Teaching and Teacher Education 186 (2027) doi.org/10.5281/zenodo.24379462

Contents lists available at ScienceDirect

Teaching and Teacher Education

journal homepage: https://www.teachingandteachereducation.org

Research paper

From Bioengineered Wetlands to Living Laboratories: Integrating NatureBased Solutions into Engineering Education for Sustainable Mining Regions

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ARTICLE INFO

Keywords:
Bioenginered
Education
Environmental Innovation
Sustainability
Nature based
Responsability

ABSTRACT

This article examines the potential of bioengineered constructed wetlands as integrated environmental and educational systems in mining-affected regions, focusing on their capacity to remove potentially toxic metals and transform engineering education through experiential learning. Drawing on an integrative review of scientific literature on nature-based solutions, environmental remediation, living laboratories, and sustainability-oriented engineering education, the study identifies opportunities for connecting technological innovation with the development of professional competencies. We argue that bioengineered wetlands should not be understood exclusively as environmental treatment infrastructure, but also as educational platforms that enable engineering students to engage with real-world environmental challenges. The proposed conceptual framework establishes a continuum of learning experiences ranging from water-quality monitoring and contaminant analysis to treatment system design, interdisciplinary problem-solving, and community-based environmental innovation. We further argue that integrating these systems into higher education curricula can strengthen technical knowledge, scientific reasoning, environmental responsibility, and sustainability competencies. The article contributes to debates on engineering education, nature-based solutions, environmental sustainability, and the development of innovative educational approaches for preparing future engineers to address the complex environmental challenges associated with mining activities.

1. Introduction

Mining activities represent a fundamental component of economic development in numerous countries, particularly in regions where mineral extraction contributes significantly to industrial production, employment, and international trade. Nevertheless, the environmental consequences associated with these activities remain a persistent challenge, especially regarding the deterioration of water resources through the discharge of mine drainage and wastewater containing potentially toxic metals and metalloids. Elements such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and zinc (Zn) can accumulate in aquatic environments, affecting ecological processes, water quality, and the sustainability of surrounding communities. Their persistence and complex chemical behaviour require treatment strategies capable of addressing both immediate contamination and long-term environmental risks.

Conventional wastewater treatment technologies have contributed substantially to the management of mining-related contamination. However, their application may involve considerable infrastructure requirements, energy consumption, chemical inputs, operational costs, and specialized maintenance. These limitations have increased interest in alternative treatment approaches that combine environmental effectiveness with ecological functionality and long-term sustainability. Within this context, constructed wetlands have emerged as promising nature-based treatment systems that integrate vegetation, microorganisms, reactive substrates, and hydraulic processes to improve contaminated water quality. Their capacity to retain or transform potentially toxic elements through adsorption, filtration, precipitation, sedimentation, ion exchange, and biological interactions has received increasing scientific attention (Yu et al., 2022; Zhang et al., 2024). Recent research has demonstrated that the performance of constructed wetlands depends on the interaction between system configuration, substrate characteristics, vegetation, microbial communities, hydraulic retention time, and the physicochemical properties of the influent. In particular, enhanced treatment approaches involving modified substrates, selected plant species, microbial processes, and hybrid configurations have been investigated to improve the removal of heavy metals and metalloids. Nevertheless, removal performance remains variable across different environmental conditions, highlighting the importance of appropriate system design, monitoring, and context-specific evaluation (Yu et al., 2022; Zhang et al., 2024). These findings indicate that bioengineered wetlands should be approached not as universally applicable treatment solutions, but as adaptable environmental technologies requiring scientific understanding and continuous engineering assessment.

Beyond their environmental function, these systems also offer an opportunity to reconsider how engineering knowledge is developed and applied within higher education. Engineering education has traditionally relied on theoretical instruction, laboratory exercises, and discipline-specific technical training. Although these approaches provide essential foundations, they may not always expose students to the complexity of environmental problems encountered in professional practice. Contemporary sustainability challenges require engineers who can integrate scientific knowledge, technological innovation, environmental responsibility, collaborative decision-making, and an understanding of the social dimensions of engineering interventions.

This challenge is particularly relevant in mining regions, where environmental engineering problems frequently involve interconnected hydrological, ecological, technological, economic, and social processes. Preparing future engineers to address these conditions requires educational approaches that move beyond the transmission of technical information and provide opportunities for students to participate in the investigation and resolution of authentic environmental problems. Experiential learning and project-based education offer possibilities for connecting academic knowledge with practical situations, allowing students to develop analytical reasoning, interdisciplinary communication, and context-sensitive engineering solutions.

One promising approach involves the incorporation of living laboratories into higher education. Living laboratories provide environments in which students, researchers, institutional actors, and external stakeholders can collaboratively investigate real-world challenges and develop innovative responses. In sustainability-oriented higher education, these environments can support transformative learning by connecting academic activities with actual environmental and societal conditions. Recent literature has identified multiple pedagogical approaches, learning processes, and sustainability-related outcomes associated with living laboratories, while also recognizing challenges concerning their implementation and educational organization (International Journal of Sustainability in Higher Education, 2024). More recent research on engineering students' experiences further highlights the relevance of living laboratories for connecting theoretical knowledge with practical engagement and collaboration with external stakeholders (European Journal of Engineering Education, 2026).

Within this educational perspective, bioengineered constructed wetlands may function as particularly relevant living laboratories. Their relatively observable treatment processes and interconnected biological, chemical, and physical mechanisms provide opportunities for students to investigate environmental engineering principles through practical activities. Students can examine water-quality parameters, analyse the behaviour of potentially toxic metals, evaluate substrate characteristics, investigate vegetation-mediated processes, and assess how different operational conditions influence treatment performance. These activities can transform constructed wetlands into learning environments in which engineering concepts are connected with scientific inquiry, environmental monitoring, system design, and sustainability assessment.

However, the educational integration of these technologies requires more than the installation of treatment infrastructure within university facilities. It involves the development of pedagogical strategies that connect environmental processes with explicit learning objectives, competency development, assessment procedures, and institutional collaboration. Without this integration, practical environmental installations may remain isolated technical demonstrations rather than structured educational environments. Therefore, the central challenge is to establish a conceptual and pedagogical relationship between the environmental performance of bioengineered wetlands and the educational outcomes expected from engineering students.

Despite growing research on constructed wetlands for heavy-metal remediation and the increasing recognition of living laboratories in sustainability education, these areas have largely developed through separate research trajectories. Studies on constructed wetlands primarily emphasize contaminant removal mechanisms, treatment configurations, substrate optimization, and operational performance. Conversely, research on engineering education

and living laboratories tends to focus on experiential learning, interdisciplinary collaboration, sustainability competencies, and student engagement. The intersection between these fields remains an opportunity for further conceptual development, particularly regarding how environmental remediation technologies can be systematically incorporated into engineering curricula in mining-affected regions.

This article addresses this intersection by examining the potential of bioengineered constructed wetlands as dual-purpose systems that combine environmental treatment functions with educational applications. Rather than assuming that their incorporation automatically produces improved learning outcomes, the study proposes an integrative perspective through which their technological characteristics can be connected with pedagogical activities, competency development, and sustainability-oriented assessment. This approach recognizes that the educational value of these systems depends on the quality of their curricular integration, the participation of relevant stakeholders, and the establishment of meaningful connections between environmental challenges and professional engineering practice.

Accordingly, the article develops an integrative conceptual framework for incorporating bioengineered constructed wetlands as living laboratories into engineering education, particularly in higher education institutions located in mining regions. It examines the technological foundations of metal removal, the pedagogical potential of experiential and interdisciplinary learning, and the competencies that can be developed through the educational use of nature-based treatment systems. In doing so, it contributes to discussions on the transformation of engineering education, the application of nature-based solutions, and the preparation of future engineers capable of addressing complex environmental sustainability challenges.

2. Theoretical and Conceptual Framework

2.1. Bioengineered Constructed Wetlands and Environmental Remediation

Constructed wetlands have become increasingly relevant within environmental engineering as nature-based treatment systems designed to improve water quality through the interaction of biological, chemical, and physical processes. Unlike conventional treatment technologies that frequently depend on intensive mechanical operations and chemical inputs, these systems reproduce selected ecological functions under controlled hydraulic and environmental conditions. Their configurations generally incorporate water-saturated substrates, emergent vegetation, microbial communities, and engineered materials that facilitate the retention, transformation, and immobilization of contaminants.

The application of constructed wetlands to mining wastewater treatment has received particular attention because mining activities can generate complex effluents containing potentially toxic metals and metalloids, including iron (Fe), manganese (Mn), arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn). These contaminants exhibit different chemical behaviours and interactions with environmental matrices, making their removal dependent on the characteristics of the influent and the operational conditions established within the treatment system. Consequently, constructed wetlands must be designed according to the specific geochemical characteristics of the contaminated water rather than through a universal treatment configuration.

Recent research has emphasized the importance of substrate selection, hydraulic configuration, vegetation, and microbial activity in determining treatment performance. In particular, adsorption-based and alkaline substrates can contribute significantly to metal retention through surface interactions, ion exchange, and precipitation processes. Furthermore, microbial communities associated with biofilms and plant rhizospheres can influence metal mobility through oxidation–reduction reactions, biological adsorption, and the modification of local chemical conditions (Zhang et al., 2024).

From an engineering perspective, constructed wetlands can be classified according to their hydraulic and operational configurations, including free-water surface systems, horizontal subsurface-flow wetlands, vertical subsurface-flow wetlands, and hybrid configurations. Each configuration presents different oxygen transfer characteristics, hydraulic retention conditions, and opportunities for interaction between contaminated water and treatment materials. These differences are particularly important in mining applications, where the oxidation state, solubility, and precipitation behaviour of metals can determine the overall effectiveness of treatment.

The development of bioengineered constructed wetlands therefore requires an integrated design approach that considers hydraulic performance, substrate reactivity, vegetation tolerance, microbial functionality, and long-term contaminant stability. This perspective positions constructed wetlands as adaptable environmental engineering systems in which ecological processes are deliberately incorporated into technological design. Their potential educational value emerges from the possibility of making these processes observable, measurable, and accessible to students through practical engineering activities.

