceptible to degradation under certain conditions. Metal oxides, although robust and reactive, tend to aggregate into larger particles, reducing their effective surface area and limiting pollutant accessibility.

Combining them into hybrid materials addresses these weaknesses. The biopolymer matrix disperses and stabilizes metal oxide nanoparticles, preventing aggregation and ensuring that active sites remain accessible. In turn, the inorganic phase reinforces the polymer structure, enhancing mechanical strength, thermal stability, and sometimes resistance to biodegradation [13].

## 2.4. Synthesis Strategies for Hybrid Materials

Several established methods are used to integrate biopolymers and metal oxides:

- Physical blending: Pre-formed metal oxide particles are mixed into a biopolymer solution and then solidified. This method is straightforward but relies on weak interactions, which can allow some leaching of metal oxides.
- In situ precipitation: Metal salts are introduced into the polymer matrix and chemically converted to metal oxides within the polymer itself, leading to strong interfacial bonding and uniform particle dispersion.
- Sol–gel synthesis: Liquid precursors undergo hydrolysis and condensation reactions within the polymer to form a metal oxide network, commonly used for $TiO_2$ and $SiO_2$.
- Surface functionalization: Chemical modification of the polymer or coating of the oxide surface to improve compatibility and adhesion between the components.

These strategies share conceptual parallels with layered double hydroxide (LDH) nanohybrid synthesis, as illustrated in **Figure 2**. While developed for therapeutic applications, LDH methods like (A) co-precipitation of metal salts, (B) ion-exchange, (C) surface functionalization, and (D) exfoliation-reassembly can be adapted for environmental remediation by substituting biomedical payloads with target pollutants (e.g., $Pb^{2+}$ for drugs, dyes for proteins). Such adaptations leverage the same interfacial control principles critical for pollutant capture [14–16]. The choice of method influences particle size, crystallinity, surface chemistry, and dispersion, all of which affect the hybrid's pollutant removal performance.

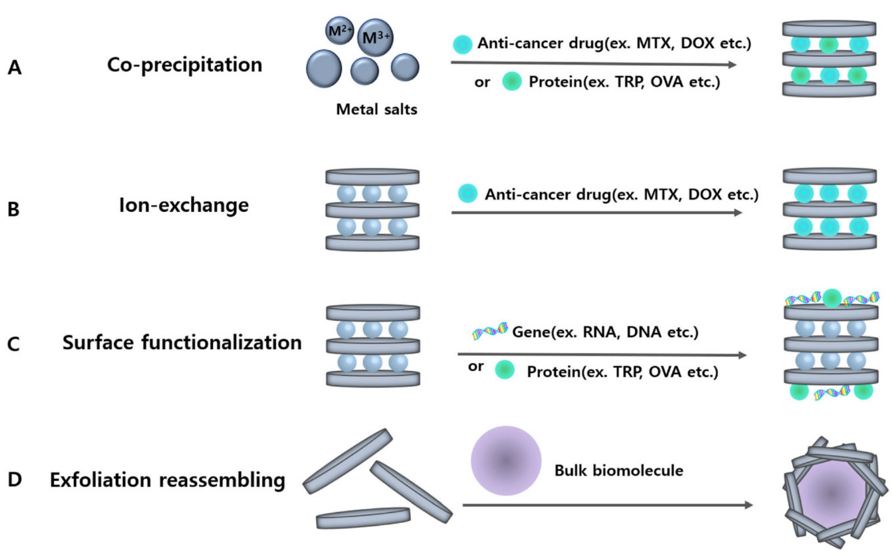


**Figure 2.** Various ways to prepare LDH nanohybrids for therapeutic application from top to bottom co-precipitation, ion exchange, surface functionalization, and exfoliation reassembling [16].

### 2.5. Role of the Polymer–Oxide Interface

The interface between the biopolymer and the metal oxide is where the hybrid's unique performance characteristics emerge. Hydrogen bonding, electrostatic forces, and sometimes covalent linkages can form between polymer functional groups and oxide surfaces. These interactions not only stabilize the composite but may also alter the electronic structure of the oxide, enhancing its catalytic or adsorptive activity. Synergistic effects at this interface often lead to higher removal capacities, faster pollutant uptake rates, and greater selectivity compared to the individual components. For example, smaller oxide nanoparticles provide more reactive surface area but must be securely anchored in the polymer to prevent leaching; uniform dispersion ensures that pollutants encounter active sites more efficiently. The degree of polymer cross-linking can influence water uptake, swelling behavior, and accessibility of binding sites, further shaping the material's performance [17,18].

The hierarchy of interaction types governing polymer-oxide interfaces is systematically classified in **Figure 3**. Class I interactions (e.g., hydrogen bonding, electrostatic) dominate in biopolymer-rich systems like chitosan-$Fe_3O_4$ hybrids, enabling reversible pollutant binding, which is ideal for regenerable adsorbents (Section 5.4). In contrast, Class II interactions (e.g., covalent grafting in alginate-$TiO_2$) enhance structural stability for long-term use in harsh environments. The lower panels further illustrate how matrix design—whether inorganic nanoparticles dispersed in biopolymers (top) or organic modifiers embedded in mineral frameworks (bottom)—dictates pollutant accessibility and reaction kinetics, as demonstrated in Sections 3.1–3.3.

**Figure 3.** Hybrid materials are general classifications. On the left, classification based on the differences between the interactions of the components, having class I and class II hybrid materials. On the right, the classification according to the matrix and filler component nature, being divided into four classifications: I–O, O–I, I–I, and O–O types.

### 2.6. Importance of Fundamental Understanding

A clear understanding of the inherent properties of biopolymers and metal oxides, as well as their interactions in hybrid form, is critical for designing high-performance remediation materials. The flexibility in choosing component types, structural configurations, and synthesis methods allows for fine-tuning toward specific contaminants—whether the goal is to adsorb toxic metals, degrade persistent organic molecules, or remove emerging pollutants that challenge traditional treatment systems. This knowledge forms the foundation upon which the diverse environmental applications of bio-inorganic hybrids are built [19].

