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Editorial

Microbial Bioremediation of Environmental Pollution

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Industrial and agricultural progress, coupled with population expansion, has led to many questions in the scientific community over the current status of environmental pollution and natural resource scarcity [1]. The emerging call for advanced waste treatment technologies has been triggered by the stringent regulations on environmental waste disposal. Bioremediation technology has been set up as an emerging and breakthrough process capable of removing and reducing persistent pollutants from polluted waste fluxes (e.g., water, soil) [2,3]. Bioremediation, regarded as a relatively cost-effective, safe and reliable environmental remediation tool [4,5], has been demonstrated to be an effective instrument to address the detrimental impacts of pollution and to render contaminated environmental compartments less polluted and free of persistent or recalcitrant compounds [6–9]. Environment compartment decontamination via microbial biomass has been highlighted as an alternative approach thanks to its unique characteristics that can be exploited for human benefit [10,11]. Microbial bioremediation is a technology insufficiently recognized, although several studies have confirmed its benefits. The use of microorganisms to remove, convert or transform environmental contaminants into safe compounds from various environmental matrices is becoming an attractive technology, not only for the scientific community, but also for entrepreneurs [12–16].

The Special Issue entitled "Microbial Bioremediation of Environmental Pollution" collected several recent works from the scientific community, including research covering complex issues related to the application of microorganisms in bioremediation. The Special Issue is currently available online at: https://www.mdpi.com/journal/processes/special_issues/microbial_bioremediation_environmental_pollution (accessed on 1 May 2023).

We feel that the advances that the contributors have reported in this Special Issue have made a significant contribution to the implementation of different microbial bioremediation strategies, highlighting the need for sustainable and advanced technologies in environmental pollution control. Regardless of the cross-disciplinary character of the varied applications involved in this particular issue, there are overlapping patterns that link the fields together, which we attempt to outline in this Special Issue. This Special Issue on microbial bioremediation comprises two reviews and seven research articles.

In the review paper of Filote and co-workers [17], the authors considered a complex analysis of the available information in the scientific literature to support the upscaling of microbial-based biosorption and bioaccumulation processes, as part of bioremediation. The main sources of contamination in the environment along with the transport and routes of persistent pollutants (heavy metals (HMs) and persistent organic pollutants (POPs)) were briefly discussed. Diverse mechanisms of HMs and POPs removal using the microorganisms involved at the extracellular and intracellular levels were also highlighted. The contribution of several factors affecting the performance of the microbial remediation of HMs and POPs in wastewater was analyzed for designing bioremediation treatment processes and scale-up strategies. The authors concluded that there is no trend in the adoption of biosorption and bioaccumulation in current wastewater treatment practices for the removal of persistent pollutants (POPs and HMs), although a large variety of these studies exist at the laboratory scale, and certain commercial biosorbents are also available for the biosorption of HMs ions. Therefore, it is obvious that further studies are needed to demonstrate the technological feasibility and environmental performance of biosorption and bioaccumulation processes at a large scale. In this regard, a sustainable scale-up process should be considered by applying the life cycle assessment (LCA) tool—a new approach employed to demonstrate the sustainability of microbial-based remediation processes [16].

In their review, Tarfeen et al. [18] set out to present a generalized picture of the bioremediation capacity of microorganisms. The authors investigated the potential applications of bacteria, fungi, algae and genetically modified microorganisms to clean up both metals and pesticides. The main sources of these pollutants in the environment, as well as their effect on human health, were identified. For example, cadmium in association with copper, lead and zinc ores has been claimed to induce damage to the skeletal system, while lead, copper and mercury have been linked to atherosclerosis and schizophrenia. The adverse effects of organochlorine pesticides predominantly comprise neurotoxicity, infertility, immunotoxicity and cancer of the reproductive system. The mechanisms of both heavy-metal and pesticide remediation using microorganisms were briefly discussed. Further, major detoxification pathways of microorganisms and bioremediation technologies were addressed together with the enhancement of bioremediation using molecular approaches such as systemic biology, gene editing and omics. Overall, their study illustrated the power of genetic engineering in developing and selecting microorganisms that have a better remedial capacity for the removal of heavy metals and pesticides [17].

