



## **Intelligent Bioremediation In The Industry 5.0 Era: A Comprehensive Review**

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### **ABSTRACT**

Heavy metals, petroleum hydrocarbons, medicines, and persistent organic pollutants have contaminated the environment to an unprecedented degree as a result of global industrialization. Despite being ecologically friendly, traditional bioremediation techniques have some drawbacks, such as delayed degradation kinetics, susceptibility to environmental changes, a narrow spectrum of pollutants, and an inability to dynamically adjust to changing contamination conditions. In order to create intelligent, adaptable environmental cleaning systems, this paper explores the intersection of cutting-edge bioremediation technologies with Industry 5.0 principles—human-centricity, sustainability, and resilience. We investigate how smart technologies such as artificial intelligence, the Internet of Things, biosensors, and cyber-physical systems may be integrated with engineered microbial and algal systems via a thorough examination of peer-reviewed literature published between 2015 and 2025. Important discoveries show that CRISPR-based genetic engineering has created microbial strains with a three-fold greater ability to accumulate heavy metals and a 2.5-fold enhanced hydrocarbon breakdown. Algal systems designed to better absorb pollutants show simultaneous CO<sub>2</sub> sequestration and wastewater treatment, with nutrient removal efficiency over 90%. When compared to traditional systems, smart bioreactors using machine learning algorithms achieve 40% quicker degradation rates and 30% reduced energy usage. The Industry 5.0 framework facilitates human-machine-biology cooperation in which created organisms carry out remedial tasks, artificial intelligence manages real-time optimization, and human knowledge directs strategic choices. Significant obstacles still exist in the areas of public acceptability, scalable implementation, regulatory framework creation, and biosafety evaluation despite these technical advancements. According to the review's findings, intelligent bioremediation in the context of Industry 5.0 is a revolutionary strategy that shifts from passive, static remediation to responsive, adaptive environmental management. To ensure responsible deployment, future research must give priority to multidisciplinary governance structures, field-scale validation studies, and standardized biosafety standards.

**Keywords:** Bioremediation, Industry 5.0, Engineered microbes, Algae, Synthetic biology, Environmental sustainability, Artificial intelligence, Biosensors, CRISPR-Cas9, Circular economy

### **1. INTRODUCTION**

Rapid industrialization, urbanization, and population increase have led to unparalleled environmental deterioration during the Anthropocene period. Contaminants such as heavy



metals, petroleum hydrocarbons, pharmaceuticals, endocrine disrupting chemicals, microplastics, and persistent organic pollutants are building up in soil, water, and air ecosystems, and global pollution has reached critical thresholds [1,2]. According to estimates from the World Health Organization, environmental pollution causes over nine million premature deaths each year, and ecosystem degradation endangers biodiversity and vital ecosystem services that are vital to human civilization [3].

Chemical precipitation, adsorption, incineration, and pump-and-treat systems are examples of conventional physicochemical remediation techniques that are often successful but have serious disadvantages. Particularly for large-scale applications involving hectares of contaminated land or millions of liters of contaminated water, these methods usually need considerable energy consumption, produce secondary contamination, require significant chemical use, and are prohibitively expensive [4,5]. A sustainable substitute that adheres to green chemistry principles is bioremediation, which uses the metabolic capacities of microbes, plants, and algae to break down or sequester toxins. However, there are intrinsic drawbacks to conventional bioremediation techniques that restrict their broad use and efficacy. These include limited pollutant range, where no single organism degrades all contaminants, slow degradation kinetics that take months to years to complete, sensitivity to environmental fluctuations like temperature and pH variations, and an incapacity to react dynamically to changing contamination scenarios [6,7].

Over the last 250 years, the industrial revolutions have gradually changed the manufacturing and technological sectors. In the late eighteenth century, Industry 1.0 developed automation using steam and water power. In the late nineteenth century, Industry 2.0 introduced electricity and mass manufacturing. Automation and electronics were introduced by Industry 3.0 in the latter half of the 20th century. Digitalization, the Internet of Things, and cyber-physical systems that allow previously unheard-of communication and data interchange define Industry 4.0, the current paradigm [8]. Building on this framework, Industry 5.0 is an evolution that re-centers human needs while using cutting-edge technology for the benefit of society as a whole. Three fundamental pillars of Industry 5.0 are identified by the European Commission: resilience, which creates robust systems that can withstand and recover from disruptions; sustainability, which develops circular economy approaches that minimize environmental impact; and human-centricity, which places human needs and interests at the center of production processes [9].

This review refers to the new paradigm that results from combining bioremediation with Industry 5.0 concepts as intelligent bioremediation. In order to develop adaptive, real-time responsive environmental cleaning systems, this method combines smart technologies like artificial intelligence, the Internet of Things, biosensors, robots, and digital twins with designed biological agents, such as microorganisms and algae [10]. Intelligent bioremediation allows for continuous monitoring, predictive optimization, and autonomous adjustment of remediation parameters based on real-time data streams, in contrast to conventional bioremediation, which functions as a static, open-loop process requiring periodic human intervention and laboratory analysis.



This thorough review attempts to summarize the state of the art regarding engineered microbial and algal systems for improved pollutant degradation, analyze how smart technologies are integrated with biological remediation agents, look at how intelligent bioremediation aligns with Industry 5.0 principles, assess issues like biosafety, regulatory barriers, and scalability concerns, and identify research gaps while suggesting future directions for the field. Conventional bioremediation, the shift from Industry 4.0 to Industry 5.0, smart bioremediation technologies, engineered microbes, engineered algae, and integration within the Industry 5.0 framework are among the thematic sections that follow the methodology section outlining the literature search strategy. Key lessons are summarized in the conclusions that follow the discussion section, which summarizes current trends and future prospects.

## **2. METHODOLOGY / LITERATURE SEARCH STRATEGY**

To guarantee thorough coverage of pertinent literature across the fields of biotechnology, environmental science, engineering, and computer science, a methodical literature search was carried out utilizing many electronic databases. While ScienceDirect offered access to extensive scientific and technical articles across Elsevier journals, PubMed/MEDLINE was searched for biomedical and biotechnological literature. Broad coverage of academic literature, including conference proceedings and grey literature, was made possible by Google Scholar. Scopus supplied interdisciplinary abstract and citation data, while Web of Science was used for high-impact peer-reviewed research with citation tracking tools. Open-access peer-reviewed material that may not be indexed in conventional databases was found by searching the Directory of Open Access Journals.

To improve retrieval relevancy, search phrases were carefully chosen and merged using Boolean operators. Bioremediation, synthetic biology, genetically modified microorganisms, engineered microbes, and CRISPR bioremediation were the main search phrases. These were integrated with Internet of Things pollution control, Industry 5.0, intelligent bioremediation, and artificial intelligence environmental monitoring. Other names included microbial consortia, circular economy bioremediation, heavy metal bioremediation, hydrocarbon degradation, plastic biodegradation, microalgae wastewater treatment, biosensors environmental, and algal genetic engineering.