## 3. Synergistic Mechanisms in Pollutant Capture

The defining advantage of hybrid bio-inorganic materials lies not simply in the sum of their components, but in the synergistic effects that emerge from their intimate integration. These synergies arise from the interplay between the chemical functionalities, structural features, and physical properties of biopolymers and metal oxides, enabling pollutant removal performance that surpasses what either material could achieve alone [20].

### 3.1. Chemical Synergy: Multi-Modal Binding Mechanisms

At the molecular level, chemical synergy manifests as the coexistence of multiple binding mechanisms within a single material. Biopolymers contribute functional groups such as amino, hydroxyl, and carboxyl moieties, which can chelate metal ions, form hydrogen bonds with polar organic compounds, or engage in electrostatic interactions with charged pollutants. Metal oxides contribute surface hydroxyl groups, coordinatively unsaturated metal sites, and, in some cases, redox-active centres capable of chemically transforming pollutants [21].

When combined, these functionalities work in concert. For example, a chitosan–$Fe_3O_4$ hybrid can capture $Pb^{2+}$ ions through amino group chelation while simultaneously forming inner-sphere complexes with the hydroxylated iron oxide surface. This dual binding pathway increases both the adsorption capacity and the selectivity for specific contaminants. In the example of organic dyes, adsorption of the dye molecules on the surface of the polymer can be facilitated either by electrostatic interactions, or 2pi to 2pi stacking, and photocatalytic combustion by $TiO_2$ nanoparticles embedded on the polymer can then be used to oxidize the adsorbed molecules, thereby turning adsorption into a form of pre-concentration in the presence of the catalyst.

This multi-modal binding is especially beneficial in remediating complex wastewater streams, which contain a mixture of contaminants, because a single hybrid material can address various contaminants simultaneously.

### 3.2. Structural Synergy: Enhanced Stability and Accessibility

There is synergy, too, in the physical structure of the hybrid. Unsupported nanoparticles of inorganic material can form larger aggregates, which severely limit available surface area. Such aggregation does not occur when embedded in a biopolymer matrix, yielding a high density of available active sites. The nanoparticles are separated by the scaffolding, which contains a flexible polymer designed to separate them and simultaneously create pores, allowing pollutants to diffuse.

In exchange, the inflexible character of the non-organic phase strengthens the structure of the polymer. Pure biopolymers easily swell in water or deform over time. This limitation is addressed by adding metal oxides, which enhance mechanical resistance and temperature stability, allowing the hybrid to PA 00354 retain most of its properties after repeated use and regeneration processes. This structural longevity is critical in terms of practical implementation when materials have to be able to perform on a monthly or even yearly basis [22].

### 3.3. Functional Synergy: Combining Adsorption and Catalysis

The potential hybrid synergy between functional groups and bio-inorganic systems has proven to be one of the most powerful, due to the unique ability of bio-inorganic systems to combine both adsorption and catalytic degradation in a material. This biopolymer portion offers a large-affinity layer that concentrates the pollutants proximally toward the metal oxide catalytic locations. Accumulated pollutants can be degraded relatively easily during transportation by an inorganic phase via photocatalysis reactions, oxidation-reduction reactions, or advanced oxidation processes [23].

Instead, as an example, hybrids in which $TiO_2$ or ZnO was used can destroy dyes, pharmaceuticals, or pesticides in the presence of light. Conversely, some organic pollutants may be oxidized, or metal ions, such as toxic ions, may be reduced by hybrids based on Fe, O, and Fe or MnO, starting with $Fe_3O_4$ or $MnO_2$. Mass transfer constraints are reduced by the adsorption step, and, particularly with unsupported oxides, also improve the apparent catalytic activity [24].

### 3.4. Prevention of Nanoparticle Leaching and Environmental Safety

The other crucial characteristic of synergy is avoiding the release of nanoparticles into the environment. When working separately, metal oxide nanoparticles could leach into treated waters, which is ecologically and health-hazardous. With a hybrid, these particles are immobilized within a biopolymer matrix, significantly decreasing the risk of release without any loss of accessibility to reactive sites. Such immobilization enhances safety as well as retention of valuable nanoparticles during use and regeneration to increase long-term cost-efficiency of the material [25].

### 3.5. Improved Regeneration and Reusability

The hybrid materials can also be easier to regenerate because of synergetic interactions. This enables the material to be chemically or thermally regenerated—without much structural collapse—based on the flexibility of the polymer and the stability of the oxide. In magnetic hybrids of $Fe_3O_4$, magnetic separation can be used in combination with regeneration, meaning the recovery of the adsorbent from solution is quick, and the cleaning/reactivation steps are simple. These synergies enhance both the economic and environmental sustainability of using the adsorbent by extending its operational life.

### 3.6. Broader Selectivity and Adaptability

Lastly, synergy increases the number of pollutants that can be effectively combated. Biopolymers alone might be selective towards cationic species, owing to the presence of negatively charged functional groups, whereas metal oxides can be functionalised to remove anionic species. When combined, they can be designed to remove not only the cation content and anions but also neutral organic molecules found in the same water stream. Such flexibility makes hybrid bio-inorganic materials particularly attractive for treating actual wastewater, which has a complicated and changing contaminant profile. Synergistic mechanisms identified in this section are presented together in **Table 1**, which aims to show how hybrid materials combine the chemical, structural, and functional benefits to excel in environmental remediation [7,26].

