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A Review On the Application of Nano-Based Materials for Environmental Remediation and Treatment of Infections

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Abstract— Nanomaterials have emerged as a frontier in applied science, offering innovative solutions in both environmental remediation and biomedical applications. Due to their high surface area, and enhanced reactivity at the nanoscale, nanomaterials exhibit superior antimicrobial efficacy and pollutant interaction capabilities. In healthcare, these materials are incorporated into creams, nail lacquers, ear drops, and dental composites, significantly improving treatment outcomes for infections in hard-to-reach areas such as nails, ears, and oral cavities. Nano-capsule-based formulations enhance drug delivery, bioavailability, and controlled release, particularly in conditions such as onychomycosis and diabetic foot ulcers. From an environmental standpoint, nanomaterials are equally impactful. Their ability to adsorb, degrade, or transform pollutants makes them critical in soil remediation. Various synthesis techniques such as top-down (e.g., mechanical milling, laser ablation) and bottom-up (e.g., sol-gel, green biosynthesis using plant extracts) are continually refined to improve efficiency, scalability, and environmental safety. This paper underscores the interdisciplinary relevance of nanomaterials and their applications in health sciences and environmental sciences.

Keywords: *Nanomaterials, Environmental remediation, Biomedical applications, Antimicrobial efficacy, Drug delivery systems, Green synthesis.*

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1. Introduction

Nanomaterials are defined as materials possessing at least one external dimension or internal/surface structure within the nanoscale range of 1 to 100 nanometers [1]. This category includes nano-objects such as nanoparticles, nano-rods, and nano-plates as well as nanostructured materials that exhibit internal architectures at the nanoscale. Due to their extremely small size, nanomaterials often exhibit novel physicochemical properties compared to their bulk counterparts. These include enhanced surface reactivity, size-dependent quantum effects, and superior mechanical, optical, and electrical behaviors [2].

The European Commission classifies a material as a nanomaterial when 50% or more of the particles by number fall within the 1–100 nm range. In certain regulatory contexts, this threshold may be adjusted to 1–50% due to specific environmental or health concerns [3], [4]. Based on elemental composition, nanomaterials can be broadly categorized into organic, inorganic, or hybrid types [5], and further classified based on structure, origin, morphology, porosity, and toxicity [2], [6]. Their unique properties have positioned nanomaterials at the forefront of innovation across diverse sectors, including medicine, energy, electronics, and environmental remediation [2], [7]. Synthesis strategies are typically divided into top-down and bottom-up approaches. Top-down methods such as ball milling, laser ablation, and lithography break down bulk materials into nanoscale units, whereas bottom-up techniques like sol-gel synthesis, chemical vapor deposition, pyrolysis, and green biosynthesis involve atom-by-atom or molecule-by-molecule assembly [2], [7].

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Although the formal discipline of nanoscience emerged only in recent decades, the use of nanostructured materials can be traced back to antiquity. Examples include asbestos-reinforced ceramics in Mesopotamia, lead sulfide-based cosmetics in ancient Egypt, and the Lycurgus Cup of the Roman Empire, renowned for its dichroic optical properties arising from embedded gold and silver nanoparticles [8]. Nanomaterials with high surface area and adsorption capacity have shown remarkable potential for environmental remediation, particularly in the removal of heavy metals, organic pollutants, and pathogens from water and soil [9]. In healthcare, metal-based nanoparticles, such as silver, copper, and zinc oxide, have demonstrated potent antimicrobial activity by generating reactive oxygen species, disrupting cell membranes, and interfering with microbial Deoxyribonucleic Acid replication [10]. These properties have led to their incorporation into wound dressings, coatings, and personal care products.

Despite these advances, research on multifunctional nanomaterials capable of addressing both biomedical and environmental threats remains limited. Additionally, concerns persist regarding their long-term toxicity, environmental persistence, and challenges in large-scale production, particularly for inorganic and metal-based nanoparticles. These limitations highlight the need for interdisciplinary research that balances efficacy with safety and sustainability.

