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A Review on Environmental Impacts and Risks of Beneficial Microorganisms

Shamsudeen Muhammad Muhammad[1]* and Bilyaminu Garba Jega[1]

1. *Department of Microbiology, Kebbi State University of Science and Technology, Aliero, Nigeria*
2. *E-mail any correspondence to: Shamsudeen Muhammad Muhammad (deenshams2000@gmail.com)*

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Abstract

The diverse realm of microorganisms, including bacteria, Achaea, fungi, protists, and viruses, plays a crucial role in supporting life on Earth. Microbes are present in various environments, such as Arctic regions and thermal vents, where they participate in vital functions like nutrient cycling, soil formation, pollutant decomposition, and symbiotic interactions with plants. Their positive effects on soil quality, plant development, and animal well-being are a result of their metabolic processes, relationships with other organisms, and utilization in different applications. While beneficial microorganisms present opportunities for improving agriculture, bioremediation, genetic modification, and sustainable biotechnology practices, safety concerns must be addressed. In agriculture, beneficial microorganisms are employed as biopesticides to reduce the use of chemical pesticides, although potential impacts on non-target species need to be considered. Bioremediation, an environmentally friendly method that uses living organisms to break down pollutants, offers benefits with minimal harm to the environment. Nonetheless, challenges such as effectiveness in extreme conditions and the risk of incomplete degradation or unintended ecological disturbances remain significant. Wastewater treatment harnesses beneficial microorganisms to degrade pollutants, leading to reduced chemical usage and the promotion of energy-efficient processes like anaerobic digestion. Yet, issues related to antibiotic resistance development and incomplete remediation are raised. Genetic engineering presents environmental advantages through genetically modified microorganisms (GMMs), assisting in bioremediation, sustainable agriculture, waste management, and bioenergy generation. However, concerns arise regarding potential ecological disruptions caused by altered microbial populations and the dissemination of antibiotic resistance genes. Addressing environmental and safety risks associated with beneficial microorganisms necessitates comprehensive approaches, including thorough risk evaluations, implementation of containment strategies, assurance of ecological harmony, and contemplation of ethical and social consequences. This study aimed to investigate the environmental impacts and safety considerations involved in the application of beneficial microorganisms.

Keywords: microorganisms; bioremediation; agriculture; genetic engineering; environmental safety

Introduction

Microorganisms, encompassing bacteria and viruses, are commonly perceived as pathogens capable of causing illness in plants, animals, and humans. However, numerous microbial species play crucial roles in maintaining ecosystem functionality. The survival of life on Earth heavily relies on microbes and the essential services they provide (1). Microorganisms inhabit diverse environments across the planet, including both living and non-living realms. From Arctic and Antarctic zones to deep-sea thermal vents, microbes thrive in a multitude of habitats (2). This vast microbial diversity spans various taxonomic categories, including bacteria, Achaea, fungi, protists, and viruses. Prokaryotes, such as bacteria and Achaea, and eukaryotes, comprising fungi, protists, and viruses, exhibit diverse characteristics, metabolic capacities, and ecological roles across habitats(3). Microbes ubiquitously influence their environments, with effects that may be positive, detrimental, or imperceptible to human observation (4). Microorganisms play pivotal roles in ecosystem dynamics through their involvement in essential processes. They contribute significantly to nutrient cycling by breaking down organic matter and recycling crucial elements like carbon, nitrogen, and phosphorus. Additionally, microorganisms form symbiotic relationships with plants, aiding in nutrient absorption and enhancing plant growth. They are integral to soil formation and maintenance, preserving soil fertility and structure. Microbes also play a vital role in pollutant decomposition, contributing to environmental clean-up efforts. Microorganisms play an important role in addressing environmental sustainability issues through nutrient cycling, bioremediation, waste management, renewable energy production, climate change mitigation, ecosystem health maintenance, and agricultural and food security enhancement (5). Microorganisms are also essential in various applications, including the production of valuable medicines, enzymes, and metabolites for pharmaceutical and food industries, as well as composting, bioremediation, and waste detoxification, contributing to soil fertility, and enhancing plant and animal health (6).

