

Biopolymer-photocatalytic hybrid systems for post-war restoration of contaminated water and soil resources

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Abstract: Armed conflicts have caused severe degradation of water and soil resources through physical disturbance, contamination by heavy metals, petroleum hydrocarbons, explosive residues, and disruption of hydrological systems. These impacts pose significant environmental and public health risks while challenging the effectiveness of conventional remediation technologies, which are often energy-intensive, expensive, and environmentally disruptive. This review critically evaluates the potential of biopolymer-based and biological remediation strategies, including biosorption, biodegradation, phytoremediation, and hybrid systems integrating biodegradable biopolymers with photocatalytic materials for the sustainable restoration of war-impacted environments. The roles of natural biopolymers, including chitosan, alginate, xanthan gum, guar gum, and lignin, are examined as sorbents, soil stabilisers, water-retaining agents, and matrices for microbial, plant-assisted, and catalyst immobilisation applications. Particular emphasis is placed on titanium dioxide (TiO₂)-based photocatalytic systems, which generate reactive oxygen species (ROS) under light irradiation to promote the oxidative degradation and mineralisation of persistent organic pollutants. The synergistic integration of biopolymers with photocatalysts offers improved adsorption capacity, enhanced catalyst stability, and greater remediation efficiency while maintaining environmental compatibility. Furthermore, this review proposes a structured experimental roadmap comprising laboratory-scale screening, soil and water microcosm investigations, pilot-scale validation, and long-term environmental monitoring to facilitate technology development and field implementation. The proposed framework provides a scientific foundation for scalable, nature-based remediation strategies and supports future research, environmental restoration initiatives, and policy development for the sustainable recovery of war-affected ecosystems in Ukraine and other conflict-impacted regions.

Keywords: biopolymers, photocatalysis, post-war environment, soil and water remediation, water resources

INTRODUCTION

Military activities represent one of the most severe anthropogenic disturbances to terrestrial and aquatic ecosystems (Mystrioti and Papassiopi, 2024). In Ukraine, large areas of agricultural land, industrial zones, floodplains, and freshwater systems have been affected by shelling, destruction of infrastructure, fuel spills, and the collapse of hydraulic structures, as reported by Leal Filho *et al.* (2024). These impacts result in complex contamination patterns involving heavy metals, petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), nitrate compounds, and residues of military explosives, combined with physical degradation of soil structure and altered hydrological regimes (Krainiuk *et al.* 2025).

Traditional remediation methods, such as excavation, soil washing, chemical stabilisation, or cement-based solidification,

are often economically prohibitive and ecologically disruptive, particularly when applied over extensive areas, as revealed in the work of Shen *et al.* (2019). As presented in the study by Delgado-Baquerizo *et al.* (2025), such approaches may irreversibly alter soil functions and biodiversity, conflicting with long-term land restoration goals. Consequently, there is increasing interest in nature-based and biologically driven remediation strategies that combine environmental safety, cost-effectiveness, and scalability (Rylott and Bruce, 2019). Because new compounds like 2,4-dinitroanisole (DNAN) are the main component in modern, safer explosive mixtures used in artillery and mortar systems, and are still emerging in the environment, research is ongoing to find ways to remediate contaminated soil (Novakovska, Belousova and Hunko, 2025), including the potential use of plants and microbes and phytoremediation measures, as mentioned in the study by

Melnychenko (2024). Furthermore, modern nitrocellulose-based propellant mixtures employ new stabilisers, such as copper compounds n-butyl-nitratoethylnitramine (Bu-NENA) and magnesium hydride (MgH_2), which increase stability and reduce thermal and mechanical sensitivity, requiring a modern environmental approach (Fernandez-Lopez, Posada-Baquero and Ortega-Calvo, 2022). Even more problematic and unpredictable remains the presence of unexploded ordnance (UXO) and land mines from armed conflicts, according to a report to Congress on UXO clearance in Ukraine (U.S. Department of State, 2025), USA, UXO continues to present a significant risk to soil quality and land use due to soil contamination with explosive residues and heavy metals.