2.2. Heavy Metal Removal Mechanisms in Constructed Wetlands

The removal of potentially toxic metals in constructed wetlands is governed by multiple interconnected mechanisms that operate simultaneously within the water column, substrate, plant rhizosphere, and microbial biofilms. Unlike organic contaminants that may undergo biological degradation, metals cannot be destroyed through conventional biological processes. Their attenuation instead depends on mechanisms that modify their chemical speciation, mobility, distribution, and retention within the treatment environment.

One of the principal mechanisms is adsorption, which involves the attachment of dissolved metal ions to reactive surfaces present in substrates, sediments, organic matter, and biofilms. Materials containing iron oxides, aluminium oxides, carbonates, and other reactive mineral phases can provide adsorption sites that facilitate metal retention. The effectiveness of this process depends on pH, ionic strength, surface characteristics, and competition between different dissolved elements.

Precipitation and co-precipitation constitute additional mechanisms through which metals can be retained within constructed wetlands. Changes in pH and oxidation–reduction conditions may promote the formation of relatively insoluble mineral phases, including metal hydroxides, carbonates, and sulfides. These compounds can accumulate within the substrate and sediment, reducing the concentration of dissolved contaminants in the treated water. However, changes in environmental conditions may subsequently destabilize some precipitated phases and lead to contaminant remobilization.

Filtration and sedimentation also contribute to contaminant retention by allowing suspended particles and metal-associated solids to become trapped within the substrate or settle in designated treatment zones. These physical processes are particularly relevant when metals are transported in association with particulate matter or precipitated compounds.

Biological processes further influence metal removal through interactions between microorganisms, vegetation, and surrounding mineral surfaces. Microbial biofilms can adsorb metal ions and modify the chemical environment through metabolic activity. Certain microorganisms also participate in oxidation–reduction reactions that influence metal speciation and precipitation. Vegetation contributes through root-mediated processes, phytostabilization, and, in selected cases, metal uptake and accumulation in plant tissues. Nevertheless, plant uptake should not be assumed to represent the dominant removal pathway, since the immobilization of metals in sediments and substrates frequently plays a more substantial role (Zhang et al., 2024).

These mechanisms demonstrate that constructed wetlands operate as complex environmental systems rather than simple filtration structures. Their treatment performance emerges from interactions among chemical equilibria, microbial metabolism, plant physiology, and hydraulic conditions. Consequently, the evaluation of these systems requires monitoring indicators such as influent and effluent metal concentrations, pH, electrical conductivity, oxidation–reduction potential, hydraulic retention time, and substrate characteristics.

For engineering education, these mechanisms provide an important foundation for applied learning. Students can investigate how changes in substrate composition influence adsorption, how pH affects metal precipitation, how vegetation modifies the rhizosphere, and how microbial communities contribute to contaminant retention. Such activities enable the integration of environmental chemistry, microbiology, hydrology, and materials engineering within a common educational framework.

2.3. Nature-Based Solutions in Mining Regions

Nature-based solutions have gained increasing recognition as approaches that use or reproduce natural processes to address environmental and societal challenges while supporting ecosystem functioning. In environmental engineering, these approaches provide opportunities to combine technological design with ecological processes, particularly in areas affected by water contamination, land degradation, and industrial activities.

Mining regions represent particularly relevant contexts for the application of nature-based solutions because their environmental challenges frequently extend beyond the immediate boundaries of extraction operations. Mine drainage, wastewater discharges, metal accumulation, and the deterioration of aquatic ecosystems can affect surrounding communities and increase pressure on water resources. Addressing these conditions requires treatment strategies that consider contaminant characteristics, environmental sensitivity, operational feasibility, and long-term ecological stability.

Constructed wetlands offer a potential nature-based approach for managing selected mining effluents through the integration of engineered substrates, vegetation, and microbial processes. Their potential advantages include relatively low energy requirements under appropriate conditions, opportunities for passive operation, ecological integration, and adaptability to different treatment scales. However, their effectiveness depends on influent chemistry, climate, available land, hydraulic design, contaminant loading, and maintenance requirements. Furthermore, the accumulation of metals in substrates and plant biomass requires appropriate monitoring and management to prevent secondary environmental risks.

A recent review of constructed wetlands for metallic wastewater treatment identifies adsorption, filtration, precipitation, co-precipitation, and ion exchange as important mechanisms, emphasizing the role of substrate properties and microbial activity in determining treatment performance (Zhang et al., 2024). Similarly, research on constructed wetlands and metal-hyperaccumulating plants highlights the importance of distinguishing between contaminant immobilization in sediments and actual removal through plant uptake (Zhang et al., 2024).

From a sustainability perspective, the application of constructed wetlands in mining regions should therefore be evaluated through multiple dimensions, including water-quality improvement, ecological stability, resource requirements, operational feasibility, and environmental risk management. Their implementation should complement, rather than automatically replace, conventional treatment technologies when contaminant concentrations or regulatory requirements demand more intensive treatment.

This context also creates educational opportunities for universities located near mining areas. Through collaborative projects involving students, researchers, mining operators, public institutions, and local communities, environmental treatment systems can become platforms for investigating regional sustainability challenges. Such collaboration can connect engineering education with local environmental priorities and promote the development of solutions adapted to specific geographical and socioeconomic conditions.

2.4. Engineering Education and Sustainability Competencies

Engineering education faces the challenge of preparing graduates to address increasingly complex technological, environmental, and societal problems. Traditional engineering curricula have generally emphasized disciplinary knowledge, mathematical modelling, technical analysis, and the development of specialized problem-solving skills. Although these competencies remain essential, contemporary environmental challenges require broader professional capabilities that enable engineers to understand interconnected systems and evaluate the consequences of technological interventions.

Sustainability-oriented engineering education emphasizes the integration of environmental, economic, social, and technological considerations into engineering practice. This approach recognizes that engineering decisions are not exclusively technical operations but interventions that influence ecosystems, communities, infrastructure, and patterns of resource consumption. Consequently, engineering students must develop the ability to evaluate alternative solutions according to their technical feasibility, environmental implications, and long-term sustainability.

Experiential learning represents an important pedagogical approach for developing these competencies. By engaging students in practical activities, collaborative projects, experimentation, and real-world problem-solving, experiential learning can connect theoretical knowledge with professional practice. A systematic literature review of experiential learning in engineering education identifies its relevance to undergraduate engineering training and examines the pedagogical elements required for effective implementation (Experiential Learning in Engineering Education, 2023).

Within the context of environmental engineering, sustainability competencies may include systems thinking, environmental assessment, scientific investigation, interdisciplinary communication, ethical responsibility, innovation, and adaptive problem-solving. These competencies are particularly relevant when students investigate environmental treatment systems that involve multiple interacting processes and uncertain operational conditions.

Bioengineered constructed wetlands provide a practical context for developing these capabilities. Their analysis requires students to understand environmental chemistry, biological processes, hydraulic behaviour, materials selection, and treatment performance. Furthermore, evaluating their implementation in mining regions requires consideration of land availability, operational costs, environmental regulations, community needs, and the long-term management of accumulated contaminants.

The integration of these systems into engineering education can therefore support a transition from predominantly discipline-based instruction toward applied and sustainability-oriented learning. Rather than treating environmental sustainability as an additional theoretical subject, this approach incorporates sustainability considerations directly into engineering design, experimentation, monitoring, and evaluation activities.

2.5. Living Laboratories and Experiential Learning

Living laboratories have emerged as educational and research environments in which real-world challenges become the basis for collaborative experimentation, knowledge generation, and innovation. In higher education, these environments connect academic institutions with external stakeholders and provide opportunities for students to participate in activities that extend beyond conventional classroom instruction.

Unlike simulated laboratory exercises, living laboratories operate within authentic socio-technical and environmental contexts. Their educational value is associated with the possibility of investigating complex problems, interacting with different stakeholders, testing

solutions, and reflecting on the consequences of practical interventions. This approach can strengthen connections between theoretical learning, professional competencies, and societal needs.

Research on sustainability-oriented living laboratories in higher education has identified different teaching and learning contexts, pedagogical interventions, learning processes, and sustainability-related outcomes. Van der Wee et al. (2024), through a review of 35 studies, demonstrate that living laboratories can support transformative learning processes, while also identifying challenges associated with their educational implementation.

Experiential learning provides a complementary theoretical foundation for understanding how students develop knowledge through participation and reflection. In this perspective, learning is not restricted to the acquisition of information but involves the interpretation of experiences, the development of conceptual understanding, and the application of knowledge to new situations.

When applied to bioengineered constructed wetlands, living laboratory activities may involve environmental sampling, water-quality monitoring, substrate characterization, experimental analysis, treatment system design, and the evaluation of contaminant removal. These activities can be organized into progressive learning experiences that connect observation, investigation, engineering design, and critical reflection.

The educational potential of this approach depends on the establishment of explicit learning objectives and assessment procedures. A constructed wetland does not automatically become an effective educational environment simply because students can observe it. Its integration requires structured activities, qualified supervision, access to appropriate monitoring equipment, safety protocols, and opportunities for students to interpret the environmental data generated by the system.

Consequently, living laboratories should be understood as intentionally designed educational environments in which infrastructure, pedagogical strategies, and stakeholder participation are connected. This distinction is essential for transforming bioengineered wetlands from isolated environmental installations into meaningful platforms for engineering education.

2.6. Conceptual Integration of Environmental Engineering and Education

The integration of bioengineered constructed wetlands into engineering education requires a conceptual framework capable of connecting environmental treatment processes with pedagogical objectives and measurable learning outcomes. Although environmental remediation and educational development have traditionally been examined through different disciplinary perspectives, their integration offers opportunities to strengthen both technological understanding and professional competency development.

The proposed conceptual perspective considers bioengineered wetlands as dual-purpose systems operating through two interconnected dimensions. The first is the environmental engineering dimension, which involves contaminant characterization, system configuration, substrate selection, vegetation management, microbial processes, hydraulic operation, and water-quality assessment. The second is the educational dimension, which involves experiential learning, scientific inquiry, interdisciplinary collaboration, engineering design, sustainability assessment, and competency development.

