SECTION «BIOLOGICAL SCIENCES»

CIRCULAR BIOTECHNOLOGIES FOR THE TREATMENT OF INDUSTRIAL EFFLUENT

Yukhym Kaliuzhnyi[1]

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Abstract. *The purpose.* The review critically examines the paradigm shift in industrial wastewater management from linear end-of-pipe treatment to integrated biotechnological systems grounded in circular bioeconomy and resource-recovery principles, with particular emphasis on synergistic coupling between anaerobic biogas generation and the mobilisation, detoxification, and valorisation of heavy metals (Pb, Zn, Cr, Ni, Cu).

Methodology. A systematic literature synthesis was performed for the period 2015-2025 using Scopus, Web of Science, PubMed, and Google Scholar, employing Boolean search strategies and inclusion criteria based on peer-reviewed status, experimental validity, and thematic relevance. Conventional physicochemical treatment trains were benchmarked against biotechnological platforms, including anaerobic digestion, biosorption, bioaccumulation, bioelectrochemical systems, and integrated bioremediation-recycling configurations.

Results. Traditional physicochemical technologies remain energy-intensive and generate hazardous metal-laden sludge, concentrated brines, and secondary pollutants, thereby perpetuating a linear disposal pathway. By contrast, anaerobic digestion offers an energy-positive route for high-strength organic effluents, with methanogenic yields enhanced by 20-40 % through substrate disintegration, trace-element bioaugmentation, and conductive material-mediated direct interspecies electron transfer. Heavy-metal biotransformation encompasses biosorptive sequestration, intracellular bioaccumulation, enzymatic bioreduction of Cr(VI) to

[1] PhD Student,
National Technical University of Ukraine
«Igor Sikorsky Kyiv Polytechnic Institute», Ukraine

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Cr(III), acidophilic bioleaching, and microbially induced bioprecipitation. Emerging hybrid systems include metal-tolerant microbial consortia, activated carbon–iron nanoparticle carriers, mycosynthesised iron oxide nanoparticles achieving 92,5 % Cu^{2+} removal, and digital twin architectures for adaptive bioprocess control.

Value/originality. The review advances a conceptual framework for anaerobic biorefineries that integrate biogas upgrading, metal recycling, and nutrient recovery within a single technological cascade. It identifies synthetic microbial ecology, metagenomic profiling, and AI-driven digitalisation as transformative pathways for designing self-regulating, climate-resilient, and resource-efficient wastewater biorefineries, thereby bridging biotechnology, materials science, and circular-economy engineering.

INTRODUCTION

The global industry faces a triple challenge: the need to radically improve water efficiency, reduce its carbon footprint and minimise its negative impact on the environment. Traditional wastewater treatment systems, generally focused on meeting discharge standards, have evolved into significant energy consumers and generators of toxic waste, such as sludge enriched with heavy metals, creating a cycle of secondary environmental problems [1; 2]. This linear approach contradicts the fundamental principles of sustainable development and the circular economy. At the same time, industrial effluents, especially those generated by the food, pulp and paper, chemical and electroplating industries, contain significant potential in the form of organic compounds with energy value, as well as inorganic components, particularly metals. The systematic loss of these resources is economically irrational. Modern biotechnology, enhanced by advances in synthetic biology, nanoscience and artificial intelligence, offers a fundamentally new concept: the transformation of conventional treatment plants into bioprocessing facilities. In this innovative model, biological processes not only degrade pollutants, but also catalyse their conversion into useful products, embodying the principle of ‘waste equals resources’ [3].

The purpose of this review is to conduct a comprehensive analysis of the technological transformation of industrial wastewater treatment systems towards a circular biotechnological model, with an emphasis on researching the synergistic mechanisms of parallel biogas production and heavy metal

utilisation, as well as identifying promising areas for the development of integrated biosystems for resource-efficient water treatment.

The object of the study is modern biotechnological systems for the comprehensive treatment of industrial wastewater, including anaerobic digestion, biosorption, bioaccumulation, biotransformation and bioelectrochemical technologies, as well as their integration into technological chains.

The relevance of the topic lies in the study of promising methods for the disposal of heavy metals (Pb, Zn, Cr, Ni, Cu), as well as the possibility of combining it with general industrial wastewater treatment processes. This problem is particularly important due to the active hostilities on the territory of Ukraine, one of the negative consequences of which is an increase in the concentrations of these chemical elements in water and soil.