**Table 1.** Summary of synergistic mechanisms in hybrid bio-inorganic materials, highlighting their roles in enhancing pollutant capture, stability, and multifunctionality.

| Mechanism | Key Features | Example Systems | Benefits |
|---|---|---|---|
| Chemical Synergy | - Multi-modal binding (chelation, H-bonding, electrostatic).<br>- Combined functional groups (e.g., $–NH_2$, –OH) and metal oxide active sites. | Chitosan–$Fe_3O_4$ ($Pb^{2+}$ capture), Alginate–$TiO_2$ (dye degradation). | Enhanced adsorption capacity and selectivity for complex pollutant mixtures. |
| Structural Synergy | - Prevents nanoparticle aggregation.<br>- Improves mechanical/thermal stability of biopolymers. | Cellulose–ZnO (porous scaffolds), Starch–$Fe_3O_4$ (magnetic recovery). | High surface area accessibility; durability for long-term use. |
| Functional Synergy | - Adsorption pre-concentrates pollutants near catalytic sites.<br>- Couples capture with degradation (e.g., photocatalysis). | Chitosan–$TiO_2$ (dye removal), Protein–$MnO_2$ (phenolic oxidation). | Simultaneous removal and detoxification of pollutants. |
| Environmental Safety | - Biopolymer immobilizes nanoparticles, reducing leaching risks. | Alginate–$Fe_3O_4$ (magnetic hybrids), Chitosan–$SiO_2$ (core-shell designs). | Safe for water treatment; minimizes nanomaterial release. |
| Regeneration & Reusability | - Polymer flexibility + oxide stability withstands regeneration cycles.<br>- Magnetic separation ($Fe_3O_4$-based hybrids). | Starch–$Fe_3O_4$ (acid washing), Cellulose–$TiO_2$ (UV self-cleaning). | Cost-effective; extends material lifespan. |
| Adaptability | - Targets cations, anions, and neutrals via tunable components. | Chitosan–$Al_2O_3$ (anion capture), Cellulose–ZnO (organic pollutants). | Broad applicability to diverse wastewater streams. |

# 4. Applications in Environmental Remediation

Hybrid bio-inorganic materials have demonstrated excellent potential to address a diverse variety of pollutants in water, soil, and industrial effluents. This is due to their inherent abilities, including high adsorption capacity, strong catalytic potential, and good structural durability, making them flexible to various environmental challenges. This section examines their use in eliminating heavy metals, organic pollutants, and emerging contaminants, supported by exemplary case studies and trends in efficacy.

## 4.1. Removal of Heavy Metals

Heavy metals such as lead ($Pb^{2+}$), cadmium ($Cd^{2+}$), chromium ($Cr^{3+}/Cr^{6+}$), mercury ($Hg^{2+}$), and arsenic ($As^{3+}/As^{5+}$) are among the most persistent and toxic environmental contaminants. They do not degrade biologically and tend to bioaccumulate in living organisms, leading to severe health problems.

Hybrid bio-inorganic materials excel in heavy metal removal due to their multi-modal binding capabilities. The biopolymer matrix provides functional groups such as $–NH_2$ and –OH that chelate cations or form hydrogen bonds, while the metal oxide component offers additional surface complexation sites and, in some cases, redox activity to transform metal ions into less soluble forms.

For example:

- Chitosan–$Fe_3O_4$ hybrids have been shown to remove $Pb^{2+}$ with adsorption capacities exceeding 200 mg/g, benefiting from both chelation and magnetic separability for easy recovery.
- Alginate–$MnO_2$ composites can oxidize $Cr^{3+}$ to $Cr^{6+}$ or vice versa, depending on pH, enabling selective removal or detoxification.
- Cellulose–ZnO hybrids demonstrate enhanced uptake of $Cd^{2+}$ due to the combination of hydroxyl-rich cellulose and ZnO surface sites.

The presence of the biopolymer prevents nanoparticle aggregation and allows the hybrid to maintain performance even in waters containing competing ions such as $Ca^{2+}$ and $Mg^{2+}$, which often reduce adsorption efficiency in conventional materials [27].

## 4.2. Removal of Organic Pollutants

Organic pollutants in water include synthetic dyes, pesticides, phenolic compounds, and pharmaceuticals. Many are toxic, carcinogenic, and resistant to biodegradation. The removal of such contaminants requires not just adsorption but often chemical transformation to render them harmless.

Hybrid materials are particularly effective here because they can integrate adsorptive concentration with catalytic degradation. For example:

- Chitosan–$TiO_2$ hybrids adsorb dye molecules via electrostatic interaction and subsequently photodegrade them under UV or visible light, leading to nearly complete mineralization.
- Starch–ZnO composites have been used to degrade pesticides like atrazine, with the starch component capturing the pesticide molecules and the ZnO generating reactive oxygen species to break down the compounds.
- Protein-based hybrids with $MnO_2$ have shown potential for oxidative degradation of phenolic contaminants through electron transfer reactions at the oxide surface.

The dual action—first binding, then breaking down the pollutant—ensures that harmful organic compounds are not simply transferred from one phase to another but are actually neutralized [28,29].

Recent advances have extended the application of hybrid bioinorganic materials to antibiotic degradation. For instance, laccase-$Cu_3(PO_4)_2$ hybrid nanoflowers (Lac-hNFs) were synthesized via a one-step process in PBS buffer (**Figure 4**). These hybrids efficiently degraded tetracycline antibiotics (TCs), reducing their toxicity, as evidenced by restored bacterial growth (E. coli) post-treatment (**Figure 4A,B**). Molecular docking simulations further elucidated the binding interactions between laccase and tigecycline (**Figure 4C**), highlighting the role of enzyme-inorganic synergy in pollutant breakdown.

