ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul1143

Role of Genetically Engineered Microbes in Wastewater Treatment

Sadaf Zia[1]; Dr. Manoranjan Bar[2]

[1]Deparment of Biotechnology, School of Science, Sona Devi University, Ghatshila, Jharkhand, India.
[2]Deparment of Chemistry, School of Science, Sona Devi University, Ghatshila, Jharkhand, India.

Publication Date: 2026/07/29

Abstract: The rapid expansion of industrial, urban, and agricultural activities has led to the continuous release of complex and persistent pollutants into aquatic ecosystems, posing significant risks to environmental sustainability and human health. Conventional wastewater treatment technologies, while widely implemented, are often constrained by high energy requirements, operational costs, incomplete removal of recalcitrant contaminants, and the generation of secondary pollutants. In recent years, genetically engineered microorganisms (GEMs) have gained considerable attention as an advanced biological approach for wastewater treatment due to their enhanced metabolic versatility and environmental compatibility. Through targeted genetic modifications, GEMs demonstrate improved capabilities for the degradation of organic pollutants, nutrient removal, heavy metal detoxification, and elimination of emerging contaminants such as pharmaceuticals and endocrine-disrupting compounds. This review critically evaluates the role of genetically engineered bacteria, fungi, and algae in wastewater treatment, focusing on their underlying mechanisms of action and application across domestic, industrial, and agricultural wastewater systems. The environmental benefits of GEM-based treatment, including reduced energy demand and improved treatment efficiency, are highlighted alongside key challenges related to biosafety, ecological risks, regulatory frameworks, and public acceptance. Recent advances in synthetic biology, genetic containment strategies, and system integration are discussed to assess future research directions and large-scale implementation potential. Overall, genetically engineered microorganisms represent a promising and sustainable solution for addressing the growing complexity of wastewater pollution when supported by robust regulatory oversight and biosafety measures.

Keywords: *Genetically Engineered Microorganisms; Wastewater Treatment; Bioremediation; Emerging Contaminants; Heavy Metal Removal.*

How to Cite: Sadaf Zia; Dr. Manoranjan Bar (2026) Role of Genetically Engineered Microbes in Wastewater Treatment. *International Journal of Innovative Science and Research Technology*, 11(7), 1785-1791.
https://doi.org/10.38124/ijisrt/26jul1143

I. INTRODUCTION

Accelerated industrialization, urban expansion, and intensified agricultural practices have substantially increased the discharge of diverse pollutants into aquatic systems. Wastewater from domestic, industrial, and agricultural activities comprises complex mixtures of organic pollutants, nutrients, heavy metals, and emerging contaminants that threaten ecosystem integrity and human health. Inadequate wastewater treatment in many regions has contributed to deteriorating water quality, biodiversity loss, and increased human exposure to toxic substances. Although physical and chemical treatment technologies remain widely used, their effectiveness is often limited by high operational costs, energy demands, incomplete removal of persistent pollutants, and secondary waste generation. Increasing regulatory pressures and the growing diversity of wastewater contaminants highlight the need for more sustainable and efficient treatment strategies. Biological treatment approaches offer environmentally compatible alternatives due to their lower energy requirements and capacity for pollutant mineralization; however, naturally occurring microbial communities often show limited efficiency under high pollutant loads or variable wastewater conditions [1-3].

Genetically engineered microorganisms are created through targeted modification or introduction of genes associated with pollutant degradation, stress tolerance, and metal resistance, enabling enhanced metabolic performance under harsh wastewater conditions. Advances in molecular biology and synthetic biology have enabled the design of microbial strains with higher specificity, faster degradation kinetics, and improved adaptability, making them promising candidates for next-generation wastewater treatment systems.

Various engineered bacteria, fungi, and algae—particularly metabolically versatile hosts such as *Pseudomonas*, *Bacillus*, and *Cupriavidus* species—have been explored for treating diverse wastewater streams, including extreme industrial effluents. Beyond enhanced degradation

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul1143

efficiency, genetic engineering enables microorganisms to perform multiple functions simultaneously. Engineered microbes can be designed to target a range of pollutants within a single system, including organic contaminants, nutrients, and metals [4-5]. This multifunctionality is particularly relevant for complex wastewater matrices where conventional treatment methods often require multiple sequential processes. Moreover, genetic modification can improve microbial tolerance to fluctuating pH, temperature, salinity, and toxic compounds, thereby ensuring stable performance under real wastewater treatment plant conditions.Despite their advantages, GEM-based applications raise biosafety, regulatory, and public acceptance concerns related to ecological risks and horizontal gene transfer. Therefore, a balanced evaluation of both the advantages and limitations of GEM-based wastewater treatment is essential for their responsible implementation [6-7].