The subject of the study is the scientific principles, technological solutions and efficiency of integrated biosystems that ensure synergistic interaction between the removal of organic pollutants and heavy metals, energy recovery in the form of biogas and recycling of material resources, in particular metals, from industrial wastewater.

This review was based on a systematic analysis, generalisation and synthesis of data published in international scientific journals. Literature sources were searched using the scientometric databases Scopus, Web of Science, PubMed, Google Scholar, as well as the electronic archives of leading publishers (Elsevier, Springer, Wiley, MDPI). The search mainly covered the period 2015–2025 to ensure data relevance, including foundational works from earlier years that are crucial to understanding the basic processes.

To achieve this goal, the following **tasks** are set in the work:

– to analyse the structural limitations and shortcomings of traditional physical-mechanical, chemical and physical-chemical methods of industrial wastewater treatment used in modern industry;

– to characterise the main types of biotechnological treatment processes, their advantages and limitations, and conduct a comparative analysis with traditional approaches using tabular data;

– to systematise knowledge of biotechnological methods for heavy metal disposal, such as biosorption, bioaccumulation, biotransformation and bioprecipitation, and consider mechanisms for their integration into treatment systems to achieve metal recycling.

1. Overview of Traditional Methods of Industrial Wastewater Treatment

The traditional industrial wastewater treatment scheme (Fig. 1) is based on the sequential application of physical-mechanical, chemical and physical-chemical operations, each of which is aimed at removing a specific fraction of pollutants. Despite the high degree of technological sophistication, these methods have a number of systemic and often interrelated shortcomings.

1.1. Mechanical and physical-chemical separation

This category includes primary methods such as sedimentation, flotation, filtration and membrane processes. They are highly effective in removing undissolved substances, oils and fats. However, highly efficient technologies such as nanofiltration and reverse osmosis, which are capable of retaining even ionic compounds, are extremely energy-intensive. Studies show that desalinating one cubic metre of water using reverse osmosis can consume between 3 and 10 kWh of electricity [3]. Moreover, these processes inevitably generate a stream of concentrated effluents, which can account for up to 25-30 % of the initial volume, the disposal of which poses a complex and economically costly problem, especially in conditions of high mineralisation or the presence of toxic components [5].

1.2. Chemical treatment

Chemical coagulation, flocculation, neutralisation and oxidation, including ozonation, are the main tools for removing colloids, phosphates, heavy metals and persistent organic compounds. The process involves the addition of reagents such as iron or aluminium salts, alkalis, acids or oxidants, which leads to the formation of a solid phase in the form of sludge, which is separated. The disadvantages of this approach are systemic: high operating costs due to the constant need for expensive reagents; the formation of significant amounts of sludge, which, due to the accumulation of heavy metals and persistent organic pollutants, is often classified as hazardous waste and requires disposal at specialised landfills [6]; as well as the risk of secondary pollution, for example, the formation of carcinogenic trihalomethanes during chlorination or excess sulphates when using traditional coagulants [7].

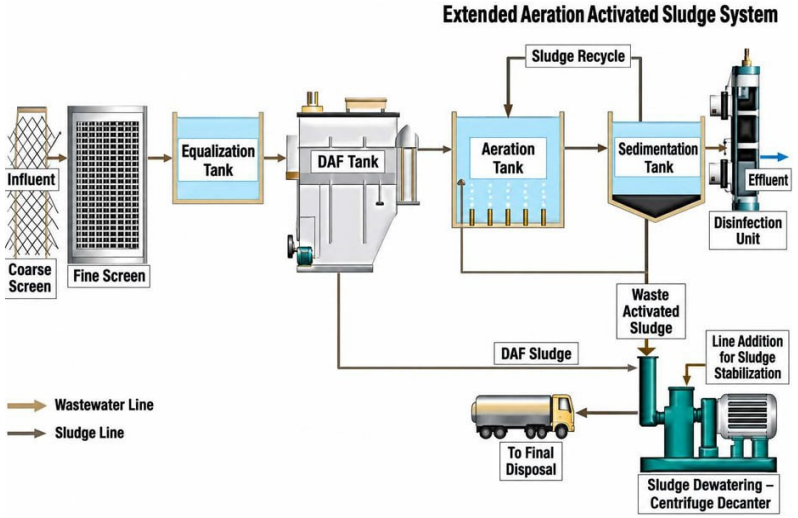


Figure 1. Schematic diagram of wastewater treatment at an industrial wastewater treatment plant [4]