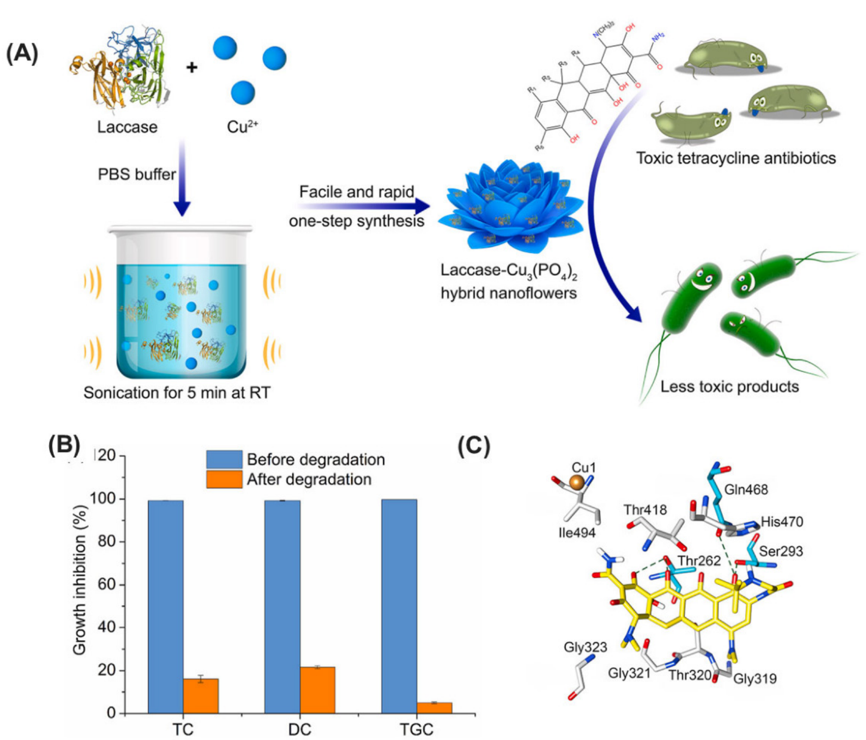


**Figure 4.** Application of Lac-hNFs for tetracycline degradation. (**A**) Schematic illustration of laccase-inorganic hybrid nanoflower (Lac-hNF) preparation for tetracycline (TC) degradation. (**B**) Bacterial growth inhibition by TCs was assessed before and after Lac-hNF treatment. Lac-hNF treatment reduced *E. coli*'s susceptibility to TCs. (**C**) Depiction of the binding interactions between laccase and tigecycline (TGC), as revealed by molecular docking simulations.

## 4.3. Removal of Emerging Contaminants

Emerging contaminants, such as endocrine-disrupting chemicals (EDCs), pharmaceuticals, personal care product residues, microplastics, and PFAS, are of growing concern due to their persistence and potential to cause ecological and health effects even at low concentrations. Many of these compounds are small, polar, and chemically stable, making them difficult to remove with conventional adsorbents.

Bio-inorganic hybrids offer new opportunities here:

- Magnetic chitosan–$Fe_3O_4$–$TiO_2$ composites have demonstrated the ability to adsorb and photodegrade pharmaceuticals like diclofenac and carbamazepine, achieving over 90% removal within hours.
- Cellulose–graphene oxide–$Fe_3O_4$ hybrids can remove bisphenol A (BPA) from water by adsorption onto the polymer–graphene network, followed by catalytic breakdown with embedded metal oxides.
- Alginate–iron oxide beads have been explored for PFAS adsorption, leveraging electrostatic attraction and hydrophobic interactions in the polymer phase, combined with oxide surface binding.

The multifunctionality of these hybrids allows for a tailored approach—modifying the polymer chemistry, oxide type, and surface properties to target specific emerging contaminants [30].

## 4.4. Field-Scale and Pilot-Scale Implementations

While most research to date has been conducted at the laboratory scale, there are promising moves toward real-world application. Pilot studies have tested hybrid materials in industrial wastewater treatment plants and contaminated groundwater sites. For instance:

- Magnetically recoverable chitosan–$Fe_3O_4$ systems have been trailed for treating electroplating wastewater, showing rapid removal of $Cr^{6+}$ and easy regeneration over multiple cycles.
- Alginate–$TiO_2$ photocatalytic beads have been tested in sunlight-driven water purification systems, treating textile dye effluents on-site without the need for external UV lamps.
- Cellulose–$Fe_3O_4$–$MnO_2$ hybrids have been applied for simultaneous removal of arsenic and organic contaminants in rural water treatment units, with regeneration possible using mild chemical washing.

These examples illustrate the adaptability of hybrid bio-inorganic materials to different scales and conditions, although scaling up remains a challenge due to material synthesis costs and long-term stability considerations [31].

## 4.5. Performance in Complex Water Matrices

A key test for any remediation material is performance in real water matrices, which contain competing ions, dissolved organic matter, and varying pH levels. Hybrid materials often maintain higher performance under such conditions compared to single-component systems because their multiple binding mechanisms reduce susceptibility to competitive inhibition. The presence of both organic and inorganic active sites ensures that even if one mechanism is hindered—for example, electrostatic binding reduced by high ionic strength—other mechanisms such as chelation or surface complexation can still operate effectively [32].

## 4.6. Environmental and Operational Benefits

Besides the high removal efficiencies, hybrids have been characterized by operational advantages, including the possibilities of attaining magnetic separability, reusability, and low-effectiveness regeneration. The immobilization of nanoparticles in the biopolymer matrix reduces the likelihood of their release into the environment, thereby eliminating safety risks associated with using free metal oxide nanoparticles.

Hybrid bio-inorganic materials have therefore proven to possess wide and versatile effects in the decontamination of varied polluted environments. These include uses in the removal of toxic heavy metals, degradation of recalcitrant organic contaminants, and addressing the increasing number of countermeasures resistant to conventional methods. These materials are highly promising as candidates to become sustainable, high-performance remediation technologies through a synergy of adsorption, catalysis, and hard structural design [33].

# 5. Challenges and Future Perspectives

The hybrid bio-inorganic materials have proven to be a potential source of sustainable environmental remediation due to their high-performance potential, versatility, and ability to incorporate multiple remedial functionalities, such as adsorption and catalysis, with excellent recovery. Nonetheless, on the path to large-scale and practical use, they encounter challenges. These problems are not just technological but also extend into material science, engineering, economics, and environmental policy. To deal with them, a comprehensive view is necessary, i.e., that which takes into account, not just the performance benchmarks of the material itself, but the possibility, security, and sustainability of the worldview life-cycle [34].

## 5.1. Material Limitations and Long-Term Stability

Though most hybrid bio-inorganic materials show remarkable adsorption capacities and catalytic efficiencies in controlled laboratory settings, their performance may decline dramatically when exposed to normal environmental conditions over the long term. Both main components, including metal oxide and biopolymer, are exposed to various methods of degradation.

By definition, biopolymers are biodegradable. Although this is an advantage for environmental compatibility, it also implies that the polymeric medium may be slowly degraded in aqueous media, where biomass proliferation is prolific due to enzymatic activity. Photodegradation of the polymer chains can also be caused by the ultraviolet radiation found in sunlight, particularly in an outdoor treatment system. Moreover, the binding capacity of the material may be reduced by chemical hydrolysis or oxidation of functional groups in polluted water due to exposure to acidic or alkaline pH, excessively high salinity, or oxidizing substances.