In the field of agriculture, beneficial microorganisms are employed as biopesticides, reducing the need for chemical pesticides (7). However, safety considerations encompass the potential adverse effects of these microorganisms on non-target species, highlighting the need for responsible application (8). In biotechnology, microorganisms are instrumental in the sustainable production of products like biofuels and pharmaceuticals, contributing to eco-friendly manufacturing processes(9). Nevertheless, safety concerns include the accidental release of genetically modified microorganisms and their potential impacts(10). Wastewater treatment utilizes beneficial microorganisms to biodegrade pollutants, reducing chemical usage and promoting energy-efficient processes like anaerobic digestion (11). However, concerns arise regarding the development of antibiotic resistance and incomplete remediation, emphasizing the importance of careful management to minimize negative environmental impacts. Genetic engineering offers potential environmental benefits through genetically modified microorganisms (GMMs), aiding in bioremediation, sustainable agriculture, waste treatment, and bioenergy production (12). However, concerns include ecological disruption due to altered microbial populations and the spread of antibiotic resistance genes, highlighting the importance of careful regulation to mitigate risks to ecosystems and human health. This review aimed to investigate the environmental benefits and safety considerations associated with the application of beneficial microorganisms.

Important Beneficial Microorganisms

The table below provides details on important beneficial microbes, including their applications, with specific examples.

Table 1: Important beneficial microbes and their applications

Area	**Applications**	**Examples**	**References**
Agriculture	Control pests and diseases in agriculture, environmentally friendly	*Bacillus thuringiensis* (Bt), *Pseudomonas*, *Yersinia*, Chromobacterium, fungi such as Beauveria, Metarhizium, Verticillium, Lecanicillium, Hirsutella, Paecilomyces	(7,13)
Bioremediation	Remediate pollutants in the environment	Pseudomonas, Alcaligens, Achromobacter, Acinetobacter, Alteromonas, Arthrobacter, Burkholderia, Bacillus, Enterobacter, Flavobacterium, Aspergillus, Curvularia, Drechslera, Fusarium, Lasiodiplodia, Mucor, Penicillium, Rhizopus, Trichoderma	(14,15)
Waste Treatment	Break down organic pollutants in wastewater, improve water quality	Longilinea, Georgenia, Desulforhabdus, Thauera, Desulfuromonas, Arcobacter, Methanosarcina, Methanosaeta, Clostridium	(16,17)
Genetic engineering	Engineered for specific applications, such as bioremediation	*Escherichia coli*, *Saccharomyces cerevisiae*, *Pichia pastoris*, *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus amyloliquefaciens*, *Aspergillus niger*, *Aspergillus oryzae*, *Trichoderma reesei*	(12,18)

Impact of Beneficial Microorganisms in Agriculture

Agriculture faces numerous challenges, including the detrimental impacts of pests such as fungi, weeds, and insects, resulting in significant annual crop yield reductions gl obally. Plant pests and diseases alone lead to a substantial 20 to 40% decrease in global crop yield(19). To address these challenges, biopesticides have emerged as effective alternatives to traditional chemical pesticides, relying on specific biological mechanisms for pest management rather than broad chemical approaches. Biopesticides encompass products containing biocontrol agents—natural organisms or substances derived from natural sources, including bacteria, fungi, viruses, protozoa, algae, and nematodes, along with their genes or metabolites(20). Microbial pesticides, a subset of biopesticides, primarily consist of microorganisms that occur naturally or are created through genetic engineering, targeting pests through various mechanisms such as toxin production, disease induction, or competitive inhibition(21).