1.3. Thermal methods

Evaporation, crystallisation and incineration are used for industrial effluents with high concentrations of contaminants. Despite maximum removal efficiency, these methods are characterised by the largest carbon footprint due to enormous energy consumption. In particular, incineration can be accompanied by emissions of dioxins, nitrogen oxides and sulphur, which requires the integration of complex and expensive gas cleaning systems [8].

Thus, traditional methods, while solving the immediate task of water purification, paradoxically create global problems: they increase energy dependence, generate toxic waste and lead to irreversible losses of potential resources. This situation creates a critical need for alternative, regenerative approaches.

2. Biotechnological Purification Methods

Biological purification is based on the use of the metabolic activity of consortia of microorganisms, including bacteria, archaea, fungi, algae and macrophytes, for the biotransformation of pollutants.

2.1. Main types of biotechnological processes

Aerobic systems, such as activated sludge, biofilters and membrane bioreactors, use microorganisms that, in the presence of molecular oxygen, oxidise organic matter to carbon dioxide and water, and also remove nitrogen through nitrification and denitrification and phosphorus. These systems are highly effective for wastewater with low to medium organic concentrations, but require significant energy consumption for forced aeration. Anaerobic systems, represented by methane tanks, UASB (Upflow Anaerobic Sludge Blanket, Fig. 2) and IC (Internal Circulation, Fig. 3) reactors, operate in the absence of oxygen. Specialised syntrophic consortia sequentially break down complex organic matter into methane, which accounts for 50-75 % of biogas, and carbon dioxide. This technology is key to the treatment of highly concentrated wastewater typical of the food and forestry industries, as it not only does not require energy for aeration, but also produces it in the form of biogas [9].

Biosorption and bioaccumulation use living or non-living biomass, such as algae, fungi, bacteria or agricultural waste, to passively bind heavy metals through functional groups on cell walls [9].

Phytoremediation, often used in the final stages, is based on the ability of aquatic plants such as duckweed or echornia to absorb heavy metals and nutrients [12].

2.2. Advantages and limitations

The fundamental advantage of biotechnologies is their focus on resource recovery rather than simple destruction. They are characterised by low energy consumption, especially in the case of anaerobic systems, or even demonstrate a positive energy balance [13]. These processes are generally more selective and environmentally friendly, as they do not produce secondary toxic products, with the exception of some undesirable compounds, such as excess hydrogen sulphide.

The main limitations of biotechnological methods include the sensitivity of microbial consortia to toxic shocks caused by high concentrations of heavy metals, pesticides or antibiotics. The speed of biological processes is usually lower compared to chemical methods. Effective operation requires skilled maintenance and a deep understanding of microbiological principles. In addition, productivity is highly dependent on temperature conditions, with an optimum range of 25-35 °C.

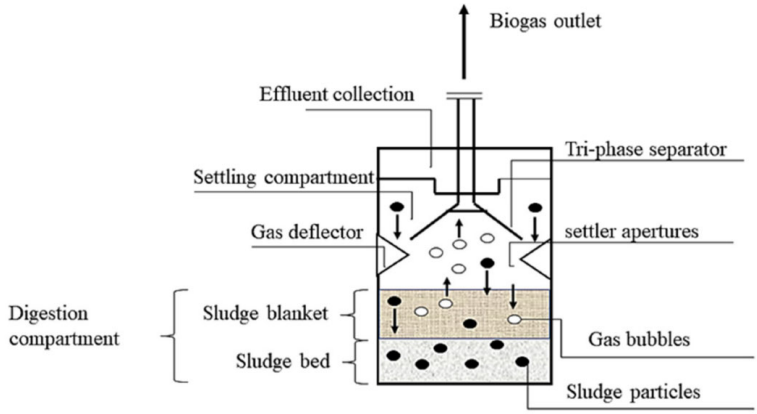


Figure 2. Schematic representation of a UASB reactor [10]