Metal oxides, on the other hand, are generally stable but are not immune to performance loss. A common problem is surface fouling—the deposition of organic matter, biofilms, or inorganic scale (such as calcium carbonate or silica) that physically blocks reactive sites. In photocatalytic systems, oxides like $TiO_2$ and ZnO can undergo photo-corrosion, where prolonged light exposure alters their surface chemistry or causes structural changes, leading to reduced catalytic activity [35,36].

To counteract these issues, researchers are exploring strategies such as:

- Cross-linking the biopolymer matrix with agents like glutaraldehyde, genipin, or ionic cross-linkers to enhance resistance against swelling, dissolution, and microbial attack.
- Protective coatings on metal oxide nanoparticles (e.g., silica shells or carbon layers) to prevent photo corrosion without blocking active sites.
- Incorporation of secondary stabilizers such as graphene derivatives, clay minerals, or silica particles to reinforce the hybrid's mechanical integrity.

The challenge lies in implementing these modifications without compromising the pollutant removal performance or significantly increasing the cost of the material.

## 5.2. Scalability and Production Cost

Scaling up the synthesis of hybrid materials from milligram-to-gram laboratory batches to kilogram-to-ton industrial quantities presents both engineering and economic hurdles. Many synthesis routes reported in the literature involve multi-step processes, carefully controlled reaction conditions, and sometimes expensive or hazardous reagents. While such conditions may be acceptable for research, they are impractical for large-scale manufacturing, especially for materials intended for deployment in low-resource regions or rural water treatment systems.

The main scalability issues include:

- Uniformity of properties: At larger volumes, controlling nanoparticle size, dispersion, and distribution within the polymer matrix becomes more difficult. Variations in these parameters can lead to inconsistent performance across different production batches.
- Availability and purity of raw materials: While biopolymers like cellulose and chitosan can be sourced from agricultural or seafood waste, their purity and chemical composition can vary significantly depending on source and extraction method. Metal oxide nanoparticles, especially with engineered morpholo-

gies or dopants, can be costly to produce at scale.

- Process economics and sustainability: Energy-intensive steps such as high-temperature calcination, vacuum drying, or solvent-based synthesis add to operational costs and carbon footprint.

To address scalability, the focus is shifting toward green and low-energy synthesis methods—for example, using plant extracts as reducing agents for metal oxide formation, producing oxides directly from industrial by-products, or developing continuous-flow synthesis reactors that operate at ambient temperature and pressure. Such methods not only reduce production cost but also align with the sustainability goals that motivate the use of hybrid materials in the first place [37].

## 5.3. Environmental Safety and Ecotoxicity Concerns

One of the stated benefits of hybrid bio-inorganic materials is the reduced environmental risk compared to using free nanoparticles. In theory, the polymer matrix immobilizes the oxide particles, preventing them from entering natural water bodies where they could harm aquatic organisms. In practice, however, the immobilization is rarely perfect. Mechanical abrasion, polymer degradation, or repeated regeneration cycles can lead to partial release of nanoparticles.

Metal oxides themselves can pose risks depending on their composition. While iron-based oxides are generally considered environmentally benign, oxides of zinc, copper, or manganese can exhibit toxicity at certain concentrations, especially toward planktonic microorganisms that form the base of aquatic food webs. Moreover, little is known about the long-term fate of these nanoparticles once released—whether they persist, dissolve, or undergo chemical transformations in natural environments [2,20,38].

This uncertainty highlights the need for comprehensive life-cycle assessments (LCA) and ecotoxicological studies that go beyond standard adsorption tests. Such evaluations should consider:

- The stability of the hybrid material under realistic environmental stresses.
- The toxicity of degradation products from both the polymer and the metal oxide.
- The behavior of the material in different ecosystems—freshwater, marine, sediment, and soil.

Designing inherently safer hybrids is also an active research area—for example, using only oxides with low toxicity profiles, incorporating natural mineral particles like kaolinite or bentonite, or engineering strong covalent bonds between polymer and oxide phases to minimize leaching [39].

## 5.4. Regeneration, Reusability, and Waste Management

For hybrid materials to be economically viable and environmentally sustainable, they must be regenerable and reusable over many cycles. Regeneration typically involves removing adsorbed pollutants from the material's surface through washing, pH adjustment, solvent extraction, or in some cases, catalytic degradation of organics directly on the material. However, these processes introduce challenges:

- Structural degradation: Harsh chemicals or repeated swelling–drying cycles can weaken the polymer–oxide interface or break down the polymer chains.
- Loss of active sites: Metal oxide surfaces can undergo irreversible changes, such as binding with non-desorbable species or structural rearrangement.
- Secondary waste streams: Regeneration produces concentrated waste containing the removed pollutants, which must be treated to prevent simply transferring the problem from one medium to another.

Innovative regeneration strategies include light-assisted self-cleaning, where photocatalytic oxides break down organic foulants without removing them from the material, and mild chelation for metal ions that selectively desorbs target contaminants without damaging the matrix. Waste minimization can also be achieved by coupling the hybrid material's regeneration step with downstream treatment processes, such as electrochemical oxidation or advanced oxidation, to neutralize the desorbed contaminants [40]. The key challenges and emerging strategies for regeneration and waste management are summarized in **Table 2**.

**Table 2.** Summary of key challenges and solutions for ensuring the regeneration, reusability, and waste management of hybrid bio-inorganic materials.

| Aspect | Challenges | Innovative Strategies |
|---|---|---|
| Structural Integrity | - Polymer–oxide interface weakened by harsh chemicals/swelling–drying cycles. | - Cross-linking polymers (e.g., glutaraldehyde).<br>- Protective coatings (e.g., silica shells). |
| Active Site Retention | - Irreversible changes to metal oxides (e.g., non-desorbable species binding). | - Light-assisted self-cleaning (photocatalytic degradation of foulants).<br>- Mild chelation for selective desorption. |
| Waste Management | - Concentrated pollutant waste from regeneration. | - Coupling with downstream treatments (e.g., electrochemical/advanced oxidation).<br>- Recovering metals for reuse. |
| Economic Viability | - High energy/cost for regeneration processes. | - Green solvents, low-energy methods (e.g., pH-triggered release). |

## 5.5. Integration into Real-World Treatment Systems

Even when a hybrid material performs well in a laboratory setting, integrating it into an operational treatment plant requires additional considerations. Water treatment facilities typically operate in continuous flow modes, where the residence time is short and contact between pollutants and the adsorbent must be maximized. Hybrid materials tested as loose powders in batch systems may not translate well to fixed-bed columns or membrane-assisted reactors due to pressure drop, clogging, or insufficient contact time.