This review provides a comprehensive and critical assessment of the role of genetically engineered microorganisms in wastewater treatment. It focuses on the mechanisms through which GEMs enhance pollutant removal, their application across different types of wastewater, and the environmental benefits they offer compared to conventional treatment approaches. In addition, the review discusses the major challenges associated with biosafety, regulation, and long-term system stability, as well as recent technological advances and future prospects for sustainable water pollution management [8].

II. BACKGROUND OF WASTEWATER TREATMENT

The increasing demand for freshwater, together with rapid population growth, industrial expansion, and urbanization, has intensified pressure on global water resources. Large volumes of wastewater generated from domestic, agricultural, and industrial activities are discharged into the environment every day, carrying a wide range of contaminants, including biodegradable organic matter, nutrients, pathogenic microorganisms, heavy metals, and emerging pollutants. When released without adequate treatment, these contaminants deteriorate water quality, threaten aquatic biodiversity, and pose significant risks to human health through the contamination of surface water and groundwater resources.

Wastewater treatment has become an essential component of sustainable water resource management because it reduces pollutant loads before wastewater is discharged into natural ecosystems or reused for agricultural and industrial purposes. Besides protecting public health, efficient treatment systems contribute to water conservation by enabling treated wastewater to serve as an alternative water source in regions experiencing freshwater scarcity. This is becoming increasingly important as climate change, irregular rainfall patterns, and growing water consumption continue to reduce the availability of clean water in many parts of the world.

Modern wastewater treatment systems are designed to remove contaminants through a combination of physical, chemical, and biological processes. While conventional treatment technologies have significantly improved sanitation worldwide, treatment efficiency varies considerably between developed and developing countries due to differences in infrastructure, financial resources, technical expertise, and regulatory implementation. Many low- and middle-income countries continue to face challenges in expanding wastewater treatment facilities, resulting in the discharge of partially treated or untreated wastewater into rivers, lakes, and coastal ecosystems.

Growing environmental regulations and increasing concern over persistent pollutants have encouraged the development of more sustainable treatment strategies. Biological treatment processes have attracted considerable attention because microorganisms naturally transform organic contaminants into simpler and less harmful compounds while consuming relatively little energy compared with many physicochemical methods. Nevertheless, naturally occurring microbial populations often exhibit limited degradation capacity when exposed to complex industrial pollutants or toxic environmental conditions. Consequently, improving microbial performance through genetic engineering has emerged as a promising strategy for enhancing wastewater treatment efficiency and environmental sustainability [8].

III. CONVENTIONAL WASTEWATER TREATMENT TECHNOLOGIES

Wastewater treatment involves a series of integrated processes that progressively remove suspended solids, organic matter, nutrients, pathogenic microorganisms, and toxic contaminants before treated water is discharged or reused. Conventional treatment systems generally consist of preliminary, primary, secondary, and tertiary treatment stages, each designed to target specific categories of pollutants.

The preliminary stage primarily removes large floating materials such as plastics, paper, sand, and gravel using screening and grit removal systems. Eliminating these materials protects downstream equipment from clogging and mechanical damage while improving the overall efficiency of the treatment process. Primary treatment subsequently separates settleable solids through sedimentation, thereby reducing suspended solids and a portion of the organic load entering biological treatment units.

Secondary treatment relies mainly on microbial activity to degrade biodegradable organic matter present in wastewater. Common biological processes include activated sludge systems, trickling filters, oxidation ponds, rotating biological contactors, and anaerobic digesters. During these processes, naturally occurring microorganisms metabolize organic compounds, converting them into carbon dioxide, water, microbial biomass, and other stable products. Biological treatment also contributes to partial removal of

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul1143

nitrogen and phosphorus depending on the operational design of the treatment facility.

As environmental regulations have become increasingly stringent, tertiary or advanced treatment has been incorporated into many wastewater treatment plants. Advanced processes may include membrane filtration, activated carbon adsorption, advanced oxidation processes, ion exchange, nutrient removal technologies, and ultraviolet or ozone disinfection. These methods improve the removal of dissolved contaminants, pathogenic microorganisms; trace organic pollutants, and residual nutrients that are not efficiently eliminated during earlier treatment stages.