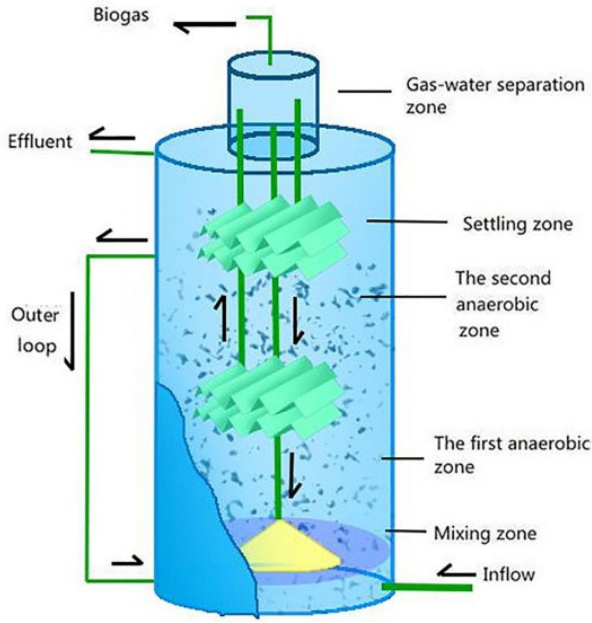


Figure 3. Schematic representation of an IC reactor [11]

A comparative overview of the main groups of industrial wastewater treatment methods is presented in Table 1, which illustrates the fundamental differences between the linear and circular concepts of treatment.

Table 1

Comparative analysis of traditional and biotechnological methods of industrial wastewater treatment

Criterion	Traditional physical-chemical/ chemical methods	Biotechnological methods
Energy balance	Mainly energy-consuming (especially membrane and thermal)	Energy-independent operation or even energy recovery (anaerobic systems) is possible
By-products	Toxic sludge, concentrated brines, chemical by-products (trihalomethanes, etc.)	Biogas (CH_4, CO_2), stabilised biomass, biopolymers, CO_2. Solid waste volumes are minimal
Effectiveness against heavy metals	High, but with the formation of toxic sludge (precipitation, ion exchange)	Medium/high due to biosorption, bioaccumulation, bioremediation. Potential for metal recycling
Operating costs	High (reagents, energy, sludge disposal)	Lower, because the 'reagent' is microorganisms. Income from biogas/resources can cover costs
Environmental footprint	High due to CO_2 emissions from energy/reagent production and toxic waste	Low, nature-like technologies promote decarbonisation
Flexibility to changes in effluent composition	Low, requires readjustment of reagent doses	Medium/high, microbial communities can adapt, but it takes time
Main objective	Achievement of discharge standards	Cleansing and restoration of energy and materials

3. Parallel Biogas Production

Anaerobic digestion is the most important biotechnology for recovering energy from organic waste. On an industrial scale, the use of highly efficient reactors such as UASB (Upflow Anaerobic Sludge Blanket) and EGSB (Expanded Granular Sludge Bed) allows for the treatment of wastewater with extremely high chemical oxygen demand [14].

3.1. Mechanism and factors limiting efficiency

Anaerobic digestion is a multi-stage synergistic process involving hydrolysis, acidogenesis, acetogenesis and methanogenesis, carried out by a specialised syntrophic consortium. The productivity of the system is often limited by a number of factors. The first limiting factor is the slow hydrolysis of resistant polymers such as cellulose and lignin. Secondly, the accumulation of intermediate products, in particular volatile fatty acids and alcohols, can lead to 'acidification' of the reactor and inhibition of methanogenesis. Thirdly, there is a critical dependence on trace elements such as nickel, cobalt, molybdenum and iron, which are necessary for the activity of key enzymes of methanogenic archaea [15]. The fourth major challenge is the presence of inhibitors, including heavy metals, ammonium, hydrogen sulphide and antibiotics, which can inhibit the activity of microorganisms [16].