Mandree et al. [19] focused on investigating the applicability of indigenous *Bacillus* spp. in the bioremediation of polycyclic aromatic hydrocarbons (PAHs) from industry-contaminated sites around Gauteng (South Africa). Two prototypes (1 and 2) were formulated considering six potential hydrocarbon-degrading strains and tested for their ability in PAH removal over 11 weeks against an un-augmented control system. The findings identified an increased efficiency of prototype 2, composed of a mixture of *Bacillus cereus* and *Bacillus subtilis* strains, in the biodegradation of PAHs and intermediates (complete degradation of naphthalene, phenanthrene and pyrene), after 74 days of treatment, compared to prototype 1. In addition, the bioaugmented system dosed with prototype 2 exhibited improved overall degradation (10–50%) of PAHs, naphthalene, phenanthrene and pyrene compared to the non-augmented control system. These results prove the potential of *Bacillus* spp. in the bioremediation of sites contaminated with PAHs. However, further research should also be performed to identify the optimum consortium approaches for fluoranthene degradation [18].

The aim of Dimova et al.'s [20] study was to determine the possible ability of *Comamonas testosteroni* bacterial strains to degrade hexachlorobenzene (included in the organochloride pesticide group that is banned for use). The ability of the *C. testosteroni* UCM B-400, B-401 and B-213 strains to decompose hexachlorobenzene was investigated for the first time in the literature, and their destructive activity was confirmed biochemically. The authors showed that the bacterial strains *C. testosteroni* UCM B-400 and B-401 can be applied for the bioremediation of soils polluted with hexachlorobenzene, since the strains were able to decrease the highest (50 mg/L) initial concentration by 41.5% and 43.8%, respectively. Statistical analysis showed that no statistically significant ($p < 0.05$) differences were obtained between the B-400 and B-401 strains. A hypothetical mechanism of hexachlorobenzene decomposition by *C. testosteroni* bacterial strains was also formulated [19].

Fahmy et al. [21] investigated the degradation of two significant pesticides (chlorantraniliprole (CAP) and flubendiamide (FBD)) and other pesticides (e.g., profenofos (PFS), cypermethrin (CYP), carbofuran (CFN) and malathion (MLN)) by different bacterial strains (*Bacillus subtilis*, *Bacillus pumilus*, *Bacillus mojavensis*, *Bacillus paramycoides*, *Pseudomonas aeruginosa* and *Alcaligenes aquatilis*), out of which six isolates showed maximum growth in the presence of CAP and FBD. The isolates were purified and further identified via biochemical and morphological tests, MALDI-TOF-MS and 16S rRNA techniques. Further, their degradation ability was investigated under different environmental conditions, e.g., temperature, pH, salt and incubation time. The optimal conditions for the biodegradation of the CAP–FBD mixture (at a concentration of 50 mg/L) using the six bacterial strains selected in this research were as follows: pH 7.0; temperature, 30–35 °C; salinity, 0.0–0.5% NaCl; incubation time of 11 days. The results suggest that the selected consortia can biodegrade and metabolize some diamide insecticides and other pesticides. Out of the six isolated bacterial strains, *P. aeruginosa* KZFS4 was identified as posing the maximum potential to degrade diamide pesticides. Moreover, the microbial consortium (no. 3)—a mixture of all six mentioned strains—exhibited strong degradation activity for all the pesticides and consequently appeared to be a potential inoculum candidate [20].

The use of plant-growth-promoting bacteria (PGPB) is an attractive strategy that can be successfully applied to improve plant growth and development, and to support phytoremediation technology. PGPB are bacteria that are able to protect plants against diseases and abiotic and biotic stresses, using a diversity of mechanisms. In this context, Minuț et al. [22] isolated different bacteria from the genera *Azotobacter*, *Bacillus* and *Pseudomonas* from the roots of *Phaseolus vulgaris* and used them as PGPB for *Sinapis alba* L., *Brassica napus* L., *Amaranthus retroflexus* L., *Linum usitatissimum* L., *Panicum miliaceum* L. and *Rumex patientia* L. plants. In a dual approach, using sterile and non-sterile soil, different effects were assessed on plant growth. Tukey's honestly significant difference (HSD) statistical analysis of the findings revealed that the observed differences in plants grown with or without the selected bacteria, in sterile or non-sterile soil, were, in some cases, insignificant when compared to the control. *Bacillus* sp. and *Pseudomonas* sp. induced the highest influence on the roots of mustard grown in sterile and non-sterile soil, respectively, while *Azotobacter* sp. provided the highest beneficial impact on rapeseed grown in non-sterile soil. It was interesting to notice that the roots and shoots of *Linum usitatissimum* L. grown in non-sterile soil and in the presence of *Pseudomonas* sp. increased by 178.38% and 15.08%, respectively. The authors highlighted the contribution of suitable PGPB in plant growth enhancement under different soil conditions and their applicability in the improvement of phytoremediation efficiency [21].