Despite their widespread use, conventional wastewater treatment technologies have several limitations. Many advanced physicochemical methods require substantial energy input, specialized equipment, and continuous chemical consumption, leading to increased operational costs. Furthermore, certain persistent contaminants, including pharmaceuticals, endocrine-disrupting compounds, microplastics, and per- and polyfluoroalkyl substances (PFAS), are only partially removed by conventional systems. The generation of chemical sludge and secondary waste also creates additional disposal challenges. These limitations have stimulated growing interest in developing innovative biological technologies, including genetically engineered microorganisms, capable of improving pollutant degradation while reducing environmental impacts and operational costs [8].

IV. MECHANISMS OF ACTION OF GENETICALLY ENGINEERED MICROORGANISMS IN WASTEWATER TREATMENT

The effectiveness of genetically engineered microorganisms in wastewater treatment is primarily attributed to their enhanced metabolic and physiological capabilities. At the molecular level, genetic modifications enable the expression of specific enzymes that catalyze the breakdown of complex and persistent pollutants. These enzymes include oxygenases, reductases, hydrolases, and dehalogenases, which facilitate the transformation of toxic compounds into less harmful or biodegradable intermediates. One of the most significant mechanisms involves the accelerated biodegradation of organic pollutants. Engineered microbes can mineralize hydrocarbons, phenols, dyes, pesticides, and pharmaceutical residues that are otherwise resistant to natural degradation. By combining metabolic pathways from different organisms within a single host, GEMs can perform sequential degradation steps more efficiently, reducing the accumulation of intermediate toxic compounds [9].

Nutrient removal represents another critical mechanism by which GEMs improve wastewater treatment performance. Excess nitrogen and phosphorus are major contributors to eutrophication in receiving water bodies. Genetically engineered nitrifying and denitrifying bacteria exhibit enhanced ammonia oxidation and nitrate reduction rates, improving nitrogen removal efficiency. Similarly, engineered phosphorus-accumulating organisms demonstrate increased capacity for intracellular phosphate storage, thereby reducing phosphorus discharge into aquatic environments [10-13].

The detoxification and immobilization of heavy metals constitute an additional mechanism of action. Through genetic modification, microbes can express metal-binding proteins, efflux pumps, or reductase enzymes that transform soluble metal ions into less toxic or insoluble forms. This reduces metal bioavailability and minimizes their ecological and health impacts. Such mechanisms are particularly valuable for treating industrial effluents and mining wastewater rich in metals such as mercury, cadmium, chromium, and arsenic.

Genetic engineering also enhances microbial resistance to environmental stressors commonly encountered in wastewater treatment systems. Modified stress response pathways improve tolerance to extreme pH, temperature variations, oxidative stress, and toxic chemicals. As a result, GEMs maintain metabolic activity and treatment efficiency under conditions that would otherwise inhibit natural microbial communities.

Emerging contaminants, including endocrine-disrupting chemicals, antibiotics, and personal care products, pose significant challenges to conventional treatment systems. GEMs can be designed to specifically recognize and degrade these compounds, reducing their persistence in treated effluents. This targeted removal capability is increasingly important for protecting aquatic ecosystems and preventing the spread of antibiotic resistance [14-15].

V. ENVIRONMENTAL SIGNIFICANCE AND SUSTAINABILITY CONSIDERATIONS

From an environmental perspective, the application of genetically engineered microorganisms offers several sustainability advantages. GEM-based treatment systems reduce reliance on energy-intensive chemical processes and minimize the generation of secondary pollutants. Their ability to achieve complete detoxification rather than simple pollutant transfer aligns with the principles of green chemistry and circular bioeconomy [16].

Furthermore, advanced genetic tools allow the development of biosafety mechanisms such as genetic containment systems, inducible gene expression, and kill switches. These strategies reduce the risk of unintended environmental persistence and enhance regulatory acceptability. The integration of GEMs with real-time monitoring systems and biosensors also enables adaptive treatment responses, improving operational efficiency and environmental protection [17].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul1143

VI. DEVELOPMENTS IN WASTEWATER TREATMENT METHODS

Technological innovations have significantly transformed wastewater treatment over the past few decades, moving beyond conventional pollutant removal toward integrated systems that emphasize sustainability, resource recovery, and environmental protection. Modern wastewater treatment plants are increasingly designed not only to purify wastewater but also to recover valuable resources such as water, nutrients, energy, and reusable materials, thereby supporting the principles of the circular economy.