3.2. Optimisation strategies for maximising biogas yield

Current research aims to overcome these limitations through physical-chemical and biological engineering. One key strategy is to pre-treat the substrate using mechanical, thermal, acid or enzymatic methods to accelerate hydrolysis. For example, ultrasonic treatment of pulp mill effluents can increase methane yield by 20-25 % [17]. Micronutrient supplementation, namely the targeted addition of deficient metals in a bioavailable chelated form, can stabilise the process and increase gas yield by 15-30%. A study by Song et al. (2018) demonstrated that the addition of cobalt and nickel to anaerobic systems treating biofuel production wastewater restored stable operation after disruption [18]. Accelerating direct interspecies electron transfer is an innovative approach. The introduction of conductive materials such as granular activated carbon, graphene or biogenic iron oxide nanoparticles into the reactor serves as 'electronic bridges' between bacteria and archaea. The work of Zhuo et al. (2023) showed that the addition of magnetite nanoparticles synthesised by Geobacter bacteria increased methane yield by 40 % and accelerated the onset of stable fermentation [19].

In addition, control and management based on advanced kinetic models, in particular the ADM1 model, combined with data from online sensors monitoring pH, volatile fatty acid concentration and gas pressure, allow stress situations to be predicted and prevented [20].

3.3. The concept of biorefining based on anaerobic fermentation

The modern vision of anaerobic fermentation goes beyond the production of raw biogas, forming the concept of an anaerobic biorefinery. In this concept, raw biogas is purified to the level of 'biomethane' with a methane content of over 95 %, which allows it to be fed into gas networks or used as an environmentally friendly fuel for transport [21]. Carbon dioxide emitted during the biogas purification stage can be captured using carbon capture technologies and used, for example, to grow microalgae as a source of additional biomass [22]. Anaerobic sludge, or residual biomass rich in nitrogen and phosphorus nutrients, can be processed into high-quality biofertilisers or serve as raw material for the synthesis of bioplastics such as polyhydroxyalkanoates [23].

4. Utilisation of Heavy Metals by Biotechnological Methods

Heavy metals such as cadmium, lead, mercury, chromium, copper, nickel and zinc in industrial effluents are not subject to biological degradation. Therefore, biotechnological approaches are aimed at changing their chemical form (valence) or physically separating them from the aqueous phase for further safe disposal or recycling.

4.1. Main mechanisms

Biosorption is a rapid process of passive binding of metal ions to the surface of living or non-living biomass by functional groups such as carboxyl, hydroxyl, amino and phosphate. Effective biosorbents include algae (*Sargassum*, *Chlorella*), fungi (*Aspergillus niger*), bacterial biomass and low-cost agricultural waste [24]. Bioaccumulation is an active process of transporting metals into cells using specific membrane systems, followed by binding with metal thiolates or polyphosphates. This process is slower but can achieve high levels of metal concentration in biomass [25]. Biotransformation involves microbial alteration of the degree of metal oxidation, which leads to a decrease in its toxicity and mobility. An example is the reduction of toxic, soluble and carcinogenic chromate ion Cr(VI) to less mobile and less toxic Cr(III). This reaction is catalysed by bacteria such as *Shewanella oneidensis* or *Pseudomonas aeruginosa*, using Cr(VI) as the final electron acceptor under anaerobic conditions [26]. Bacterial leaching

uses acidophilic chemolithotrophic bacteria, in particular *Acidithiobacillus ferrooxidans* (Fig. 4) and *A. thiooxidans*, to dissolve metals from solid matrices such as sludge or sediments.

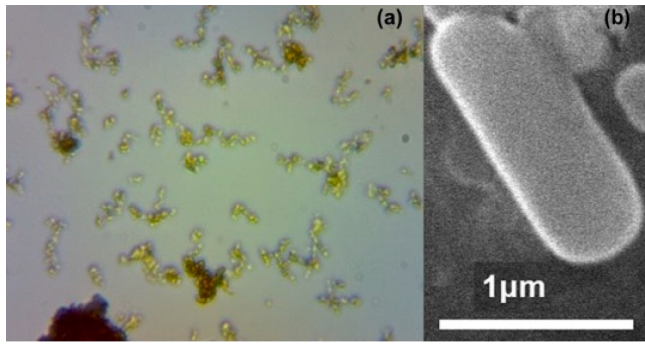


Figure 4. Acidophilic chemolithotrophic bacteria: a) *Acidithiobacillus ferrooxidans* bacterial cells from a solution obtained as a result of a biohydrometallurgical process, observed under an optical microscope (40×); b) A single bacterial cell, image obtained using electron microscopy (20,000×) [29]

The mechanism is based on the bacterial oxidation of iron (Fe^{2+} to Fe^{3+}) or sulphur, which generates sulphuric acid and iron (III) ions that dissolve metals, making them available for further hydrometallurgical extraction and recycling [27]. Bioprecipitation is a process of microbially induced precipitation of metals in the form of insoluble compounds, such as sulphides with the participation of sulphate-reducing bacteria or carbonates with the help of urease-active bacteria. Precipitated metal sulphides, such as CuS or ZnS, are highly stable and can be easily separated mechanically [28].

