ISSN: 2472-3703 DOI: 10.6911/WSRJ.202602_12(2).0002

Research Status and Challenges of Domestic Sewage Treatment Technology in Mining Areas

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Abstract

Due to the impact of mining activities, domestic sewage in mining areas contains heavy metals, high salt content, and refractory organic matter, making its treatment significantly more difficult than urban sewage. This article systematically reviews the research progress in this field in recent years, indicating that the bio-physicochemical combined process has become a mainstream technology. The treatment efficiency can be improved through microbial agent enhancement, membrane material modification, and ecological restoration. However, heavy metal inhibition and low-temperature inactivation remain core challenges. In the future, focus should be placed on resource recovery and intelligent operation and maintenance to promote sustainable treatment of mining area sewage.

Keywords

Mine area domestic sewage; Heavy metal removal; Membrane bioreactor; Constructed wetland; Resource utilization.

1. INTRODUCTION

As a fundamental pillar of the national economy, mining secures critical raw-material supply, yet its rapid expansion simultaneously spawns a spectrum of environmental disturbances. Foremost among these is mine domestic sewage—a hybrid wastewater stream generated in miners' dormitories, canteens, offices and subsequently commingled with mineral-laden surface runoff. This matrix has emerged as a recalcitrant node in mine-site water management because its pollutant portfolio is both chemically intricate and ecologically hazardous [1]. In contrast to municipal sewage, whose composition is relatively predictable, mine-derived domestic effluent is governed by pronounced diurnal and seasonal swings triggered by local topography, arid climate extremes and ore-body mineralogy. Superimposed on conventional organic loads are mine-specific contaminants: toxic metalloids (As, Cd, Cr), ionic salts approaching brine strength, and persistent flotation reagents that migrate through dust deposition, equipment wash-down and tailings percolation, jointly constituting a "composite pollution" signature [2]. The co-presence of these stressors exerts a synergistic antimicrobial effect: heavy metals disrupt respiratory enzymes, elevated salinity plasmolyzes cells, while surfactant residuals embed within cell membranes, collectively suppressing carbon oxidation, nitrification and phosphorus uptake in standard biological reactors. Consequently, treatment

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efficiency deteriorates, sludge settleability collapses, and effluent quality fails to meet even lenient discharge limits, underscoring the urgent need for intensified, mine-specific technological intervention rather than direct transfer of urban wastewater solutions.

Although bio-physicochemical hybrid trains have been installed at several mine sites, engineering reality still lags behind environmental ambition. Heavy metals steadily accumulate in recirculating liquors, eventually poisoning activated-sludge consortia; hypersaline infiltration collapses floc structure, provoking viscous bulking that eludes conventional polymer dosing; winter temperature drops at high-altitude pits suppress nitrifier and methanogen kinetics, causing NH_4^+-N and COD breakthrough; most critically, metal-laden sludge is classified as hazardous waste, yet its stabilization, volume reduction and final land exclusion remain technically immature and economically punitive. As China's "dual-carbon" strategy tightens energy and emission budgets, these unresolved bottlenecks oblige the sector to abandon the "treat-and-discharge" mindset and move toward resource-recovery paradigms that valorize water, nutrients, metals and biogas while minimizing residual footprints. Synthesizing domestic and international pilot data, this review therefore revisits mine sewage complexity, appraises intensification options and distils countermeasure pathways, providing a knowledge base for designers committed to low-carbon, circular engineering practice [3].

2. WATER QUALITY CHARACTERISTICS: TRACING THE COMPLEXITY TO ITS SOURCE

The complexity of the water quality of domestic sewage in mining areas is rooted in the deep coupling between mining activities and domestic wastewater; this coupling is not merely additive but multiplicative, so that every domestic litre becomes a vector for mining-borne contaminants and every mining splash becomes a reinforcer of domestic fouling. This type of sewage therefore carries, in the same fluctuating matrix, both the predictable pollutants of conventional domestic sewage—carbon, nitrogen, phosphorus, surfactants, microorganisms—and the less predictable but steadily enriched heavy metals, high salinity, and refractory organic compounds that arise from the special environmental migration pathways characteristic of mining areas, pathways that turn simple sewers into diffuse hydrometallurgical circuits and simple septic tanks into long-term geochemical reactors, thereby forming a unique "composite pollution" system whose behaviour cannot be read from either municipal or purely industrial handbooks.