Biopolymers and biological remediation techniques have gained attention as promising tools for soil and water restoration (Chang *et al.*, 2020; Zhang and Liu, 2023). Biopolymers can immobilise contaminants, reduce erosion, enhance water retention, and serve as matrices for beneficial microorganisms, while biological agents are capable of transforming or degrading toxic compounds, as emphasised in the study by Alam *et al.* (2025). The work by Geris *et al.* (2024) also shows the principle of soil mycoremediation, where the role of fungi is remarkably effective in the decomposition of difficult-to-decompose compounds (e.g. explosives) often found in soils after conflicts. This review synthesises current knowledge on biopolymer-based, biological, and photocatalytic remediation strategies and critically evaluates their applicability to post-war environmental recovery in Ukraine (Khvesyk and Ilina, 2023), with particular emphasis on contaminated soil and water systems. Beyond summarising existing remediation principles, the primary objective of this work is to develop a structured decision-making and experimental roadmap for selecting, adapting, and validating the most suitable remediation approaches under diverse post-conflict environmental conditions. This roadmap is intended to guide future laboratory

research, pilot-scale implementation, and policy-oriented restoration planning by linking contaminant type, site conditions, material functionality, and ecological safety to practical remediation design.

While various remediation strategies exist independently, their synergistic potential for war-impacted zones remains poorly defined. Therefore, the primary objective of this review is not only to synthesise current knowledge on biopolymer-photocatalytic interfaces but also to establish a structured, evidence-based experimental roadmap. By integrating laboratory screening with field-scale validation pathways, this work aims to provide a decision-making framework for selecting and adapting nature-based remediation principles specifically tailored to the heterogeneous contamination profiles of post-war environments.

MATERIALS AND METHODS

MAJOR CONTAMINANTS IN POST-WAR SOIL AND WATER

Post-war environments are characterised by heterogeneous contamination profiles reported in work Broomandi *et al.* (2020). Heavy metals such as lead, cadmium, copper, nickel, and zinc originate from ammunition, destroyed vehicles, and industrial facilities. Petroleum hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) are released from fuel storage sites, military equipment, and damaged transport infrastructure. In addition, residues of explosives (e.g., 2,4,6-trinitrotoluene (TNT), 1, 3, 5-trinitro-1, 3, 5-triazacyclohexane (RDX)) and elevated nutrient loads may enter soils and waters, posing risks to ecosystems and human health as represented in Table 1.

Modern conflicts introduce not only conventional contaminants such as heavy metals and hydrocarbons but also emerging pollutants including PFAS and depleted uranium

Table 1. Major contaminants of post-war soils and waters in Ukraine

Contaminant group	Typical sources	Environmental risks
Heavy metals (Pb^{2+} , Cd^{2+} , Ni^{2+} , Cu^{2+})	ammunition fragments, damaged vehicles, industrial debris	toxicity, bioaccumulation, soil ecosystem disruption (Dmytrukha, Kozlov and Herasimova, 2024)
Petroleum hydrocarbons and PAHs	fuel spills, military machinery, damaged storage facilities	carcinogenicity, persistence, oxygen depletion in aquatic systems (Xia <i>et al.</i> , 2020)
Explosives residues (TNT, RDX)	military operations, unexploded ordnance, demolition activities	acute and chronic toxicity to soil organisms and aquatic life (Bernstein and Ronen, 2012)
Nutrients (NO_3^- , NH_4^+)	disturbed soils, agricultural runoff from damaged land	eutrophication and algal blooms in surface waters (Kotsis, 2025)
Fuel oil from decaying shipwrecks	sunken naval vessels and damaged maritime infrastructure	continuous leakage of carcinogenic petroleum compounds contaminating marine sediments and marine food webs (Shcherbakov <i>et al.</i> , 2025)
PFAS	firefighting foams, military equipment, industrial materials used during conflicts	highly persistent “forever chemicals”, endocrine disruption, immune toxicity, groundwater contamination (Koban and Pfluger, 2023)
Depleted uranium residues	armour-piercing munitions and military equipment	radiological and chemical toxicity, long-term soil and groundwater contamination (Kuzmanović <i>et al.</i> 2025)

Explanations: PAHs = polycyclic aromatic hydrocarbons, TNT = 2,4,6-trinitrotoluene, RDX = 1, 3, 5-trinitro-1, 3, 5-triazacyclohexane, PFAS = per- and polyfluoroalkyl substances.

Source: own elaboration based on the literature.

residues. Additionally, deteriorating shipwrecks and damaged maritime infrastructure can release petroleum fuels for decades, representing a persistent source of marine contamination.