Table 2 provides general examples of specialised microbial consortia for the treatment of industrial wastewater.

Table 2

Examples of specialised microbial consortia for industrial wastewater treatment

Wastewater type/ contaminants	Examples of key microorganisms	Main function and mechanism
Heavy metal effluents	*Pseudomonas aeruginosa*, *Geobacter spp.*, *Rhodopseudomonas palustris*	Biosorption, bioaccumulation and biotransformation of metals into less toxic or mobile forms [30; 31; 32]
Wastewater containing persistent organic pollutants (petroleum products, pesticides)	*Bacillus subtilis*, *Pseudomonas putida*, *Penicillium chrysogenum*	Production of specific enzymes for breaking down complex hydrocarbon chains and aromatic compounds [33]
Pharmaceutical effluents (antibiotics, xenobiotics)	Consortia based on *Klebsiella pneumoniae*, *Enterobacter cloacae*, specific fungi	Cometabolism and cooperative degradation of persistent molecules that are difficult to decompose by individual species [34]
Concentrated organic effluents (distilleries, breweries)	Consortia of *Micrococcus*, *Flavobacterium*, *Pseudomonas*, *Bacillus*	Effective anaerobic fermentation of high concentrations of organic matter with maximum biogas yield [35]

4.2. Integration with purification and recycling systems

Modern technological solutions seek to integrate the mechanisms described above into a single technological chain. The pre-biosorption strategy involves the use of inexpensive biosorbents, such as grain or wood waste, in the early stages to protect sensitive biological systems, such as activated sludge or anaerobic reactors, from the toxic effects of metals. Bioelectrochemical systems for metal recovery, such as microbial fuel cells (MFCs) or electrolytic reactors, offer an elegant solution: effluent containing organic matter and metals is fed into a chamber with an anode, where bacteria oxidise organic compounds, generating an electric current. At the cathode, this current causes electrochemical reduction and precipitation of metals in pure metallic form (e.g., $Cu^{2+} + 2e^{-} \rightarrow Cu^{0}$). Thus, the technology simultaneously provides water purification, energy generation and the extraction of valuable metals [36]. Cascade detoxification and recycling systems are organised in such a way that

the effluent first passes through a stage of bioremediation of Cr(VI) to Cr(III), then Cr(III) is removed by coagulation, and the resulting sludge is transferred to the bioleaching stage for extraction of chromium as a commercial product [37].

4.3. Prospects for nanobiotechnology, genomics and synthetic biology

A promising direction is the combination of biotechnological methods with nanotechnologies to create effective sorption materials. Research by El-Shanshoury et al. (2025) demonstrated the possibility of 'green' synthesis of iron oxide nanoparticles (IONPs) using a cell-free extract of the fungus *Aspergillus niger*, which is resistant to heavy metals. The resulting mycosynthesised nanoparticles showed high efficiency in removing metals from synthetic wastewater: 92,5 % for Cu^{2+}, 84,8 % for Mn^{2+}, 80,8 % for Cr^{3+}, 72,8 % for Fe^{3+} and 70,3 % for Zn^{2+}. In real industrial effluents, the efficiency of Zn^{2+} and Fe^{3+} removal reached 78,8 % and 90,7 %, respectively [38]. This approach is an environmentally safe alternative to chemical methods of synthesising nanosorbents.

The emergence of omics technologies opens up new horizons for metal bioremediation. Metagenomics allows the identification of new, uncultured bacterial species with unique detoxification mechanisms [39]. Genetic engineering provides tools for improving existing strains: it is possible to increase the expression of metal-binding proteins, such as metallothioneins, and introduce new transporters or enzymes for the respiratory recovery of metals.