To guarantee quality and relevance, inclusion requirements were strictly enforced. To ensure coverage of the most current advancements while capturing fundamental discoveries, only peer-reviewed publications published between 2015 and 2025 were taken into consideration. Research on smart technologies combined with bioremediation or engineered biological systems for pollution degradation was mandated. As long as they were published in English, had well-defined procedures, and produced repeatable outcomes, both review papers and original studies with solid methodology were accepted.

Non-peer-reviewed materials, such as conference abstracts and preprints without further validation, were excluded based on certain criteria. Articles that did not discuss environmental applications and studies that only addressed physicochemical remediation without biological components were not included. Publications published before to 2015 were not included, with the exception of fundamental historical ideas that were necessary for context, such the early



discoveries of CRISPR or the creation of the TOL plasmid. Studies with inadequate methodological information and opinion articles without evidence were also disqualified. About 2,150 articles from all databases were found in the first search. 512 papers were chosen for full-text examination after the 1,663 remaining articles were filtered by title and abstract after 487 duplicates were eliminated. 196 papers were included in this thorough examination after quality and relevance assessments. This final set included 27 book chapters from reputable publishers like Elsevier, Springer Nature, Wiley, Frontiers, and Nature Publishing Group that provided in-depth coverage of specialized topics, 151 original research articles that contributed specific findings, and 18 major reviews that offered a broad perspective.

### **3. MAIN BODY / THEMATIC REVIEW SECTIONS**

#### **3.1 Overview of Bioremediation**

The term "bioremediation" refers to a variety of methods that are mostly categorized by treatment location. Depending on the site's features, the kinds of contaminants present, and the regulations in place, each method has unique benefits and drawbacks. Treating toxins at the original site without excavation or pumping is known as "in situ bioremediation." It has many benefits, such as less disturbance to the site, reduced costs, and the capacity to treat deep pollution that would not be accessible by excavation [11]. In order to increase the activity of native microbial populations already present at the contaminated site, biostimulation—one of the most popular in situ techniques—involves adding nutrients like nitrogen and phosphorus, electron donors or acceptors like oxygen and nitrate, or other amendments. When oxygen is added to petroleum hydrocarbon cleanup by air sparging or oxygen-releasing chemicals, aerobic degradation rates are usually two to three times higher than under unaltered circumstances [12]. In order to support native communities that may not have the catabolic pathways required for full pollution breakdown, bioaugmentation entails the introduction of specialist microbial strains, either wild-type or synthetic. When quick cleanup is needed to fulfill regulatory deadlines or stop contaminant movement, or when indigenous people lack specialized enzymatic capabilities, this strategy is very helpful [13]. Natural attenuation depends on unsupported natural processes such as biodegradation, dispersion, dilution, and sorption, and it is regularly monitored to confirm that cleaning objectives are being met. Although economically appealing, this method requires thorough site characterization and sustained dedication, which sometimes takes decades for full restoration [14]. Plants are used in phytoremediation to absorb pollutants through phytoextraction, stabilize them through phytostabilization, or degrade them through phytodegradation. Hyperaccumulator plants, like *Thlaspi caerulescens*, can effectively concentrate metals from large soil volumes by accumulating up to three percent zinc in dry biomass [15].

Ex situ bioremediation, which offers more process control but comes with higher costs and site disturbance that may restrict public acceptability, necessitates transferring contaminated material for treatment elsewhere [16]. Depending on the bioavailability of the contaminants and the climate, biopiles, which are aerated heaps of contaminated soil with nutrient addition and leachate collecting systems, usually achieve 75 to 85 percent hydrocarbon reduction after six to twelve months of operation [17]. Because of their optimal conditions and constant



mixing, bioreactors provide controlled vessel systems for slurry or liquid-phase treatment that allow for exact control of temperature, pH, nutrient levels, and oxygen transfer. Degradation rates are usually 10–100 times quicker than in situ methods [18]. Land farming, which is efficient for petroleum hydrocarbons but requires extensive land areas that may not be accessible near urban pollution locations, entails spreading contaminated soil and promoting microbial activity by periodic tilling, fertilizer addition, and moisture management [19]. In a controlled environment, composting combines contaminated material with organic amendments like manure or agricultural waste. The thermophilic temperatures produced by microbial activity speed up the breakdown of resistant substances like explosives and polycyclic aromatic hydrocarbons [20].

Through enzymatic pathways that have developed over millions of years of exposure to naturally occurring organic substances, microbial bioremediation uses bacteria, fungus, and actinomycetes to degrade pollutants. *Pseudomonas putida*, *Bacillus subtilis*, *Rhodococcus erythropolis*, and *Acinetobacter calcoaceticus* are examples of bacteria with exceptional metabolic versatility. They break down hydrocarbons, pesticides, and industrial chemicals using hydrolases that cleave ester and amide bonds, dioxygenases that incorporate both atoms of molecular oxygen into aromatic rings, and monooxygenases that add single oxygen atoms [21].

Extracellular lignin-modifying enzymes like laccases, manganese peroxidases, and lignin peroxidases are produced by fungi, especially white-rot fungi like *Phanerochaete chrysosporium*, *Trametes versicolor*, and *Pleurotus ostreatus*. These enzymes use radical-based oxidation mechanisms to non-specifically break down recalcitrant aromatic compounds like polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and artificial dyes [22].

In most applications, phytoremediation uses plants to clean up the environment via a variety of simultaneous techniques. Indian mustard, *Brassica juncea*, has been shown to effectively accumulate lead, cadmium, and selenium from polluted soils [23]. Phytoextraction entails the absorption and accumulation of pollutants in harvestable tissues. Phytostabilization reduces bioavailability and stops groundwater leaching while immobilizing pollutants in root zones via precipitation as insoluble forms or root sorption [24]. Phytodegradation is the metabolic breakdown of organic pollutants in plant tissues by means of enzymes such as laccases, nitroreductases, and dehalogenases that change them into less harmful forms [25]. Through root exudates that include organic acids, sugars, and amino acids that stimulate microbial activity and encourage co-metabolic transformation of pollutants, rhizodegradation improves microbial degradation in the rhizosphere [26]. Selenium volatilization by *Brassica juncea* and mercury volatilization by transgenic plants expressing bacterial mercuric reductase, which transforms ionic mercury into elemental mercury vapor, are examples of how phytovolatilization entails absorption and release as volatile forms [27]. Algal bioremediation uses macroalgae like *Ulva lactuca*, *Sargassum* species, and *Gracilaria corticata* as well as microalgae like *Chlorella vulgaris*, *Scenedesmus obliquus*, *Chlamydomonas reinhardtii*, and *Haematococcus pluvialis* to remove pollutants from wastewater and sequester CO<sub>2</sub> from industrial emissions [28, 29]. Algae have several advantages over terrestrial plants, such as



photosynthetic CO<sub>2</sub> fixation rates that are 10 to 50 times faster, effective nutrient uptake that removes nitrogen and phosphorus at efficiencies exceeding 90 percent in optimized systems, heavy metal biosorption through cell wall polysaccharides that contain carboxyl, hydroxyl, and amino groups that bind metals through electrostatic interactions, organic pollutant degradation through mixed-function oxygenases and peroxidases, and the production of valuable biomass co-products such as lipids for biodiesel, carbohydrates for bioethanol, and pigments for high-value applications [30].