These dimensions are connected through a sequence of educational and technological activities. First, students identify an environmental problem associated with mining-related water contamination. Second, they investigate the physicochemical characteristics of the affected water and identify relevant treatment requirements. Third, they examine the design and operational principles of constructed wetlands. Fourth, they participate in monitoring or modelling activities to evaluate treatment behaviour. Finally, they interpret the results, assess the sustainability implications, and propose engineering improvements. This process establishes a relationship between technical activities and educational outcomes. For example, water-quality monitoring can contribute to scientific investigation competencies, substrate characterization can strengthen materials and environmental chemistry knowledge, and treatment system design can support engineering decision-making and systems thinking. Similarly, collaborative projects involving universities and local stakeholders can strengthen interdisciplinary communication and contextual understanding.

The proposed integration also recognizes that environmental performance and educational effectiveness must be assessed separately. A wetland may achieve satisfactory contaminant retention without necessarily generating meaningful learning outcomes. Conversely, a highly valuable educational activity may involve a pilot system whose treatment performance is limited or still under investigation. Therefore, both dimensions require independent indicators and evaluation procedures.

In this sense, the integration of environmental engineering and education should not be interpreted as the simple incorporation of technological infrastructure into university facilities. It represents a broader educational strategy through which real environmental systems become structured opportunities for scientific learning, technological innovation, and sustainability-oriented professional development.

The resulting conceptual framework provides the theoretical foundation for positioning bioengineered constructed wetlands as living laboratories in mining regions. It also establishes the basis for developing an educational-technological model that connects environmental remediation, experiential learning, competency assessment, and university–community collaboration.

3. Research Methodology

3.1. Research Design

This study adopts an integrative literature review design to examine the relationship between bioengineered constructed wetlands, environmental remediation, and sustainability-oriented engineering education. An integrative approach was selected because the research problem encompasses multiple disciplinary perspectives and requires the examination of diverse forms of scientific evidence, including environmental engineering studies, educational research, conceptual contributions, and investigations addressing nature-based solutions.

Unlike reviews restricted to a single type of empirical evidence, integrative reviews allow the synthesis of different research methodologies and theoretical perspectives, providing opportunities to identify conceptual relationships, emerging research directions, and knowledge gaps (Whittemore & Knafl, 2005). This methodological orientation is particularly appropriate for the present study because the proposed integration of constructed wetlands into engineering education involves both technological and pedagogical dimensions.

The research design is structured around four interconnected analytical dimensions: (1) the technological foundations of bioengineered wetlands and their capacity to retain potentially toxic metals; (2) the environmental and sustainability challenges associated with mining regions; (3) the pedagogical approaches supporting experiential learning and living laboratories in engineering education; and (4) the development of an integrated educational-technological framework.

The review follows a transparent and reproducible literature identification and selection procedure. Reporting principles from PRISMA 2020 are used to guide the documentation of the identification, screening, eligibility, and inclusion stages, without treating the integrative review as a completed systematic review or implying that quantitative meta-analysis has been conducted (Page et al., 2021).

The final analytical stage involves synthesizing the selected literature to identify relationships between environmental treatment processes, educational activities, and sustainability competencies. These relationships provide the conceptual basis for the proposed framework.

3.2. Integrative Literature Review Approach

The integrative review approach was selected to facilitate the examination of scientific contributions originating from environmental engineering, ecological treatment technologies, higher education, and sustainability research. The central purpose is not simply to summarize existing publications but to establish an analytical connection between research domains that have frequently developed independently.

Following the methodological principles proposed by Whittemore and Knafl (2005), the review is organized into five interconnected stages: problem identification, literature searching, data evaluation, data analysis, and presentation of the synthesis. These stages provide a structured basis for identifying relevant evidence and examining the conceptual relationships emerging from the selected studies.

During the problem identification stage, the review establishes the central research question concerning how bioengineered constructed wetlands can contribute simultaneously to environmental remediation and engineering education. The literature search stage identifies publications addressing the technological, environmental, and pedagogical dimensions of this question.

The data evaluation stage examines the relevance and methodological characteristics of the selected publications. Subsequently, the analysis stage organizes the evidence into thematic categories, allowing the identification of common concepts, complementary findings, methodological differences, and unresolved research questions.

Finally, the synthesis stage integrates the identified themes into an educational-technological framework. This framework is intended to explain how environmental treatment infrastructure can become an organized learning environment through which engineering students develop technical, scientific, interdisciplinary, and sustainability-related competencies.

The integrative nature of this methodology allows the inclusion of empirical investigations, systematic reviews, theoretical studies, and conceptual contributions, provided that they offer relevant evidence for understanding the relationship between environmental engineering and higher education.

3.3. Literature Search Strategy

The proposed literature search will be conducted using multidisciplinary scientific databases to identify publications addressing constructed wetlands, heavy-metal remediation, engineering education, living laboratories, and sustainability competencies. The principal databases selected for the review are Scopus, Web of Science, ERIC, and Engineering Village. ScienceDirect will also be consulted as a supplementary source for identifying relevant publications and accessing full-text scientific contributions.

The selection of these databases responds to the interdisciplinary nature of the research. Scopus and Web of Science provide broad coverage of environmental engineering and sustainability research, while ERIC offers specialized literature on educational processes, curriculum development, and higher education. Engineering Village provides an additional perspective on technological design and engineering applications.

The search strategy will combine keywords related to environmental treatment technologies and educational approaches. Boolean operators, quotation marks, and truncation will be used according to the search functionalities of each database.

The principal search expressions will include combinations of the following terms:

("constructed wetlands" OR "bioengineered wetlands" OR "engineered wetlands") AND ("heavy metals" OR "toxic metals" OR "mine drainage" OR "mining wastewater")

("constructed wetlands" OR "nature-based solutions") AND ("engineering education" OR "higher education" OR "environmental education")

("living laboratories" OR "living labs") AND ("engineering students" OR "engineering education" OR "sustainability competencies")

("experiential learning" OR "project-based learning") AND ("environmental engineering" OR "sustainability education")

Additional combinations will be used to identify studies addressing interdisciplinary learning, environmental monitoring, sustainable engineering design, and university–community collaboration.

The search will prioritize publications published between January 2015 and November 2026, while allowing the inclusion of earlier foundational studies when they provide essential theoretical or methodological contributions. Publications in English, Spanish, and Portuguese will be considered to incorporate relevant international research and evidence from Latin American mining contexts.

The search process will record the database, search date, complete search expression, publication period, and number of records retrieved. This documentation will support transparency and facilitate subsequent replication of the review.

3.4. Inclusion and Exclusion Criteria

The inclusion and exclusion criteria will be established before the screening process to ensure consistency in the identification of relevant publications. The criteria are designed to capture research addressing either the environmental engineering dimension or the educational dimension of the proposed framework, as well as studies explicitly connecting both perspectives.

Publications will be considered eligible when they address at least one of the following areas: (1) constructed wetlands for the treatment of wastewater containing potentially toxic metals; (2) bioengineered or nature-based treatment systems applicable to mining-affected environments; (3) engineering education incorporating experiential learning, sustainability, or environmental problem-solving; (4) living laboratories in higher education; or (5) competency-based approaches connecting environmental engineering and sustainability education.

Empirical studies, systematic reviews, integrative reviews, conceptual papers, and theoretically grounded contributions will be considered, provided that their content is relevant to the research objectives and sufficient information is available for analysis.

Publications will be excluded when they focus exclusively on unrelated wastewater treatment technologies, do not provide a meaningful connection with the research dimensions, lack sufficient methodological or conceptual information, or consist of non-scientific promotional material. Duplicate records and publications for which the full text cannot be obtained after reasonable retrieval attempts will also be excluded.

The application of these criteria will prioritize scientific relevance and conceptual contribution rather than the publication's disciplinary classification alone. This approach is necessary because the research problem requires evidence from both environmental engineering and educational research.

3.5. Literature Selection and Screening

The literature selection process will follow a structured sequence consisting of identification, duplicate removal, title and abstract screening, full-text assessment, and final inclusion. Initially, records retrieved from the selected databases will be exported into a reference management system to facilitate organization and duplicate identification.

Following duplicate removal, titles and abstracts will be examined against the predefined eligibility criteria. Publications that demonstrate potential relevance will proceed to full-text

assessment, where their objectives, methodologies, findings, and contributions to the research questions will be evaluated.

The selection procedure will distinguish between studies primarily addressing environmental engineering and those focusing on engineering education. This distinction will facilitate the identification of evidence from both research domains while preserving their respective methodological characteristics.

The final selection will include publications that provide relevant information for at least one of the analytical dimensions of the study. The number of records identified, duplicates removed, publications screened, full texts assessed, and studies included will be documented in a PRISMA 2020 flow diagram.

Disagreements concerning eligibility, where more than one reviewer is involved, will be resolved through discussion and the re-examination of the established criteria. The reasons for excluding full-text publications will be documented to improve transparency.

No numerical results regarding the number of selected studies will be reported until the database searches and screening procedures have actually been completed.

3.6. Data Extraction and Thematic Analysis

Data extraction will be conducted using a structured matrix designed to capture the principal characteristics and scientific contributions of each included publication. The extraction process will consider bibliographic information, research objectives, methodological approaches, study contexts, principal findings, and relevance to the proposed educational-technological framework.

For environmental engineering publications, particular attention will be given to wetland configuration, contaminant characteristics, substrate composition, vegetation, microbial processes, hydraulic conditions, and reported treatment performance. When available, quantitative information concerning influent and effluent concentrations, removal efficiencies, and operational parameters will be recorded.

For engineering education publications, the analysis will focus on pedagogical approaches, learning environments, student participation, sustainability competencies, assessment strategies, interdisciplinary collaboration, and institutional conditions influencing educational implementation.

The extracted information will subsequently be examined through thematic analysis. Following the flexible analytical approach described by Braun and Clarke (2006), the process will involve familiarization with the literature, initial coding, identification of thematic patterns, refinement of analytical categories, and interpretation of the relationships between emerging themes.

The analysis will be organized around five principal themes:

1. Environmental remediation mechanisms and technological configurations of constructed wetlands.
2. Nature-based solutions and environmental sustainability in mining regions.
3. Experiential learning and living laboratories in engineering education.
4. Development and assessment of technical and sustainability competencies.
5. Institutional and pedagogical conditions for integrating environmental infrastructure into higher education.