One major area of advancement is membrane-based treatment technology. Processes such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis provide highly efficient separation of suspended particles, microorganisms, dissolved salts, and trace organic contaminants. These technologies have become important components of wastewater recycling systems because they produce high-quality treated water suitable for industrial applications, agricultural irrigation, and, in some cases, potable reuse following additional purification steps.

Biological treatment technologies have also undergone substantial improvements. High-rate anaerobic reactors, moving bed biofilm reactors (MBBRs), membrane bioreactors (MBRs), sequencing batch reactors (SBRs), and integrated fixed-film activated sludge systems have enhanced treatment efficiency while reducing land requirements and energy consumption. These advanced biological systems promote stable microbial communities capable of achieving more effective removal of organic matter and nutrients under varying operational conditions.

In parallel, advanced oxidation processes, photocatalysis, electrochemical treatment, and adsorption technologies have been developed to address contaminants that resist conventional biological degradation. These approaches generate highly reactive species capable of oxidizing complex organic molecules into simpler compounds, thereby improving the removal of pharmaceuticals, pesticides, dyes, and other emerging pollutants.

Recent progress in biotechnology has introduced genetically engineered microorganisms as promising alternatives for overcoming the limitations of natural microbial populations. By modifying genes responsible for metabolic activity, pollutant transport, stress tolerance, and enzyme production, engineered microorganisms can degrade a broader range of contaminants with greater efficiency than naturally occurring strains. Advances in synthetic biology, genome editing, and metabolic engineering have further accelerated the development of microbial systems with enhanced specificity, stability, and environmental adaptability.

Future wastewater treatment is expected to integrate smart monitoring technologies, artificial intelligence, biosensors, and automated process control with advanced biological systems. Such integrated approaches will enable continuous optimization of treatment performance, rapid detection of contaminants, and efficient resource recovery while minimizing environmental impacts. As these technologies mature, wastewater treatment facilities are expected to evolve into sustainable biorefineries that contribute not only to pollution control but also to renewable energy generation, nutrient recycling, and water reuse [18].

VII. GEMS FOR ENVIRONMENTAL RESCUE AGAINST POLLUTANTS

Bioremediation is confirmed to be the only effective tool for cleaner, safer, sustainable and cost effective decontamination of the polluted sites. Hence, choosing the correct microbial strain in terms of its potential, rapid growth and nutrition responses and then, engineering is indeed a very strenuous task. Genetically engineered microorganisms (GEMs) have emerged as a promising tool for environmental rescue by enhancing the natural biodegradation potential of microorganisms through targeted genetic modifications. Unlike native microbial strains, GEMs are designed to express specific catabolic enzymes, transport proteins, or stress-resistance genes that enable them to efficiently degrade, transform, or immobilize a broad spectrum of environmental pollutants. These engineered microorganisms have demonstrated remarkable capabilities in removing petroleum hydrocarbons, chlorinated solvents, polycyclic aromatic hydrocarbons (PAHs), pesticides, synthetic dyes, pharmaceuticals, endocrine-disrupting chemicals, and toxic heavy metals from contaminated soil and wastewater. By integrating multiple degradation pathways into a single microbial host, GEMs can simultaneously metabolize complex pollutant mixtures while maintaining higher survival rates under adverse environmental conditions such as extreme pH, high salinity, elevated temperatures, and toxic chemical concentrations. Consequently, they offer a sustainable and environmentally friendly alternative to conventional physicochemical remediation technologies, which are often energy-intensive, costly, and may generate secondary pollutants.

Recent advances in synthetic biology, metabolic engineering, and genome editing have further expanded the application of GEMs in environmental remediation. Technologies such as CRISPR-Cas systems, pathway engineering, and synthetic gene circuits allow researchers to develop microorganisms with improved substrate specificity, faster degradation kinetics, and enhanced biosafety through genetic containment mechanisms, including inducible kill switches and auxotrophic designs. In addition to pollutant degradation, engineered microbes are being explored for biosensing applications, enabling the rapid detection of environmental contaminants while simultaneously initiating remediation processes. Despite these advantages, large-scale environmental deployment of GEMs requires careful evaluation of ecological risks, including horizontal gene transfer, long-term genetic stability, and regulatory compliance. Therefore, future research should focus on balancing enhanced remediation efficiency with robust biosafety strategies to ensure the responsible and sustainable

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul1143

implementation of GEM-based technologies for environmental protection [19-22].