Conventional bioremediation has several limitations that have prevented its widespread use and efficacy, despite its potential as an ecologically beneficial method. Since it may take two to five years for soil systems to completely degrade high-molecular-weight polycyclic aromatic hydrocarbons, slow kinetics constitute a fundamental limitation. Biological processes operate on timescales of months to years, which are frequently incompatible with urgent remediation needs [31]. Applications are further complicated by environmental sensitivity: temperature changes impact enzyme kinetics, pH changes change the ionization states of pollutants and cellular components, oxygen availability determines aerobic versus anaerobic degradation pathways, and nutrient constraints limit microbial growth and metabolic activity [32]. Another significant issue is pollutant bioavailability, as many pollutants are trapped in micropores, sorbed to organic matter, or aged in soil matrices, making them inaccessible to microorganisms even in situations when degradation potential is available [33]. Trichloroethylene partial degradation to vinyl chloride, a more hazardous and carcinogenic chemical than the parent pollutant, is an example of how incomplete degradation may lead to the buildup of dangerous intermediates [34]. Because no single creature can break down every contaminant, locations with mixed contamination that include both organic chemicals and heavy metals need numerous techniques or sequential treatments [35]. The difficulties of real-time evaluation, which usually requires frequent sampling and laboratory analysis with time delays of days to weeks that hinder prompt action when circumstances vary from ideal, is the root cause of monitoring issues [36]. Because of environmental stressors that laboratory cultures never experience, competition from native microorganisms, predation by protozoa and bacteriophages, and heterogeneity in contaminant distribution, laboratory successes frequently fail to translate to field conditions [37].

### **3.2 Transition from Industry 4.0 to Industry 5.0**

Over the last 250 years, the industrial revolutions have gradually changed the manufacturing and technological sectors. Each revolution has introduced fundamentally new capabilities while building upon earlier advancements. The steam engine and mechanical manufacturing equipment, which took the role of manual production techniques, are examples of Industry 1.0 in the late eighteenth century, which automated production using water and steam power. With the advent of mass manufacturing and electricity in the late nineteenth century, Industry 2.0—which was typified by division of labor, assembly lines, and electrical power distribution—made it possible to achieve previously unheard-of productivity increases. Automation and electronics were introduced by Industry 3.0 in the late 20th century, along with computers, programmable logic controllers, and early robots that decreased the need for human interaction



in repetitive activities. Early in the twenty-first century, Industry 4.0 stands for digitalization, the Internet of Things, and cyber-physical systems. Key technologies include cloud computing, big data analytics, artificial intelligence, and networked smart systems that allow for predictive maintenance and real-time optimization [38, 39].

Industry 5.0 is a development that acknowledges that technology must not only meet efficiency and productivity goals, but also human and planetary demands. Instead of replacing Industry 4.0, it is a strategic progression that builds on its technical underpinnings and refocuses its application toward more general social objectives [40]. Three interrelated elements set the European Commission's Industry 5.0 framework apart from earlier industrial paradigms. With people maintaining control over crucial choices while automation takes care of hazardous or repetitive jobs, human-centricity guarantees that technologies adapt to human requirements rather than humans adapting to technology. This translates to protecting vulnerable populations who are disproportionately exposed to pollution, creating green employment that provide sustainable livelihoods, and meaningfully including the community in remediation choices in environmental situations [41,42].

With industrial systems striving for net-zero emissions, integration of renewable energy, and regeneration of natural systems, sustainability directs the development of circular economy strategies that reduce resource consumption and environmental effect. By producing biofuels, bioplastics, and recovered metals, bioremediation turns treatment facilities from cost centers into income generators by recovering valuable resources from waste streams rather than just getting rid of pollutants [43]. Resilience creates strong systems that can endure and bounce back from shocks like pandemics, resource shortages, climate change, and geopolitical crises. In situations when traditional remediation systems would fail, resilient remediation systems remain functioning by adapting to shifting environmental conditions, new pollution threats, and infrastructural interruptions [44].

When one considers the shortcomings of traditional methods, this framework's applicability to environmental technology becomes clear. In addition to addressing environmental justice issues that have historically disadvantaged low-income and minority communities living close to contaminated sites, human-centric remediation makes sure that cleanup technologies meet community needs and take into account local knowledge about contamination history and exposure pathways. Closed-loop systems that recover resources from waste streams and reduce energy consumption are necessary for sustainable remediation. These systems are in line with circular economy ideas, which acknowledge garbage as an out-of-place resource. Systems that can operate in a variety of environmental circumstances and adjust to new contamination concerns, such as microplastics and per- and polyfluoroalkyl compounds that were not previously identified as pollutants, are necessary for resilient remediation [45].

### **3.3 Smart Bioremediation Technologies**

In order to identify pollutants, biosensors are analytical devices that combine biological recognition components with physicochemical transducers. Recent developments allow real-time, in situ monitoring, which was previously not feasible with laboratory-based analytical procedures [46,47]. Whole-cell biosensors use genetically modified microorganisms with



reporter genes like luciferase,  $\beta$ -galactosidase, or green fluorescent protein that, when exposed to pollutants, create detectable optical or electrochemical signals. Real-time BTEX detection with sensitivity in the micromolar range is made possible by a *Pseudomonas putida* strain that has a toluene-responsive promoter linked to lux genes. This continuous monitoring capacity exposes daily and weather-related variations in pollutant concentrations [48]. These techniques provide ecologically relevant information that more accurately predicts toxicity and remediation potential than total chemical analysis because they identify bioavailable pollutant fractions rather than total concentrations [49].

Transcription-translation machinery is encapsulated in vitro by cell-free biosensors, allowing detection without the live organism containment issues that hamper regulatory clearance for field deployment. Because no biological organisms are discharged, these systems provide decreased regulatory obstacles, improved stability with shelf lifetimes of six to twelve months, and quick reaction times in minutes as opposed to hours. Researchers at Northwestern University created a cell-free arsenic sensor that showed sensitivity equivalent to whole-cell systems without the related biocontainment restrictions, detecting concentrations as low as ten micrograms per liter in thirty minutes [50].

