Review Article

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Environmental Remediation of Antibiotic and Pharmaceutical Pollutants using Phyconanomaterials

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ABSTRACT

Phyconanotechnology, an area of study that looks at the synthesis of nanometals using algae, has recently grown. This can be found in the environment as well as in freshwater. The technique of phycoremediation uses microalgae, macroalgae and cyanobacteria for the degradation of waste or bio information of pollutants. Metals, including gold and metal oxides, silver and titanium oxides, are also used for environmental remediation. Concerns regarding the possible detrimental impacts of ecological pollutants on the biosphere are developing as they have been found and measured in more significant numbers in all three environments namely, air, water, and soil. Due to widespread human consumption and untreated release into the environment, heavy metals and dyes are a significant source of concern. In recent times, there has been an exploration of the potential of nanomaterials to combat environmental pollution. The effectiveness of these materials against various dyes and heavy metals has been demonstrated. Most species have been shown to use mechanisms including biosorption, accumulation, degradation, volatilization, and complexation. The precise mechanism underlying the phycoremediation technique is yet unknown. This article examines environmental contamination, its associated public health risks, and remediation strategies. It also discusses the mechanisms of nanoparticle synthesis and their characterization techniques, with particular emphasis on the role of algal bioactive compounds as reducing, capping, or stabilizing agents in nanoparticle fabrication.

Keywords: Phycoremediation; *Cyanobacteria*; Environmental pollutants; Nanoparticles; Stabilizing agents.

1. INTRODUCTION

Recent studies have demonstrated that one strategy to address global environmental concerns is to use naturally occurring green ingredients in the biogenesis of microalgae-derived nanoparticles. Phyconanotechnology refers to the green synthesis of metal nanoparticles using algae (microalgae, macroalgae, and cyanobacteria), where bioactive compounds such as proteins, polysaccharides, and pigments act as reducing, capping, and stabilizing agents (Chan *et al*. 2022).

Green nanoparticles have gained a lot of attention due to their widespread biocompatibility and vast potential for application as antimicrobials, catalysts, biofuel producers, cancer/gene treatment, and sensitization. The intrinsic qualities of nanomaterials are remarkable because of their unique form, composition, larger volume/superficial area, and constituent purity. There are numerous methods available for creating nanoparticles. Both chemical and physical synthesis techniques are expensive, and also generate hazardous by-products. Out of all the synthesis methods available, the green synthesis techniques show the most significant promise because they use environmentally friendly ingredients to synthesize nanoparticles and do not generate hazardous chemicals or significant waste (Mukherjee, 2021). However, the use of algae as a practical substrate for secure, biocompatible, non-toxic, economical, and ecologically friendly synthesis techniques is gaining traction (Alprol *et al*. 2023). Despite extensive research on the potential applications of marine algae as food, feed, insecticides, additives, and medications, the current paradigm is shifting to algae-mediated green nanoparticle (NP) production. When metal salts are transformed into metal, metal oxide, or bimetallic nanoparticles, the natural substance generated from algae acts as a stabilizing, reducing, or capping agent. Algal biosynthesized NPs have been investigated for their potential applications in medicine due to their excellent and noteworthy physicochemical features. These applications include biocompatibility, free radical scavenging, antifungal, antibacterial, antioxidant and anticancer effects (Alnadhari *et al*. 2021). The use of algae, plants, fungi, and bacteria to eliminate, degrade, or detoxify organic contaminants in aquatic systems has gained attention recently. In marine environments, algae are used in biomonitoring process and management of organic pollutants. Nevertheless, the use of microalgae in the remediation of aquatic environments contaminated by organic matter is still relatively new (Chekroun, 2014). According to (Suresh and Ravishankar, 2004), algae

show promise in both the hyperaccumulation of heavy metals and the breakdown of xenobiotics, which are environmental sustainability benefits from bioremediation by microalgae (Godoy and Sánchez, 2020). The microalgae found in freshwater and saltwater environments are highly productive, taxonomically diversified and significant to ecological world (Zeiler *et al*. 1995). Furthermore, (Bhatt *et al*. 2022) stated that the biomass produced by algae has enormous potential as a feedstock for the manufacture of biofuel. Because microalgae can scavenge metals from pollutants in nutrients, effluent water, and airborne deposition into open ponds, the biomass they produce occasionally contains levels of metals that are too high to be used as food (Priyadarshani, 2012).