VIII. CHALLENGES IN COMMERCIALIZATION OF GENETICALLY ENGINEERED MICROORGANISMS (GEMS) FOR WASTEWATER TREATMENT

Although genetically engineered microorganisms (GEMs) have demonstrated remarkable potential for enhancing wastewater treatment efficiency, their commercialization remains limited due to several scientific, technical, regulatory, and socioeconomic challenges. The transition from laboratory-scale research to full-scale industrial application requires overcoming barriers related to biosafety, economic feasibility, public perception, and operational reliability. Addressing these challenges is essential to ensure the safe, sustainable, and economically viable deployment of GEM-based technologies in wastewater treatment systems.

One of the primary obstacles to commercialization is Biosafety and environmental risk**.** The accidental release of GEMs into natural ecosystems may result in unintended ecological consequences, including disruption of native microbial communities and horizontal gene transfer to indigenous microorganisms. The transfer of engineered genes, particularly those associated with antibiotic resistance or enhanced metabolic functions, could alter ecosystem dynamics and create unforeseen environmental risks. Consequently, stringent biosafety assessments and effective biological containment strategies, such as genetic kill switches, auxotrophic mutants, and inducible suicide systems, are necessary before environmental application.

Another significant challenge is the genetic stability of engineered microorganisms during long-term operation. Many GEMs maintain their enhanced metabolic functions under controlled laboratory conditions but may lose engineered traits after prolonged cultivation or exposure to fluctuating environmental conditions in wastewater treatment plants. Mutations, plasmid instability, and selective pressure can reduce the effectiveness of engineered strains over time, necessitating continuous monitoring and optimization to ensure stable performance.

The complex composition of wastewater further complicates commercialization. Industrial and municipal wastewater contains diverse mixtures of organic compounds, heavy metals, pharmaceuticals, antibiotics, and other emerging contaminants. Environmental factors such as pH, temperature, salinity, dissolved oxygen, and toxic substances can influence microbial survival and metabolic activity. As a result, engineered microorganisms that perform efficiently under laboratory conditions may exhibit reduced degradation efficiency in real wastewater environments, limiting their large-scale applicability.

Economic considerations also play a crucial role in commercialization. The development of genetically engineered strains requires advanced molecular biology techniques, specialized infrastructure, skilled personnel, and extensive validation studies, all of which increase production costs. Furthermore, large-scale cultivation, downstream processing, quality control, and continuous monitoring contribute to operational expenses. In many regions, conventional biological treatment systems remain more cost-effective, making industries reluctant to adopt GEM-based technologies without clear evidence of long-term economic benefits.

The regulatory landscape represents another major barrier. Most countries have strict regulations governing the environmental release and commercial use of genetically modified organisms. Regulatory approval often requires comprehensive evaluations of environmental safety, human health risks, genetic stability, and ecological impact, making the approval process lengthy and expensive. Moreover, the absence of harmonized international regulatory frameworks creates uncertainty for industries seeking global implementation of GEM-based wastewater treatment technologies.

Public acceptance is equally important for successful commercialization. Concerns regarding genetically modified organisms, potential ecological risks, and ethical issues often influence public perception. Negative attitudes toward GMOs may reduce societal acceptance of wastewater treatment systems employing engineered microorganisms, even when scientific evidence demonstrates their safety. Transparent communication, public engagement, and education regarding the environmental benefits and biosafety measures associated with GEMs are therefore essential to improve public confidence.

Finally, competition with indigenous microbial communities presents an operational challenge. Native microorganisms already present in wastewater treatment systems are well adapted to local environmental conditions and may outcompete introduced engineered strains for nutrients and ecological niches. This competition can reduce the persistence and effectiveness of GEMs, limiting their contribution to pollutant degradation. Future research should focus on developing robust microbial consortia, improving host adaptability, and integrating synthetic biology with advanced bioprocess engineering to enhance the long-term performance of engineered microorganisms under real-world conditions.