2. Method

This review is based on an extensive search of peer-reviewed literature on nanomaterials and their biomedical and environmental applications. Sources were retrieved primarily from reputable scientific databases such as PubMed, Scopus, Web of Science, Google Scholar, and ScienceDirect. Keywords used included: *"Nanomaterials," "Environmental remediation," "Biomedical applications," "Antimicrobial efficacy," "Drug delivery systems," "Green synthesis"*. Selection was limited to studies published between 2011 and 2023, with emphasis on recent advancements. Articles were chosen based on relevance, clarity of data, and credibility of experimental or review design. Preference was given to open-access journals, high-impact factor publications, and review articles to provide a comprehensive yet focused synthesis.

3. Results and Discussion

3.1 Nanoscience in Environmental Remediation

Human activities continue to degrade environmental quality; however, nanostructured materials offer promising sustainable alternatives. In the energy sector, nano-catalysts have been shown to improve fuel combustion efficiency and reduce greenhouse gas emissions by facilitating oxygen storage and release during combustion. Similarly, nano-lubricants and nano-coatings lower engine friction, thereby decreasing carbon emissions. Beyond fossil fuel optimization, nanotechnology significantly enhances renewable energy systems such as biofuels, hydrogen cells, and solar technologies, reducing global dependence on conventional energy sources [11].

In environmental remediation, specific nanomaterials have demonstrated the ability to break down pollutants, such as industrial dyes in wastewater, and to absorb greenhouse gases, thereby supporting climate change mitigation. In architecture, nanostructured materials are being integrated into construction elements such as windows, roofs, coatings, and insulation materials. Innovations including nano-glass, carbon nanotubes, nano-silica, and polymer-based nanocomposites are currently improving energy storage, solar energy conversion. They may enable refrigerant-free cooling, highlighting the potential of nanotechnology in driving green and sustainable building design [12]. This indicates that nanotechnology is not only reducing emissions but also reshaping sustainable design practices across multiple industries

i. **Nanoscience as a remedy to water pollution:** Human activities such as industrialization, urbanization, and agricultural expansion contribute significantly to surface water contamination. These water bodies often receive direct discharges of untreated or inadequately treated wastewater, including sewage, greywater, and industrial effluents. Such discharges typically contain pathogens, pharmaceutical residues, toxic metals, and a wide array of organic

pollutants ranging from micro-pollutants and emerging contaminants to xenobiotic compounds [13], [14]. Advanced oxidation processes, particularly photo-catalysis, have been widely studied for degrading these pollutants into less harmful substances such as carbon dioxide and water, evidenced by reductions in total organic carbon. Nanotechnology further enhances wastewater treatment through the use of functionalized nanoparticles (nano-adsorbents) engineered for targeted removal of heavy metals, dyes, pesticides, and toxins. Zeolites, known for their affordability and excellent adsorption capacity, are commonly employed as molecular sieves, ion exchangers, and catalysts in water treatment [15], [16]. Additionally, polymer-based nano-adsorbents offer broad-spectrum remediation, effectively removing pathogens, microorganisms, and persistent organic contaminants [17].

ii. **Nanoscience as remediation for oil spills:** Nanotechnology has also shown considerable promise in oil spill remediation through the development of novel materials such as membranes, filters, sponges, and dispersants. Although oil is not inherently magnetic, the use of iron-doped, water-repellent nanoparticles enables magnetic separation of oil from water, allowing for efficient recovery and potential reuse. The effectiveness of this approach is influenced by several factors, including the material's adsorption capacity, selectivity for organic compounds, and sorption rate, of surface chemistry to target specific pollutants [18]. Commonly used nanomaterials for such applications include nano zero-valent iron, carbon nanotubes, aerogels, nanocomposites, sponges, and zeolites, each offering unique advantages in sorption efficiency, environmental compatibility, and reusability [19]. Comparatively, magnetic nanomaterials like iron-doped particles allow easier recovery, but cost and environmental safety are still being evaluated.