Algal nanoparticle synthesis involves both enzymatic and non-enzymatic pathways, with non-enzymatic routes generally dominating in extracellular synthesis (Alnadhari *et al*. 2021). Species like Spirulina, Chlorella, and Sargassum vary in nanoparticle production efficiency and pollutant remediation. Chlorella produces smaller AgNPs while Sargassum excels at biosorption (Mukherjee *et al*. 2021). Environmental conditions (pH, temperature, and light) critically affect the shape, size, and stability of the synthesized nanoparticles. Neutral pH and moderate light yield smaller and stable particles (Chan *et al*. 2022).

2. ROLE OF PHYCONANOMATERIALS IN REMEDIATION

Heavy metals, volatile organic compounds, sand, oil, and grease are all included in the wastewater. Most common method to eliminate environmental pollutants involves neutralizing the reaction with sulphuric acid. Traditional techniques for removing heavy metals from the environment are more costly and less proficient. These techniques typically involve the use of additional chemical substances that have adverse environmental effects. One environmentally safe and friendly approach to ecological recovery is bioremediation. It makes use of the biological processes that are present in both plants and microbes to get rid of dangerous contaminants and bring the ecosystem back to normal. It is an economical method for removal of hazardous waste (Akhere and Chukwuka, 2023).

As an alternative to traditional bio adsorbents, microalgae can be used to absorb heavy metals (Asiandu and Wahyudi, 2021). The photosynthesis of microalgae is crucial to the breakdown of pollutants. The addition of glucose nutrients may improve the development and capacity of microalgae to break down organic contaminants in the treatment of wastewater. Compounds are removed through the processes of biosorption and biodegradation. Microalgae can recycle inorganic fertilizers that leach into agricultural drainage water due to their ability to assimilate nitrogen in the forms of nitrate, nitrite, urea, and ammonium, as well as phosphorus in the forms of polyphosphate and orthophosphate. Furthermore, microalgae can decompose organic waste, eliminate heavy metals, and regulate the quantities of biological and chemical oxygen demand in water bodies (Salah *et al*. 2023). Because of their ability to photosynthesize, transform solar energy into useful biomasses, and absorb elements like phosphorus and nitrogen that cause eutrophication, phycoremediation is an appealing technique (Wurochekke *et al*. 2021).

Phycoremediation uses micro- or macro algae to bio-transform or remove pollutants from wastewater, including harmful compounds and nutrients. There are various applications of phycoremediation namely, (i) nutrient removal from municipal wastewater and organic matter-rich effluents; (ii) utilizing algae-based biosorbents to remove nutrients and xenobiotic chemicals; (iii) treating acidic and metal wastewaters; (iv) storing CO_2; (v) transforming and degrading xenobiotics; and (vi) use of algae-based biosensors for toxic compound detection (Ahmad, 2013).

Monoraphidium braunii, Selenastrum capricornutum, Agmenellum quadruplicatum, Pediastrum tetras, Ankistrodesmus fusiformis and *Amphora coffeaeformis* are among the microalgae utilized in the elimination of organic pollutants (Razak and Sharip, 2020). Algae used in wastewater treatment can also eliminate hydrocarbons, heavy metals, phosphates, and nitrates (Kaloudas, 2021). The procedure involves removing phosphate and nitrogen from wastewater while also giving aerobic bacteria in the culture oxygen. Microalgae's excellent photosynthetic efficiency and growth rates make them a dependable method of biological wastewater treatment. Additionally, microalgae have a high capacity for nutrient uptake and have the ability to remove heavy metals, nitrogen, and phosphorus from wastewater (Emparan, 2019). When used in wastewater treatment, microalgae can guarantee that water is treated without hazardous mixtures and reduce the eutrophication problem. Additionally, wastewater can be used as growth medium for microalgae to rapidly increase biomass production. Consequently, exploring microalgal cultivation in wastewater treatment systems may represent an effective option for tertiary treatment (Moondra, 2021).

