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Environmental applications of bacteria in water and soil treatment: A Review

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Abstract
The bacterial properties for a better environment have attracted a great deal of attention in recent years. This review focuses on the bacterial applications for the human and animal populations, environmental applications to improve water quality for crops, and polluted soil for changing environmental characteristics due to the expanse of polluted areas for crop production, and finally, the discussion raises other aspects and the way forward in aggressively developing bacterial technologies for environmental improvement. The review aims to capture the latest information on various potential uses of bacteria for improving environmental qualities, including benefits of the bactericidal applications for humans and animals, and environmental applications for water for crops and soil for crop growth. Several case studies are presented, where bacteria have capacities for removing heavy metals, preventing algal bloom in rivers, and reducing Oman crude oil and n-alkanes, as well as their antifungal activity, production of siderophores, induction of systemic resistance, and plant growth promotion. These examples demonstrate the implementation of successful in situ strategies of bacteria being used in different parts of the world. Results from this study suggested the potential role of bacterial magnetotactic for new options in in-situ environmental remediation of heavy metal and pose new perspectives for further studies and sustainable management of resources for overall ecosystem restoration.

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1. Introduction

The extensive review on the bacterial properties for a better environment is divided into four distinct sections including benefits of the bacterial applications for the human and animal populations, environmental applications to improve water quality for crops, and polluted soil for changing environmental characteristics due to the expanse of polluted areas for crop production, and finally, the discussion raises other aspects and the way forward in aggressively developing bacterial technologies for environmental improvement. Overall, the scientific publication investigates the latest updates for the application of bacteria in the environment. The potential of environmental applications of bacteria in water and soil treatment is the main thrust. (Siddharth *et al*.2021) (Eras-Muñoz *et al*., 2022) [37, 14]

The increasing pollution in the environment has raised concerns because of the harmful effects of pollutants on humans, animals, and plants. Sustainable development and modern economic growth are the causes and the most effective solutions for environmental pollution. In comparison to conservative methods to control environmental pollution, biotechnology in general and microbiology, in particular, can directly contribute to environmental quality improvement because of the presence of a variety of beneficial microorganisms in the environment. Despite a massive increase in research over recent decades, research gaps are still present among the scientists and researchers in the comprehensive field of the bacterial diversity present in polluted sites and their environmental applications. Unique separated studies of bacteria for sustainable and harmless environmental qualities helped researchers to focus in this review mainly on the bacterial applications for different qualitative polluted areas, especially for water for crop production and soil for crop growth. The review aims to capture the latest information on various potential uses of bacteria for mending polluted water for crop quality and also for changing soil/land characteristics for food production. Environmental applications of bacteria can be promoted in many areas for higher productivity and clean environmental resources to control global pollution. (Olaniyan and Adetunji 2021) [28] (Singh *et al*.2020) [39] (Bertola *et al*., 2021) [3] (Borchert *et al*.2021) [5]

2. Bacterial processes in water treatment

Treatment of water and sludges from municipal and industrial sources is being improved as a result of current research in biology, engineering, and microbiology. For the systems dealing with municipal wastewater, the focus of research has turned towards the removal of biodegradable organic matter; nitrogen removal in a two-step nitrification-denitrification process; complete nitrogen removal in a biological nitrification-denitrification system; accumulation of phosphorus in the biomass (bio-P process); sulfide and odour removal; and the removal and/or biologically based inactivation of enteric microorganisms. In the treatment of industrial effluents, the degradation of hazardous chemicals and the removal of toxicants have been a major area of research interest. Bacterial processes can be divided into twelve main activities, and they were described by Walker *et al*. In this paper, we pay greater attention to processes concerning water. (Hasan & Muhammad, 2020) [19] (Md Anawar & Chowdhury, 2020) [27]

Given the great technological and economic advances in the twentieth and twenty-first centuries, the efforts of modern science have focused on the utilization of bacteria to improve water quality through specific processes. Most bacterial processes in environmental technology are dedicated to two topics: biological nutrient removal and the biological degradation of undesirable organic pollutants contributing to water and land contamination. The first obviously concerns the maintenance of the correct chemical equilibrium, which is crucial to sustaining the desired ecosystem. The second is directly associated with limiting the problems in water and soils caused by organic contaminants. (Hlordzi *et al*.2020) (Wen *et al*.2020) [44]