These themes will be examined comparatively to identify conceptual connections and differences between the environmental and educational research domains. Particular attention will be given to how specific technological activities can be translated into structured educational experiences and measurable learning objectives.

The resulting thematic synthesis will provide the analytical foundation for the development of the proposed conceptual framework.

3.7. Conceptual Framework Development

The conceptual framework will be developed through the integration of the principal findings identified across the environmental engineering and engineering education literature. Its purpose is to establish a coherent relationship between the technological characteristics of bioengineered constructed wetlands, the educational activities that can be developed around these systems, and the competencies expected from engineering students.

The framework will be organized into four interconnected components. The first component, environmental infrastructure, will address the design and operation of constructed wetlands, including substrate selection, vegetation, microbial processes, and hydraulic configuration. The second component, experiential learning activities, will incorporate environmental monitoring, water-quality analysis, treatment system evaluation, experimental investigation, and engineering design.

The third component will focus on competency development, encompassing scientific reasoning, technical knowledge, systems thinking, interdisciplinary collaboration, environmental responsibility, and sustainable decision-making. The fourth component will address assessment and institutional integration, including environmental performance indicators, educational evaluation, curriculum alignment, and collaboration between universities, industries, public institutions, and local communities.

The relationships among these components will be examined to establish how environmental engineering infrastructure can support structured learning processes. The framework will also distinguish environmental indicators from educational indicators, recognizing that technological effectiveness and learning effectiveness represent different dimensions requiring independent evaluation.

The proposed model will be presented as a conceptual contribution derived from the literature synthesis rather than as an experimentally validated educational intervention. Its applicability and effectiveness will therefore require subsequent empirical evaluation through pilot implementations, student assessments, and environmental performance monitoring.

3.8. Methodological Limitations

The proposed methodology presents several limitations that should be considered when interpreting the findings. First, the interdisciplinary nature of the research may generate differences in terminology, research objectives, and methodological standards across environmental engineering and educational studies. These differences may complicate direct comparisons between publications and require careful interpretation during the synthesis process.

Second, the availability of relevant publications may vary across databases, languages, and geographical contexts. Although the proposed search strategy includes multidisciplinary databases and publications in English, Spanish, and Portuguese, some relevant studies may remain unidentified.

Third, the environmental performance of constructed wetlands is highly dependent on local conditions, including contaminant composition, climate, substrate characteristics, vegetation, and hydraulic operation. Consequently, technological findings obtained in one mining region cannot automatically be generalized to other geographical settings.

Fourth, the educational framework developed through the integrative review will represent a conceptual proposal rather than evidence of demonstrated improvements in student competencies. Its effectiveness will need to be examined through future empirical research involving students, educators, environmental monitoring activities, and institutional implementation.

Finally, the absence of a direct experimental component means that the present study will not establish causal relationships between the use of bioengineered wetlands and improvements in educational outcomes or environmental quality. These limitations reinforce the importance of distinguishing conceptual contributions from experimentally validated findings.

4. Environmental Engineering Foundations of Bioengineered Wetlands

4.1. Engineering Principles of Constructed Wetlands

Constructed wetlands are engineered ecological systems designed to reproduce selected functions of natural wetlands under controlled environmental and hydraulic conditions. Their design combines physical infrastructure with biological and geochemical processes to facilitate contaminant retention and transformation. From an environmental engineering perspective, these systems require the integration of hydraulic structures, treatment substrates, vegetation, microbial communities, and operational components that determine their overall performance.

The engineering configuration of constructed wetlands is generally determined by the characteristics of the wastewater, the nature of the contaminants, the required treatment objectives, and the environmental conditions of the installation site. Among the most commonly employed configurations are free-water surface wetlands, horizontal subsurface-flow wetlands, vertical subsurface-flow wetlands, and hybrid systems. Each configuration provides different conditions for water movement, oxygen transfer, contact between contaminants and reactive materials, and biological activity.

Free-water surface systems allow wastewater to flow through shallow vegetated areas, where sedimentation, filtration, oxidation, and biological interactions contribute to treatment. Horizontal subsurface-flow systems direct wastewater through a porous substrate, maintaining water below the surface and promoting interactions with microbial biofilms and reactive media. Vertical subsurface-flow systems distribute wastewater over a substrate bed, allowing downward movement and greater opportunities for oxygen transfer under appropriate operating conditions.

In mining wastewater applications, the selection of a particular configuration must consider the chemical composition of the influent, particularly acidity, alkalinity, dissolved iron, manganese, and other potentially toxic elements. For example, aerobic conditions may facilitate iron oxidation and subsequent precipitation, whereas reducing conditions may support sulfate-reducing microbial processes and the formation of metal sulfides. Consequently, the hydraulic and biological configuration must be aligned with the dominant contaminant-removal mechanisms.

Recent research emphasizes that the effectiveness of constructed wetlands depends on the interaction between hydraulic retention time, pH, redox conditions, support media, vegetation, and influent geochemistry. A 2026 systematic review and meta-analysis of mining effluents identified different controlling factors for iron and manganese removal, demonstrating that the treatment of these elements requires configuration-specific engineering decisions (Key Structural and Operational Factors for the Efficient Removal of Iron and Manganese from Mining Effluents in Constructed Wetlands, 2026).

These engineering principles provide an important educational foundation because students can investigate how design decisions influence treatment processes. The comparison of different wetland configurations can be incorporated into engineering design exercises, allowing students to evaluate alternatives according to hydraulic behaviour, contaminant characteristics, environmental constraints, and operational requirements.

4.2. Hydraulic and Hydrological Design

Hydraulic design represents one of the fundamental components determining the performance and operational stability of constructed wetlands. The movement of water through the treatment system influences contact time between contaminants and reactive materials, oxygen availability, sedimentation, microbial activity, and the distribution of pollutants throughout the substrate. Consequently, hydraulic conditions must be considered during both the design and operational stages.

Several parameters are particularly relevant, including hydraulic retention time (HRT), hydraulic loading rate (HLR), hydraulic gradient, water depth, substrate porosity, and effective treatment volume. Hydraulic retention time describes the period during which wastewater remains within the treatment system, whereas hydraulic loading rate represents the volume of water applied per unit of wetland surface area over a specified period. These parameters influence the degree of interaction between wastewater and the biological and physicochemical components of the wetland.

These relationships provide initial engineering estimates, although actual hydraulic behaviour may differ because of short-circuiting, dead zones, preferential flow paths, clogging, and variations in substrate porosity. Therefore, effective hydraulic performance should be evaluated through appropriate monitoring and, where necessary, tracer studies and hydraulic modelling.

Recent research has emphasized that hydraulic gradients, substrate porosity, aspect ratios, water depth, hydraulic loading rate, and hydraulic retention time jointly influence treatment efficiency and the long-term operation of constructed wetlands (Review of Hydraulic Conditions Optimization for Constructed Wetlands, 2024).

For mining wastewater, hydraulic design must also consider variations in influent flow and contaminant loading. Excessive hydraulic loading may reduce contact time and compromise treatment performance, while insufficient hydraulic capacity may increase retention of solids and contribute to clogging. Accordingly, hydraulic optimization should be based on the specific characteristics of the wastewater and the intended removal mechanisms.

From an educational perspective, hydraulic design offers opportunities for students to apply fluid mechanics, environmental modelling, mathematical analysis, and engineering design principles. Students can calculate theoretical retention times, estimate surface loading rates, compare system configurations, and evaluate how changes in hydraulic conditions may influence contaminant treatment. Such activities connect fundamental engineering subjects with practical environmental applications.

4.3. Substrate Selection and Reactive Materials

The substrate constitutes one of the most important components of constructed wetlands because it provides structural support for vegetation, facilitates water movement, and supplies reactive surfaces for contaminant retention. Its physical, chemical, and mineralogical characteristics influence adsorption, ion exchange, filtration, precipitation, and microbial colonization. Consequently, substrate selection represents a fundamental engineering decision when designing wetlands for the treatment of mining wastewater.

Commonly employed materials include gravel, sand, limestone, zeolite, organic matter, iron-rich materials, and selected industrial by-products. Their suitability depends on hydraulic conductivity, porosity, surface area, chemical stability, availability, cost, and potential environmental risks. Materials containing calcium carbonate, for example, may contribute to acidity neutralization, whereas iron-rich substrates may provide reactive surfaces for the retention of selected contaminants.

Mineral substrates can contribute to metal immobilization through adsorption and ion exchange, while alkaline materials may promote the formation of relatively insoluble metal compounds under appropriate chemical conditions. Organic substrates can provide carbon sources for microbial processes, including sulfate reduction, which may facilitate metal sulfide precipitation. However, their decomposition can also modify redox conditions and potentially influence metal mobility.

The selection of reactive materials must therefore consider both their initial treatment capacity and their long-term stability. The accumulation of contaminants may progressively

modify substrate properties, reduce reactive surface availability, and affect hydraulic conductivity. Furthermore, some industrial by-products may contain undesirable elements that could be released under changing environmental conditions. Their use requires prior characterization and environmental safety assessment.

Research on constructed wetlands for metallic wastewater treatment identifies adsorption, filtration, precipitation, and ion exchange as important removal mechanisms, highlighting the contribution of alkaline and adsorption-based substrates to treatment performance (Zhang et al., 2024).

For engineering education, substrate characterization can provide a practical learning activity connecting materials science, environmental chemistry, and geotechnical principles. Students can compare porosity, particle size distribution, pH, electrical conductivity, and adsorption behaviour to understand how material properties influence treatment performance. This approach can also encourage the responsible evaluation of locally available materials and the potential application of circular economy principles in environmental infrastructure design.

4.4. Vegetation and Microbial Interactions

Vegetation and microbial communities constitute essential biological components of constructed wetlands, contributing to the establishment of treatment conditions and the interaction between wastewater and reactive substrates. Their functions extend beyond the direct uptake of contaminants, involving the modification of rhizosphere conditions, microbial colonization, organic matter cycling, and the regulation of local oxidation–reduction processes.