BIOPOLYMER-BASED REMEDIATION APPROACHES

Biopolymers are natural or biodegradable polymeric materials derived from renewable resources, as reported in an investigation (Jha *et al.*, 2024). Due to the presence of functional groups such as hydroxyl, amino, and carboxyl groups, these materials can interact with contaminants, soil particles, and water molecules. As a result, biopolymers have gained increasing attention in environmental remediation applications, particularly in the treatment of contaminated water and soil systems. Their advantages include environmental compatibility, biodegradability, and potential for recycling and reuse, making them an attractive alternative to conventional synthetic polymers (Kumar, Yadav and Raj, 2024). Various biopolymers have been investigated for pollutant removal, adsorption processes, and stabilisation of contaminated soils, even potentially applicable for uranium recovery from seawater, as presented in the work of Hamza *et al.* (2022). The most commonly used biopolymers for environmental remediation are summarised in Table 2.

Biopolymers can reduce contaminant mobility, enhance soil aggregation, and improve water availability, particularly in degraded or sandy soils. However, they typically immobilise rather than destroy pollutants, which highlights the importance of combined strategies (Colmenares, Varma and Lisowski, 2016).

BIOLOGICAL ALTERNATIVES TO BIOPOLYMER-BASED REMEDIATION

Biosorption

Biosorption, as an ecofriendly biological process, relies on the passive binding of contaminants by biological materials such as microbial biomass (Tsytlishvili, 2025), algae, or biochar-supported biofilms (Wu *et al.*, 2025). Functional groups on cell walls enable efficient uptake of metal ions and organic compounds.

Biodegradation and biotransformation

Microbial biomass such as *Pseudomonas*, *Rhodococcus*, *Bacillus* and *Streptomyces*, as well as culture fluids released into the soil, can metabolise petroleum hydrocarbons and some explosive

residues, as presented in the study by Ghadge *et al.* (2026). Fungal enzymes (e.g., *Laccases*, *Peroxidases*) further enhance the degradation of recalcitrant organics (Biliavska *et al.*, 2024).

Phytoremediation

The study by Kafle *et al.* (2022) demonstrated that heavy metals, organic pollutants, radionuclides, and antibiotics can be detoxified using plants. Plants contribute through phytoextraction, phytostabilisation, and rhizodegradation, as, for instance, in the study by Burdová *et al.* (2025). Their effectiveness can be improved by biopolymers that retain moisture and support rhizosphere microbial communities (Didenko, 2024). The work of Fernández-López *et al.* (2024) presents perspectives on methods for the restoration of soils contaminated by military activities, as well as bioremediation strategies to reduce the hazards associated with chemical pollution.

Well-known removal mechanisms for water and soil restoration by wetland for post-war restoration were described in the study by Spieles (2022). In their works, Shevchuk *et al.* (2023) and Didur *et al.* (2025) propose post-war ecosystem restoration in Ukraine; pathways and strategies towards sustainable and resilient environmental recovery have been presented by Melnykovich *et al.* (2026).

RESULTS AND DISCUSSION

HYBRID BIOPOLYMER-PHOTOCATALYST MECHANISM FOR ADVANCED WATER REMEDIATION

Onotri *et al.* (2017) presented a methodology utilising solar photocatalytic processes for treating washing soil, which faced economic restrictions, while Sokolsky (2024) introduced a novel approach to photocatalytic methods in post-war restoration. As shown in the work of Alzahrani, Alamry, and Hussein (2025), biopolymers have potential military use and environmental implications, highlighting the need for continued research and investment to enhance their feasibility and effectiveness (Tazwar *et al.*, 2026). In addition, the study by Fouda-Mbanga, Prabakaran and Pillay (2021) presented the possibility of regeneration and reuse of spent carbohydrate biopolymer adsorbents for the removal of heavy metals (Cd^{2+} , Pb^{2+} , Zn^{2+}) from wastewater. Combining photocatalysis with biopolymer agents enhances

Table 2. Biopolymers used for soil and water remediation

Biopolymer	Primary function	Target contaminants	Advantages	Limitations
Chitosan	adsorption, flocculation	heavy metals, dyes	high adsorption affinity, biodegradable, non-toxic	pH sensitivity
Alginate	encapsulation, immobilisation	heavy metals, organic pollutants	mild processing conditions, good gel formation	limited mechanical strength
Xanthan gum	soil stabilisation	soil erosion, metal mobility	improves soil structure and stability	limited sorption capacity
Guar gum	water retention, soil conditioning	drought-affected soils	low cost, biodegradable, improves water retention	rapid biodegradation under certain conditions
Lignin	adsorption and photocatalyst support	organic pollutants, heavy metals	renewable and abundant, high adsorption capacity due to phenolic functional groups	limited water solubility, impurities from different sources may affect performance

Source: own study.