2.1. Biological nutrient removal

Bacteria carry out either assimilation or dissimilation of nitrogen. Assimilatory studies are based on the ability of microbial cells to remove nitrogen from the environment in order to synthesize cellular compounds. Nitrogen can be assimilated by microorganisms in the form of nitrate, nitrite, and ammonia. However, in industrial and domestic sewage treatment, ammonium and nitrate are the primary ions requiring removal. One of the nitrogen removal mechanisms that occur is related to anoxic ammonium oxidation (anammox), and the other is denitrification. Nitrification (ammonia oxidation + nitrite oxidation) is used to accomplish ammonia removal in the nitrification-denitrification process, resulting in the accumulation of nitrite or nitrate. Ammonium nitrogen is the form of inorganic nitrogen most commonly encountered in the environment. Phosphorus exists in various chemical states in the environment. In biological and chemical materials, organic forms and inorganic forms of phosphorus endure. Many studies from around the world confirm that several categories of microorganisms, especially bacteria, play critical roles in diverse removals of nutrients from different sources. (Martínez-Espinosa, 2020) [26] (Song *et al*.2021) [40] (Rahimi *et al*., 2020) [31]

Biological nutrient removal is an essential process in water purification, which aims to eliminate biogenic compounds (nitrogen and phosphorus) from the environment. Traditionally, processes of nitrogen and phosphorus elimination from effluents are called biological nutrient removal (BNR). Such a system can be used to alleviate water pollution and reduce various problems: (1) nitrogen, ammonia, and other nitrogenous compounds released into the water body can lead to alterations of physico-chemical and biological factors; (2) high concentrations of nitrogen and phosphorus induce eutrophication; (3) supporting the abundant growth of phytoplankton, eutrophication leads to turbidity reduction, which results in changes in the fauna and flora; and (4) decreases in the amount of dissolved oxygen affect the survival and welfare of aquatic organisms. (Zhou *et al*., 2022) [47] (Hasan *et al*. 2021) [20]

2.2. Biodegradation of organic pollutants

Consequently, the biodegradation of organic pollutants, including both anoxic and aerobic biodegradation, has been well documented in both terrestrial and aquatic ecosystems, which is essential for biogeochemical cycles. Various researchers already addressed the adverse effects of organic pollutants and the realism of biodegradation of organic pollutants through bacteria because they can adapt to these pollutants and degrade them to their less toxic forms. Moreover, they already suggested that bacteria have the capability to degrade a wide range of toxic compounds that are widely distributed in the environment. Thus, the current review focuses on the potential of bacteria that are involved in the process of biodegradation of organic pollutants in connection with the biogeochemical cycle of substances in aquatic systems for their use in a commercial bioremediation system. (Victor *et al*. 2020) [42] (Siddiqa & Faisal, 2021) [38]

During the past years, the release of several organic pollutants including dyes, heavy metals, synthetic compounds, etc. from various sources like agricultural fields, industries, and domestic activities has reached a worrying level. In comparison with using different strategies and technologies to eradicate pollutants from contaminated water, biodegradation of organic pollutants is a simple and more acceptable approach to overcome these problems. This seems slightly difficult to some extent due to the persistent nature of the pollutants causing environmental imbalance and threats to existing flora and fauna. Bacteria are known to adopt one of the primary routes to oxidize organic chemicals that serve not only as an energy source but also as a carbon and nitrogen source for cell development. (Yang *et al*., 2021) [46] (Fuhrmann, 2021) [17]

3. Bacterial Processes in Soil Treatment

In contrast, some traditional soil treatments based on beneficial bacteria have been frequently reported to not only improve soil fertility and its quality for fruit or crop growth, but also consequently enhance fruit and crop yields and fruit quality. Bacterial processes might be potential candidates for soil health improvement. Soil treatment using such bacterial processes is identified to be able to suppress specific soil diseases and effectively enhance plant protection. A variety of distinct mechanisms of actions of the bacteria are addressed, such as their antifungal activity, production of siderophores, induction of systemic resistance, and plant growth promotion. From previous reports, a major victim of these phenomena is soil pathogens. Contaminated soils are also frequently identified as an important original source of pollution in surrounding ecological areas where soil properties are not suitable for mineralization and/or immobilization of contaminants and sustainable ecological restorations. Because the contaminated soils and ecological areas can harbor distinct or varied exogenous microorganisms, the use of indigenous bacteria and remedial processes for their functional mechanisms reportedly widen the range of ecological applications for bacterial processes in contaminated soils. (Jayaraman *et al*. 2021) [22] (De Corato, 2020) [10] (De Corato, 2020) [11]