Biopesticides, which are obtained from natural sources such as bacteria, plants, and minerals, provide safer alternatives to chemical pesticides by leveraging processes such as toxin generation, antibiosis, and systemic resistance, hence lowering chemical use in agriculture. Biopesticides, particularly bacterial biopesticides, minimize the use of chemicals in agriculture by providing ecologically friendly alternatives through processes such as competition, host resistance induction, and pest or pathogen inhibition(22). Compared to typical chemical pesticides, biocontrol agents provide target specificity, less ecosystem harm, increased crop quality, decreased chemical reliance, and lower environmental pollution concerns. Biocontrol agents have benefits such as low toxicity, target specificity, rapid disintegration, and little influence on non-target species, making them ecologically benign alternatives to standard chemical pesticides(23).

Positive Impacts

Reduction in Chemical Usage: Beneficial microorganisms serve as biopesticides, reducing the reliance on chemical pesticides. These biocontrol agents offer several advantages, including precise targeting of specific pests, safety for non-target organisms and the environment, effectiveness against pesticide-resistant pests, and compatibility with integrated pest management (IPM) practices (24).

Plant Growth Promotion**:** Certain beneficial microbes, such as mycorrhizal fungi and growth-promoting bacteria, form symbiotic relationships with plants, enhancing nutrient uptake. This leads to increased crop yields without the need for additional chemical fertilizers (25).

Negative Impacts

Non-Target Effects**:** Some biopesticides may inadvertently affect non-target insects, including beneficial pollinators. Unintended consequences can arise through direct contact, water contamination, or pesticide residue consumption. For instance, research on neonicotinoid seed-treated soybeans revealed unintended impacts on beneficial insects like predatory species, highlighting the importance of careful biopesticide selection and application (26).

Ecological Disruption: Beneficial microorganisms can potentially alter the native microbial communities in the soil, disrupting ecosystem dynamics. Factors such as competition for resources, antimicrobial compound production, and modification of soil pH can reshape soil microbiota. While nitrogen-fixing bacteria and mycorrhizal fungi contribute to nutrient availability, their introduction may influence soil microbial communities and overall soil health (27,28)

Impact of Beneficial Microorganisms in Bioremediation

Bioremediation, a technology employing living organisms to degrade, remove, or transform contaminants in soil, water, or air, offers a promising approach to environmental cleanup (29). This process utilizes indigenous or genetically modified microbes to detoxify contaminated environments by metabolizing pollutants into harmless substances. Bioremediation is versatile and capable of degrading various contaminants such as hydrocarbons, heavy metals, pesticides, and organic compounds (30). One of its key advantages is its ability to be applied directly to the contaminated site, reducing the need for extensive soil removal and transportation, thereby minimizing environmental impact(15). Moreover, bioremediation aligns with sustainability principles, harnessing natural processes to restore ecosystems.

Positive Impacts

Environmental Clean-up: Bioremediation offers an efficient and eco-friendly strategy for remediating contaminated sites, providing a natural process with minimal harmful side effects. This approach is environmentally sustainable, as microorganisms break down or transform pollutants into less harmful substances (31).

Applicability to Various Contaminants**:** Bioremediation is versatile and applicable to a wide range of contaminants, including oil spills, heavy metals, pesticides, and organic pollutants. Different microbial strains can be selected or engineered to target specific pollutants, reducing their harmful effects on the environment (32).

Natural and Sustainable**:** Bioremediation is a natural and sustainable process, that harnesses the power of naturally occurring microorganisms. It reduces reliance on synthetic chemicals and minimizes the environmental footprint associated with cleanup efforts (33).

Negative Impacts

Limited Applicability in Extreme Environments**:** Bioremediation may be less effective in extreme environmental conditions, such as high acidity, salinity, or low nutrient availability. Optimizing conditions for microbial activity in such environments can be challenging (34).

Potential Release of Harmful Metabolites**:** During bioremediation, microorganisms may produce metabolites as byproducts, some of which could be harmful or have unknown ecological effects. Concerns arise about unintended consequences, such as the formation of more toxic intermediates during pollutant degradation (35).