To facilitate integration, materials may need to be processed into granules, pellets, or composite membranes with optimized size, porosity, and mechanical strength. For example, embedding hybrid materials into polymeric membrane matrices can enable simultaneous filtration and adsorption, while immobilizing them in packed beds allows for continuous operation. The choice of configuration will depend on the nature of the contaminant, the required throughput, and the infrastructure available.

There is also potential for hybrid material combinations—pairing bio-inorganic hybrids with other treatment technologies such as biological filtration, ion exchange resins, or UV-based advanced oxidation—to create multi-barrier systems capable of handling complex and variable pollutant loads [41].

## 5.6. Future Research and Innovation Pathways

Several promising directions can help overcome current challenges and accelerate the transition from laboratory prototypes to field-ready solutions:

- Sustainable raw materials: Sourcing biopolymers from abundant waste streams (e.g., chitosan from crustacean shells, cellulose from agricultural residues) and using industrial waste-derived metal oxides to reduce cost and environmental burden.
- Interface engineering: Using surface chemistry modifications, molecular linkers, or bio-inspired adhesion mechanisms (e.g., polydopamine coatings) to strengthen polymer–oxide bonding and improve long-term stability.
- Multi-functionality: Designing hybrids with combined adsorption, catalytic degradation, antimicrobial activity, and sensing capabilities to address multiple challenges in a single treatment step.
- Data-driven design: Employing computational modeling, machine learning, and high-throughput screening to predict optimal polymer–oxide combinations for specific pollutants.
- Field validation: Moving beyond laboratory-scale experiments to long-term pilot trials in industrial and municipal treatment plants, with performance monitoring under real operating conditions [42].

## 5.7. Outlook

The field of hybrid bio-inorganic materials for environmental remediation is poised at an exciting stage. The fundamental principles of their design are well established, and proof-of-concept studies have demonstrated their ability to outperform conventional adsorbents and catalysts. However, realizing their full potential will require addressing the interconnected challenges of durability, safety, scalability, and integration into practical systems.

With continued innovation in green synthesis, molecular-level interface control, and process engineering, these hybrids could become a cornerstone of sustainable water and soil treatment technologies. Their ability to combine renewable, biodegradable polymers with the powerful reactivity of metal oxides positions them uniquely to tackle the increasingly complex pollution problems of the modern world—provided that we match scientific ingenuity with responsible engineering and environmental stewardship.

## 6. Conclusions

Hybrid bio-inorganic materials, formed by integrating naturally derived biopolymers with reactive metal oxides, have emerged as one of the most versatile and promising classes of materials for environmental remediation. By combining the chemical diversity and renewability of biopolymers with the high surface area, catalytic potential, and robust physicochemical properties of metal oxides, these hybrids achieve a level of pollutant capture performance that exceeds what either component can offer on its own. The synergies between the organic and inorganic phases—whether in the form of multi-modal binding, enhanced structural stability, or the coupling of adsorption with catalytic degradation—are the central reason for their effectiveness across such a broad spectrum of contaminants.

Over the past decade, research has demonstrated their capacity to remove toxic heavy metals, degrade persistent organic pollutants, and even target emerging contaminants such as pharmaceuticals, endocrine disruptors, and PFAS. Their flexibility in form, including powders, beads, membranes, and coatings, further enhances their potential for integration into a wide variety of treatment systems, at any scale from small-scale rural treatment units to large industrial wastewater plants. Their functionality is also expanded by additional features, such as magnetic separability, photocatalytic activity, and antimicrobial properties, making them favorable options as multifunctional remediation platforms.

Nevertheless, barriers such as translating laboratory successes into real life still limit this process. Problems in long-term stability, scalability, environmental safety, and incorporation into existing treatment infrastructure continue to be topics of active investigation. The performance of hybrids in controlled settings does not always carry over to complex natural water matrices, where competing ions, variable pH, and natural organic matter can interfere with pollutant capture. Moreover, ensuring that these materials can be produced cost-effectively, regenerated repeatedly without significant loss of activity, and disposed of safely is essential for their adoption in practice.

The future development of hybrid bio-inorganic materials will likely be shaped by advances in green synthesis methods, molecular-level interface engineering, and data-driven material optimization. Leveraging abundant waste-derived biopolymers and low-toxicity oxides can help reduce costs and environmental impact, while computational modeling can guide the selection of optimal polymer–oxide combinations for specific remediation challenges. Importantly, long-term pilot studies and field trials must become a greater priority to validate laboratory findings under real environmental conditions, providing the performance data and reliability metrics that industry and regulatory bodies require for adoption.

As environmental pollution becomes increasingly complex—both in the diversity of contaminants and in the scale of the problem—the need for multifunctional, sustainable, and adaptable remediation technologies will only intensify. Hybrid bio-inorganic materials are uniquely positioned to meet this need. By uniting the principles of green chemistry, nanotechnology, and environmental engineering, they offer a pathway toward remediation solutions that are not only effective but also aligned with the broader goals of environmental stewardship and sustainable development. With continued interdisciplinary collaboration, these materials could transition from innovative research concepts to indispensable tools in the global effort to restore and protect our ecosystems.

## Author Contributions

Both authors contributed equally to the conception, design, data collection, analysis, and writing of this study. Both authors have read and agreed to the published version of the manuscript.

## Funding

This work received no external funding.


## Institutional Review Board Statement

Not applicable.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

Not applicable.

## Conflicts of Interest

The authors declare that there is no conflict of interest.