To increase sensitivity and allow for the multiplexed detection of many contaminants at once, nano-biosensors use nanomaterials such as graphene, carbon nanotubes, quantum dots, and gold nanoparticles. Through aggregation-induced color changes that are apparent to the unaided eye, gold nanoparticle-based colorimetric sensors can detect mercury ions at concentrations as low as three nanomolar in ten minutes, allowing field deployment without the need for specialist equipment [51]. Aptamers, single-stranded DNA or RNA sequences chosen by Systematic Evolution of Ligands by Exponential Enrichment to bind particular pollutants with high affinity, are used in DNA-based biosensors to achieve electrochemical detection limits of 0.1 picograms per milliliter for bisphenol A, a common endocrine-disrupting chemical [52].

Distributed sensor arrays are used by Internet of Things-enabled environmental monitoring networks to continually send data on pollutant concentrations, physicochemical parameters including pH, temperature, dissolved oxygen, and oxidation-reduction potential, as well as biological activity indicators. LoRaWAN offers kilometer-range communication with minimal power consumption, making it ideal for distant monitoring in areas without cellular service. Wireless communication protocols have been tailored for environmental monitoring applications. While 5G networks provide high-bandwidth real-time video and data transfer for vital infrastructure monitoring, NB-IoT allows cellular network integration for urban applications with current infrastructure [53,54].

Through constant data feeds, these networks produce digital fingerprints of damaged areas, giving cleanup experts access to previously unattainable capabilities. Instead of applying modifications uniformly, customized treatment is guided by the variability in pollutant distribution shown by spatiotemporal mapping of pollution plumes with meter-scale resolution. Response times for early warning systems for pollution incidents are less than fifteen minutes, allowing for action before pollutants move to sensitive receptors like surface water bodies or



drinking water wells. Instead of gathering samples from predefined sites regardless of pollution levels, adaptive sampling systems concentrate monitoring resources on hot spots found via real-time analysis. Continuous data streams, as opposed to sporadic sampling events that can overlook significant temporal differences, are used to validate remediation progress [55].

Fifty sensor nodes measuring pH, dissolved oxygen, conductivity, turbidity, and heavy metals are integrated into a smart river monitoring system in South Korea. The system transmits data every ten minutes to a central artificial intelligence platform, which then sends out pollution alerts when parameters surpass threshold values. In its first year of use, this approach identified three industrial discharge occurrences that traditional weekly monitoring would have missed, allowing for a regulatory reaction in a matter of hours as opposed to weeks [56].

The enormous datasets produced by sensor networks are processed by artificial intelligence and machine learning algorithms to extract useful information that would be hard to get via human examination. Based on past data and current inputs, predictive modeling using machine learning algorithms predicts pollutant behavior, degradation rates, and ideal remediation settings. By taking into consideration the regional heterogeneity in hydraulic conductivity that deterministic models are unable to capture, random forest algorithms trained on historical data predict pollutant transport in heterogeneous aquifers with 85 to 92 percent accuracy [57]. Farmers may modify application timing and minimize off-site movement by using neural networks that include meteorological data to forecast pesticide runoff occurrences 24 to 48 hours ahead of time [58].

In order to improve degradation efficiency and minimize energy consumption, bioreactor settings are adjusted in real time via process optimization using reinforcement learning algorithms. By continuously modifying hydraulic retention time, nutrient dosing, aeration rate, and mixing speed based on real-time sensor data, a smart bioreactor for phenol degradation developed at the Technical University of Denmark achieved 95% removal with 30% less energy use than conventional operation [59]. Deep learning-based pattern recognition finds relationships between degradation performance and microbial community structure obtained from metagenomic sequencing, directing bioaugmentation tactics. Selecting the best augmentation strains based on community environment is made possible by convolutional neural networks that analyze 16S rRNA gene sequences and estimate community functional potential with 88% accuracy [60].

By combining real-time sensor data with mechanistic models, digital twins build virtual versions of actual bioremediation systems that mimic system behavior in a variety of circumstances. By using weather forecasts and seasonal groundwater level fluctuations, a digital twin of a groundwater remediation system at a former industrial site in Germany was able to predict contaminant breakthrough six months ahead of time, allowing for the proactive installation of additional extraction wells before contamination reached a drinking water well [61]. In order to predict pollutant dynamics and ecological restoration outcomes with mean squared errors as low as 0.012, the Bio-DANN model, which stands for Biogeochemical-Deep Attention Neural Network, combines biogeochemical process models with attention



mechanisms. This model significantly outperforms traditional models that are unable to capture the intricate interactions between biological, chemical, and physical processes [62].

Real-time sensors, automated control systems, and robotic sampling platforms are features of next-generation bioreactors that change treatment from batch procedures to continuous, adaptive operations. In order to provide ideal circumstances without overfeeding, which wastes resources, or underfeeding, which restricts decomposition, automated nutrient feeding systems base additions on metabolic activity sensors that measure oxygen absorption rate and carbon dioxide evolution rate. By using predictive algorithms to anticipate changes based on influent characteristics and weather predictions, pH and temperature regulation maintains ideal conditions without the oscillations that come with feedback-only control. Inline spectroscopy, such as UV-Vis, near-infrared, and Raman spectroscopy, continuously monitors degradation products to offer real-time data on treatment progress without the delays of laboratory examination. Early defect identification and automatic recalibration are made possible by self-diagnostic capabilities, which save downtime and guarantee reliable performance [63,64].

Pharmaceutical compounds, such as diclofenac and carbamazepine, are completely degraded in membrane bioreactors with artificial intelligence control at environmentally relevant concentrations of ten to one hundred micrograms per liter. Sludge retention time is adjusted in real time based on degradation efficiency. Despite changes in influent composition that lead to the failure of traditional systems, our adaptive technique retains performance [65]. Through accurate current management that preserves ideal reducing conditions, automated microbial electrolysis cells improve reductive dechlorination of chlorinated solvents. By preserving the delicate balance between hydrogen production for dechlorination and inhibition of methanogens that compete for electrons, artificial intelligence-optimized systems remove 99 percent of trichloroethylene in seven days as opposed to twenty-one days for conventional operation [66].

### **3.4 Engineered Microbes in Bioremediation**

By precisely manipulating genetic material, the synthetic biology revolution has made it possible to engineer microbial biocatalysts with degradation capabilities far greater than those found in nature [67,68]. Through RNA-guided nucleases that produce specific DNA breaks, CRISPR-Cas systems—which stand for Clustered Regularly Interspaced Short Palindromic Repeats—allow for accurate genome editing in a variety of microorganisms. CRISPR-Cas9 produces double-strand breaks for gene knock-out, which removes competing metabolic pathways that divert resources from pollutant degradation, and gene knock-in, which allows the insertion of heterologous degradation pathways from species that cannot be cultivated or directly applied. In improved systems, editing efficiency may approach 70–90%, allowing for the quick creation of many strain variations for testing [69].