3.2 Nanoparticles in Medical Sciences

Throughout history, humans have sought cures for disease and injury, and today, nanotechnology presents new possibilities in modern medicine. Medical nanotech employs precisely engineered nanoscale devices and structures to monitor, repair, regulate, and protect biological systems at the molecular level [20].

Chemotherapy administration: Nanotechnology has emerged as a powerful tool in cancer therapy by enabling the targeted delivery of anticancer drugs to tumor sites. This targeted approach significantly improves drug pharmacokinetics and minimizes systemic toxicity, which is often a major drawback of conventional chemotherapy. The ability to tailor the size and surface properties of nanoparticles plays a critical role in enhancing drug bioavailability and cellular uptake. Notably, the efficiency of nanoparticle-based delivery systems is closely linked to particle size, which influences their circulation time and accumulation at tumor sites via the enhanced permeability and retention effect. Beyond drug delivery, nanoparticles are also employed in molecular imaging, facilitating the detection of genetic mutations and the study of functional characteristics of cancer cells [21]. These advances demonstrate Nano-medicine's potential for precision therapy, although more clinical trials are needed to validate safety across populations.

i. **Nano-bots:** Nano-bots, microscopic robotic systems typically sized between 50 to 100 nanometers, are designed to perform precise biomedical tasks at the cellular and molecular levels. One of their most innovative applications lies in targeted drug delivery, where they can selectively identify and attack diseased cells, particularly cancer cells, while minimizing damage to surrounding healthy tissue. Smart pills embedded with nano-bots not only enhance therapeutic precision but also enable real-time data transmission, facilitating personalized treatment and continuous monitoring. Furthermore, nanotechnology is transforming diagnostic procedures by enabling in-vitro diagnostics that are more accessible, cost-effective, and less invasive than traditional methods [22]. This shift toward nano-assisted diagnostics promises broader access to healthcare, especially in resource-limited settings.

ii. **Treatment of wounds:** Tissue regeneration is vital in reconstructive and transplant medicine, especially after illness or injury. Research now focuses on replicating tissue structure and function using nanotechnology, which harnesses the unique properties of materials at the

nanoscale that differ from their bulk forms. Because the nanoscale aligns with many biological processes, it enables precise interaction with Deoxyribonucleic Acid and targeted drug delivery. Nanoscience supports personalized therapies by manipulating proteins and other biological structures at the molecular level, offering more effective treatments with fewer side effects [23].

3.2.1 Nanomaterials for Treatment of Infections

3.2.1.1 Nanomaterial for Nail Infection

Nano-capsules

Nano-capsules are nanoscale carriers used in drug delivery systems, typically consisting of a central core, either solid or liquid, encased within a polymer-based shell. The core often contains a lipophilic solvent, such as oil, which is ideal for enclosing hydrophobic or lipophilic drugs. Commonly used synthetic polymers in nano-capsule formulations include poly (lactic acid) and poly(lactide-co-glycolide). Delivering antifungal agents through nano-capsules allows for controlled drug release, improved antifungal activity, and enhanced penetration. Several studies have explored the effectiveness of nano-capsules in treating onychomycosis.

[24] developed and assessed nano-capsules and nano-emulsions containing Melaleuca alternifolia (tea tree oil) in a model of onychomycosis. The formulations were tested against Trichophyton rubrum using two models, and the fungal colony diameter was measured to evaluate effectiveness. Results showed that the nano-capsules with tea tree oil exhibited superior antifungal activity and improved cellular penetration compared to other formulations. In another study, pullulan-based nail formulations containing nano-capsules demonstrated favorable viscosity for nail application and showed reduced skin irritation compared to free drugs and commercial treatments [25]. These formulations were considered promising for onychomycosis therapy. Additionally, studies involving confocal microscopy and fluorescent markers like Nile Red investigated drug penetration into the nail plate. A formulation containing tioconazole-loaded nano-capsules achieved deeper and more prolonged drug delivery, with penetration depths of 90–160 μm observed after seven days. Enhanced nail poration further improved the permeability of these nano-capsule systems [26].