Overall, while genetically engineered microorganisms hold considerable promise for next-generation wastewater treatment, overcoming challenges related to Biosafety, genetic stability, regulatory compliance, economic viability, public acceptance, and operational performance is essential for their successful commercialization. Continued advances in synthetic biology, genome engineering, and microbial containment technologies, supported by evidence-based regulatory policies, are expected to facilitate the responsible translation of GEM research from laboratory studies to practical industrial applications [24-27].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul1143

IX. FUTURE PERSPECTIVE

Genetically engineered microorganisms (GEMs) are expected to play an increasingly important role in the future of sustainable wastewater treatment. Advances in synthetic biology, CRISPR-based genome editing, and metabolic engineering will enable the development of microbial strains with enhanced pollutant degradation efficiency, greater environmental adaptability, and improved genetic stability. Future research is likely to focus on engineering microbial consortia capable of simultaneously removing multiple contaminants, including heavy metals, pharmaceuticals, endocrine-disrupting compounds, and micro plastics.

The integration of artificial intelligence, genome-scale metabolic modeling, and biosensor technologies is expected to optimize strain design and enable real-time monitoring of treatment processes. At the same time, the development of robust Biosafety measures, such as genetic kill switches and biological containment systems, will be essential to minimize ecological risks and facilitate regulatory approval. With continued technological advancements and supportive regulatory frameworks, GEM-based wastewater treatment has the potential to become a safe, efficient, and environmentally sustainable approach for addressing global water pollution while contributing to resource recovery and the circular bioeconomy [27-29].

X. CONCLUSION

Genetically engineered microorganisms represent a promising and innovative approach to addressing the growing complexity of wastewater pollution. By overcoming the metabolic and physiological limitations of natural microbial populations, GEMs enable more efficient degradation of recalcitrant pollutants, improved nutrient removal, and enhanced resistance to environmental stress. Advances in genetic engineering and synthetic biology have further expanded their functional potential while improving control over microbial behavior.

Nevertheless, the successful implementation of GEM-based wastewater treatment systems depends on addressing biosafety concerns, regulatory challenges, and public acceptance. Continued research focusing on genetic stability, ecological impact assessment, and containment strategies will be essential for responsible application. With appropriate safeguards and regulatory support, genetically engineered microorganisms have the potential to play a significant role in sustainable wastewater management and environmental pollution control [30].

REFERENCES

[1]. Abha, S., Singh, C.S. Hydrocarbon pollution: effects on living organisms, remediation of contaminated environments, and effects of heavy metals co-contamination on bioremediation, Introduction to Enhanced Oil Recovery (EOR) Processes and Bioremediation of Oil Contaminated Sites; 2012; 186-206.

[2]. Ahn, Y., Jung, H., Tatavarty, R., Choi, H., Yang, J., Kim, IS. Monitoring of petroleum hydrocarbon degradative potential of indigenous microorganisms in ozonated soil, Biodegradation, 16; 2005; 45-56.

[3]. Ah-You, K., Suleiman, M., Jaworski, J. Biotechnology and cleaner production in Canada, Program for Energy Research and Development (PERD); 2000; 1-96.

[4]. Ajayi, T.O., Ogunbayo, A.O. Achieving environmental sustainability in wastewater treatment by phytoremediation with water hyacinth (*Eichhorniacrassipes*), Sustainable Development 7; 2012; 80-90.

[5]. Alivisatos, P. The use of nanocrystals in biological detection, Nature Biotechnology, 22; 2004; 47-52.

[6]. González, J., Sánchez, M.E., Gómez, X. Enhancing anaerobic digestion: the effect of carbon conductive materials, C J Carbon Research, 4; 2018; 59.

[7]. Luo, R., et al. Insights into the relationship of reactive oxygen species and anions in persulfate-based advanced oxidation processes for saline organic wastewater treatment, Environmental Science: Water Research & Technology, 8; 2022; 465-483.

[8]. Morin-Crini, N., Crini, G. Eau industriellescontaminées, Presses Universitaires de Franche-Comté; 2017; 1-513.

[9]. Oladimeji, T.E., Odunlami, O.A. Review on the impact of heavy metals from industrial wastewater effluent and removal technologies, Heliyon, 10; 2024; e40370.

[10]. Rafeeq, H., Afsheen, N., Rafique, S., Arshad, A., Intisar, M., Hussain, A., Bilal, M., Iqbal, H.M.N. genetically engineered microorganisms for environmental remediation, Chemosphere, 310; 2023; 136751.

[11]. Saini, S., Tewari, S., Dwivedi, J., Sharma, V. Biofilm mediated wastewater treatment: a comprehensive review, Materials Advances, 4; 2023; 1415-1443.