3. APPLICATIONS OF PHYCONANOMATERIALS IN ANTIBIOTICS

Many algal strains (microalgae, macroalgae and cyanobacteria) have been used to green synthesize nanoparticles. These organisms consist of bioactive molecules and secondary metabolites. They are capable of acting as capping, stabilizing and reducing agents for manufactured nanoparticles. The materials or products which are prepared from green algae are more efficient,

reliable and renewable. These products are also cost-efficient and environment friendly (Dubey *et al*. 2023).

Fig. 1 represents the properties of algal-based nanoparticles.

The algal nanoparticles have been developed as a connectivity site between biotechnology and nanotechnology, which created vast novel materials and multiple uses. The study reports that easy synthesis methods for the metal nanomaterials occupy the biomaterial extracts source of various reducing agents (Sharma *et al*. 2014). These particles have multiple properties, including characteristics that are mechanical, magnetic, thermal, dielectric, optical, chemical, electronic, electrical, and biological. So, these nanoparticles are used in various fields (Abboud *et al*. 2014). Macroscopic marine algae or seaweeds have the capability of producing hydrocolloids, which are agar and alginates. The macroscopic marine algae include brown algae and red algae, which hold a high scope in cosmetics since there is the presence of minerals, sugar, vitamins, lipids, amino acids and other biological compounds. The environment has been facing the demand for generating eco-friendly products. So, algae and algae-based products play a crucial role in promoting environment-friendly products. Also, these biological components from algae are gradually increasing their importance in various surroundings and also essential uses such as biofuel production, CO_2 segregation, wastewater treatment, oxygen discharge and reducing greenhouse gas effects (Bilal *et al*. 2018). These marine-based nanoparticles have been surveyed over various networks carrying forward the algae-based nanoparticles. These nanoparticle preparations have limited size, shape and structural nature. The algal-based nanoparticles having a limited measurement under 100 nm in the preparation of nanosheets, nanotubes and nanowires have various usages (Alnadhari *et al*. 2021).

4. REMOVAL OF POLLUTANTS USING PHYCONANOMATERIALS

Organic pollutants found in wastewater from a variety of sectors, including dyes, can negatively impact aquatic life and are gravely detrimental to human health, including flora and fauna. These dyes are also resistant to biodegradation. Numerous nanomaterials have been investigated in great detail for the removal of organic contaminants from the aqueous phase. These include graphitic carbon nitride (g-C_3N_4), semiconductors, photocatalysts, carbon-based materials, TiO_2, and ZnO since heavy metals cannot biodegrade.

4.1 Removal of Pollutants *via* Heavy Metals

Heavy metal ions are accumulated in huge quantities by algae, which can also be recycled into more malleable forms. The purpose of algae was to be model organisms for the manufacture of many kinds of nanomaterials, particularly metal nanoparticles, due to their appealing characteristics. After utilizing an algal extract to incubate the parent metallic solution, nanoparticle production begins (Alipour *et al*. 2021).

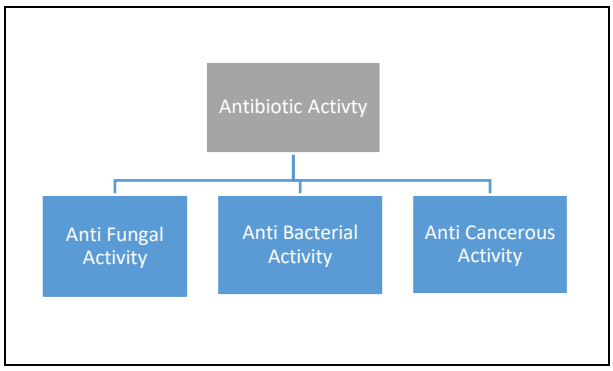


Fig. 1: Algal-based nanoparticles with different antibiotic activities (Source: Khan *et al.* 2022)

