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Review Article

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Biotechnological Approaches for Water Pollution Control and Sustainable Water Resource Management: A Review

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Abstract | **Background:** Increasing pressure on global water resources due to pollution, climate change and population growth necessitates innovative and sustainable solutions. Biotechnology has emerged as a promising approach for addressing water contamination and improving water use efficiency. **Objective:** This review explores the role of biotechnology in mitigating water pollution, enhancing water conservation and supporting sustainable agricultural practices under conditions of water scarcity. **Discussion:** Biotechnological applications, including the use of microorganisms, bioengineered systems and plant-based innovations, play a crucial role in water purification and reuse. Microbial processes contribute to the degradation of pollutants and facilitate wastewater treatment, enabling safe recycling of water resources. In agriculture, biotechnology enhances crop tolerance to abiotic stresses such as drought, salinity, extreme temperatures and frost, thereby reducing water demand. Additionally, plant–microbe interactions improve water uptake efficiency and support cultivation in arid and semi-arid regions. These strategies collectively contribute to optimizing water utilization and maintaining environmental balance. **Conclusion:** Biotechnology provides effective and sustainable tools for controlling water pollution and improving water resource management. Its integration into environmental and agricultural systems offers significant potential for addressing global water scarcity and ensuring long-term ecological sustainability.

Key Words Biotechnology Applications, Water Pollution Control, Wastewater Treatment, Microbial Bioremediation, Water Reuse, Sustainable Agriculture, Abiotic Stress Tolerance, Environmental Sustainability

INTRODUCTION

Water pollution is defined as any direct or indirect physical, chemical, or biological change in the quality of water. Because it becomes hazardous when used, it has a negative impact on living beings and water quality. Water pollution is defined by the World Health Organization as any change in the components included in its composition that occurs, directly or indirectly, as a result of human activity, making this water less suited for the natural purposes intended for it [1]. Humans, according to the United Nations Group of Global Experts (GEMSAMP), cause corruption and disruption to water quality in a variety of ways, resulting in a disruption in its environmental and ecological system, reducing its ability to perform its natural role and making it harmful when used, or losing much of its economic value according to the United Nations' third World Water Report, 1.5 billion people do not have access to safe drinking water and the average individual consumption is 400 liters per day, which may be enough for an individual in some African countries for a month. However, water scarcity is not the only issue; dirty water also causes many diseases in developing countries, such as cholera and typhoid, because the water accessible in these developing countries is generally filthy and causes infections. Every day, around 6,000 children die as a result of these disorders [2].

The important significance that water plays for this planet and its inhabitants is typically summed up by the expression "water is life water falling from the sky serves as the foundation for life on Earth, either directly or indirectly, live in a time of immense change and human

activities that have put ever-increasing strains on all of the world's resources, especially the most valuable resource, water. Water scarcity is an unavoidable risk due to factors such as poor water management, a lack of resources and population growth, particularly in emerging nations, as many analysts expect water to be a major cause of international conflicts in the coming years, seawater desalination plants are expensive, many scientists are looking for other, less expensive methods, such as a technique to reuse shower water, where that water can be used to irrigate land instead of wasting it or pouring it into the sea and then resorting to desalinating seawater [3].

Types of Water Pollution

Chemical Pollution: Water has a toxic effect as a result of the presence of dangerous chemicals in it, such as lead, cadmium compounds, pesticides and mercury, which can be divided into a type that can dissolve and another type that can accumulate and this type leads to the death of living organisms or the contracting of diseases that can affect humans if they eat these organisms [4].

Natural Pollution

This type alters the natural qualities of water, rendering it unsafe for drinking or ingestion. Humans, the temperature of the water and its salinity change and the suspended materials increase, whether of organic or inorganic origin. An increase in water salinity often results from an increase in the amount of evaporation of lake or river water, particularly on dry days with no renewal and this also causes it to acquire an unpleasant odor or its color or taste changes due to high amounts of certain compounds in it, posing a serious hazard to health and natural pollution emerges in the water's color, flavor and smell.

Water Pollutants

Water Pollution with Agricultural Waste: The agricultural industry is regarded the world's largest consumer of fresh water resources, as well as one of the sources. Water pollution is dangerous because rainfall causes the transfer of fertilizers, pesticides and animal waste from farms and livestock breeding areas and the transfer of these nutrients and pathogens such as bacteria and viruses into waterways and pollution with these nutrients, represented by an increase in nitrogen and phosphorus in the water or air, causes the proliferation of green algae, which causes harmful cyanosis. Chemical fertilizers and insecticides are also used in agriculture for treatment and development.