3.2.1.2 Nanomaterials for Toe Infection

Diabetes mellitus

Diabetes mellitus is a major chronic metabolic disorder that leads to several complications, one of the most serious being diabetic foot ulcers. These ulcers affect approximately 15–30% of individuals with diabetes, and this prevalence is expected to grow in the coming years [27]. Diabetes mellitus presents significant treatment challenges, including persistent infections, impaired inflammatory responses, hindered angiogenesis, and inadequate extracellular matrix components.

Nano-emulsions

Nano-emulsions colloidal dispersions with nanoscale droplet sizes are emerging as effective nanotechnology based delivery platforms for topical treatments. Their advantageous physicochemical characteristics and high patient tolerance make them suitable for wound care, particularly in diabetic wound healing [28]. Recent advancements highlight the efficacy of nano-emulsion-based therapeutics in promoting skin repair.

[29] developed a topical gel containing homogenized Aloe-vera gel and an insulin loaded nano-emulsion composed of oleic acid, polyethylene glycol 400, and Tween 80. This formulation demonstrated excellent permeation, spread ability, and stability. In diabetic rat models, the treated groups exhibited significant antidiabetic effects ($p < 0.001$) and a notable increase in wound contraction (up to 75%). Histological analysis confirmed improvements in tissue architecture. Furthermore, the gel formulation was non-toxic and safe for topical use, showing no signs of irritation. The combined action of insulin and Aloe vera in the nano-emulsion gel proved effective in accelerating wound closure, positioning it as a promising approach for managing diabetic wounds.

Nano-liposomes

Nano-liposomes are nano-sized vesicles known for their biocompatibility, safety, and effectiveness in drug delivery. Their use spans several fields, including cancer therapy, diagnostics, gene delivery, agriculture, and wound healing [30]. In wound treatment, nano-liposomes offer targeted

delivery and improved bioavailability of therapeutic agents. [31] Investigated the role of adenosine triphosphate-loaded nano-liposomes and found that they modulate gene expression involved in wound healing. Through ribonucleic acid sequencing, they observed an upregulation of noncoding ribonucleic acids, particularly U1 small nuclear ribonucleic acid and U1 spliceosome ribonucleic acid, after treatment with adenosine triphosphate-loaded nano-liposomes. These ribonucleic acids accelerate pre-ribonucleic acid splicing, ultimately leading to increased protein synthesis. The outcome is enhanced epithelialization, neovascularization, macrophage activity, and cell proliferation, all vital to effective wound repair.

Furthermore, adenosine triphosphate-loaded nano-liposomes overcome the cell membrane barrier, enabling intracellular adenosine triphosphate delivery and promoting energy metabolism in cells. This capability boosts mitochondrial function and speeds up healing in diabetic wounds. The study concludes that nano-liposome-based Adenosine Triphosphate delivery holds promise in modulating the extracellular matrix and improving macrophage infiltration at the wound site, making it a potent strategy for enhancing diabetic wound healing.

3.2.1.3 Nanomaterials for Ear Infection

The inner ear is highly susceptible to infections caused by viruses, bacteria, or fungi. If not promptly managed, these infections can result in hearing impairment or potentially spread through the temporal bone, leading to serious intracranial complications. Treating inner ear infections remains a significant clinical challenge due to the organ's deep anatomical location, which limits effective drug delivery. To address this, the application of nanoparticles has emerged as a promising therapeutic strategy. Various types of nanoparticles, including inorganic, lipid-based, and polymeric formulations, have been developed and evaluated. These nano-carriers have demonstrated success in achieving controlled drug release, enhancing uptake by target cells, and minimizing systemic side effects [32].