Wetland plants provide structural support for microbial biofilms through their roots, stems, and submerged surfaces. Their root systems can influence substrate stability, water movement, and the distribution of oxygen within localized zones. Some macrophytes facilitate oxygen transfer into the rhizosphere, creating microsites where aerobic microbial processes can occur alongside anaerobic processes in surrounding saturated sediments.

Microorganisms participate in several mechanisms relevant to metal treatment. These include biosorption, biofilm formation, oxidation–reduction reactions, organic matter decomposition, and the transformation of sulfur compounds. Sulfate-reducing bacteria, for example, can generate sulfide under suitable anaerobic conditions, potentially promoting the precipitation of dissolved metals as relatively insoluble sulfide compounds. Other microbial groups can influence iron oxidation and the formation of mineral precipitates.

The relationship between vegetation and metal removal requires careful interpretation. Although plants can accumulate certain elements in their tissues, direct plant uptake does not necessarily represent the principal removal mechanism in constructed wetlands. Research indicates that immobilization in sediments and substrates can play a more substantial role in the retention of heavy metals and metalloids. Therefore, the contribution of vegetation should also be evaluated through its indirect effects on filtration, microbial activity, hydrodynamics, and geochemical conditions (Zhang et al., 2024; Opitz et al., 2021).

Plant selection should consider tolerance to the contaminant concentrations present in the influent, adaptability to local climatic conditions, root development, biomass production, and potential ecological risks. In mining regions, the use of native or locally adapted species may offer advantages in terms of ecological compatibility and maintenance. Nevertheless, the selection process should be supported by experimental evaluation rather than assuming that all wetland plants are suitable for contaminated environments.

The management of contaminated vegetation is also an important consideration. When plants accumulate potentially toxic elements, their harvesting, handling, transport, and disposal must be evaluated to prevent secondary contamination. Similarly, sediments and substrates containing accumulated metals may require monitoring and appropriate management at the end of their operational life.

From an educational perspective, vegetation and microbial interactions offer opportunities for integrating microbiology, plant physiology, environmental chemistry, and ecological engineering. Students can investigate root-zone processes, compare plant tolerance, examine microbial functions, and evaluate the relationship between biological activity and treatment performance. These activities can strengthen interdisciplinary understanding while demonstrating how biological systems contribute to engineered environmental solutions.

4.5. Metal Removal and Immobilization

Mechanisms

The attenuation of potentially toxic metals in constructed wetlands results from a combination of physicochemical and biological mechanisms that influence contaminant mobility, chemical speciation, and distribution within the treatment system. Unlike biodegradable organic pollutants, metallic elements cannot be destroyed through conventional biological degradation. Their removal from the aqueous phase therefore depends on processes that facilitate retention, transformation, precipitation, or transfer into other environmental compartments.

Adsorption represents an important mechanism through which dissolved metal ions interact with reactive surfaces in substrates, sediments, organic matter, and microbial biofilms. The extent of adsorption depends on the chemical properties of the metal, pH, competing ions, surface charge, and characteristics of the reactive material.

Precipitation and co-precipitation provide additional pathways for metal immobilization. Changes in pH and oxidation–reduction conditions may promote the formation of hydroxides, carbonates, and sulfides. These compounds can accumulate within the wetland substrate, reducing the concentration of dissolved metals in the treated water.

Ion exchange involves the replacement of ions associated with substrate surfaces by dissolved metal ions. This mechanism may be particularly relevant when materials with suitable exchange capacity, such as selected zeolites, are incorporated into the treatment bed.

Filtration and sedimentation contribute to the retention of suspended solids and metal-associated particles. Vegetation and substrate structures can reduce water velocity, facilitate particle deposition, and increase contact between contaminated water and reactive surfaces.

Biological interactions further influence the distribution of metals within the wetland. Microbial biosorption and changes in local geochemical conditions can promote metal retention, while plant-associated processes may contribute to immobilization and, in selected cases, uptake into biomass.

Importantly, immobilization should not automatically be interpreted as permanent removal. Changes in pH, redox potential, water chemistry, or substrate conditions may cause previously retained contaminants to become mobile again. Therefore, the long-term performance of constructed wetlands requires consideration of both effluent quality and the stability of accumulated contaminants.

This indicator provides a measure of the reduction in aqueous concentration, but it does not independently identify the mechanism responsible for contaminant retention or establish the long-term stability of the accumulated metal.

A more comprehensive evaluation should therefore combine concentration measurements with mass balances, substrate characterization, sediment analysis, and, when relevant, plant tissue assessment. Such an approach helps distinguish actual contaminant transfer and immobilization from temporary changes in aqueous concentration.

These processes provide an important foundation for engineering education because they allow students to connect environmental chemistry, mass balance calculations, microbial processes, and treatment system evaluation within a single practical learning environment.

4.6. Environmental Performance Indicators

The evaluation of constructed wetlands requires a set of environmental performance indicators capable of describing treatment effectiveness, operational stability, and potential environmental risks. Although contaminant removal efficiency represents an important measure, relying exclusively on this parameter may provide an incomplete understanding of system performance. A comprehensive evaluation should integrate water-quality measurements, hydraulic indicators, substrate characteristics, and biological parameters.

The first group of indicators concerns influent and effluent water quality. Relevant measurements include the concentrations of selected metals and metalloids, pH, electrical conductivity, turbidity, suspended solids, and other parameters determined by the characteristics of the mining wastewater. Monitoring should consider the chemical forms of contaminants when these are relevant to mobility, toxicity, and treatment mechanisms.

The second group involves hydraulic performance. Hydraulic retention time, hydraulic loading rate, flow distribution, water depth, and evidence of clogging provide information about the operational conditions governing treatment. Variations in these parameters can influence contaminant contact time and the development of appropriate chemical and biological environments.

The third group addresses biological and substrate-related performance. Vegetation survival, root development, biomass accumulation, microbial activity, substrate porosity, and changes in mineral composition may provide information about the condition and long-term functioning of the system.

A fourth group involves sustainability and operational indicators, including energy requirements, maintenance frequency, material consumption, land requirements, and management of metal-enriched sediments and biomass. These indicators can support comparisons between different treatment configurations and provide a broader perspective on environmental feasibility.

For educational applications, performance indicators can also be connected with student learning activities. Water-quality monitoring can assess scientific investigation skills, hydraulic calculations can demonstrate engineering knowledge, and the interpretation of contaminant accumulation can support environmental risk assessment.

The proposed approach therefore distinguishes two complementary evaluation dimensions: environmental performance and educational performance. Environmental indicators determine whether the wetland operates according to its treatment objectives, whereas educational indicators examine whether its incorporation into the curriculum supports the intended development of engineering competencies.

4.7. Operational Challenges and Long-Term Sustainability

Despite their potential environmental and educational applications, bioengineered constructed wetlands present several operational challenges that must be considered during their design, implementation, and long-term management. Their effectiveness depends on the compatibility between contaminant characteristics, hydraulic conditions, substrate properties, vegetation, and microbial processes. Consequently, treatment performance cannot be assumed to remain constant under changing environmental conditions.

One relevant challenge is substrate clogging, which may result from the accumulation of suspended solids, precipitated minerals, and biological material. Clogging can alter hydraulic conductivity, generate preferential flow paths, and reduce effective treatment volume. Appropriate pretreatment, substrate selection, hydraulic management, and periodic inspection may help reduce these risks.

Another challenge concerns the accumulation and potential remobilization of metals. Although precipitation and adsorption can reduce dissolved contaminant concentrations, changes in pH and redox conditions may destabilize retained compounds. Therefore, monitoring should extend beyond effluent concentrations to include substrate and sediment characteristics.

Vegetation management represents an additional operational consideration. Plant species must be compatible with the local climate and contaminant conditions, while accumulated biomass may require controlled harvesting and appropriate disposal. Similarly, microbial activity can vary with temperature, organic matter availability, oxygen conditions, and influent chemistry, influencing the stability of treatment processes.

Long-term sustainability also requires evaluating land availability, maintenance requirements, operational costs, and the suitability of the system for local environmental conditions. In mining regions, these factors are particularly important because the composition of contaminated water may vary according to extraction processes, seasonal conditions, and mine closure activities.

From an educational perspective, these operational challenges should not be considered merely as limitations. They can also become opportunities for applied learning, enabling students to investigate system failures, propose engineering modifications, assess environmental risks, and develop adaptive management strategies.

Consequently, the long-term sustainability of bioengineered wetlands depends not only on their initial treatment performance but also on their capacity to maintain hydraulic functionality, contaminant retention, ecological stability, and safe operational conditions. Integrating these considerations into engineering education can contribute to the preparation of professionals capable of evaluating environmental technologies throughout their operational life cycle.

5. Bioengineered Wetlands as Living Laboratories

5.1. Integration of Wetland Systems into Engineering Curricula

The integration of bioengineered constructed wetlands into engineering curricula represents an opportunity to connect environmental technologies with competency-based educational approaches. Rather than introducing wetlands exclusively as theoretical examples within environmental engineering courses, their incorporation as practical learning environments can facilitate the development of technical knowledge through direct engagement with environmental systems.

Engineering curricula can incorporate constructed wetlands through different educational formats, including laboratory activities, semester-long design projects, interdisciplinary research assignments, field investigations, and collaborative initiatives with external stakeholders. These activities can be adapted to undergraduate and postgraduate programmes in civil engineering, environmental engineering, agricultural engineering, and related disciplines.

At the introductory level, students can examine the ecological and engineering principles governing constructed wetlands, including contaminant transport, substrate characteristics, vegetation functions, and hydraulic behaviour. At more advanced levels, learning activities can involve experimental system design, water-quality monitoring, treatment performance assessment, and the evaluation of alternative configurations for mining wastewater treatment.

The educational integration of these systems also requires alignment with course learning outcomes. Environmental chemistry courses may focus on metal speciation and precipitation processes, while hydrology and fluid mechanics courses can examine hydraulic retention time and water distribution. Microbiology courses may investigate microbial communities and their contribution to contaminant immobilization, whereas environmental engineering design courses can integrate these elements into comprehensive treatment proposals.