remediation efficiency (Xisto *et al.* 2024). In their study, Estrada-Vázquez *et al.* (2024) recommend the use of support for the catalyst by biopolymers for degradation of agricultural pollutants. In the present study, a portable water purification system with cylindrical porous ceramic filters coated with biopolymer Pr-doped-TiO₂ composites (Tsytlshvili, 2026) integrated into solar-driven photoreactor is presented, which is based on the principle of synergistic interactions between pollutant adsorption, reactive oxygen species generation, and mass transport within hybrid photocatalytic systems – simultaneous immobilisation of inorganic pollutants and photocatalytic mineralisation of persistent organics under solar irradiation. Technologically, we will develop a novel class of multifunctional treatment materials based on biopolymer-immobilised photocatalytic foam filters (Figs. 1–2).

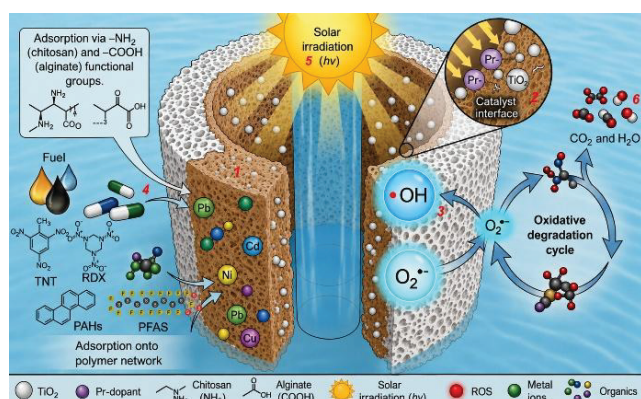


Fig. 1. Hybrid biopolymer-photocatalyst mechanism for advanced water purification; PAHs, TNT, RDX, PFAS as in Tab. 1; 1 = polymer network, 2 = Pr-doped TiO₂ nanoparticles, 3 = generated reactive oxygen species (ROS), 4 = degradation of contaminants, 5 = solar irradiation, 6 = inorganic metabolites; source: own study



Fig. 2. Visualisation of biopolymers on a photocatalytic foam filter: xanthan gum, guar gum, chitosan, sodium alginate and lignin; source: own study

The mechanism of hybrid photocatalysis is realised on a layer of TiO₂ nanoparticles, which serves as an adsorption support for the biopolymer hydrogel matrix. Organic pollutants are captured by the polymer network via the -NH₂ and -COOH functional groups (1), increasing their local concentration on the catalyst surface, where reactive oxygen species generated under the influence of light promote their oxidative degradation and

mineralisation. A hydrogel layer will deposit onto praseodymium doped titanium dioxide nanoparticles (Pr-doped TiO₂) coated aluminium foam (2) via dip-coating followed by alkaline gelation. Solar irradiation activates TiO₂ and generated reactive oxygen species (ROS) – hydroxyl radicals (•OH) and O₂^{•-} (3); the resulting biopolymer-photocatalyst composite will be evaluated for photocatalytic degradation of contaminants (4) under solar irradiation (5) into smaller inorganic compounds such as water and carbon dioxide (6). Adsorption-photocatalysis synergy was assessed by comparing removal efficiency with control systems. Additionally, key benefits of biopolymers include preventing TiO₂ leaching, increasing contact with contaminants, reducing charge recombination, and stabilising nanoparticles.

In addition to chitosan and lignin, other natural polysaccharides such as xanthan gum, guar gum, and sodium alginate can significantly enhance the stability and performance of hybrid photocatalytic systems for water remediation.

Chitosan will enhance pollutant capture through electrostatic interactions with contaminant molecules, lignin will improve visible-light activity by facilitating electron transfer and narrowing the band gap, and guar gum will provide mechanical durability while preventing catalyst leaching during continuous flow operation. The resulting system will operate through a synergistic “catch-and-kill” mechanism, where pollutants are first adsorbed, then oxidatively degraded under light irradiation, and finally removed through *in situ* regeneration of adsorption sites.

Xanthan gum functions primarily as a rheological stabiliser and matrix-forming biopolymer. Due to its highly branched polysaccharide structure containing carboxyl and hydroxyl functional groups, xanthan gum can create a viscous hydrogel network that immobilises photocatalytic particles while improving pollutant adsorption. The negatively charged functional groups promote electrostatic interactions with cationic contaminants and enhance mass transfer of pollutants toward active photocatalytic sites.