Incomplete Degradation**:** Bioremediation may not always result in the complete degradation of contaminants into harmless substances due to environmental conditions and soil or water characteristics. This incomplete degradation can lead to the formation of intermediary compounds that still pose environmental risks (36).

Distortion of Natural Microbial Community**:** When bioaugmentation introduces non-native organisms into an environment, there is a risk of these organisms significantly impacting the functionality of the natural microbial community, potentially leading to adverse environmental effects (37).

Impact of Beneficial Microorganisms in Wastewater Treatment

Wastewater treatment is a critical process aimed at removing contaminants from wastewater, ensuring its safe reintroduction into the water cycle. Anthropogenic activities often lead to the release of hazardous inorganic and organic pollutants into water bodies, posing significant threats to terrestrial ecosystems and global environmental health (38). Microorganisms play a central role in wastewater treatment, facilitating the biodegradation of both inorganic and organic materials. Bacteria, fungi, and microfauna are instrumental in breaking down organic compounds, contributing to the stabilization of biological systems (39). However, the utilization of beneficial microorganisms in wastewater treatment can yield both positive and negative environmental impacts.

Positive Impact

***Biodegradation and Detoxification*:** Beneficial microorganisms play a crucial role in breaking down organic pollutants in wastewater, facilitating biodegradation and detoxification processes. By effectively degrading natural organic compounds, microorganisms contribute significantly to maintaining ecological balance and reducing harmful substances, thus promoting environmental cleanliness (40).

***Reduced Chemical Usage*:** Microorganisms in wastewater treatment can reduce reliance on chemical treatments, offering a more environmentally friendly and cost-effective alternative. Biological remediation or bioremediation minimizes the introduction of potentially harmful chemicals into the environment, making it a sustainable approach to wastewater management (41).

Energy Efficiency: Microbial processes in wastewater treatment, such as anaerobic digestion, can be more energy-efficient compared to traditional methods. Anaerobic digestion, which converts waste into biogas, not only produces energy but also reduces biomass waste, mitigates pollution, and yields nutrient-rich fertilizer as a valuable by-product (42,43)

Negative Impacts

***Development of Antibiotic Resistance and Genetic Transfer*:** Wastewater treatment plants (WWTPs) can contribute to the development and spread of antibiotic resistance among environmental microorganisms. Exposure to antibiotics and other chemical substances in WWTPs can facilitate the horizontal transfer of antibiotic-resistance genes, posing risks to environmental and human health (44,45).

***Incomplete Remediation and Residual Contamination*:** Microbial treatments may not universally eliminate all contaminants, leading to incomplete remediation and residual contamination. Some pollutants may resist transformation into non-toxic forms, persisting in the environment and potentially causing long-term environmental issues (15,46).

Impact of Beneficial Microorganisms in Genetic Engineering

Modern biotechnology has enabled the transfer of genetic material between unrelated species, leading to the creation of genetically modified organisms (GMOs) with altered characteristics (47). Genetic engineering (GE) finds applications in various domains, including agriculture, pharmaceuticals, and environmental protection, aiming to enhance human well-being (48). While GE offers numerous benefits, it is essential to ensure that genetically engineered organisms do not harm ecosystems or human health when released into the environment (49).

Positive Impact

Bioremediation: Genetically engineered microbes (GEMs) show promise in bioremediation applications by improving the degradation of chemical pollutants. Engineered metabolic pathways or modifications to existing pathways can enhance degradation rates, contributing to more efficient pollutant removal (50,51).

***Agriculture*:** Genetically modified microorganisms (GMMs) can enhance nutrient availability in soil, improve crop yields, and reduce reliance on chemical fertilizers, promoting sustainable agricultural practices. Certain bacteria can positively impact plant growth and mitigate damage caused by pathogens or pests, leading to enhanced yields (52).