The sources of pollution can be clearly divided into four categories, yet these categories continually overlap and back-feed: domestic activity sources such as kitchen waste, excreta, washing wastewater and other everyday discharges; mining activity migration sources such as atmospheric dust deposition and equipment cleaning water mixing that lead to the steady enrichment of heavy metals such as As, Cd, Cr; regional environmental superimposed sources such as the continuous water evaporation and concentration that occur in arid areas and that inevitably push up total dissolved solids far beyond domestic norms; and chemical mixing sources such as rainwater washing that causes the repeated infiltration of flotation agents, lubricant degradation products and other process chemicals into what was originally a domestic collection network. It is worth noting that about 15 % of the heavy metal load is directly attributed to mining migration, and this single non-domestic fraction constitutes the essential difference between mine-impacted sewage and ordinary sewage, a difference that persists regardless of how diligently household water-saving measures are applied.

From the perspective of pollutant concentration, data from multiple mining areas across the country reveal significant characteristics that repeat themselves from north to south and from coal to metal mines: conventional pollutants such as chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N), and total phosphorus (TP) are generally higher than those in urban

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domestic sewage, while the characteristic pollutants highlight the crisis even more sharply—arsenic (As) and cadmium (Cd) are almost undetectable in ordinary sewage, and the total dissolved solids (TDS) in arid mining areas can reach up to six times that of ordinary sewage, so that flotation agent residues become notably difficult to treat with the biological tools that work elsewhere. These components trigger three core issues: firstly, the synergistic inhibitory effect of heavy metals is manifested as a significant decrease in nitrifying bacteria activity when Cd^{2+} and As^{3+} act in combination [5]; secondly, high-salt biotoxicity leads to a substantial increase in the sludge volume index (SVI), inducing severe sludge bulking that cannot be tamed by the usual polymer dose [6]; thirdly, the accumulation of refractory organics extends the biodegradation half-life of mineral processing agents to 72 hours, far exceeding that of ordinary surfactants and thereby stretching biological systems beyond their design safety margins. See Figure 1 for details.

The spatiotemporal variability of water quality further complicates treatment efforts, because the same sewer must serve shift-change surges, seasonal cloudbursts and process-maintenance lulls in rapid succession. Water volume is influenced by the shift system of miners, with peak flows in the morning and evening reaching 2–3 times the daily average and with the intervening trough still carrying a high-strength load; seasonal variations manifest as an increase in TDS concentration during the dry season and a surge in suspended solids (SS) and heavy metal loads due to surface runoff during the rainy season; the production correlation is reflected in a 25 % reduction in COD when washing wastewater decreases during the maintenance period of the mineral processing plant, only to rebound the moment the mills restart. This variability, driven by a combination of human, natural, and production factors, results in dynamic load impacts that arrive without the warning periods enjoyed by municipal plant operators. It is evident, therefore, that mine area domestic sewage constitutes a complex pollution system characterized by "high load, multiple toxins, and strong variability," and its unique water quality characteristics necessitate customized treatment processes endowed with strong resilience and wide adaptability if consistent compliance is ever to be achieved.

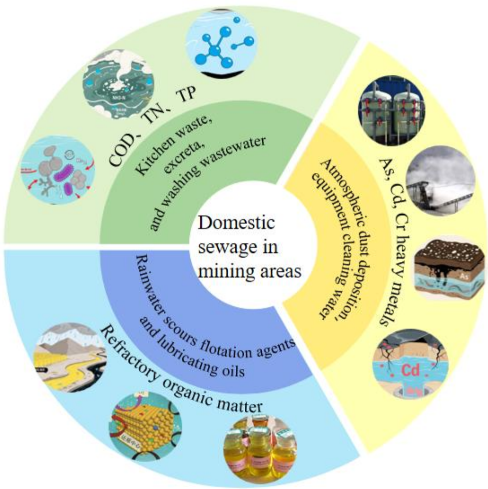

Figure 1. Main characteristics and sources of domestic sewage in mining areas

3. EXISTING CHALLENGES AND RESEARCH PROGRESS IN TREATMENT TECHNOLOGY

The multiple stressful environments that inevitably confront any domestic-sewage treatment facility located within a mining district urgently demand decisive breakthroughs across four intertwined technical bottlenecks: the need for reliable biological-inhibition enhancement, the equally critical requirement for robust sludge-instability control, the persistent challenge of

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low-temperature adaptability, and the overarching necessity for stringent secondary-pollution prevention and control.