Research on living laboratories in engineering education has demonstrated how existing facilities and operational infrastructure can be transformed into experiential learning environments. In particular, studies involving building engineering education illustrate the potential of using real operational systems as sources of technical information, investigation, and applied student learning (Living Labs as an Opportunity for Experiential Learning in Building Engineering Education, 2021).

The integration of constructed wetlands into engineering curricula should therefore be understood as a curricular strategy rather than an isolated practical activity. Its effectiveness depends on the relationship between technological infrastructure, teaching objectives, student participation, assessment procedures, and the broader educational context. By establishing these connections, universities can provide learning experiences that more closely reflect the interdisciplinary nature of environmental engineering practice.

5.2. Experiential and Project-Based Learning

Experiential learning provides a pedagogical foundation for connecting engineering theory with practical investigation and professional problem-solving. In this approach, students develop knowledge through active participation in learning experiences, reflection on observed processes, conceptual interpretation, and the application of acquired knowledge to new situations.

Within the context of bioengineered constructed wetlands, experiential learning can be organized around project-based activities that require students to investigate specific environmental problems and develop technically justified solutions. Rather than receiving predetermined answers, students are encouraged to formulate research questions, identify relevant variables, collect information, evaluate alternative approaches, and communicate their findings.

A semester-long educational project could begin with the characterization of a hypothetical or experimentally prepared mining wastewater sample. Students would subsequently identify the relevant contaminants, establish treatment objectives, investigate suitable wetland configurations, select appropriate substrates, and develop a preliminary engineering design. Depending on available infrastructure and safety conditions, the project could also incorporate laboratory-scale experiments or numerical simulations.

The learning process can be structured around successive activities involving problem identification, scientific investigation, engineering design, experimental evaluation, and critical reflection. This organization allows students to connect theoretical principles with practical decisions while recognizing the uncertainties associated with environmental systems.

Project-based learning can also support interdisciplinary collaboration. For example, students specializing in environmental engineering may investigate treatment mechanisms, while students with backgrounds in agricultural engineering may examine vegetation selection and biomass management. Students specializing in civil engineering may contribute to hydraulic design and structural considerations, creating opportunities for collaborative knowledge development.

Evidence from engineering education research illustrates the relevance of living laboratories and experiential learning for connecting technical knowledge with authentic operational environments. Studies on engineering students' participation in living laboratories also emphasize the importance of collaboration with academic and external stakeholders when addressing real-world challenges (Social and Cognitive Dimensions of Engineering Students' Learning: Bridging Theory and Practice in Living Labs, 2026).

Accordingly, project-based learning through constructed wetlands can provide a structured educational environment in which students develop engineering judgement, technical communication, teamwork, and the capacity to formulate solutions that respond to specific environmental conditions.

5.3. Environmental Monitoring as an Educational Activity

Environmental monitoring constitutes an essential component of constructed wetland operation and provides an important opportunity for developing scientific and technical competencies among engineering students. Through systematic observation and measurement, students can examine how environmental conditions influence contaminant behaviour and treatment performance.

In an educational setting, monitoring activities may include the collection of influent and effluent samples, measurement of physicochemical parameters, characterization of substrates, and analysis of selected metal concentrations. These activities provide practical opportunities to apply analytical chemistry, environmental microbiology, hydrology, and statistical interpretation.

Students can investigate variations in pH, electrical conductivity, oxidation–reduction potential, turbidity, and metal concentrations under different operating conditions. The resulting information can be used to examine relationships between environmental variables and treatment performance, while also identifying limitations associated with sampling procedures, analytical uncertainty, and temporal variability.

An important educational consideration is the distinction between observing a change in contaminant concentration and demonstrating the mechanism responsible for that change. For example, a reduction in dissolved metal concentration does not necessarily establish permanent contaminant removal, since metals may have been transferred to sediments, substrates, or plant biomass. Therefore, students should be encouraged to interpret monitoring results within the context of mass balance, chemical speciation, and potential remobilization.

Digital technologies can further support environmental monitoring through data acquisition systems, sensor networks, geographic information systems, and digital dashboards. These tools can facilitate the visualization of temporal variations, comparison of treatment configurations, and identification of operational conditions requiring attention.

Monitoring activities can also generate authentic research questions for undergraduate dissertations, postgraduate projects, and interdisciplinary research initiatives. By working with environmental data, students can develop competencies in scientific documentation, analytical interpretation, evidence-based decision-making, and environmental reporting.

Consequently, environmental monitoring should be considered not merely an operational requirement of constructed wetlands but also a central educational activity through which students learn to investigate environmental systems using scientific methods and engineering principles.

5.4. Interdisciplinary Learning Environments

The complexity of mining-related environmental challenges requires engineering professionals to integrate knowledge from multiple scientific and technological disciplines. Contaminated water treatment involves interactions between hydrological processes, environmental chemistry, microbiology, ecological functions, materials engineering, and environmental management. Consequently, the educational application of bioengineered constructed wetlands provides an opportunity to establish interdisciplinary learning environments in which students examine environmental problems from complementary perspectives.

Interdisciplinary learning involves the integration of concepts, methodologies, and analytical approaches originating from different academic fields. In the context of constructed wetlands, environmental engineering provides the technical foundations for treatment system design, while biology contributes knowledge concerning vegetation and microbial interactions. Chemistry facilitates the understanding of metal speciation and precipitation, whereas hydrology explains water movement and hydraulic performance. Environmental management and sustainability studies contribute perspectives concerning resource allocation, ecological risks, and long-term operational feasibility.

The integration of these disciplines can be organized through collaborative academic projects in which students assume complementary responsibilities. For example, one group may investigate the physicochemical characteristics of mining wastewater, another may evaluate the suitability of reactive substrates, and a third may examine vegetation selection and microbial processes. These contributions can subsequently be integrated into a common engineering proposal that considers treatment effectiveness and environmental sustainability.

Interdisciplinary learning also requires the development of communication and collaborative decision-making skills. Students must explain technical information to individuals with different disciplinary backgrounds, reconcile alternative interpretations, and justify decisions using scientific evidence. These processes can strengthen their capacity to work within multidisciplinary engineering teams.

Living laboratories provide an appropriate context for this type of learning because they facilitate interactions between academic disciplines, physical infrastructure, and external stakeholders. Research on higher education living laboratories has identified interdisciplinary collaboration, experiential learning, and engagement with real-world contexts as important characteristics of sustainability-oriented educational environments (van der Wee et al., 2024).

Within this perspective, bioengineered wetlands can function as shared learning environments in which students develop a broader understanding of environmental engineering problems. Their educational contribution therefore extends beyond specialized technical knowledge, supporting the development of professionals capable of integrating different forms of expertise when designing sustainable solutions for mining-affected regions.

6. Proposed Integrated Educational-Technological Framework

6.1. Rationale and General Structure of the Proposed Framework

The integration of bioengineered constructed wetlands into engineering education requires an approach that goes beyond the conventional use of environmental infrastructure as an illustrative teaching resource. Although constructed wetlands are primarily designed to treat contaminated water through physical, chemical, and biological processes, their operational complexity also provides opportunities for students to investigate environmental problems, evaluate engineering alternatives, and develop solutions under real-world conditions. Their incorporation into higher education can therefore establish a dual-purpose system in which environmental treatment and professional learning are interconnected but independently assessed.

Building on the literature concerning sustainability-oriented Living Labs and experiential engineering education, this article proposes an Integrated Educational-Technological Framework (IETF). The framework conceptualizes bioengineered wetlands as multifunctional learning environments that connect environmental infrastructure, treatment processes, applied engineering activities, sustainability competencies, performance assessment, and institutional collaboration. This approach is consistent with research emphasizing the importance of authentic engineering problems and collaborative environments in connecting theoretical knowledge with professional practice (O'Brien et al., 2021; van der Wee et al., 2024; Pehkonen et al., 2026).

The proposed framework is organized into six complementary dimensions:

1. Environmental Infrastructure: the physical system in which contaminated water is treated and monitored.
2. Bioengineered Treatment Processes: the physical, chemical, and biological mechanisms responsible for contaminant retention, immobilization, and transformation.
3. Experiential Learning Activities: structured educational activities through which students investigate, design, operate, and evaluate the system.
4. Engineering Sustainability Competencies: the technical, analytical, interdisciplinary, and ethical capacities developed through practical engagement.
5. Environmental and Educational Performance Assessment: the independent evaluation of treatment performance and student learning outcomes.
6. Institutional and Community Integration: the organizational arrangements connecting universities, mining stakeholders, local communities, and environmental authorities.

These dimensions are not intended to operate as isolated components. Instead, they constitute an interconnected system in which environmental information informs educational activities, student analysis contributes to engineering decision-making, and institutional collaboration supports the continuity and relevance of the learning environment.

6.2. Dimension I: Environmental Infrastructure as the Foundation of the Living Laboratory

The first dimension establishes the physical and operational foundation of the framework. Bioengineered constructed wetlands are considered environmental infrastructure capable of receiving and treating mining-affected water under controlled or semi-controlled conditions. Depending on the characteristics of the wastewater, the installation may incorporate surface-flow wetlands, subsurface-flow systems, hybrid configurations, or treatment units combining different substrate and vegetation arrangements.

From an educational perspective, the infrastructure must be designed to generate information that can be interpreted by students and used to support engineering decisions. Consequently, the system should incorporate identifiable treatment stages, accessible sampling points, hydraulic monitoring components, and clearly documented operational conditions.

The infrastructure may include the following elements:

- An influent collection and characterization unit.
- Preliminary treatment or sedimentation structures, where required.
- One or more constructed wetland treatment cells.
- Reactive substrates selected according to the target contaminants.
- Macrophytes compatible with the environmental conditions.
- Sampling points at the inlet, intermediate treatment stages, and outlet.
- Flow measurement and water-level monitoring equipment.
- A designated area for sediment, substrate, and biomass characterization.
- Safety and maintenance facilities for students and technical personnel.

The selection of these components must respond to the chemical composition of the mining effluent, hydraulic requirements, climatic conditions, land availability, and applicable environmental standards. A wetland designed for acidic mine drainage containing iron and manganese, for example, may require different substrate characteristics and operating conditions from a system intended to treat water containing other potentially toxic metals.