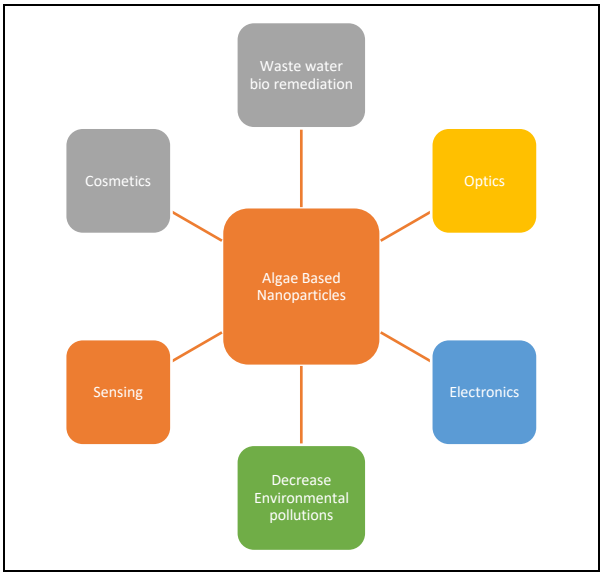


Fig. 2: Uses of algal-based nanomaterials in various fields (Khan *et al.* 2022)

Table 1. Biological applications

Biological Applications
Food
Feed
Additives
Drugs
Pesticides
Medicines
Catalytic activity for bacterial toxin removal and bioremediation

Source: Alnadhari *et al.* (2021)

4.2 Removal of Pollutants *via* Algae

Algae include biological substances that aid in returning the charge of metal ions to zero, including phycobilins, pigments, antioxidants (Anvar, *et al*. 2023), carbohydrates, polyunsaturated fatty acids, oils, lipids, proteins, and minerals. A three-step process is involved in bio regeneration. Metal ions are present in the activation phase nucleated and reduced as a result of the enzyme liberating the algae cells, which is indicated by a colour change in the solution (Chaudhary *et al*. 2020). When nucleated metallic components are combined, they form a variety of thermodynamically stable nanoparticles with different sizes and forms. The final form of the nanoparticles is achieved during the growth and final phases. The physical characteristics of nanoparticles are influenced by various parameters, such as pH, substrate concentration, temperature, time, agitation, and static conditions.

Table 2. Classification, characteristics, and uses of nanomaterials across industries

Nanomaterials	Approximate Sizes (nm)	Uses	Properties
Nanopores	5 nm-10 nm	Nucleic acid detection (DNA and RNA), COD measurement, and organic pollutant degradation	Rejection of ions, rectifying transport of ions
Nanowires	Diameter 1–100 nm	Elimination of organic contaminants, heavy metals, and lithium-ion batteries	Wave direction, heat stability, electric flow, and electrochemical characteristics
Carbon tubes	Diameter 1–100 nm	Pb(II) removal, water filtration, and inorganic and organic pollutant removal	High strength

Source: Chaudhary *et al.* (2020)

4.3 Removal of Pollutants *via* Nanoparticles

Depending on where the nanoparticles originate, the biosynthesis of algae nanoparticles can be either extracellular or intracellular (Chaudhary *et al*. 2020). Copper, silver, and gold metal nanoparticles have been produced extensively from brown algae. More than half of the data on various metal nanoparticles are related to the manufacture of silver nanoparticles by multiple strains of algae. Stated differently, their applications span a wide range of industries, including but not restricted to clothing, jewellery, pharmaceutical delivery, wound care, paints, and dental metals and dental alloys (Chokshi *et al*. 2016). A report states that *Turbinaria conoides* microalgae was used to create ball-shaped silver nanoparticles (96 nm in size), which showed remarkable antibacterial properties against *Escherichia coli*, *Candida albicans*, *Staphylococcus epidermidis*, *Aspergillus niger*, and *Staphylococcus aureus*. The use of nanoparticles as a novel strategy for the biological cleaning up of contaminated places has received particular attention lately. Algal-produced nanoparticles were studied as potential bio-remediation agents. For instance, while processing under visible light, *U. lactuca*-manufactured silver nanoparticles accelerated the degradation of methyl orange (Roychoudhury *et al*. 2016).