For example, a genetically modified strain of *Escherichia coli* expressing hydrogen sulphide-producing enzymes has demonstrated high efficiency in precipitating cadmium in the form of CdS sulphide [40].

5. Analysis of Advanced Research in Integrated Systems

Contemporary scientific works focus on the creation of synergistic systems, where biogas production and metal recycling processes do not simply run parallel, but complement and reinforce each other.

The implementation of this approach requires the solution of a number of complex scientific and technical problems (Fig. 5).

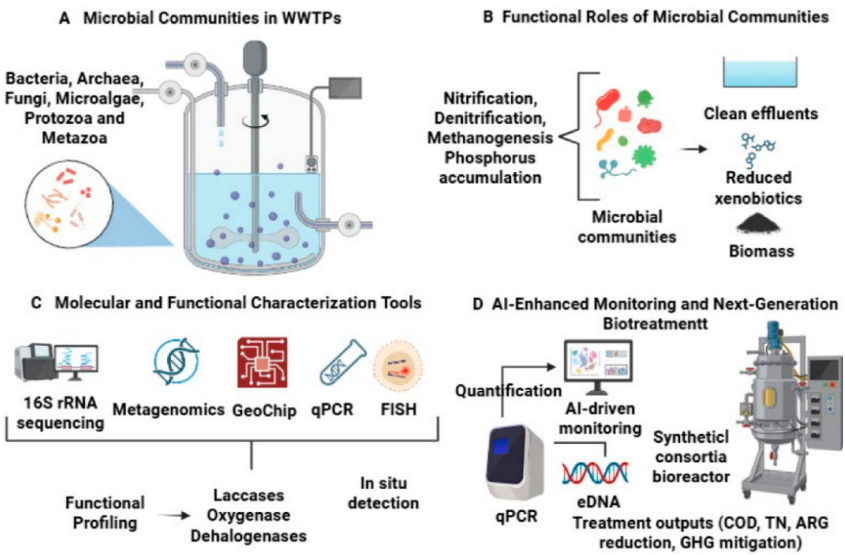


Figure 5. Ecological diversity, functional dynamics, molecular profiling, and new biotechnological innovations in microbial communities of wastewater treatment plants [43]

5.1. Modification of microbial consortia for metal resistance

The toxicity of heavy metals remains a key obstacle to stable and efficient anaerobic digestion. Recent studies have focused on the formation or selection of consortia capable of functioning in their presence. Experiments have shown that the addition of selenium can stimulate the *in situ* formation of biogenic nanoparticles of elemental selenium (Se^0), which, in turn, effectively bind heavy metal ions, such as mercury (Hg^{2+}), thereby detoxifying the environment for methanogenic archaea [41]. Another promising approach is the pre-adaptation (acidulation) of anaerobic sludge to low metal concentrations. Such adaptation stimulates the production of extra-polymeric substances that perform the function of metal chelation, creating a protective barrier around microbial cells [42].

5.2. The concept of 'metabolic separation' in integrated systems

To treat complex effluents, such as electroplating effluents with organic additives, intelligent systems are being developed with flow separation or optimal treatment sequencing. The 'metals first' approach is effective in conditions of high metal concentration. It involves their preliminary removal using a bioelectrochemical system or low-cost biosorption, after which the effluent, purified of toxicants, is sent to an anaerobic reactor for effective fermentation [44]. An alternative 'energy first, metals second' strategy is used for effluents with a predominantly organic fraction and moderate metal content. In this case, the main anaerobic fermentation takes place in the first stage, with heavy metals partially retained in the anaerobic sludge biomass. This metal-enriched sludge then becomes the raw material for the bioleaching stage, where metals are extracted for recycling and the organic residue is further stabilised [44].

5.3. Development of hybrid materials and carrier engineering

New carriers for immobilising microorganisms are being actively researched, combining several functions: biomass fixation, electronic conductivity to accelerate interspecies electron transfer, and sorption capacity for metals. Examples of such hybrid materials are granulated activated carbon modified with iron nanoparticles. In this system, activated carbon serves as an ideal basis for biofilm formation, while iron nanoparticles simultaneously improve direct electronic bonds between microorganisms and effectively sorb metals through ligand exchange and co-precipitation reactions [45]. Biocomposites (Fig. 6) based on biopolymers, such as alginate or chitosan granules, which encapsulate Shewanella bacterial biomass together with magnetite nanoparticles, are also promising.