Guar gum, a galactomannan polysaccharide derived from guar beans, contributes to the mechanical reinforcement and structural stability of the composite material. Its strong hydrogen-bonding capability allows it to form stable polymeric films or gels on porous substrates such as ceramic or metallic foam filters. In photocatalytic systems, guar gum improves catalyst retention, prevents nanoparticle aggregation, and enhances the durability of the catalytic layer during long-term continuous flow operation.

Sodium alginate, extracted from brown algae, plays a critical role in forming highly porous hydrogel structures capable of encapsulating photocatalysts. In the presence of divalent cations such as Ca²⁺, sodium alginate forms a three-dimensional crosslinked network that immobilises catalytic particles and provides a high surface area for pollutant adsorption. The abundance of carboxylate groups in alginate enhances the binding of metal ions, antibiotics, and organic pollutants, thereby increasing local pollutant concentration near photocatalytically active sites and improving degradation efficiency.

Together, these biopolymers can create multifunctional hydrogel-supported photocatalytic architectures, where the biopolymer matrix provides adsorption, structural stability, and mass transfer control, while the semiconductor catalyst (Pr-doped TiO₂) performs oxidative degradation under visible light irradiation. This integrated approach enables a synergistic “adsorb-

concentrate-photodegrade” mechanism, improving contaminant removal efficiency while minimising catalyst loss and enabling sustainable water treatment technologies.

Contrastive conventional powdered catalysts that require complex post-treatment separation, as shown in the critical review by Ahmadi *et al.* (2025), are open-cell ceramic foam filters that will serve as stable three-dimensional scaffolds enabling high flow rates, low pressure drop, and efficient light penetration. Immobilisation of photocatalysts within a chitosan-lignin-guar gum hydrogel matrix will create a “smart filter” capable of simultaneous adsorption, photocatalytic degradation, and structural stabilisation. This research vector can be implemented and associated with strategic ways of post-war restoration (Lavrenko *et al.* 2025).

Overall, the project is expected to deliver a scalable, energy-efficient, and environmentally safe hybrid photocatalytic technology capable of significantly improving pollutant removal from wastewater while addressing key limitations of current advanced oxidation processes. Such integrated systems are particularly suitable for large-scale, low-intensity restoration efforts. Therefore, long-term planning based on the IUCN Global Standard for Nature-based Solutions (IUCN, 2020) and the recommendations of Nelson *et al.* (2024) is essential to ensure the long-term sustainability and effectiveness of ecosystem restoration efforts.

EXPERIMENTAL ROADMAP AND IMPLICATIONS FOR POST-WAR RECOVERY IN UKRAINE

The results and discussion section is structured not only to evaluate individual remediation mechanisms but also to translate these principles into an adaptive experimental and implementation roadmap for post-war environmental restoration. The transition from conventional remediation to advanced hybrid systems requires a systematic evaluation of material performance and environmental applicability. Following the analysis of individual biopolymer functions, biological remediation pathways, and photocatalytic mechanisms, this section integrates these

findings into a unified framework for remediation design. By comparing and synthesising these approaches, the review identifies how different remediation components can be selected, integrated, and optimised according to contaminant profiles, environmental matrices, and field-scale constraints. In particular, the “catch-and-kill” mechanism of hybrid biopolymer-photocatalysts, as presented in Figure 1, is the core operational principle supporting a staged implementation strategy, progressing systematically from laboratory-scale material screening and process optimisation to pilot studies and modular field deployment in war-impacted environments. This framework supports the development of scalable, environmentally safe, and application-oriented remediation strategies for the restoration of contaminated ecosystems.

A staged experimental approach is essential for validating biopolymer-photocatalytic hybrid system remediation strategies and ensuring their successful transition from laboratory research to field-scale application (Fig. 3). Initial laboratory experiments focus on evaluating the adsorption capacity, photocatalytic activity, and degradation kinetics of biopolymer-based materials under controlled conditions. These tests allow optimisation of material composition and operating parameters.

The next stage involves intermediate-scale experiments using flow-through systems that simulate real environmental conditions. These studies assess pollutant removal efficiency, hydraulic performance, and catalyst stability under continuous operation. Comprehensive regeneration and reuse of biopolymer adsorbents will be conducted. Acute phytotoxicity and biotoxicity testing of purified water will also be performed.

Finally, field-scale implementation should focus on the deployment of modular treatment units capable of operating in contaminated environments. Such systems may include immobilised photocatalytic foams, hydrogel-based filtration units, or solar-driven reactors designed for decentralised remediation. Field validation is crucial for assessing long-term performance, environmental safety, and cost-effectiveness under real environmental conditions.