Hexavalent chromium (Cr^{6+}), the most toxic form of chromium, has multiple side effects on human health when found in our environment, especially in processing liquid effluents. However, the ability of microorganisms to remediate water fluxes contaminated with this particular metal has been demonstrated in several papers. In this respect, Roșca et al. [23] proved the applicability of *Bacillus megaterium* and *Rhodotorula* sp. biomass inactivated via thermal treatments in Cr^{6+} biosorption, under a series of influencing factors such as pH, biosorbent dose, initial concentration of the metal in solution, temperature and contact time. The results showed that Cr^{6+} removal via biosorption on *Bacillus megaterium* and *Rhodotorula* sp. was strongly influenced by the solution pH, the extracellular reduction being the principal mechanism involved in hexavalent chromium biosorption (demonstrated by linking the SEM-EDX results with the FTIR spectral analysis and interpretation of the isotherms and kinetics). *Bacillus megaterium* demonstrated an uptake capacity of 34.80 mg/g, while *Rhodotorula* sp. exhibited a capacity of 47.70 mg/g, under the optimum environmental conditions (pH = 1, biosorbent dosage of 8 g/L, 25 °C, contact time of 48 h and an initial Cr^{6+} concentration in solution of 402.52 mg/L). Finally, the experimental data were modeled using nonlinear forms of the Langmuir, Freundlich, Redlich–Peterson, Javanovic, Hill and dual mode models, among which the Freundlich isotherm showed the best fits of the biosorption data, with correlation coefficient (R^2) values of 0.9432 and 0.9382 [22].

Another study performed by Silva et al. [24] investigated the removal of atrazine (a herbicide) and two heavy metals (copper and zinc) from aqueous solutions using a permeable biosorbent bio-barrier reactor (PBR) developed with a bacterial biofilm of *Rhizobium viscosum* supported on 13X zeolite. A toxicity assessment was firstly performed to test the capacity of the selected bacteria to remove the pollutants in a single, dual or ternary mixture system. In this regard, concentrations of atrazine bellow 7 mg/L did not affect the growth of *R. viscosum*, while the growth of bacteria was inhibited by copper and zinc in binary solutions for all the concentrations tested (5 to 40 mg/L). In a ternary mixture (atrazine/copper/zinc) experiment, the results obtained after 24 h of exposure were compared with those obtained with a culture previously adapted to these contaminants. The hypothesis of previously acclimated bacteria showed acceptable results, probably due to the capacity of bacteria to develop detoxification strategies when subsequently exposed to a heavy-metal-contaminated medium. Finally, the development of a permeable bio-barrier with an immobilized biofilm was successfully performed in this research article, with removal rates of 85%, 95% and 25% for copper, zinc and atrazine, respectively, showing the potential of this system for application in sustainable and low-cost bioremediation approaches [23].

In the last paper, Erazo and Agudelo-Escobar [25] investigated the use of open-cathode microbial fuel cells (MFCs) to reduce the organic matter of native microbial communities in wastewater from a wet coffee processing plant located in Antioquia, Colombia. The authors demonstrated that native microbial communities present in wet coffee processing caused an increase in the electrogenic potential of non-conventional MFCs, simultaneously with the ability to remove organic matter. The MFCs operated for 21 days in both open-circuit and closed-circuit operation modes. The degradation rates reached 500–600 mg/L/day, indicating the metabolic capacity of the microbial community in the MFCs to achieve the decontamination of wastewater from the coffee agroindustry. These results are very important, since there are limited reports on the application of MFC techniques in combination with native microbial communities derived specifically from specific wastewaters [24].

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This Special Issue covers a variety of issues starting with the identification of the main sources of pollutants and contamination in the environment, further explaining the mechanisms involved in microbial remediation along with the primary influencing factors of the process. Further, different microorganisms were tested in the removal of some toxic pollutants from contaminated media, the results being favorable, demonstrating the efficiency of the microbial process, at least at the laboratory scale. Some new insights in the field are also included. Although there is clear evidence of the effectiveness of the microbial process, more in-depth research is needed for scaling up. In this regard, the life cycle assessment (LCA) tool can be used to demonstrate the sustainability of microbial-based remediation processes.

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