Microbial populations in soils and the trends of different microbial communities can change with the quality of soils in regard to organic or other nutrient content over a long-time contamination period. However, compared to bacterial processes in water treatment, bacterial processes in soil treatment have been less reported. Microbe-based bioremediation is well-recognized to be successful for pollution cleanup in different polluted soils. The applications and performances of a series of bacteria and their metabolites are shown to enhance heavy metal phytoextraction, phytostabilization, and rhizoaccumulation of hyperaccumulator and nonhyperaccumulating plants. Moreover, strains within a species exhibit selective plant root colonization capability and distinct stress responses and plant growth-promotion abilities. (Fierer *et al*., 2021) [16] (Thiele-Bruhn *et al*. 2020) [41]

3.1. Bioremediation of contaminated soils

Soaps, cleaning solvents, petroleum products, and heavy metals are categories of pollutants that have multitudes of either inorganic or organic substrates upon which bacteria routinely feed and grow. Soil bacteria break down toxicants by stimulating a range of oxidative, hydrolytic, conjugating, and polymerization reactions. Bioremediation can be applied to protected, agricultural, and land reclamation, enhancing the potential value of a site and its surrounding ecosystems. Many environmental objectives for responding to contaminated soils relate to achieving reductions in pollutant toxicity, and bioremediation, in turn, can be highly effective in fostering ecosystem recovery. Bacterial detoxification of toxicants usually involves a two-step strategy, removing bioavailable forms from ready contact with microorganisms, and thereafter the transformation/destruction of those toxic forms. The conversion of toxic chlorinated organic compounds or heavy metals by bacteria into non-hazardous mineral forms, involving transformation to a more soluble pathway is not always recommended since many sub-products intermediates remain extremely toxic. (Shahid & Khan, 2022) [33] (Wołejko *et al*.2020) [45] (Maqsood *et al*.2023) [25]

Contamination of soil with deleterious chemicals is a widespread and persistent pollution problem. In industrialized and developing world countries, it is estimated that the number of severely damaged soil sites could be two to three hundred thousand. Approximately 6,000 new contaminated land sites are currently identified annually in just England and Wales alone. Bacteria share a major portion of this immense burden mainly due to their ease of adaptation, energy-efficient lifestyle, and vast metabolic capacities. The application of bacterial strains, consortia, immobilized or genetically modified systems has produced a range of practical outcomes and been labeled under the term bioremediation. Many of the polluted soils upon which bacteria have been employed as agents have been rescued from serious pathogen-related and physical hazards. (Riley *et al*. 2022; Cui & Lu, 2023) [32, 9]

3.2. Soil Health Improvement

In addition to bacteria's dominant function in effectively degrading or removing contaminants, they offer a secondary but highly valuable benefit to life in the soil. This should be taken into account and broadened in scope as an implementable and compatible population for wearing a lighter hat in real-world hope and expectation while reestablishing and reconstituting the importance of our soil and water resources and looking at the underground mold in a more comprehensive way. Soil is the foundation of one of humanity's major food supplies and protects about 200 years of the world's valuable consumer consumerism because of its characteristics of rich and mud-unchanging rocks and environments. Soil conservation, field use, and soil essential in ecosystem productivity are related to Hani Anhe compound-wield-metal biodegradation, and whether nature conserves and maintains or reduces the global and diverse potential of soil fertility and soil quality. (Ahmad *et al*.2022; Liu *et al*., 2020) [21, 24]

Bacteria have been extensively utilized in many applications for effective soil treatments. In particular, some types of bacteria are able to resist excessive metal concentrations or prevent heavy metal transfer from soil to living organisms. They lend precious assistance to metal phytoremediation and have the potential to be used as bioinoculants across an extended area of contaminated soils. Moreover, bacteria add various nutrients, such as seed-priming iron and phosphate (P), controlling P lysis harm in soils, relieving drought stress, improving yttrium stress and sulfur absorption, and transporting Zn to wheat grain. Because the vast majority of plants rely on soil nutrients and organisms to complete a portion of their life cycle, such as material decomposition and transformation, wastewater treatment, and metal bioavailability between mediums, in this category, we focused on the likely effects of bacterial use in improving soil quality and vitality. (Gonzalez and Ghneim-Herrera 2021; Fakhar *et al*.2022; Barra Caracciolo & Terenzi, 2021) [18, 15, 2]

4. Case Studies of Bacterial Applications in Environmental Treatment

Bacterial applications in the treatment of contaminated soils. The polluted contaminated soils were distributed in sandtrap columns in order to keep the sand traps in non-dripping site conditions. Contaminants introduced in the experimental area included carbon tetrachloride, hexachlorobenzene, HCH lindane, and phorate. Soil treatments for n-alkane remedy with alkane-based were reported. Bacterial applications where the complete degradation of organic compounds resulted in detoxification of vinyl chloride are also presented. (Chan *et al*.2022) [6] (Bhatt *et al*. 2021) [4]