To meet the first of these demands, the biological-enhancement strategy currently under intensive investigation involves the deliberate addition of carefully selected heavy-metal-tolerant functional bacterial strains that, by virtue of resistance genes carried within their own genome, can actively secrete Cd^{2+} chelators or otherwise immobilise the ion, thereby allowing the biological treatment system to maintain a satisfactorily high COD removal rate even when the influent repeatedly imposes cadmium stress [7].

Parallel to metal toxicity, the issue of sludge bulking brought about by high salinity is no less severe, because the elevated mineralisation disrupts the delicate charge balance that normally keeps flocs compact, leading to SVI values that exceed the normal threshold and that herald massive solids washout; recent research has nevertheless demonstrated that a carefully managed salinity-gradient acclimation method, in which the salt load is increased only gradually, can selectively enrich halophilic bacterial communities whose secreted hydrophobic extracellular polymeric substances reinforce the floc structure and, in so doing, stabilise the SVI within a range that permits steady operation.

Finally, to counter the seasonal challenge of biological inactivation that strikes during winter nights in high-altitude mining areas, a coupling scheme that combines psychrophilic bacterial agents with membrane technology is revealing noteworthy potential: on the one hand, the supplementary addition of psychrophilic nitrifying bacteria compensates for the well-documented shortfall in ammonia-oxidation rate that otherwise accompanies low temperature [8], while, on the other hand, the physical retention exerted by the membrane bioreactor (MBR) membranes slows the temperature-driven loss of biomass, thereby preserving both nitrifier abundance and overall removal efficiency throughout the coldest months [9].

3.1. Biological Treatment Enhancement Direction

In response to the dual pressure exerted by heavy-metal stress and the persistence of difficult-to-degrade organic matter that typify mining-area domestic sewage, the deliberate addition of stress-resistant functional microbial agents—when operated in concert with a refined membrane-material process coupling—has recently emerged as a strategically attractive option that continues to show significant, and steadily expanding, potential. Taking the specific control of heavy-metal cadmium (Cd) pollution as an immediately instructive example, published studies have uniformly illustrated that the introduction of carefully selected Cd-resistant bacterial strains into conventional sequencing-batch (SBR) reactors allows those strains to secrete extracellular polymeric substances (EPS) that are rich in carboxyl, hydroxyl and amino functional groups; these secretions efficiently chelate free Cd^{2+} ions present in the bulk liquid, thereby forming a robust extracellular barrier that markedly reduces the onward migration of toxic ions across cellular envelopes and, in so doing, preserves the metabolic vitality of the overall biocoenosis [10].

Parallel to, and fully complementary with, this biological safeguard, the collaborative innovation pathway offered by modern membrane bioreactor (MBR) technology supplies a convincing answer to the intertwined challenges of rapid membrane fouling and incomplete organic degradation that are repeatedly triggered by residual flotation agents. On the one hand, the adoption of hydrophilically modified membrane materials—whether through surface grafting, nano-coating or blended polymer synthesis—renders the membrane surface measurably more resistant to hydrophobic foulants, an alteration that translates directly into a visibly higher sustainable membrane flux and into a substantially extended operational service life before chemical cleaning becomes unavoidable [11]. On the other hand, the strategic coupling of an upstream or sidestream ozone oxidation unit, capitalising upon the strong, non-selective oxidising power inherent to molecular ozone, succeeds in rupturing the resilient

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carbon-chain backbones characteristic of flotation-agent residuals, thereby raising the overall TOC removal rate of those recalcitrant compounds within the integrated system and simultaneously alleviating the downstream biological and membrane burden [12].