## References


[1] Li, J., Lu, Y., Shi, Y., et al., 2011. Environmental Pollution by Persistent Toxic Substances and Health Risk in an Industrial Area of China. Journal of Environmental Sciences. 23(8), 1359–1367. DOI: https://doi.org/10.1016/S1001-0742(10)60554-2

[2] Ruiz-Hitzky, E., Ariga, K., Lvov, Y.M., 2008. Bio-Inorganic Hybrid Nanomaterials: Strategies, Synthesis, Characterization and Applications. John Wiley & Sons: Heidelberg, Germany. DOI: https://doi.org/10.1002/9783527621446

[3] Ruiz-Hitzky, E., Aranda, P., Darder, M., et al., 2010. Hybrid Materials Based on Clays for Environmental and Biomedical Applications. Journal of Materials Chemistry. 20(42), 9306–9321. DOI: https://doi.org/10.1039/C0JM00432D

[4] Koyale, P.A., Panda, D.K., Delekar, S.D., 2022. Human Development and Metal Oxides Nexus. In: Delekar, S.D. (ed.). Advances in Metal Oxides and Their Composites for Emerging Applications. Elsevier: Amsterdam, Netherlands. pp. 3–5.

[5] Sanchez, C., Belleville, P., Popall, M., et al., 2011. Applications of Advanced Hybrid Organic–Inorganic Nanomaterials: From Laboratory to Market. Chemical Society Reviews. 40(2), 696–753. DOI: https://doi.org/10.1039/C0CS00136H

[6] Villa, C., Rosa, R., Corradi, A., et al., 2011. Microwaves-Mediated Preparation of Organoclays as Organic-/Bio-Inorganic Hybrid Materials. Current Organic Chemistry. 15(2), 284–295. DOI: https://doi.org/10.2174/138527211793979781

[7] Nicole, L., Laberty-Robert, C., Rozes, L., et al., 2014. Hybrid Materials Science: A Promised Land for the Integrative Design of Multifunctional Materials. Nanoscale. 6(12), 6267–6292. DOI: https://doi.org/10.1039/C4NR01788A

[8] Nurazzi, N.M., Asyraf, M.R.M., Athiyah, S.F., et al., 2021. A Review on Mechanical Performance of Hybrid Natural Fiber Polymer Composites for Structural Applications. Polymers. 13(13), 2170. DOI: https://doi.org/10.3390/polym13132170

[9] Vilatela, J.J., Eder, D., 2012. Nanocarbon Composites and Hybrids in Sustainability: A Review. ChemSusChem. 5(3), 456–478. DOI: https://doi.org/10.1002/cssc.201100536

[10] Belbéoch, C., Lejeune, J., Vroman, P., et al., 2021. Silkworm and Spider Silk Electrospinning: A Review. Environmental Chemistry Letters. 19, 1737–1763. DOI: https://doi.org/10.1007/s10311-020-01147-x

[11] Lefèvre, T., Auger, M., 2016. Spider Silk as a Blueprint for Greener Materials: A Review. International Materials Reviews. 61(2), 127–153. DOI: https://doi.org/10.1080/09506608.2016.1148894

[12] Tahir, M.B., Rafique, M., Rafique, M.S., et al., 2020. Metal Oxide- and Metal Sulfide-Based Nanomaterials as Photocatalysts. In: Tahir, M.B., Rafique, M., Rafique, M.S. (eds.). Nanotechnology and Photocatalysis for Environmental Applications. Elsevier: Amsterdam, Netherlands. pp. 77–96. DOI: https://doi.org/10.1016/B978-0-12-821192-2.00006-1

[13] Boury, B., 2016. Biopolymers for Biomimetic Processing of Metal Oxides. In: Ehrlich, H. (ed.). Extreme Biomimetics. Springer: Cham, Switzerland. pp. 135–189. DOI: https://doi.org/10.1007/978-3-319-45340-8_6

[14] Gon, M., Tanaka, K., Chujo, Y., 2017. Creative Synthesis of Organic–Inorganic Molecular Hybrid Materials. Bulletin of the Chemical Society of Japan. 90(5), 463–474. DOI: https://doi.org/10.1007/978-3-319-45340-8_6

[15] Sanchez, C., Boissiere, C., Cassaignon, S., et al., 2014. Molecular Engineering of Functional Inorganic and Hybrid Materials. Chemistry of Materials. 26(1), 221–238. DOI: https://doi.org/10.1021/cm402528b

[16] Lee, J., Seo, H.S., Park, W., et al., 2022. Biofunctional Layered Double Hydroxide Nanohybrids for Cancer

Therapy. Materials. 15(22), 7977. DOI: https://doi.org/10.3390/ma15227977

[17] Boury, B., Plumejeau, S., 2015. Metal Oxides and Polysaccharides: An Efficient Hybrid Association for Materials Chemistry. Green Chemistry. 17(1), 72–88. DOI: https://doi.org/10.1039/C4GC00957F

[18] Mane, N.S., Tripathi, S., Hemadri, V., 2022. Effect of Biopolymers on Stability and Properties of Aqueous Hybrid Metal Oxide Nanofluids in Thermal Applications. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 643, 128777. DOI: https://doi.org/10.1016/j.colsurfa.2022.128777

[19] Pletincx, S., Fockaert, L.L.I., Mol, J.M.C., et al., 2019. Probing the Formation and Degradation of Chemical Interactions from Model Molecule/Metal Oxide to Buried Polymer/Metal Oxide Interfaces. npj Materials Degradation. 3, 23. DOI: https://doi.org/10.1038/s41529-019-0085-2

[20] Saveleva, M.S., Eftekhari, K., Abalymov, A., et al., 2019. Hierarchy of Hybrid Materials—The Place of Inorganics-in-Organics in It, Their Composition and Applications. Frontiers in Chemistry. 7, 179. DOI: https://doi.org/10.3389/fchem.2019.00179

[21] George, A., Sanjay, M.R., Srisuk, R., et al., 2020. A Comprehensive Review on Chemical Properties and Applications of Biopolymers and Their Composites. International Journal of Biological Macromolecules. 154, 329–338. DOI: https://doi.org/10.1016/j.ijbiomac.2020.03.120

[22] Gupta, R., Chauhan, H., Garg, V.K., et al., 2022. Chemical and Physical Properties of Nanoparticles and Hybrid Materials. In: Koduru, J.R., Karri, R.R., Mubarak, N.M., et al. (eds.). Sustainable Nanotechnology for Environmental Remediation. Elsevier: Amsterdam, Netherlands. pp. 199–220. DOI: https://doi.org/10.1016/B978-0-12-824547-7.00024-2