Chemical pesticides have become one of the technological tools to boost agricultural productivity and combat severe diseases for humans and animals in the last few years of this century, with a spectacular increase in global production in the previous few years. It is a chemical that kills or hinders the reproduction and spread of living organisms that compete for food, property and health with humans. Insecticides, herbicides and fungicides are the three types and their chemical composition is divided into two parts: organic pesticides, such as plant derivatives like nicotine and radiation and inorganic pesticides like cyanic compounds in powder, liquid, or emulsion form. Because of their small size, rivers and lakes have been able to naturally purify themselves for more than two thousand years. The waste disposed of was primarily human waste, but with the expansion of societies, the large increase in population, the agricultural revolution and the resulting waste of complex composition and loaded with chemicals and various biological pollutants, most water bodies lost their ability to self-technology and pollution spread to a large extent, resulting in polluted rivers. These countries have made significant efforts to purify the water of bodies of water in Europe, such as the Rhine and Danube Rivers and others and the significant Lakes in North America and some of them have been crowned with success, as happened in the River Thames in England, the majority of river pollution are caused by sewage and agricultural sewage.

Oil Pollution of Water

Oil spills in the seas and oceans have a wide range of effects on water quality, as oil can make drinking water unsafe to drink and the release of large amounts of oil into the oceans and seas destroys the ecosystems that rely on them. Oil spills also reduce the amount of oxygen in the aquatic environment. The main sources of oil-related water contamination include leaks from storage facilities, spills during transportation and the intentional placement of trash in sewage systems, also spontaneously leak from its reserves at the ocean's bottom.

Water Pollution by Industrial Waste

Many industries locations across the world contribute primarily to water pollution since they produce waste in the form of dangerous chemicals and pollutants, as well as proper waste management systems. As a result, in such rare circumstances, industrial waste is thrown into neighboring freshwater systems, contributing to contamination, particularly if not handled. Factory water and waste account for 60% of total pollutants in seas, lakes and rivers, with the majority of pollutants coming from tanning plants, lead, mercury, copper, nickel, paints, cement, glass, detergents, dairy sterilization plants, slaughterhouses and sugar refining plants, in addition to hydrocarbon pollution. Most factories in developing nations and even those in rich countries, do not follow industrial drainage standards and instead dump their waste into bodies of water. Toxic waste was discovered in the water of rivers and seas around factories in the United States.

According to a report issued by the United Nations Office for Human Settlements in Africa during a conference held in Nairobi, Kenya in 2002, there are more than 5 million deaths in Africa each year, including one

million children, as a result of diseases caused by water pollution, remarkable thing is that Africa has 50 fresh rivers and lakes, but 66 percent of its inhabitants does not have access to clean drinking water, only ten countries have safe drinking water and 900 African citizens are ravaged by disease due to water pollution. Traditional water filtration procedures do not remove industrial contaminants such hydrocarbons and other pollutants including organics, pesticides and other chemicals, one type of industrial pollution is the use of river and lake water for cooling by some factories and power plants, resulting in a rise in water temperature that negatively affects biochemical reactions and aquatic species in the water. Pollution of fresh water causes people to become infected with infectious diseases that immediately destroy their health among these diseases are cholera, typhoid, hepatitis, malaria, poisoning and other diseases that cause human death, as five million people die each year from diseases transmitted by polluted water, including four million children.

Household Waste

Some countries gather and dump household waste in the oceans and it can take anywhere from two to 200 years for their domestic debris to breakdown in rivers nearby, inflicting harm to aquatic life and increasing flood risk.

Radioactive Waste

Radioactive materials are employed in power plants; radioactive waste is also a source of water contamination. Nuclear processes are used in industrial, medical and other scientific applications. It can also be found in timepieces, luminous watches, television sets and X-ray machines, as well as other radioactive isotopes that occur naturally in the environment and, if not properly disposed of, can cause contamination.

Sewage

Water used in homes and industrial processes is all considered wastewater and it includes water from bathtubs, toilets, commercial, industrial and agricultural activities and rainwater runoff, when rain carries road salts, oils, grease, chemicals and debris from surfaces into waterways. Bacteria, viruses and parasites abound in wastewater, several diseases, including cholera, typhoid and polio, are spread. Microorganisms are involved in the transformation of methane, sulfur, phosphorus and nitrate. In aerobic and anaerobic settings, methane bacteria generate methane gas, whereas putrefaction bacteria make ammonia, which is converted to nitrate, which forms the greenness of water and appears on the surface form a green layer on the surface of water tanks, lakes and seashores. The bulk of them are found in stagnant water and prevent oxygen from entering the water. Blue eye disease in children is caused by an increase in green weeds. Pollution concerns are predicted to worsen over time as cities' populations grow and the need for sewage and human waste disposal grows, in addition to sewage waste generated by industrial clusters that grow in size and quantity.

Thermal Pollution

It is the degradation of water quality caused by changes in ocean temperature. The use of water as a coolant for power stations and industry is a common source of this contamination. When the water is returned to nature at a higher temperature, the oxygen support diminishes based on the temperature difference, affecting the environmental structure totally. Many marine organisms have adapted to live at greater temperatures when a power plant starts or ceases for any reason. At a particular temperature, you may die suddenly from what is known as thermal shock.