3.2. Materialization Technology: Targeted Removal of Characteristic Pollutants

In response to the deep removal needs of characteristic pollutants such as heavy metals and recalcitrant organic compounds in domestic sewage in mining areas, physical and chemical technology has become a key supplement to biological treatment due to its rapid response and anti toxicity advantages. In terms of heavy metal removal, coagulation precipitation is the most widely used physicochemical process in engineering. By adding composite coagulants, free $Cd^{2+}$and Pb^{2+}ions can be efficiently captured, forming floc sedimentation separation, achieving a heavy metal removal rate of over 80%. Especially for mining wastewater with significant concentration fluctuations, its rapid polymerization ability can effectively buffer heavy metal load shocks. For arsenic pollution with strong biological toxicity and low concentration, adsorption technology exhibits unique advantages: using iron-based modified biochar as an adsorbent, the rich surface iron oxide sites can specifically bind $As^{3+}$and adsorb most of As. This material also has magnetic recovery properties, avoiding the risk of secondary pollution.

3.3. Ecological Treatment Technology: A Low-Carbon Path

Artificial wetland technology has attracted much attention in wastewater treatment in mining areas due to its low-carbon characteristics, but the limitations of traditional single-stage wetlands in low-temperature environments and heavy metal accumulation risks urgently need to be overcome. To address the issue of low-temperature biological activity inhibition, the vertical horizontal flow cascade process significantly improves the thermal stability of the system by constructing a multi-stage oxidation-reduction microenvironment. The vertical flow unit utilizes the insulation performance of the packing layer to delay heat loss and enhance atmospheric reoxygenation efficiency; Horizontal flow units promote anaerobic denitrification by extending hydraulic retention time [13-14].

To address the long-term retention risk of heavy metals in wetland sediment, the hyperaccumulation plant remediation technology has been innovatively integrated: planting centipede grass at the end of the wetland, the phenolic acid substances secreted by its root system can activate solid-phase arsenic, and efficiently transport $As^{5+}$to the aboveground part through phosphate transporters.

4. CONCLUSION

Although significant progress has been made in the current research on domestic sewage treatment in mining areas through the synergistic technology of biology, physics, chemistry, and ecology - the addition of stress tolerant bacterial agents can alleviate Cd^{2+}toxicity and improve COD removal efficiency in SBR systems, the vertical flow horizontal flow constructed wetland cascade process maintains NH_4^+-N removal rate at low temperatures through microenvironment optimization, and iron-based modified biochar internship achieves adsorption of $As^{3+}$and magnetic recovery - the synergistic inhibition of heavy metals and high salinity, low-temperature biological inactivation, and safe disposal of heavy metal containing sludge are still the core bottlenecks restricting engineering applications. The sludge swelling caused by high salinity relies on complex salinity gradient domestication and control. The disposal cost of heavy metal containing sludge is high, and traditional landfill poses ecological risks. The residual flotation agent further hinders the stability of the treatment system.

In order to better understand the efficient treatment technology of domestic sewage in mining areas, further research can be considered from the following three aspects in the future:

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1) By combining metagenomics technology, we aim to reveal the metabolic response mechanisms of microbial communities under heavy metal and salt stress, and develop targeted anti stress microbial agents.

2) Innovative gradient anti salt biofilm carrier coupled with salinity adaptive microbial enrichment strategy, achieving steady-state control of sludge structure under high salinity shock load.

3) Accelerate the regeneration and reuse of domestic sewage in mining areas, achieve "quality treatment cascade reuse", promote water resource recycling, and reduce water costs in mining areas.

ACKNOWLEDGEMENTS

This work was supported by the Natural Science Foundation of China (22406055), Natural Science Foundation of Hebei (E2023209067), Hebei Yanzhao Golden Platform Talent Gathering Plan (HJYB202526), Tangshan Applied Basic Research Science and Technology Plan Project (25130218B), Youth Scholars Promotion Plan of the North China University of Science and Technology (QNTJ202310), and Innovation and Entrepreneurship Training Program for College Students (S202510081103).

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