***Waste Treatment*:** GMMs play a crucial role in wastewater treatment by effectively removing heavy metals and contaminants. Genetic manipulation allows the customization of microorganisms to target specific contaminants, presenting a sustainable method for water treatment (53,54)

***Bioenergy Production*:** Genetically engineered microbes contribute to bioenergy production by improving metabolic capabilities for biofuel synthesis. Engineered strains can efficiently metabolize various biomass sources to produce biofuels such as biodiesel, bioethanol, and biogas (43,55)

Negative Impact

Ecological Disruption: Genetic manipulation of microbes can disrupt the ecological balance by introducing new forms that colonize new environments, potentially impacting microbial, plant, or animal communities. Examples include toxigenic algae causing health problems due to human-induced environmental changes(48,56).

Spread of Resistance: Genetically altered microorganisms may spread antibiotic resistance genes through various mechanisms, posing risks to human and animal health. Livestock can act as reservoirs for antibiotic resistance genes, contributing to their dissemination to humans through consumption or environmental exposure(20,57).

Strategies for Mitigating Environmental and Safety Risks

Strategies for mitigating environmental and safety risks associated with beneficial microorganisms involve implementing various measures to ensure responsible deployment and minimize potential adverse impacts. One key approach is Environmental Risk Assessment (ERA), a systematic procedure aimed at determining the potential environmental consequences of a proposed project or activity (58). ERA considers factors such as the characteristics of microorganisms, their survival dynamics in the environment, and the potential for gene transfer or unforeseen effects. Responsible and safe handling of microorganisms, particularly those potentially pathogenic, is essential to ensure the health of laboratory personnel, the community, and the environment. Containment measures play a crucial role in this regard, aiming to reduce or eliminate exposure of laboratory workers, other individuals, and the external environment to potentially hazardous agents (59). This involves implementing both physical and biological containment measures to limit the spread of harmful effects of beneficial microorganisms. Engagement with stakeholders, including the general public, scientists, and regulatory organizations, is also vital. This dialogue allows for discussions on the ethical, social, and cultural implications of releasing helpful bacteria into the environment. By involving stakeholders in the decision-making process, concerns can be addressed, and consensus on appropriate actions can be reached. Stakeholder involvement is critical in this process because it aids in understanding values, beliefs, and preferences surrounding gene drive technology and genetically modified microorganisms, resulting in acceptance and confidence in their usage for pest control and pollution reduction. Engaging stakeholders helps to resolve issues, improve transparency, and include varied viewpoints, resulting in better informed decision-making and successful risk management measure(60). Mitigating the environmental and safety issues associated with genetically altered microbes requires a variety of solutions. Genetic biocontainment devices are critical for preventing the unlawful spread of GMOs into the ecosystem. Furthermore, genomic editing techniques provide targeted gene inactivation to manage environmental infections, minimizing dangers to both ecological security and human health(61) Furthermore, selecting or designing helpful microorganisms that are eco-friendly to the target environment is crucial (27). Factors such as temperature, pH, and nutrient availability should be considered to enhance the survival and effectiveness of these microorganisms. By aligning the characteristics of beneficial microorganisms with the specific conditions of the environment, the likelihood of adverse impacts can be minimized, thus contributing to safer and more sustainable deployment practices.

Conclusion

In conclusion, the appropriate utilization of beneficial microorganisms necessitates a holistic approach to address environmental and safety concerns. By employing methods such as thorough risk evaluation, containment protocols, ethical and social considerations, and ensuring ecological harmony, stakeholders can reduce potential negative consequences while capitalizing on the possible advantages of these microorganisms. By prioritizing careful management and responsible decision-making, we can ensure the safe and sustainable utilization of beneficial microorganisms for various applications, thereby safeguarding both ecosystems and human health in the process.

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Conflict of interest

The authors state no conflict of interest.

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