[12]. Sathya, R., Arasu, M.V., Al-Dhabi, N.A., Vijayaraghavan, P., Ilavenil, S., Rejiniemon, T.S. Towards sustainable wastewater treatment by biological methods: challenges and advantages of recent technologies, Urban Climate, 47; 2023; 101378.

[13]. Shi, J., et al. Review on treatment technology of salt wastewater in coal chemical industry of China, Desalination, 493; 2020; 114640.

[14]. Singh, D., Goswami, R.K., Agrawal, K., et al. Bioinspired remediation of wastewater: a contemporary approach for environmental cleanup, Current Research in Green and Sustainable Chemistry, 5; 2022; 100289.

[15]. Song, X., et al. Application of a spiral symmetric stream anaerobic bioreactor for treating saline pharmaceutical wastewater, Water Research, 205; 2021; 117671.

[16]. Teh, C.Y., et al. Recent advancement of coagulation–flocculation and its application in wastewater treatment, Industrial & Engineering Chemistry Research, 55; 2016; 4363-4389.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jul1143

[17]. Van Vliet, M.T., Flörke, M., Wada, Y. Quality matters for water scarcity, Nature Geoscience, 10; 2017; 800-802.

[18]. Yadav, D., Rangabhashiyam, S., Verma, P., et al. Environmental and health impacts of contaminants of emerging concerns: recent treatment challenges and approaches, Chemosphere, 272; 2021; 129492.

[19]. Rafeeq H, Afsheen N, Rafique S, Arshad A, Intisar M, Hussain A, Bilal M, Iqbal HMN. Genetically engineered microorganisms for environmental remediation. *Chemosphere,* 2023; 310:136751.

[20]. Liu L, Bilal M, Duan X, Iqbal HMN. Mitigation of environmental pollution by genetically engineered bacteria: Current challenges and future perspectives. *Science of the Total Environment*, 2019; 667:444–454.

[21]. Urgun-Demirtas M, Stark B, Pagilla K. Use of genetically engineered microorganisms (GEMs) for the bioremediation of contaminants. *Critical Reviews in Biotechnology,* 2006; 26(3):145–164.

[22]. Pant G, Garlapati D, Agrawal U, Prasuna RG, Mathimani T, Pugazhendhi A. Biological approaches practised using genetically engineered microbes for a sustainable environment: A review**.** *Journal of Hazardous Materials,* 2021; 405:124631.

[23]. Rafeeq H, Afsheen N, Rafique S, Arshad A, Intisar M, Hussain A, Bilal M, Iqbal HMN. Genetically engineered microorganisms for environmental remediation. *Chemospher,* 2023; 310:136751.

[24]. Pant G, Garlapati D, Agrawal U, Prasuna RG, Mathimani T, Pugazhendhi A. Biological approaches practised using genetically engineered microbes for a sustainable environment: A review. *Journal of Hazardous Materials*, 2021; 405:124631.

[25]. Urgun-Demirtas M, Stark B, Pagilla K. Use of genetically engineered microorganisms (GEMs) for the bioremediation of contaminants. *Critical Reviews in Biotechnology,* 2006; 26(3):145–164.

[26]. Sayler GS, Ripp S. Field applications of genetically engineered microorganisms for bioremediation processes. *Current Opinion in Biotechnology,* 2000; 11(3):286–289.

[27]. Rafeeq H, Afsheen N, Rafique S, Arshad A, Intisar M, Hussain A, Bilal M, Iqbal HMN. Genetically engineered microorganisms for environmental remediation. *Chemosphere,* 2023; 310:136751.

[28]. Liu L, Bilal M, Duan X, Iqbal HMN. Mitigation of environmental pollution by genetically engineered bacteria: Current challenges and future perspectives. *Science of the Total Environment,* 2019; 667:444–454.

[29]. Pant G, Garlapati D, Agrawal U, Prasuna RG, Mathimani T, Pugazhendhi A. Biological approaches practised using genetically engineered microbes for a sustainable environment: A review. *Journal of Hazardous Materials,* 2021; 405:124631.

[30]. Zhang, Y.Q., Han, J.L., Cheng, H.Y., Wang, H.C., Liu, T.J., Liang, B., Wang, A.J. Hypersaline organic wastewater treatment: biotechnological advances and engineering challenges, Environmental Science and Ecotechnology, 24; 2025; 100542.