[23] Rejinold, N.S., Choi, G., Choy, J.-H., 2022. Bio-Inorganic Layered Double Hydroxide Nanohybrids in Photochemotherapy: A Mini Review. International Journal of Molecular Sciences. 23(19), 11862. DOI: https://doi.org/10.3390/ijms231911862

[24] Singh, J., Kumar, S., Rishikesh, et al., 2020. Fabrication of ZnO–TiO2 Nanohybrids for Rapid Sunlight Driven Photodegradation of Textile Dyes and Antibiotic Residue Molecules. Optical Materials. 107, 110138. DOI: https://doi.org/10.1016/j.optmat.2020.110138

[25] Bhatt, I., Tripathi, B.N., 2011. Interaction of Engineered Nanoparticles with Various Components of the Environment and Possible Strategies for Their Risk Assessment. Chemosphere. 82(3), 308–317. DOI: https://doi.org/10.1016/j.chemosphere.2010.10.011

[26] Gomez-Romero, P., 2001. Hybrid Organic–Inorganic Materials—In Search of Synergic Activity. Advanced Materials. 13(3), 163–174. DOI: https://doi.org/10.1002/1521-4095(200102)13:3<163::AID-ADMA163>3.0.CO;2-U

[27] Afolabi, M., Onukogu, O.A., Igunma, T.O., et al., 2022. Systematic Review of Adsorbent Materials for Heavy Metal Removal in Continuous Wastewater Flow Systems. Journal of Frontiers in Multidisciplinary Research. 3(1), 294–310. DOI: https://doi.org/10.54660/.JFMR.2022.3.1.294-310

[28] Hanafi, M.F., Sapawe, N., 2020. A Review on the Water Problem Associated with Organic Pollutants Derived from Phenol, Methyl Orange, and Remazol Brilliant Blue Dyes. Materials Today: Proceedings. 31, A141–A150. DOI: https://doi.org/10.1016/j.matpr.2021.01.258

[29] Rashed, M.N., 2013. Adsorption Technique for the Removal of Organic Pollutants from Water and Wastewater. In: Rashed, M.N. (ed.). Organic Pollutants—Monitoring, Risk and Treatment. IntechOpen: London, UK. pp. 3–28. DOI: http://dx.doi.org/10.5772/intechopen.82022

[30] Maddela, N.R., Ramakrishnan, B., Kakarla, D., et al., 2022. Major Contaminants of Emerging Concern in Soils: A Perspective on Potential Health Risks. RSC Advances. 12(20), 12396–12415. DOI: https://doi.org/10.1039/D1RA09072K

[31] Liu, F., Panagiotakos, D., 2022. Real-World Data: A Brief Review of the Methods, Applications, Challenges and Opportunities. BMC Medical Research Methodology. 22, 287. DOI: https://doi.org/10.1186/s12874-022-01768-6

[32] Cai, J., Niu, B., Xie, Q., et al., 2022. Accurate Removal of Toxic Organic Pollutants from Complex Water Matrices. Environmental Science & Technology. 56(5), 2917–2935. DOI: https://doi.org/10.1021/acs.est.1c07824

[33] Contreras-Mateus, M., Hethnawi, A., Mheibesh, Y., et al., 2022. Applications of Nanoparticles in Energy and the Environment: Enhanced Oil Upgrading and Recovery and Cleaning Up Energy Effluents. In: Boul, P.J. (ed.). Energy Transition: Climate Action and Circularity. American Chemical Society: Washington, DC, USA. pp. 169–267. DOI: https://doi.org/10.1021/bk-2022-1412.ch005

[34] Iqbal, H.M., Bilal, M., Nguyen, T.A., et al., 2021. Biodegradation and Biodeterioration at the Nanoscale. Elsevier: Amsterdam, Netherlands.

[35] Lu, D., Zhang, T., Gutierrez, L., et al., 2016. Influence

of Surface Properties of Filtration-Layer Metal Oxide on Ceramic Membrane Fouling During Ultrafiltration of Oil/Water Emulsion. Environmental Science & Technology. 50(9), 4668–4674. DOI: https://doi.org/10.1021/acs.est.5b04151

[36] Taylor, C.M., Ramirez-Canon, A., Wenk, J., et al., 2019. Enhancing the Photo-Corrosion Resistance of ZnO Nanowire Photocatalysts. Journal of Hazardous Materials. 378, 120799. DOI: https://doi.org/10.1016/j.jhazmat.2019.120799

[37] Jana, N.R., 2005. Gram-Scale Synthesis of Soluble, Near-Monodisperse Gold Nanorods and Other Anisotropic Nanoparticles. Small. 1(8–9), 875–882. DOI: https://doi.org/10.1002/smll.200500014

[38] Sanchez, C., Julián, B., Belleville, P., et al., 2005. Applications of Hybrid Organic–Inorganic Nanocomposites. Journal of Materials Chemistry. 15(35–36), 3559–3592. DOI: https://doi.org/10.1039/B509097K

[39] Fantke, P., Aurisano, N., Bare, J., et al., 2018. Toward Harmonizing Ecotoxicity Characterization in Life Cycle Impact Assessment. Environmental Toxicology and Chemistry. 37(12), 2955–2971. DOI: https://doi.org/10.1002/etc.4261

[40] Dumée, L.F., 2022. Circular Materials and Circular Design—Review on Challenges Towards Sustainable Manufacturing and Recycling. Circular Economy and Sustainability. 2, 9–23. DOI: https://doi.org/10.1007/s43615-021-00085-2

[41] Ang, W.L., Mohammad, A.W., Hilal, N., et al., 2015. A Review on the Applicability of Integrated/Hybrid Membrane Processes in Water Treatment and Desalination Plants. Desalination. 363, 2–18. DOI: https://doi.org/10.1016/j.desal.2014.03.008

[42] Brooks, S.M., Alper, H.S., 2021. Applications, Challenges, and Needs for Employing Synthetic Biology Beyond the Lab. Nature Communications. 12(1), 1390. DOI: https://doi.org/10.1038/s41467-021-21740-0