5. ANTIBIOTIC REMEDIATION IN PHYCONANOMATERIALS

Environmental pollutants have been increasing in the atmosphere, and they are also responsible for harmful effects. The main reason behind the problem is the usage of heavy metals and colouring dyes in large-scale industries, which are dumped directly into the environment. Recently, it has been detected that nanomaterials play a significant role against dyes and heavy metals. In this way, the algal-based nanoparticles play a vital role against dyes and heavy metals. These phyconanoparticles are synthesized by algal biomass. This article includes environmental remediation by phyconanomaterials. (Mukherjee *et al*. 2021). The discovery of algal-based nanomaterials is an excellent remediating agent that takes action under the contamination of various wastes. The waste includes industrial waste, medical waste and so on. The concentrated algae, which contains fluid extracted from *Turbinaria conoides* and *Sargassum tenerrimum*, utilizes a reducing agent (Ramakrishna *et al*. 2016).

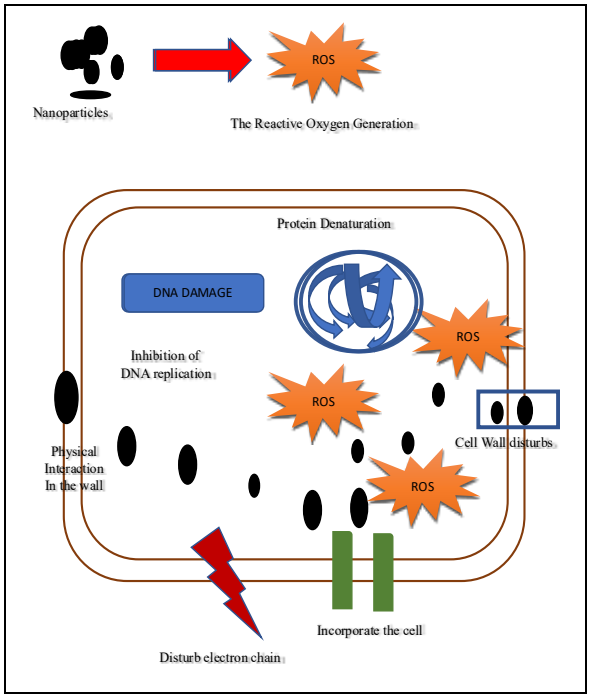


Fig. 3: Mediation of algae into nanoparticles against bacteria (Source: Kumar *et al.* (2023)

Table 3. Algae and nanomaterials synthesized from them

Name of the Algae	Synthesized Nanomaterial
Cholorophyceae, Rodophyceae, Eugleana,	Metal nanoparticles
Ulva fasciata, Lyngbya majuscule, Chlorella vulgaris and *Spirullina plantensis, Phaeophyceae*	Silver nanoparticles
Naviculla atomus and *Diadesmis gallica*	Gold nanoparticles

Source: Mukherjee *et al*. (2021)

Antimicrobial resistance arises when microorganisms such as bacteria, viruses, fungi, and parasites cease to react to antimicrobial medications that have been blooming in recent years, and this turns into the most medical issue. So, the process of creating metallic silver nanoparticles involved reducing aqueous Ag^+ ions using *Klebsiella pneumonia*. The nanoparticles contribute antimicrobial activity against antibiotics against *Staphylococcus aureus* and *Escherichia coli*. The highest effects are seen in penicillin G and amoxicillin against *S. aureus* (Shahverdi *et al*. 2007). Using microalgae, the biological production of nanoparticles is an easy and environment-friendly technique which controls the use of various toxic chemicals. These algal-based nanoparticles are instrumental because they have unique mechanical, physical, and chemical properties. Greener nanoparticle synthesis is a hot topic in many scientific domains since it protects and enhances the environment without posing any harm. The synthesis of nanoparticles derived from algae has garnered increased attention in recent years as a subject of study (Kumar *et al*. 2023).

5.1 *Sargassum muticum* Algae

Samples of the algae *Sargassum muticum*, the principal bio-based reducing agent for green synthesis of AgNPs. The Gram-positive bacteria (*B. subtilis*) and gram-negative bacteria (*E. coli*) can be controlled or killed by the algal extracts and production of AgNPs, which can be involved in the antibacterial activity and that activity can be verified in the disc diffusion assay (Azwatul *et al*. 2023). The silver nanoparticles, which are produced by algal nanoparticles, are an excellent green approach and; they have the best biomedical usage, and they are environmentally friendly readily biodegradable. These nanoparticles from algae show a good response to catalysis during the degradation of organic dyes (Dubey *et al*. 2023). The defatted algal biomass can also synthesize the silver nanomaterial.