Nuclear Pollution

There are major damages resulting from the use of this energy, including that nuclear generators cause pollution Seas and oceans, as they work to raise their temperature significantly because they require large amounts of water for cooling, which leads to the death of marine organisms, which are among the most important food resources and this falls under what is called thermal or physical pollution.

Biotechnologies

Biotechnology is considered one of the most growing and advanced technical sciences in the current era and it is a rapid development of genetic engineering. It is an applied science that aims to find, develop and use multiple biological and molecular techniques to bring about desired genetic changes in living organisms based on the scientific method for testing a theoretical hypothesis using molecular biology methods. Therefore, we can define biotechnology as: the science that deals with methods of using biological systems, a living organism or parts of it, to produce a useful product or service, as it has had a major impact on all aspects of life and has created many technical revolutions in the world of agriculture, industry, medicine, medicine, food, environment, etc. from all areas of human activities [6].

Biotechnologies have already succeeded in enhancing immunity to a wide variety of environmental stresses, such as enhancing the resistance of crops to harsh climatic conditions, such as frost, extreme heat, salinity or drought, but there are still many challenges to optimally exploiting these technologies because this requires controlling complex sets of factors. Genetics and the use of appropriate methods to select drought-tolerant plants [7]. Biotechnology also provides a golden opportunity to rationalize water consumption by using effective biological methods to improve the efficiency of water use in agriculture by using microorganisms to help plants overcome water scarcity. It also helps in optimal exploitation of water by reusing and purifying water.

The Role of Biotechnology in Enhancing Water Security

In early 2009, the Food and Agriculture Organization issued a statement on water scarcity and biotechnology, which mainly focused on the use of biotechnology to increase water efficiency in agriculture, the use of microorganisms in the field of wastewater treatment and the inoculation of crops and forest trees with mycorrhiza fungi, which includes a wide range of tools with varying degrees of technical sophistication and requiring different levels [8], They can be used to reduce water scarcity in agriculture, such as the employment of a variety of plant biotechnologies (for example, genetic techniques in plant molecular breeding programs and microbial biotechnologies such as Mycorrhiza fungus as an organic fertilizer). There was general agreement that biotechnology could play an important role in addressing the challenge of water scarcity in developing countries, developing the most important solutions to the problems of water pollution and scarcity and the ability to design biotechnology-based wastewater treatment systems in such a way that they could participate in products such as biogas as an important part of biotechnology to reduce water pollution [9].

The most serious threat to food production in the future will come from the drought that will befall many countries of the world. Experts believe that there are a number of different biotechnologies that can be used to produce crops that are more capable of facing water scarcity in agriculture, such as genetic modification techniques and the production of stress-resistant plant mutations. Environment, modern genetic engineering methods and molecular parameterization techniques, which are the most important weapons that help produce new plants that are compatible with new climatic conditions, although many high-tech biotechnology is widely available in some countries of the world, the use of these technologies is still expensive in developing countries [10]. Scientists can search for genetic patterns of plants that are resistant to drought and salinity and that tolerate high temperatures in germplasm that is characterized by a high level of genetic diversity by examining a large number of these plants within the specific environment in which such plants can be cultivated. [7].

Many experts argue that molecular biology techniques are already pricey and should only be employed when there are no other options. Some recent biotechnology research has indicated that plant breeding for drought resistance can also be implemented successfully without the need for high-cost techniques such as selecting strains in the laboratory through tissue culture technology, which most developing countries have succeeded in utilizing to improve the crops grown in them. Plant strains that can withstand environmental stresses, particularly drought, have already been selected and drought-tolerant varieties of wheat and rice have been produced using this technology, in addition to the peaceful use of nuclear energy to create mutations for drought-tolerant plants [11]. The majority of contemporary genetically modified crops are produced by the corporate sector in big developed countries, many farmers in poor countries plant these crops. According to research, there is a strong economic feasibility of utilizing genetic modification to generate drought-tolerant crops [12]. Given the complexity of the genetic traits associated with such traits, adaptation to water scarcity and pollution has achieved some notable successes after using traditional breeding techniques and molecular genetics techniques in the field of tolerance to salt stress (salinity), which is a trait closely related to the ability of plants to tolerate drought. However, due to the sensitivity of these plants, concerns about their impact on many biological and genetic systems, concerns about the safety of GM crops and concerns that they may cause more problems in the agricultural community that are resistant to drought and other environmental stresses are unlikely to be used in the near future [13]. The use of modern biotechnological methods, as well as the exploitation of genomic information and other tools, provide a huge wealth of information and a better understanding of the changes in cellular metabolism caused by drought and to combine modern technology tools such as bioinformatics, bemoaning, proteomics and others to improve drought tolerance traits in many important, high-yielding crops and the need to benefit from traditional biotechnologies rather than exploiting th Tissue culture methods, for example, are an excellent way to select drought-tolerant plant strains and establish a new generation, a new hybrid species of drought-tolerant and high-yielding crops [14].