Multiplex editing with a single CRISPR RNA is made possible by CRISPR-Cas12a, often referred to as Cpf1. This allows for the simultaneous optimization of many pathway genes that would otherwise need sequential editing with Cas9. When designing intricate degradation pathways involving many enzymes, where coordinated expression is necessary to prevent intermediate buildup, this feature is very useful [70]. Without permanently altering DNA,



CRISPR interference and CRISPR activation use catalytically dead Cas9 coupled with transcriptional regulators to control gene expression. Target genes are silenced when dCas9 fuses with transcriptional repressors like KRAB, but expression may be increased up to fifty times when dCas9 fuses with activators like VP64, allowing for the fine-tuning of pathway flow without the permanent alterations associated with deletion or overexpression [71].

With plasmid-based expression, novel degradation capabilities may be quickly implemented without the time-consuming process of chromosomal integration by using multi-copy plasmids encoding catabolic genes. High gene dosage and associated high enzyme output are provided by plasmid copy numbers ranging from ten to five hundred per cell. RK2, RSF1010, and pBBR1 are examples of broad-host-range vectors that promote transfer across phylogenetically different bacteria, allowing the deployment of optimized pathways in organisms that are well-adapted to certain environmental circumstances [72]. Long-term efficacy is limited by the difficulty of maintaining plasmid stability without antibiotic selection in environmental applications where the addition of selective agents is either unfeasible or illegal [73].

Gene regulatory networks created by synthetic biology circuits allow for complex behaviors that are not feasible with straightforward constitutive expression. Promoters from degradation operons, such the Pm promoter from the TOL plasmid, are used in pollutant-responsive gene expression to drive reporter or effector genes exclusively in the presence of pollutants. Similar to the effectiveness of natural regulatory systems, this regulatory logic ensures quick reaction when pollutants arise while conserving metabolic resources when they are not present [74]. By identifying pathway intermediates and modifying enzyme expression appropriately, metabolic flux redirection uses dynamic sensor-regulator systems to reroute carbon flow toward full mineralization and avoid the buildup of hazardous intermediates that impede further degradation [75].

The serious safety risk that modified organisms may remain in the environment after cleanup is finished and might cause ecological disturbance is addressed by biocontainment techniques. Kill switches that use toxin-antitoxin pairs, such Hok and Sok or MazF and MazE, are activated when they leave the remediation site. These switches are triggered by environmental cues, such as cell density, temperature changes, or pollutant depletion. The Harvard University-developed Deadman and Passcode switches provide significant containment by achieving a five-log decrease in survival upon activation, which means that only one in 100,000 cells survive the switch [76]. Through long-lasting DNA alterations that build up over time, CRISPR-based recording devices record environmental exposure and allow for post-release monitoring to ascertain if organisms have stayed inside specified treatment zones [77]. Encapsulation in alginate beads, silica matrices, or polymer membranes provides a physical barrier that supports genetic confinement by preventing organism release but allowing pollutant diffusion to reach encapsulated cells [78].

The practical potential of these techniques across a variety of contamination classes is shown by examples of modified bacteria for pollutant breakdown. High-molecular-weight polycyclic aromatic hydrocarbons like pyrene and benzo[a]pyrene, which are particularly resistant because of their stability and low bioavailability, are 2.5 times more readily broken down by



*Pseudomonas putida* KT2440 that has been modified with additional dioxygenases, such as *nah*, *phn*, and *phd* genes. By introducing the TOL plasmid pWW0, toluene and xylene may mineralize with full conversion to carbon dioxide, preventing the build-up of partly oxidized intermediates that are indicative of natural attenuation [79,80].

In comparison to wild-type cells lacking these specialized metal-binding proteins, *Escherichia coli* expressing metallothioneins, such as mouse MT-I and human MT-II, accumulate cadmium at 25 milligrams per gram dry weight, mercury at 15 milligrams per gram, and arsenic at 10 milligrams per gram, indicating a three-fold increased capacity for heavy metal remediation [81]. By improving metal accessibility and removing the need for metal transport into the cell, surface display of metal-binding peptides, such as hexahistidine, and synthetic phytochelatin made of repeating Glu-Cys units on outer membrane proteins, such as Lpp-OmpA and ice nucleation protein, increases biosorption efficiency [82].

Reductive dehalogenases from other organisms expressed in more manageable hosts have been added to *Dehalococcoides mccartyi* strains for the breakdown of chlorinated compounds, even though these strains are challenging to directly engineer because to their stringent anaerobic needs and restricted genetic tools. *Dehalococcoides tceA* gene-expressing *Desulfitobacterium hafniense* dechlorinates trichloroethylene to ethene without accumulating vinyl chloride, the hazardous intermediate that afflicts both natural attenuation and traditional bioremediation [83].

*Ideonella sakaiensis* PETase and MHETase enzymes have been heterologously produced in *Bacillus subtilis* and *Escherichia coli* for the breakdown of polyethylene terephthalate. Variants with five-fold improved thermostability—which raises the ideal temperature from 30 to 45 degrees Celsius—and three-fold increased activity—which permits significant deterioration in days as opposed to weeks—were created by directed evolution [84,85]. In terms of pesticide degradation, *Sphingobium indicum* modified with more copies of the *lin* pathway genes breaks down hexachlorocyclohexane isomers three times more quickly, reaching 95% elimination in seven days as opposed to three weeks for strains of the wild type [86].

In contrast to single strains, synthetic microbial consortia—engineered communities of many species with division of labor—offer benefits that have drawn more and more attention in recent years. A three-member consortium consisting of *Pseudomonas*, *Sphingomonas*, and *Rhodococcus* species achieved complete mineralization of phenanthrene without intermediate accumulation that happens with any single species [87]. This shows that complete mineralization is possible when one species initiates attack on complex pollutants and others metabolize the resulting intermediates. Through cross-feeding, syntrophic relationships facilitate thermodynamically unfavorable processes; methanogenic consortia use interspecies electron transfer to couple fatty acid oxidation to methane generation, which would not be feasible for any single organism [88]. Because the loss of one species allows others to continue vital services, community redundancy increases resilience by acting as a buffer against environmental changes and predators [89]. The distribution of pathway genes across many strains results in a reduced metabolic load, which lessens stress on individual organisms that



may otherwise be overburdened by the needs of producing a large number of heterologous proteins [90].

As knowledge of microbial interactions advances, design approaches for synthetic consortia continue to change. As shown by *Escherichia coli* strains designed for dehalogenation in strain A and aromatic ring cleavage in strain B, which together achieve 95% degradation of 2,4-dichlorophenol, cooperative division of labor allocates distinct pathway steps to separate strains [91]. Biofilm-forming strains are used in spatial structuring to provide sensitive degrader organisms protection matrices that allow them to remain in situations where planktonic cell washing would occur [92]. In order to ensure that enzymes emerge concurrently rather than sequentially with corresponding intermediate buildup, quorum sensing coordination uses communication circuits to coordinate timing of gene expression throughout the consortium [93].