Microalgal water extract was prepared from *Acutodesmus dimorphus* after the extraction of lipids. This extract was used in the preparation of silver nanoparticles. The antioxidant activity of these silver nanoparticles was evaluated by 2,20-azino- biophosphate (3-ethylbenzothiazoline-6-sulfonic acid) (Borah *et al*. 2020). *Padina tetrastromatica* reduced the growth of some species such as *P. aeuroginosa*, *Klebsiella planticola*, and *Bacillus subtilis* (Salem *et al*. 2020).

Table 4: Comparative efficiency of algal species in nanoparticle synthesis and pollutant removal

Algal Species	Type of Nanoparticle Synthesized	Pollutant Targeted / Application	Efficiency / Remark	Reference
Chlorella vulgaris	Silver (AgNPs), Zinc oxide (ZnONPs)	Heavy metals, dyes, antibiotics	High stability and uniform nanoparticles (~10–30 nm) with antimicrobial effects	Mukherjee *et al*. (2021)
Spirulina platensis	Selenium, Gold (AuNPs), AgNPs	Antioxidant, antibacterial, biomedical	High bioactivity, produces well-capped nanoparticles with antioxidant potential	Alipour *et al*. (2021)
Sargassum muticum	AgNPs	Heavy metals (Pb^{2+}, Cd^{2+}), dyes	High biosorption efficiency due to rich polysaccharide matrix	Azwatul *et al*. (2023)
Ulva fasciata	Silver nanoparticles	Organic dyes, *E. coli* (bioremediation)	Rapid extracellular nanoparticle synthesis, eco-friendly	Roychoudhury *et al*. (2016)
Scenedesmus obliquus	AgNPs	Photocatalysis (dye degradation), antibacterial	Excellent photocatalytic performance under visible light	Kumar *et al*. (2023)
Lyngbya majuscula	AgNPs	Pharmaceutical pollutants	Strong reducing capability; produces nanoparticles <50 nm	Mukherjee *et al*. (2021)
Padina tetrastromatica	Iron oxide (Fe_3O_4-NPs)	Biofilm inhibition, wastewater treatment	Effective against *P. aeruginosa*, *K. planticola*, and *B. subtilis*	Salem *et al*. (2020)

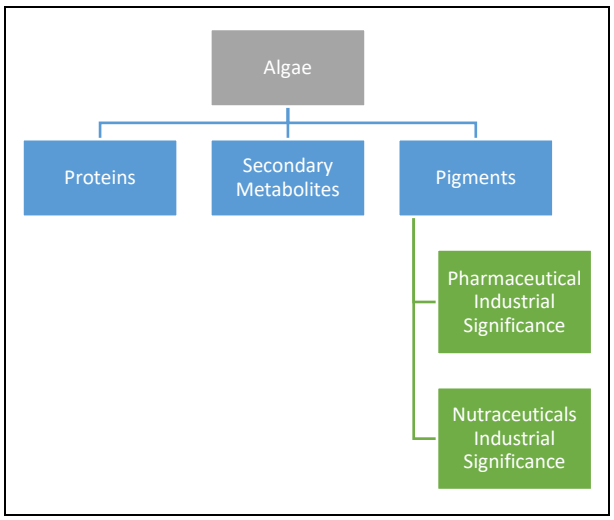


Fig. 4: Suppression in algae (AlNadhari *et al.* 2021)

Algae contain proteins, secondary metabolites, and pigments that have potential use in the pharmaceutical, industrial, and nutraceutical sectors, as well as in the treatment of inflammation, oxidation, and cancer. The red macroalgae and brown algae are involved in antibiotic and anti-inflammatory activities. They can also produce terpenes, acetogenins and polyphenols. Phenolic chemicals found in abundance in marine red algae have been shown to possess antibacterial, antioxidant, antiviral, and antifungal properties (Alnadhari *et al*. 2021). Microalgae can fight against the dyes and metal ions. Ramakrishna *et al*. (2016) employed unicellular green microalgae Scenedesmus species to synthesise AgNPs in both intracellular and extracellular environments. The synthesized algal-based nanoparticles exhibit high antimicrobial activity against Gram-positive and Gram-negative bacteria.