Plant hybridization techniques, embryo rescue techniques, anther cultivation techniques and mutation generation techniques also provide ideal ways to produce new types of drought-resistant hybrid rice and wheat. Many countries have succeeded in arriving at several modern methods for generating drought-resistant lines from rice, peanut and walnut plants using traditional breeding methods with modern biotechnological methods represented by tissue culture and traditional breeding methods or by using molecular techniques, as they can play an important role in the field of Providing assistance to developing countries in enhancing their capabilities in growing drought-resistant crops and evaluating their performance[15].

Biological Methods for Improving Water Use Efficiency in Agriculture

The use of organisms known as mycorrhiza to help plants overcome water scarcity is one of the most effective biotechnological strategies that can be used to improve water usage efficiency in agriculture. These bacteria can be employed as a bio-fertilizer to boost development and increase the plant's ability to absorb water of microbes to improve plant water consumption is one of the most exciting topics and it demonstrates the potential that

biotechnology and microbiology offer to reduce the effects of drought on plants; however, there are numerous technical challenges that prevent the use of these microbes as natural fertilizers in some developing countries [8].

Several experiments using microbial fertilizers have resulted in lower organic fertilizer consumption, lower irrigation water requirements, lower disease and pest incidence, increased crop productivity and quality and improved soil water retention. In addition, research has shown that the efficiency of water absorption in plants can be increased in the presence of other microbes. For example, using mycorrhizae can aid boost water efficiency, especially when combined with the use of other beneficial species like Streptococcus bacteria. Rhizobium, when coupled, increases growth by utilizing low-cost sources such as phosphorus and rock phosphate. Scientists must use a simple, low-cost approach to encourage farmers in developing countries to use microbes as organic fertilizer by inoculating crops with commercially produced microbial strains of fungi and bacteria that can provide a significant increase in the capacity of many plant roots improving its ability to absorb water and other nutrients [16].

The Role of Biotechnology in Wastewater Treatment

Although there are many major challenges for human health and environmental integrity, many applications of biotechnology that can play a useful role in wastewater treatment, including the use of plants and microbes [17], biotechnology offers an important way for farmers in developing countries to address water scarcity by recycling used water and treating it before using it again in agriculture. Biotechnology can help improve water treatment by creating biological agents that detect heavy metals, herbicides and other pollutants in wastewater [18]. It can also create bio-filters to remove pollutants from water, such as heavy metals. For example, biological filters have been developed by developing the use of dry materials from floating aquatic ferns known for their ability to absorb heavy metals, research is still ongoing in the field of using cyanobacteria, which is also known for its ability to absorb heavy metals, as a biofilter to developed strains of algae to remove heavy metals, nitrogen and phosphorus from wastewater in order to make them safe for reuse in agriculture and to provide a suitable environment. Pollution of irrigation groundwater causes numerous environmental and health issues. However, in the Indian state of West Bengal, some herbs, including flowering and non-flowering plants and some types of crops that absorb high levels of arsenic are available and they have been used in the biological treatment of soil pollution as filters to prevent toxic arsenic particles from returning to the ecosystem [19]. Although genetic modification approaches represent a new sanctuary for generating organisms capable of isolating and accumulating heavy metals from waste and polluted water, the focus should be on non-genetically modified plants and organisms for the time being. As a result, it was critical to focus on developing solutions to water pollution and scarcity problems, as well as the ability to design biotechnology-based wastewater treatment systems in such a way that they achieve participation in products such as biogas as an important part of vital technologies to reduce water pollution [11,20].

CONCLUSIONS

Many organisms provide a golden means of decomposing toxic substances with the ability to produce oils, fertilizers and biogas at the same time, leading to the development of many businesses and opportunities. Many algae and other microscopic plant species can help extract nutrients from dirty water while also removing pollutants. As a result, it supplies numerous sources of fuel, food, or fertilizer and it can provide low-cost alternatives for producing significant volumes of energy, such as biogas for heating or other residential needs and produce sludge that can be used for revaccination or fertilizer and treated water that can be used to irrigate agricultural crops and have been achieved in the Netherlands, Germany and Russia after adopting biosystems as a means of treating water from these biotechnologies to confront the challenge of water scarcity and pollution, as biotechnology plays an important and very effective role in managing water resources around the world in general and holds a promising future for the management of agricultural water resources and improving the efficiency of its use, which will have a great impact on making the most of the available resources, especially after the world enters the stage of water scarcity for the coming years, especially the Middle East region and Iraq particular.

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