Integrated waste treatment and energy recovery from organic wastes are made possible by co-culture systems that combine fermentative bacteria that hydrolyze complex organic molecules with methanogenic archaea that convert the resultant intermediates to methane. Through methods that circumvent conventional hydrogen transfer and its related thermodynamic restrictions, direct interspecies electron transfer induced by conductive materials such as biochar, magnetite, and granular activated carbon increases syntrophic performance by two to four times [94].

Despite decades of study, there have been no commercial uses of modified microorganisms for environmental bioremediation due to significant deployment challenges, despite impressive laboratory accomplishments. Concerns regarding the ecological effects on native microbial communities, the possibility of horizontal gene transfer that could spread engineered traits to other organisms, and unforeseen consequences like disruption of food webs and alteration of ecosystem functions that might not be noticeable until after large-scale deployment are raised by biosafety concerns regarding the environmental release of genetically modified organisms [95,96].

These issues are addressed by biocontainment solutions that are being developed using a variety of complimentary techniques. Auxotrophy creates creatures that cannot live outside of controlled surroundings by engineering dependency on non-natural substances not available in natural habitats, such as synthetic amino acids like biphenylalanine or non-standard nucleobases. The efficacy of this strategy was shown by the fact that a *Pseudomonas* strain that was reliant on synthetic biphenylalanine did not survive after seven days in soil microcosms, while wild-type longevity exceeded six months [97]. Redundant containment is provided via kill switches that use toxin-antitoxin systems that are triggered by environmental cues such as pollutant depletion, temperature changes, or cell density. Even in the event that auxotrophy fails, the Deadman and Passcode switches provide significant confinement by achieving a five-log decrease in survival upon activation [98]. Physical confinement, such as encapsulation in alginate beads, silica matrices, or polymer membranes, offers a barrier that supports genetic strategies by preventing organism escape but allowing pollutant passage [99].



Another significant issue is horizontal gene transfer, which might result in unexpected degradation capabilities or ecological problems when catabolic plasmids spread to native bacteria via conjugation, transformation, or transduction. Because chromosomal genes transmit at far lower rates than mobile plasmids, engineered systems that use chromosomal integration instead of plasmids minimize transfer risks by 100–1000 times [100]. Additional protections include the use of non-mobile genetic elements and the disabling of conjugation machinery by the deletion of transfer genes; nonetheless, transfer risk cannot be completely eliminated [101]. Companies and academics looking to use these technologies face difficulties since different jurisdictions have very different regulations regarding the discharge of modified microorganisms into the environment. Contained usage is governed by Directive 2009/41/EC in the EU, while purposeful release is covered by Directive 2001/18/EC, which calls for thorough risk assessment, public engagement, and case-by-case approval in a procedure that usually takes three to five years [102]. The Toxic Substances Control Act governs commercial use in the US, while NIH guidelines cover research applications. Before any uncontrolled release, the microbial products of biotechnology framework must undergo tiered testing from laboratory microcosms to contained field trials [103]. China has approved field experiments of modified microorganisms for agricultural uses, which may indicate a more liberal attitude to environmental release. Japan and China are two Asian countries with developing frameworks [104].

### **3.5 Engineered Algae in Bioremediation**

Macroalgae such *Ulva lactuca*, *Sargassum* species, and *Gracilaria corticata*, as well as microalgae like *Chlorella vulgaris*, *Scenedesmus obliquus*, *Chlamydomonas reinhardtii*, and *Haematococcus pluvialis*, provide special benefits for bioremediation that support microbial systems [105,106]. Under ideal circumstances, their production reaches 20 to 30 grams of biomass per square meter per day, allowing for simultaneous carbon absorption and pollution removal [107]. Their photosynthetic CO<sub>2</sub> fixation occurs at rates 10 to 50 times quicker than terrestrial plants. In optimal systems that avoid eutrophication of receiving waters, nutrient absorption effectively removes phosphorus as orthophosphate and nitrogen as ammonium, nitrate, and nitrite, with removal efficiencies surpassing 80% for phosphorus and 90% for nitrogen [108].

Cell wall polysaccharides, such as alginate, sulfated polysaccharides, and cellulose, include carboxyl, hydroxyl, and amino groups that bind metals by complexation and electrostatic interactions. This process is known as heavy metal biosorption. For lead, cadmium, and copper, biosorption capabilities range from 100 to 300 milligrams per gram. The use of non-living biomass eliminates toxicity issues and permits metal recovery by desorption [109]. Pesticides, medications, and polycyclic aromatic hydrocarbons are among the xenobiotics that are broken down by mixed-function oxygenases, peroxidases, and dioxygenases. Eighty percent of the medication carbamazepine, which is famously resistant to bacterial breakdown, is broken down by *Chlorella* species in ten days [110]. Economic incentives that offset treatment costs are provided by valuable biomass co-products such as lipids for biodiesel at 20 to 50 percent



dry weight, carbohydrates for bioethanol at 30 to 60 percent dry weight, and pigments like chlorophylls, carotenoids, and phycobiliproteins for high-value applications [111].

Algal bioremediation capabilities are now greater than those seen in nature because to genetic improvements. *Chlamydomonas reinhardtii* expressing *Arabidopsis* phytochelatin synthase accumulates three times more cadmium at 45 milligrams per gram dry weight than wild-type cells, indicating that improved heavy metal uptake through overexpression of metallothioneins MT-I and MT-II and phytochelatin synthases increases metal accumulation [112]. Hexahistidine and synthetic phytochelatin synthases are examples of metal-binding peptides whose surface display on algal cell walls increases biosorption capacity without compromising cell viability because these peptides directly access metals without needing to be transported inside the cell [113].

By introducing heterologous degradation enzymes, enhanced enzyme synthesis increases the spectrum of pollutants beyond what is possible in nature. Bisphenol A and nonylphenol, which are substances resistant to algal degradation by native enzymes, are 90% efficiently broken down by laccases from white-rot fungi like *Trametes versicolor* produced in *Chlamydomonas* [114]. Pharmaceuticals such as diclofenac and ibuprofen are broken down by cytochrome P450 enzymes from mammals produced in cyanobacteria at rates of five to ten milligrams per liter per day, offering a way to remove developing pollutants from wastewater [115]. Treatment of coal tar-contaminated locations is made possible by the 2.5-fold enhancement of polycyclic aromatic hydrocarbon breakdown by manganese peroxidase from *Phanerochaete chrysosporium* expressed in *Chlorella* [116].

Deployment in a variety of settings that might normally restrict algal production is made possible by engineered growth characteristics that are optimized. Consistent performance across diurnal and seasonal changes is made possible by improved light consumption by decreased chlorophyll antenna size, which avoids photoinhibition at high light intensities while preserving photosynthetic efficiency at low light [117]. Operating in temperatures where natural algae would face thermal stress is made possible by the production of heat shock proteins and desaturases that preserve membrane fluidity [118]. The utilization of brackish or saltwater is made possible by salinity resistance via  $\text{Na}^+/\text{H}^+$  antiporters and compatible solute synthesis, freeing freshwater resources for other use [119].