The main pollutant removal mechanisms are biosorption through surface functional groups and photocatalytic degradation through generation of reactive oxygen species (ROS) (Bhatt *et al*. 2022). Algal biomass can be utilized in multiple cycles of remediation with some decrease in efficacy (Alipour *et al*. 2021). Scalability barriers include culture contamination, nanoparticle recovery, and regulation (Moondra *et al*. 2021). Compared to traditional catalysts such as TiO_2 or ZnO, algal nanoparticles can have great efficacy under visible light, have greater sustainability, and may have reduced levels of photostability (Kumar *et al*. 2023).

6. CONTROLLING THE PHARMACEUTICAL CONTAMINANTS WITH PHYCONANOMATERIALS

Numerous chemical and microbiological pollutants that are harmful to human and environmental health can be found in drinking water. Furthermore, there is an ecological risk when drugs or drug compounds are found in surface and groundwater. This is particularly true given that the effects on aquatic organisms are little established and the consequences on human health are unclear. Ensuring water safety requires an understanding of the sources of contamination and how these could reach the water supply. One of the primary causes of pharmaceutical pollution in the environment may be hospitals (Bagheri *et al*. 2016).

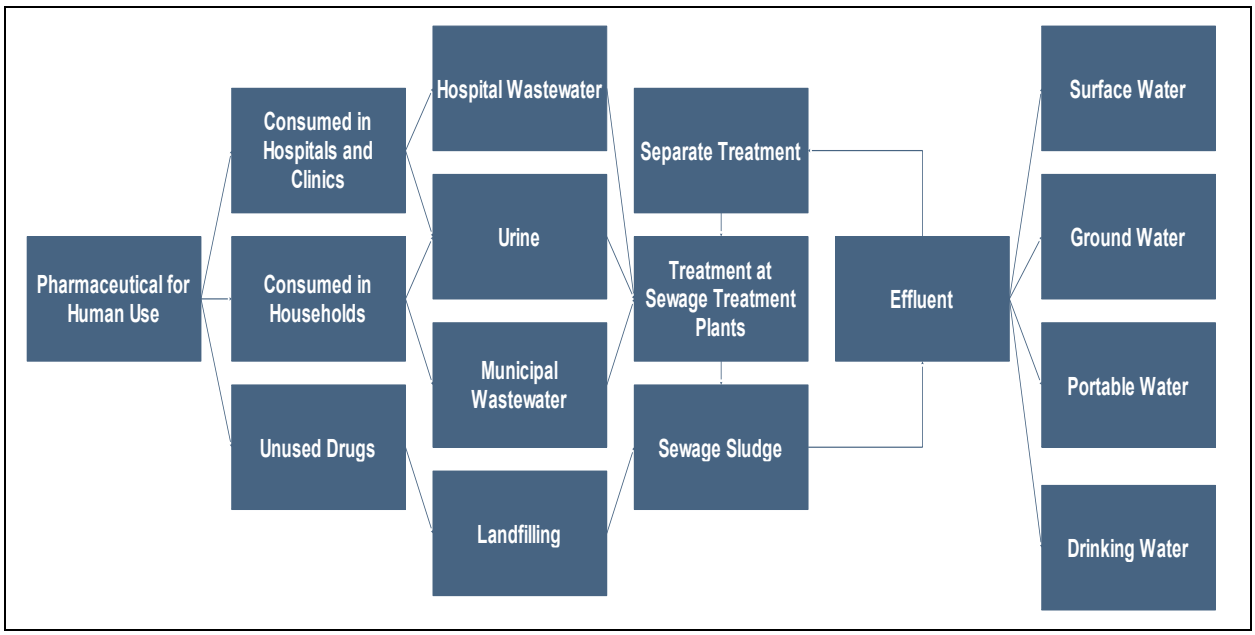


Fig. 5: Pathways for pharmaceutical contamination in the water environment

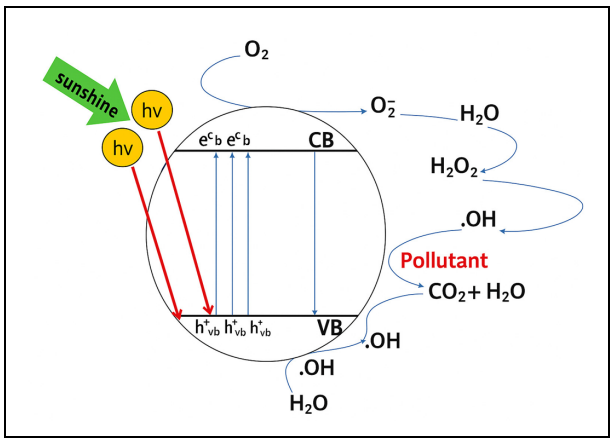


Fig. 6: Photocatalysis for pollutant degradation (Source: Liravi, 2023)

Photocatalytic process can degrade pharmaceutical contaminants. The photoexcitation of electrons from semiconductor materials is the basis for the operation of heterogeneous photocatalysis technology. Photocatalysis is the process of converting solar energy into chemical energy. The valence band (VB) and conduction band (CB) characterize semiconductor materials. The band gap in semiconductors is the difference in energy between the valence and conduction bands. When sunlight or artificial light radiation strikes semiconductors, the excited electrons (e-) from VB travel into CB, creating a positive hole (h+) VB. The excited electrons and positive holes undergo several redox processes that produce radical species such as $OH^{\bullet}$, H_2O_2, and $O_2^{\bullet-}$ (Liravi, 2023)