The educational value of the infrastructure depends on its capacity to make environmental processes observable and measurable. Students should be able to connect the physical

configuration of the wetland with its treatment behavior, identifying how changes in hydraulic loading, retention time, substrate properties, and vegetation may influence environmental performance.

Accordingly, the infrastructure is not simply a demonstration facility. It functions as an operational engineering system that generates authentic problems, measurable variables, and opportunities for iterative investigation.

6.3. Dimension II: Bioengineered Treatment Processes as a Technological Learning Platform

The second dimension focuses on the treatment mechanisms occurring within the constructed wetland. These mechanisms provide the scientific and technological content through which students develop an understanding of environmental engineering principles. The framework identifies five interconnected treatment processes:

a. Physical processes. These include sedimentation, filtration, and particle retention. Students can investigate how hydraulic conditions, particle characteristics, and substrate configuration influence the movement and accumulation of suspended materials.

b. Chemical processes. Adsorption, precipitation, complexation, and oxidation–reduction reactions may influence the mobility and distribution of metals. Their importance depends on pH, redox conditions, chemical composition, and the characteristics of the treatment medium.

c. Biological processes. Microorganisms associated with substrates and plant roots can influence geochemical conditions and contribute to transformations affecting metal mobility and retention.

d. Phytoremediation-related processes. Macrophytes may contribute to contaminant retention, rhizosphere development, and changes in the chemical conditions surrounding their roots. Metal accumulation in plant tissues must be evaluated rather than assumed, because uptake varies according to species, metal, and environmental conditions.

e. Substrate-mediated immobilization. Mineral and organic materials can provide reactive surfaces and chemical conditions that favor metal retention. Their performance may change over time as sorption sites become occupied or geochemical conditions evolve.

These processes create opportunities for students to examine the relationship between treatment mechanisms and operational performance. For instance, an observed decrease in dissolved metal concentration may result from precipitation or adsorption rather than permanent removal from the system. Therefore, students must distinguish between aqueous-phase concentration reduction, total metal retention, and long-term environmental stability.

This distinction is particularly important in mining regions, where accumulated metals may become mobile again under changing pH or redox conditions. The framework consequently incorporates the characterization of sediments, substrates, and plant biomass as part of the educational and environmental monitoring process.

By examining these processes, students can develop a mechanistic understanding of constructed wetlands rather than relying exclusively on final treatment-efficiency values.

6.4. Dimension III: Experiential Learning Activities and Engineering Problem-Solving

The third dimension translates the operation of the wetland into structured learning activities. It establishes how students interact with the infrastructure, collect information, interpret results, and develop engineering proposals.

The proposed framework organizes experiential learning into five progressive activities.

Activity 1. Environmental diagnosis and problem identification

Students characterize the mining-affected water and identify the principal environmental challenges. Activities may include reviewing available water-quality information, measuring pH and electrical conductivity, determining selected metal concentrations, and identifying the main operational constraints.

The purpose is to establish an evidence-based understanding of the environmental problem before proposing a technological intervention.

Activity 2. Engineering design and technological selection

Students evaluate alternative wetland configurations, considering treatment objectives, hydraulic conditions, substrate properties, vegetation, available space, and maintenance requirements. They may develop preliminary design calculations and compare technological alternatives according to technical, environmental, and economic criteria.

Activity 3. Monitoring and experimental observation

Students participate in systematic monitoring of the wetland. They collect samples, record operational variables, organize analytical information, and compare influent and effluent characteristics. Where appropriate, they may examine differences between treatment cells or operating conditions.

All sampling and analytical activities must follow established laboratory procedures, institutional safety requirements, and applicable environmental protocols.

Activity 4. Data interpretation and engineering optimization

Students analyze the information generated by the treatment system, identify potential operational limitations, and formulate improvement proposals. These may include modifications to hydraulic loading, retention time, substrate composition, vegetation management, or maintenance procedures.

Optimization proposals should be justified using environmental evidence and engineering principles rather than unsupported assumptions.

Activity 5. Technical communication and stakeholder presentation

Students prepare technical reports, design proposals, monitoring summaries, and presentations for academic and external stakeholders. This activity strengthens their ability to communicate engineering decisions to audiences with different levels of technical knowledge.

The progression from diagnosis to communication establishes a learning sequence that connects scientific knowledge with professional engineering practice. It also reflects the potential of Living Labs to connect academic learning with practical challenges and stakeholder participation (O'Brien et al., 2021; Pehkonen et al., 2026).

6.5. Dimension IV: Development of Engineering Sustainability Competencies

The fourth dimension identifies the professional competencies that may be strengthened through participation in the proposed Living Laboratory. The framework does not assume that exposure to environmental infrastructure automatically produces sustainability competencies. Rather, these competencies must be translated into explicit learning outcomes, supported by structured activities, and assessed through observable evidence.

The proposed competency areas include:

Systems-thinking competency. Students understand the relationships between water chemistry, hydraulic behavior, substrate characteristics, biological processes, environmental conditions, and mining activities. They recognize that treatment performance depends on interactions among multiple system components.

Technical and analytical competency. Students apply environmental engineering principles, interpret monitoring data, perform calculations, and evaluate treatment alternatives using appropriate scientific and engineering methods.

Critical and anticipatory competency. Students assess technological limitations, identify potential environmental risks, and consider the long-term consequences of metal accumulation, substrate exhaustion, and changing geochemical conditions.

Strategic problem-solving competency. Students formulate technically feasible interventions, compare alternatives, and propose operational improvements based on environmental evidence and resource constraints.

Interdisciplinary competency. Students integrate knowledge from environmental engineering, chemistry, microbiology, hydrology, ecology, data analysis, and environmental management.

Collaborative and communication competency. Students work in multidisciplinary teams, communicate technical findings, and engage with stakeholders affected by mining-related environmental challenges.

Ethical and social responsibility competency. Students consider environmental protection, public health, community concerns, transparency, and the responsible management of contaminated materials.

These competencies are consistent with the broader direction of sustainability-oriented engineering education, which emphasizes the integration of technical knowledge, systems thinking, collaborative problem-solving, and the capacity to address complex real-world challenges (van der Wee et al., 2024; Pehkonen et al., 2026).

The proposed framework therefore positions competency development as an explicit educational outcome rather than an assumed secondary benefit of environmental experimentation.

6.6. Dimension V: Integrated Environmental and Educational Performance Assessment

The fifth dimension establishes the evaluation structure of the proposed framework. A central principle is that environmental treatment performance and educational effectiveness must be assessed separately. A wetland may demonstrate satisfactory contaminant retention without necessarily producing measurable improvements in student competencies. Conversely, students may develop strong analytical and design capabilities even when the treatment system experiences operational limitations.

The framework therefore proposes two complementary assessment domains.

A. Environmental performance indicators

Environmental assessment focuses on the behavior and operational reliability of the treatment system. Relevant indicators may include:

- Influent and effluent concentrations of selected metals.
- Changes in pH and electrical conductivity.
- Suspended solids concentration.
- Hydraulic loading rate.
- Hydraulic retention time.
- Flow stability and water-level variation.
- Metal accumulation in substrates and sediments.
- Metal concentrations in plant tissues, when relevant.
- Evidence of remobilization under changing environmental conditions.
- Maintenance requirements and operational continuity.

Where:

- (RE) = apparent removal efficiency (%).
- (C_i) = influent concentration of the selected metal.
- (C_e) = effluent concentration of the selected metal.

This indicator should be interpreted alongside mass-balance information and measurements of metal accumulation in the wetland components. A reduction in dissolved concentration alone does not establish permanent elimination of the contaminant.

B. Educational performance indicators

Educational assessment examines whether students demonstrate the competencies established in the curriculum. Potential indicators include:

- Ability to identify and explain environmental engineering problems.
- Accuracy in interpreting water-quality data.
- Application of hydraulic and treatment-design principles.
- Ability to compare technological alternatives.
- Quality of engineering optimization proposals.
- Understanding of contaminant mobility and long-term environmental risks.
- Participation in interdisciplinary teamwork.
- Quality of technical reports and presentations.
- Ability to justify decisions using scientific evidence.
- Demonstration of ethical and environmental responsibility.

These indicators can be evaluated through pre- and post-activity assessments, technical reports, design portfolios, laboratory records, project presentations, reflective journals, and competency-based rubrics.

C. Integration of the two assessment domains

The relationship between environmental and educational assessment is established through the use of shared evidence. For example, monitoring data may simultaneously support the evaluation of treatment performance and the assessment of students' ability to interpret environmental information. However, the criteria used to evaluate each outcome must remain distinct.

The following matrix summarizes the proposed relationship between the six framework dimensions and their corresponding evidence.

Framework dimension	Main activity	Proposed evidence
Environmental infrastructure	Wetland configuration and operation	Technical plans, infrastructure records, operational logs
Treatment processes	Investigation of metal retention mechanisms	Water-quality measurements, substrate and biomass analyses
Experiential learning	Diagnosis, design, monitoring, and optimization	Laboratory records, calculations, project reports
Sustainability competencies	Application of technical and interdisciplinary knowledge	Competency rubrics, design portfolios, presentations
Performance assessment	Evaluation of environmental and educational outcomes	Treatment indicators, assessment instruments, learning evidence
Institutional integration	Collaboration and knowledge transfer	Partnership agreements, stakeholder reports, documented recommendations

This assessment structure is intended to support continuous improvement. Environmental monitoring can identify technical problems, while educational evaluation can reveal whether learning activities are adequately aligned with the intended competencies.

6.7. Dimension VI: Institutional and Community Integration

The sixth dimension recognizes that the implementation of a constructed wetland as a Living Laboratory requires more than technical infrastructure and academic activities. Its continuity depends on institutional coordination, access to environmental information, safety arrangements, and collaboration with relevant stakeholders.

Universities may establish partnerships with mining companies, environmental authorities, municipalities, research institutions, and local communities. These relationships can facilitate access to environmental problems, technical expertise, monitoring information, and opportunities for applied research.