Bacterial applications in the treatment of contaminated water. Bacteria were denoted to remove Hg2+, Cd2+, and Ag+ and to fix these heavy metals in cofferdams or slurry which could be later stored or recultivated depending on the applicable legislation. Bacteria metabolize algae in TGF in order to reduce them directly in the river. Corrosion of steel was inhibited by the Cu bacteria, with an additional effect to increase the strength of steel. (El-Reash *et al*.2023) [13] (Shahzad *et al*.) [34]

For three decades, bacteria have been used to improve environmental quality by reducing pollutants from water and soil. This review reports a small selection of case studies about the application of bacterial processes of environmental bioremediation. First, some case studies about water pollution are presented where bacteria have capacities for removing heavy metals, preventing algal bloom in rivers, and reducing Oman crude oil and n-alkanes. Second, the application of bacteria to the treatment of contaminated soils with pollutants such as organic solvents or pesticides and not requiring an extra inoculation steps is described. These examples demonstrate the implementation of successful in situ strategies of bacteria being used in different parts of the world. The influence of the researcher is stressed as well as the length of the incubation periods, detailing the excellent degradation capacity of some pure bacterial cultures. Tables summarizing the metabolic processes and the technical results are presented. (Sharma, 2021) [35] (Wei *et al*. 2020) [1] (Priyadarshanee and Das 2021) [29]

5. Challenges and Future Directions

To develop environmental applications of bacteria and microbial products in the future, the following five points should be taken into consideration. (1) Research into bacterial community structure and genetic characteristics throughout the water cycle - Studies that can improve understanding from source to point of use. (2) Integration with solar-powered technology - To enhance the capability of treatment of the solution for water use would be attractive. (3) Isolation of strains with high adaptation under heavy metals from contaminated water or soil. (4) The development of environmental applications can be considered using other technologies such as flocs for adsorption on small particles in water because biofilms have a limited role only in compressing large-size particles. (5) It is necessary to be developed into a practical application of the advanced DNA technologies or chip clottings that allow for total analysis of the form. These have the potential to be among the emerging forefront of environmental microbiology and biotechnology. (Shilei *et al*.2020) [36] (Qi *et al*. 2022) [30]

Despite the great potential for bacterial technology in environmental applications, various challenges still need to be resolved. First, although many environmentally beneficial bacteria and their underlying mechanisms of action have been studied and revealed, for the application of bacterial agents in large-scale water, soil, and other environmental treatment, an imperatively important path becomes to decrease the cost for the production of a large number of cells. Second, until now, bacterial processes have not been widely practiced in either conventional centralized treatment or on-site treatment with advanced aerobic and anaerobic treatment. There is still a gap between bench-scale studies and full-scale applications, deterring the transition of research discoveries. In order to commercialize the technology and further expand the scope of its applications, viable bacterial systems will be made. Third, the ecological safety and regulation need to be taken into consideration. (Duffner *et al*.2021; Cliff *et al*.2023; Levasseur *et al*., 2020) [12, 7, 23]

6. Conclusion

Despite all the benefits of Earth Materials, the potentials of using bacteria-based EM for a specific application have not been established. Moreover, natural enrichment and co-enrichment have not practically been used for bacteria-based EM, and the impacts of EM, especially bacterial magnetotactic in treating AMR through the research areas of the current review, have not been elucidated. The lack of broad study relating to these aspects highlights the importance to create a platform which is capable of closing the existing knowledge. Emerging findings also shed light on the implications of optimizing biologically segregated environments in manipulating the biogeochemical cycling of the environmental wetlands for sequestration of nutrients. The development of this ecosystem services, the potential emerging into new applications, agrees with those of the previous researches, which underscore the requirement for further investigations.

The review focuses on applications of bacteria in water and soil treatment, discussing bacterial phosphate uptake for water eutrophication and denitrification through nitrate and nitrite reduction, as well as antibacterial mechanisms of bacteria. Bacterial processes and chemotaxis involving bacteria magnetotactic have received more attention for potential application in different fields. Therefore, in this review, we discuss environmental applications of this novel bacteria aiming towards opportunities to answer interactions of bacteria with heavy metals, as well as the potential implication of this novel bacteria in the treatment of antimicrobial resistance. In general, literature has shown that bacteria constitute an important part of many treatment processes and provide the most promising effect of eutrophication treatment when optimized. Evidence supports the potential of utilizing bacterial magnetotactic to treat some heavy metals in the water environment (in situ remediation), as well as human health from a variety of views. Results from this study suggested the potential role of bacterial magnetotactic for new options in in-situ environmental remediation of heavy metals and pose new perspectives for further studies and sustainable management of resources for overall ecosystem restoration.

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