Pharmaceutical and personal care products are frequently discharged from human waste into environmental water resources without being entirely removed by conventional wastewater treatment facilities. Because of this, their traces are commonly found in significant amounts in wastewater streams, groundwater sources, and surface water (Ma *et al*. 2015). According to (Baran *et al*. 2011), the negative impacts of these pollutants are first observed in aquatic species and then spread to people by ingestion of food or water. Strategies for evaluating the effects of these substances and then neutralizing them *via* effective water treatment techniques must be developed. Sulphonamides, which are classified as broad-spectrum antibiotics, are one such instance. In addition to adsorption, xenobiotics can also be broken down into smaller, harmless molecules through the use of reactive species produced by photocatalysts in the presence of light (Li and Shi, 2016). Despite having exceptional qualities like greater electrical conductivity and narrower band gap energies, graphene cannot function alone due to self-aggregation between graphene sheets, which reduces its catalytic activity, and its 1.79 eV band gap, which prevents it from functioning in visible light (Anirudhan and Deepa, 2017). Therefore, graphene has been coupled with TiO_2, ZnO, Ag_3PO_4, and Bi-based oxides to improve its catalytic efficiency and create graphene-based photocatalysts.

7. SCALABILITY AND PRACTICAL CHALLENGES IN PHYCONANOTECHNOLOGY

Maintaining algal cultures in large-scale open pond or photobioreactor systems, which are vulnerable to contamination, environmental changes, and decreased nanoparticle yield, is one of the main challenges. Furthermore, it is still technically difficult to standardize nanoparticle size and concentration for repeatable outcomes. At commercial scales, the harvesting and subsequent processing of algae and nanoparticles can also be prohibitively expensive and time-consuming. To ensure viability for real-world applications, addressing these issues calls for integrated engineering approaches, economic feasibility assessments, and pilot-scale studies (Moondra *et al*. 2021; Kumar *et al*. 2023).

8. CONCLUSION

This review focuses on Phyconanotechnology in tackling environmentally harmful pathogenic antibiotics and other pharmaceuticals. Nanoparticles produced by algae are environmentally sustainable, green and economically cost-effective. Algae have the best potential for removing pollutants through biosorption and photocatalysis. Future work should focus on increasing yield, integrating phyconanotechnology into existing wastewater treatment systems, and evaluating and documenting the environmental safety of large-scale phyconanotechnology applications.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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