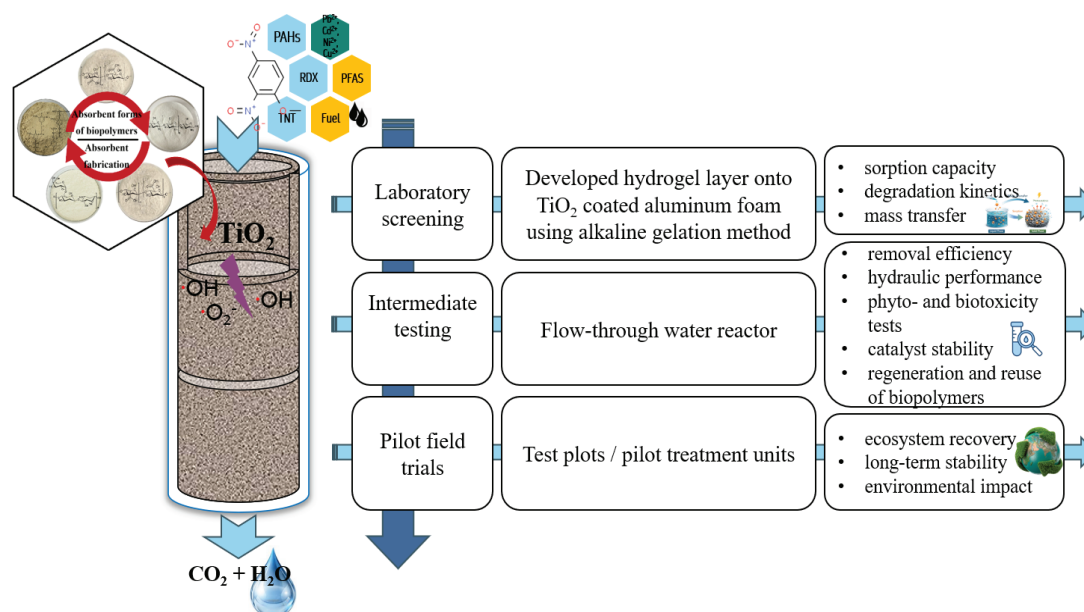


Fig. 3. Experimental roadmap from laboratory screening to field-scale application; PAHs, TNT, RDX, PFAS as in Tab. 1; source: own study

CONCLUSIONS

Environmental degradation caused by armed conflicts is becoming an increasingly serious global problem, leading to severe contamination of water and soil resources with fuels, heavy metals and other persistent pollutants, affecting biodiversity and human health. The restoration of these ecosystems requires innovative, efficient, and sustainable remediation technologies capable of addressing complex contaminant mixtures under diverse environmental conditions. This review highlights the potential of biopolymer-photocatalytic hybrid systems as promising solutions for the remediation of war-impacted environments.

Biopolymers derived from renewable resources, including chitosan, alginate, lignin, xanthan gum, and guar gum, offer several advantages such as biodegradability, low toxicity, and the presence of functional groups that enhance adsorption and interaction with contaminants. When integrated with semiconductor photocatalysts such as titanium dioxide (TiO₂), these materials form multifunctional hybrid systems capable of simultaneously capturing pollutants and degrading them through photocatalytic oxidation. This synergistic adsorption-photocatalysis mechanism enhances contaminant removal efficiency while stabilising the photocatalyst and reducing the risk of nanoparticle release.

Recent advances in materials engineering have enabled the development of diverse hybrid configurations, including hydrogels, immobilised foam filters, and composite nanostructures. These systems demonstrate promising capabilities for degrading pharmaceuticals, organic pollutants, and heavy metals in both water and soil matrices. Such hybrid technologies are particularly relevant for post-conflict environmental restoration, where rapid, adaptable, and decentralised treatment solutions are often required.

However, several challenges remain before large-scale implementation can be achieved, including improving visible-light photocatalytic activity, enhancing long-term material stability, optimising reactor design for field applications, and ensuring environmental safety and cost-effectiveness. The experimental roadmap proposed in this review highlights future research directions such as smart biopolymer matrices with tunable properties, solar-driven photocatalytic systems, and modular treatment units for contaminated regions.

Overall, biopolymer-photocatalytic hybrid technologies represent a promising pathway toward sustainable restoration of water and soil resources in war-affected environments.

CONFLICT OF INTERESTS

The author declares no conflict of interests.

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