Lipid Nanoparticles

Various lipid-based nanoparticles have been explored for drug delivery to the inner ear [33]. Among them, lipid core nano-capsules, solid lipid nanoparticles, and phospholipid based nanoparticles are particularly promising due to their biocompatibility and ability to carry both hydrophilic and lipophilic therapeutic agents [33], [34]. Lipid-based nanoparticles typically feature a central lipid phase composed of triglycerides or mineral oils, encapsulated by a shell containing lecithin, polyethylene glycol, or poloxamers for stabilization [35-37]. These nanoparticles can be engineered to deliver hydrophobic drugs with controlled release kinetics [35]. Research has demonstrated their ability to penetrate the round window membrane and distribute within various cell populations of the inner ear, supporting their therapeutic potential for treating inner ear infections [37].

Solid Lipid Nanoparticles, another type of lipid-based nanoparticle, have also shown potential for inner ear drug delivery [38]. These submicron carriers offer high drug loading and favorable phase interactions, contributing to enhanced drug performance [39]. As they consist of lipids that remain solid at body temperature, SLNs allow for better drug stability and controlled release than liquid systems [33]. Additionally, Solid Lipid Nanoparticles can protect cochlear tissues and improve drug bioavailability in vivo [40]. Furthermore, Solid Lipid Nanoparticles loaded with antibacterial oligonucleotides have shown promise in combating E. coli, presenting a novel alternative to traditional antibiotics [41].

3.2.1.4 Nanomaterials for Tooth Infections

Operative Nano-dentistry and Nano-Glass Ionomers

Nano-glass ionomers are created by incorporating nanoparticles into traditional glass ionomer cements, enhancing properties like polishability, aesthetics, and wear resistance [20]. These improved formulations utilize nano-fillers and nano-clusters to boost mechanical characteristics [20]. As a result, nano-glass ionomers exhibit superior translucency, compressive strength, and elasticity compared to conventional types [42]. Their fluoride-releasing capability makes them particularly effective on surfaces exposed to topical fluoride and in preventing dental caries [43]. Applications of such nanomaterials extend to restorative techniques, core buildups, and treatments requiring high crystallinity and improved mechanical integrity [44], [45]. Bioactive additives like hydroxyapatite and fluorapatite further enhance their functionality [46] with examples including chitosan nanoparticles, nano-hydroxyapatite, and nano-fluorapatite.

Dental Nanocomposites

Dental nanocomposites are advanced materials made by embedding nanoparticles into a matrix, commonly polymers, metals, or ceramics [47]. These nanoparticles are uniformly dispersed in dental resins and coatings, improving their mechanical and aesthetic properties. Current research aims to address shortcomings in traditional composites, such as polymerization shrinkage, weak coatings, and poor aesthetic outcomes [47]. Nanocomposites are widely favored in clinical dentistry for their enhanced durability and anti-caries capabilities [48], [49]. Alumino silicate-based nano-fillers are commonly used due to their excellent mechanical and optical characteristics, such as increased hardness, improved flexural strength, translucency, and color retention [50], [51]. These materials are also employed in restorative applications to mimic enamel properties, prevent decay, and support fractured tooth repair through their ion-releasing and structural qualities [52], [53].

4. Conclusion

Nanomaterials represent a rapidly advancing field with transformative potential in medicine, and environmental remediation. The distinctive nanoscale properties of nanomaterials such as high surface area, enhanced reactivity, and quantum effects enable their effectiveness across a wide range of applications, including antimicrobial coatings, dental therapies, water purification, and heavy metal removal. Notably, the overlap in properties that benefit both biomedical and environmental uses underscores the vast, yet underexplored, potential of multifunctional nanomaterials to simultaneously address public health and environmental challenges Despite these advantages, challenges remain. Concerns about toxicity, environmental persistence, and safe disposal limit broader adoption. Moreover, while individual applications of nanomaterials are well-explored, research on multi-functional, dual-purpose nanomaterials remains sparse. Bridging this gap through interdisciplinary research, especially in green synthesis and biocompatibility assessment, is crucial.

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