By improving accumulation for integrated bioremediation and biofuel generation, lipid route engineering generates financial incentives for treatment. Acetyl-CoA carboxylase and diacylglycerol acyltransferase overexpression raises the lipid content to 55 percent dry weight, which may be used as feedstock for biodiesel and reduce treatment costs [120].

The practical potential of modified algal systems is shown by applications in CO<sub>2</sub> sequestration and wastewater treatment. High-rate algal ponds and sophisticated oxidation techniques are used in integrated algal wastewater treatment to simultaneously remove nutrients, inactivate pathogens, and produce useful biomass [121,122]. By absorption into biomass and ammonia volatilization at high pH, nitrogen elimination reaches 85 to 95 percent. By digestion and precipitation as calcium phosphate at high pH, phosphorus elimination reaches 70–90%. Bacterial-algal interactions result in a 75–85% decrease in chemical oxygen demand.



Predation, high pH, and UV exposure reduce pathogens by three to four log units [123]. By producing oxygen via algae and exchanging CO<sub>2</sub> with bacteria, algal-bacterial consortia improve the decomposition of organic waste while reducing aeration costs by 50% when compared to traditional activated sludge [124].

By using microalgae culture in conjunction with industrial flue gas, CO<sub>2</sub> bioremediation produces biofuels, animal feed, or bioplastics while capturing carbon. Under ideal circumstances, CO<sub>2</sub> fixation rates may reach 1.5 to 2.5 grams per liter per day. Strains that are resistant to NO<sub>x</sub> and SO<sub>x</sub>, which restrict local algae, and tolerant to high CO<sub>2</sub> concentrations of 15 to 20 percent have been developed [125]. 30 to 50 tons of biomass per acre are produced annually, which serves as feedstock for a variety of goods [126].

By concentrating diluted metals from mine drainage or industrial effluents, heavy metal recovery using algal biosorption systems enables resource recovery that compensates treatment expenses. 95% of the metal in solutions with parts per million concentrations is removed using biosorption columns filled with immobilized algae biomass. Reusing biomass over many cycles is made possible by metal desorption and recovery at 90 to 95 percent efficiency using diluted acids. Revenue from recovered metals, such as copper, nickel, and gold, converts treatment from a cost center to a profit center [127].

### **3.6 Integration In Industry 5.0 Framework**

Industry 5.0 sees people and intelligent systems collaborating to achieve goals that neither could achieve on its own. This corresponds to a triadic cooperation in intelligent bioremediation, where each member provides special skills [128,129]. Strategic choices, such as site characterization and remediation target formulation based on community needs and values that cannot be reduced to computer optimization, are guided by human knowledge. Humans perform risk-benefit analysis and ethical monitoring, making decisions about acceptable trade-offs that robots are unable to understand. Artificial intelligence lacks the interpersonal skills and contextual awareness needed for stakeholder engagement and regulatory compliance. Appropriate responses are determined by human judgment when automated systems come across new scenarios that are not included in their training data. Scientific data is supplemented by local and traditional ecological knowledge that has been gathered over generations of contact with particular settings [130]. Because of the amount and complexity of data involved, artificial intelligence systems are able to manage tactical optimization that is beyond human skills. Millions of data points are processed every second by real-time data analysis from sensor networks, which finds patterns and abnormalities that are not evident to human observers. In order to predict future circumstances, hundreds of factors, such as microbial activity, groundwater levels, and weather predictions, are included into predictive models of pollutant fate and transit. Early warning detection allows for action before issues worsen by seeing deviations from anticipated behavior in a matter of seconds. In order to maintain maximum performance without human intervention, routine modifications of nutrition dosage, aeration, and mixing take place continually depending on real-time circumstances. Energy and resource allocation optimization maximizes treatment efficacy while minimizing expenses [131,132].



Engineered biological agents use characteristics that machines cannot match to carry out remedial tasks. Evolved enzymatic machinery that operates at room temperature and pressure without requiring energy-intensive inputs is responsible for the degradation, transformation, and sequestration of pollutants. Through the use of synthetic biology circuits, self-regulation allows organisms to modify their metabolism in response to environmental factors and contaminant availability. Reporter gene communication with monitoring systems provide ongoing input on the condition of the organism and the effectiveness of therapy. Regulatory mechanisms that only produce the right enzymes when necessary allow for adaptation to shifting pollutant profiles [133].

Based on values, objectives, and limitations that represent social priorities, this trinity establishes a framework in which people decide what and why. Through scheduling, prediction, and optimization that maximizes efficiency within human-defined bounds, artificial intelligence decides how and when. Through catalysis, transformation, and sequestration, engineered biology transforms contaminants into lucrative resources or safe products [134].

Pilot-scale project case studies show how useful this integrated strategy may be. On a two-hectare location in Belgium, a smart bioaugmentation system for petroleum hydrocarbons combined many technologies into a working system [135]. Whole-cell bioluminescent *Pseudomonas* strains that released light in proportion to pollutant levels were used by in situ biosensors to measure BTEX concentrations. IoT-enabled telemetry used LoRaWAN to send data every fifteen minutes, resulting in a continuous data stream that showed weather-related and daily variations. Based on current circumstances and past trends, machine learning algorithms using random forest models projected the ideal dosage of nutrients and oxygen. Nutrients, oxygen, and altered *Pseudomonas putida* harboring the TOL plasmid were supplied at precisely regulated rates using an automated injection system. When exceptions occurred, operator action was made possible via a human supervisory control dashboard with alarm systems. The results showed 25% cheaper running costs, 40% quicker degradation than traditional biostimulation, and complete completion in 18 months as opposed to the anticipated 30 months [136].

On a 0.5-hectare plot in Spain, an algal biorefinery with AI optimization combined high-rate algal ponds with automated harvesting by centrifugation and settling. Algal health and treatment efficacy were continuously monitored using real-time chlorophyll fluorescence and nutrition sensors. Based on weather predictions, biomass concentration, and lipid content, deep learning algorithms identified the best time to harvest. Harvested biomass was converted into biofuels and animal feed by automated extraction systems, which created income to cover operational expenses. Operator supervision was made possible via dashboard display, which provided alarms when parameters strayed from ideal ranges. The technology demonstrated both economic feasibility and environmental effectiveness, removing 95% of the nutrients from wastewater and making money from biomass co-products [137].

Drone-based multispectral imagery for plant health monitoring was integrated with willow and poplar plantations for metal phytoextraction in a phytoremediation 5.0 project for agricultural waste treatment. Soil sensor networks monitored moisture content and pollutant bioavailability,



giving information for choices about irrigation and amendments. Accurate cleaning completion projections were made possible by artificial intelligence algorithms that forecasted remediation timetables based on growth rates and metal uptake. In order to foster trust and incorporate local knowledge about site history and land use, community participatory monitoring projects included locals in data collecting and interpretation [138].