Such granules effectively reduce Cr(VI) due to the combined action of bacteria and magnetite, while the chitosan matrix additionally sorbs the reduced Cr(III) [46].

5.4. Digital twins and data-driven management.

The extraordinary complexity of integrated biotechnological systems requires a new, cognitive level of control. In response to this challenge, digital twins are being created – virtual dynamic copies of physical installations that integrate data from extensive IoT sensor networks

(pH, redox potential, electrical conductivity, real-time spectroscopy), the results of periodic metagenomic analysis, and advanced machine learning algorithms [46; 47].

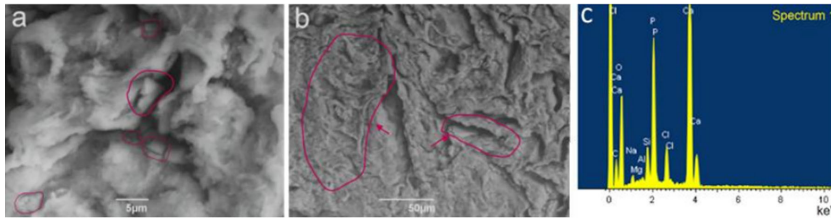


Figure 6. Microscopic images of the HA-Alg composite: a) HA-Alg surface with marked areas of analysis (4000x magnification), b) HA-Alg surface at 400x magnification; c) corresponding spectra of the HA-Alg composite [50]

Such systems are capable of predicting biogas productivity based on the dynamics of microbial composition [48], determine the optimal times and doses for adding nutrients or correcting pH, and detect the earliest signs of microbial stress, such as excessive accumulation of volatile fatty acids or hydrogen sulphide, and suggest preventive corrective actions [49].

CONCLUSIONS

Traditional physical-mechanical, chemical and physical-chemical treatment methods remain technologically mature but fundamentally linear and resource-inefficient. They are characterised by high energy consumption, significant operating costs and the generation of toxic secondary waste, including heavy-metal-enriched sludge, concentrated brines and hazardous oxidation by-products. Biotechnological methods offer a regenerative alternative focused on transforming waste into resources, operating with a low or positive energy balance and minimising toxic by-products. However, their wider implementation still requires addressing sensitivity to toxic shocks, slower reaction kinetics and the need for skilled process control.

Anaerobic digestion is a key biotechnology for energy recovery from highly concentrated organic waste streams, particularly effluents from the food, pulp and paper, brewery and distillery industries. Its multi-stage

mechanism, carried out by specialised syntrophic consortia, can be optimised through substrate pretreatment, targeted trace-element supplementation and acceleration of direct interspecies electron transfer using conductive materials, increasing methane yield by 20–40% and improving process stability.

Biotechnological heavy metal removal encompasses biosorption, bioaccumulation, biotransformation, bioleaching and bioprecipitation, offering an environmentally safe alternative to chemical precipitation and creating real opportunities for metal recycling. The integration of these mechanisms into bioelectrochemical systems and cascade schemes enables sequential detoxification of effluents and extraction of metals in commercial form. Advances in genomics, synthetic biology and green nanotechnology, such as mycosynthesised iron oxide nanoparticles achieving 92,5% Cu^{2+} removal, are enhancing the efficiency and selectivity of metal-binding and recovery processes.

Cutting-edge research demonstrates a clear trend towards synergistic integrated systems in which biogas production and metal recovery reinforce each other. Key achievements include the modification of microbial consortia for increased metal resistance, and the use of digital twins with machine learning for adaptive process control. These developments form the scientific and technological basis for autonomous biorefineries of the future.

The transition to integrated biotechnological systems requires further interdisciplinary convergence of microbiology, engineering, chemistry, materials science, genomics and computer science. Future research should prioritise pilot- and demonstration-scale validation on real industrial effluents, techno-economic and life-cycle assessment, integration with renewable energy sources, and the development of regulatory frameworks for the safe use of engineered microorganisms and recovered metals. For Ukraine, these approaches are of particular strategic importance, given the need for post-war remediation of water and soil contaminated with heavy metals and the reconstruction of industrial infrastructure on circular, energy-independent and climate-resilient principles.

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