Integration has advantages that go beyond the particular performance gains seen in pilot programs. With automatic corrective actions that stop treatment failures, real-time monitoring and adaptive reaction allow for the prompt identification of system disturbances such as pollution spikes, toxicity incidents, or performance reductions. Artificial intelligence-optimized resource allocation improves efficiency by minimizing energy, nutrient, and amendment inputs while optimizing degradation rates, cutting expenses, and reducing environmental impact. By seeing emerging issues before they result in downtime, predictive maintenance helps avoid expensive equipment breakdowns. Data documentation offers thorough records for public communication and regulatory reporting, fostering confidence via openness [139].

#### **4. DISCUSSION**

Thanks to developments in synthetic biology, artificial intelligence, and sensor technology that were unthinkable ten years ago, biological engineering and digital technologies are rapidly merging in intelligent bioremediation. CRISPR-based techniques, which five years ago needed months of work, are now finished in days or weeks, demonstrating the rapid speed of genetic engineering progress. Machine learning algorithms, which learn from streaming data to constantly improve performance, have evolved from research curiosities to useful technologies used in operational systems. Dense monitoring networks that were previously unaffordable are now possible because to a decrease in sensor prices and an increase in capabilities [140].

Despite these developments, there are still important issues that need to be resolved before intelligent bioremediation is widely used. Concerns about the biosafety of releasing modified organisms into the environment are still unsolved, and there is no agreement on acceptable risk levels or suitable containment techniques. The innovation urge that propels American and Asian methods clashes with the cautious concept adopted by European regulators, resulting in regulatory fragmentation that impedes international cooperation and technology transfer [141,142].

The regulatory frameworks that were created in the 1980s and 1990s for first-generation genetically modified organisms are not appropriate for synthetic biology products that have many engineered features, intricate regulatory circuits, and well-designed containment systems. When hundreds of designs are feasible, case-by-case evaluation procedures that made sense when there were just a few changed creatures became impractical. There is an urgent need for new regulatory strategies focused on functional containment verification rather than presumptive risk assessment and on product attributes rather than method [143]. There are issues with public acceptability that cannot be solved by technical fixes alone. Regardless of the scientific agreement about safety, decades of debate surrounding genetically modified foods have led to distrust about genetic engineering that extends to environmental



applications. Building trust and integrating varied viewpoints into technology development and deployment would need meaningful community participation that starts before initiatives are planned rather than after choices are made [144].

Despite proven operational benefits, cost is still a hurdle since the initial outlay for sensors, control systems, and modified organisms is more than that of traditional options. Business strategies that extract value from recovered resources, such as metals, biofuels, and bioplastics, may reduce expenses and provide financial incentives for uptake. Recognizing the climatic advantages of biological CO<sub>2</sub> sequestration in addition to pollution removal, carbon credits and other ecosystem service payments might further enhance economics [145].

The requirement for standardized biosafety procedures that allow comparability across studies and regulatory countries is one of the research gaps that need attention. Risk assessment and technology transfer are now made more difficult by the fact that each research organization has its own containment and monitoring strategies. Because laboratory accomplishments have frequently failed to predict field performance owing to uncontrolled factors and interactions that cannot be duplicated in controlled conditions, field-scale validation studies are desperately required. Only a small number of pilot programs have reached field deployment, and the majority of published research is still conducted in laboratories. To direct responsible innovation, interdisciplinary governance frameworks including biologists, engineers, social scientists, ethicists, and community representatives are required, guaranteeing that technology capabilities advance concurrently with ethical frameworks for their application [146].

According to future projections, intelligent bioremediation will transition from stand-alone systems to integrated parts of larger environmental management networks. Future systems will take part in watershed-scale monitoring and response networks, exchanging data and coordinating activities across several sites, as opposed to addressing individual polluted sites in isolation. Treatment facilities will become resource recovery centers rather than trash disposal endpoints thanks to circular economy integration, which will extract value from waste streams while preserving environmental quality. As severe weather events strain traditional treatment systems, climate resilience will become more crucial, with intelligent bioremediation providing adaptive capability that static methods do not [147].

## **5. CONCLUSION**

A revolutionary paradigm shift from passive, static remediation to adaptive, responsive environmental management has been revealed by this thorough analysis of the confluence of cutting-edge bioremediation technologies with Industry 5.0 concepts. When compared to wild-type organisms, engineered microorganisms and algae that have been modified using CRISPR-based genetic engineering and synthetic biology have much better pollutant degradation capabilities. The inclusion of dioxygenase genes raises hydrocarbon breakdown rates by 2.5 times, the expression of metallothionein increases heavy metal buildup by 3 times, and the creation of heterologous enzymes makes emerging pollutants, such as microplastics, degradable.

Previously unattainable real-time monitoring, predictive optimization, and autonomous process modification are made feasible by smart technologies such as digital twins, biosensors, Internet



of Things networks, and artificial intelligence. Machine learning algorithms optimize treatment parameters while learning from experience, IoT networks generate continuous data streams that reveal temporal and spatial patterns invisible to traditional monitoring, and biosensors detect bioavailable pollutant fractions at parts per billion concentrations. By using these technologies, smart bioreactors may achieve 40% quicker deterioration while using 30% less energy.

The needs of next-generation environmental remediation are impressively aligned with the Industry 5.0 paradigm of human-centricity, sustainability, and resilience. Human-centric design guarantees that technologies integrate local knowledge and meet community requirements. Circular economy strategies that recover resources from waste streams are necessary for sustainability. Systems that can tolerate disturbances and adjust to changing circumstances are necessary for resilience. Artificial intelligence optimization, engineered biology execution, and human knowledge work together in a triadic manner to provide capabilities that beyond those of any one component alone.

Despite these developments, there are still important issues that need to be resolved before intelligent bioremediation may reach its full potential. Strong containment techniques that have been proven in the field are necessary due to biosafety issues. For synthetic biology products to be accommodated, regulatory frameworks must be updated. Transparent governance and genuine involvement are necessary for public acceptability. Innovative business models and ecosystem service value are necessary to overcome cost obstacles.

Standardized biosafety procedures that allow comparisons across studies and jurisdictions must be given top priority in future research. To close the gap between laboratory success and practical deployment, field-scale validation studies are desperately required. In order to ensure that technology capabilities evolve concurrently with ethical frameworks for their application, interdisciplinary governance frameworks must direct responsible innovation. Given that environmental issues cut across academic lines, cooperation across the biological sciences, engineering, computer science, social science, and regulatory policy is necessary for the future. In the age of Industry 5.0, intelligent bioremediation provides not just better technology but also a whole new method of environmental stewardship that is sensitive, adaptable, and in line with the welfare of people and the planet.

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