However, collaboration must be governed by clear responsibilities. The proposed framework identifies five institutional requirements:

1. Academic coordination: integration of wetland activities into relevant courses, research projects, and engineering curricula.
2. Technical management: designation of personnel responsible for system operation, maintenance, and environmental monitoring.
3. Safety and environmental governance: establishment of procedures for handling contaminated water, sediments, substrates, and biomass.
4. Stakeholder participation: development of mechanisms for communicating environmental objectives, technical findings, and potential community implications.
5. Knowledge continuity: preservation of monitoring records, technical documentation, and educational materials beyond individual academic semesters.

Institutional integration is particularly important in mining regions, where environmental challenges may extend beyond the duration of a university course or research project. A long-term perspective allows the Living Laboratory to generate cumulative environmental information and support successive generations of students.

The framework also recognizes that access to mining-affected sites may be restricted. Consequently, universities without direct access to operational mining facilities may implement pilot-scale systems using appropriately characterized water, synthetic solutions under controlled conditions, or authorized historical datasets. Such alternatives can provide educational opportunities without exposing students or ecosystems to uncontrolled contamination.

6.8. Operational Sequence of the Proposed Framework

The six dimensions are implemented through a continuous sequence that connects environmental diagnosis, technological design, experiential learning, performance evaluation, and institutional feedback.

The proposed sequence comprises five operational stages:

Stage 1. Contextual diagnosis. The university and its partners identify a relevant environmental challenge, characterize the available information, and establish the educational objectives of the Living Laboratory.

Stage 2. System design and implementation. The technical team defines the wetland configuration, treatment objectives, monitoring requirements, safety measures, and operational responsibilities.

Stage 3. Curriculum integration. Academic staff translate the system's technical characteristics into learning activities, assignments, project objectives, and competency-based assessment criteria.

Stage 4. Monitoring and evaluation. Students and technical personnel collect and interpret environmental data while educators evaluate the development of the intended engineering competencies.

Stage 5. Feedback and continuous improvement. Environmental and educational evidence is reviewed to identify opportunities for system optimization, curriculum improvement, and stronger stakeholder collaboration.

This sequence should be understood as iterative rather than strictly linear. Results obtained during monitoring may require changes to the technical design, while educational assessment may lead to modifications in teaching activities or assessment instruments.

6.9. Conceptual Propositions of the Framework

Based on the integration of environmental engineering, Living Laboratory approaches, and sustainability-oriented engineering education, the proposed framework advances six conceptual propositions:

Proposition 1. The integration of bioengineered constructed wetlands into engineering education creates opportunities to connect environmental remediation principles with authentic professional learning experiences.

Proposition 2. The educational value of constructed wetlands increases when treatment processes are translated into structured learning activities involving diagnosis, design, monitoring, and optimization.

Proposition 3. The use of environmental monitoring data as an educational resource can strengthen students' technical and analytical competencies when data interpretation is explicitly incorporated into curricular objectives.

Proposition 4. Interdisciplinary collaboration is necessary to develop a comprehensive understanding of mining-related water contamination because treatment performance involves interacting hydraulic, chemical, biological, and ecological processes.

Proposition 5. The independent assessment of environmental and educational outcomes is essential for determining whether the Living Laboratory achieves both its remediation and educational objectives.

Proposition 6. Institutional and community collaboration supports the long-term continuity, contextual relevance, and potential transferability of the proposed framework.

These propositions provide a conceptual basis for future empirical research. Their validity and practical applicability should be examined through pilot implementations, comparative educational studies, and longitudinal monitoring of environmental and learning outcomes.

6.10. Expected Contribution and Transferability of the Framework

The principal contribution of the Integrated Educational-Technological Framework is its articulation of environmental treatment infrastructure and engineering education within a single operational model. Rather than treating constructed wetlands exclusively as treatment technologies or isolated educational demonstrations, the framework positions them as systems capable of generating environmental information, supporting applied engineering projects, and strengthening sustainability-oriented professional competencies.

Its transferability depends on contextual adaptation. Mining regions differ in terms of contaminant composition, climate, hydrological conditions, available materials, regulatory requirements, and institutional capacity. Therefore, the framework does not prescribe a universal wetland configuration or a standardized treatment solution. Instead, it provides a flexible structure that can be adapted to local environmental conditions and educational priorities.

The framework may be particularly relevant to universities located in regions where mining activities generate persistent water-quality challenges. In these contexts, collaboration between environmental engineering programs and local stakeholders could transform selected treatment installations into platforms for applied research, technical training, and environmental knowledge exchange.

Nevertheless, the framework remains a conceptual proposal. Its effectiveness cannot be established solely through theoretical integration or the existence of a constructed wetland. Empirical validation will require evidence concerning treatment performance, student competency development, institutional feasibility, and the continuity of collaborative arrangements.

Ultimately, the proposed framework seeks to establish a practical connection between environmental engineering innovation and the transformation of engineering education. By integrating bioengineered wetlands into structured Living Laboratory environments, universities may strengthen the preparation of engineers capable of addressing complex environmental challenges through scientifically grounded, socially responsible, and technologically feasible solutions.

7. Discussion

7.1. Repositioning Bioengineered Wetlands within Engineering Education

The proposed Integrated Educational-Technological Framework offers a perspective that extends the conventional understanding of constructed wetlands as passive or nature-based treatment systems. Its central contribution is to position these infrastructures as environments in which environmental engineering practice and professional learning can be developed simultaneously. This perspective responds to the need to connect engineering education with complex environmental challenges that cannot be adequately understood through theoretical instruction alone.

The literature on constructed wetlands demonstrates that their treatment performance depends on the interaction of hydraulic, chemical, biological, and material-related processes. The removal of potentially toxic metals is influenced by substrate characteristics, pH, redox conditions, retention time, vegetation, and microbial activity (Zhang et al., 2024; Rochinha et al., 2026). These interacting variables provide an appropriate context for engineering education because they require students to understand systems as dynamic configurations rather than as isolated technological components.

From this perspective, the proposed framework changes the educational role of environmental infrastructure. Instead of using wetlands only as examples during lectures, universities can incorporate them into structured learning experiences involving environmental diagnosis, technological design, sampling, data interpretation, and optimization. Students can therefore engage with the same types of decisions that characterize professional environmental engineering practice.

This integration is particularly relevant to mining regions, where water contamination requires context-sensitive solutions and long-term environmental management. Engineering graduates must be prepared not only to identify treatment technologies but also to evaluate their technical feasibility, environmental implications, operational limitations, and social relevance.

Nevertheless, the educational value of a Living Laboratory should not be confused with the environmental effectiveness of its infrastructure. The framework therefore proposes two complementary objectives: improving the understanding and management of contaminated water while developing competencies required for responsible engineering practice.

7.2. The Importance of Understanding Metal Fate Rather Than Only Removal Efficiency

One of the most important implications of integrating constructed wetlands into engineering education concerns the interpretation of contaminant removal. Conventional treatment assessments frequently emphasize differences between influent and effluent concentrations. Although these measurements are essential, they may provide an incomplete representation of the environmental fate of metals within a wetland.

Research indicates that immobilization in sediments and substrates can represent a major mechanism of heavy-metal retention, whereas direct plant uptake may be less efficient than commonly assumed (Zhang et al., 2024). Consequently, a decrease in aqueous metal concentration does not necessarily demonstrate that the contaminant has been permanently eliminated from the treatment system.

This distinction has important consequences for engineering education. Students should be trained to distinguish among concentration reduction, metal immobilization, accumulation, and potential remobilization. They should also understand that changes in pH, redox conditions, substrate saturation, and other environmental variables may influence the stability of retained metals.

The proposed framework incorporates this distinction by including the characterization of sediments, substrates, and plant biomass in environmental monitoring activities. This approach encourages students to move beyond the calculation of apparent removal efficiency and consider the broader mass balance and long-term environmental behavior of contaminants.

Recent evidence concerning mining effluents further reinforces this requirement. Rochinha et al. (2026) identify important differences between iron and manganese removal, showing that their performance depends on distinct combinations of hydraulic, physicochemical, and biological conditions. Their findings illustrate why treatment systems cannot be evaluated using a single generalized efficiency indicator.

For engineering education, this means that students should investigate not only whether a wetland reduces contaminant concentrations but also why its performance changes, where the retained metals accumulate, and under which conditions environmental risks may reappear.

7.3. From Experiential Learning to Competency-Based Engineering Education

The proposed framework also contributes to discussions about how experiential learning can be incorporated into engineering curricula. Traditional engineering instruction frequently separates theoretical concepts from the practical conditions under which engineering decisions must be made. This separation may limit students' ability to integrate technical knowledge when addressing complex environmental problems.

Living Laboratories offer an opportunity to reduce this gap by providing learning environments in which theoretical principles are applied to real or realistically simulated systems. O'Brien et al. (2021) discuss the potential of Living Labs for experiential learning in building engineering education, while van der Wee et al. (2024) identify relevant characteristics and challenges associated with sustainability-oriented Living Labs in higher education.

In the context of bioengineered wetlands, experiential learning can be organized around a sequence of authentic engineering activities. Students first characterize an environmental problem, then evaluate technological alternatives, participate in monitoring, interpret operational information, and formulate improvement proposals. This sequence encourages the application of knowledge across different stages of engineering problem-solving.

However, participation alone is not sufficient to demonstrate competency development. A student may collect water samples without developing the ability to interpret chemical results or relate them to treatment mechanisms. Similarly, participation in a design project does not necessarily demonstrate the ability to justify a technological alternative through appropriate engineering criteria.

For this reason, the proposed framework emphasizes the alignment of learning activities, intended competencies, and assessment instruments. Each educational activity should be associated with observable outcomes. For example, the interpretation of water-quality data may be evaluated through students' ability to identify concentration changes, explain potential treatment mechanisms, recognize analytical limitations, and formulate evidence-

based recommendations.

This competency-based approach can help universities determine whether Living Laboratory activities produce meaningful educational outcomes rather than simply increasing students' exposure to environmental infrastructure.

7.4. Interdisciplinarity as a Requirement for Addressing Mining-Related Water Contamination

Mining-related water contamination is a multidimensional environmental problem. Its characterization and treatment involve knowledge from hydrology, environmental chemistry, microbiology, ecology, materials science, and engineering design. Consequently, educational approaches based exclusively on a single disciplinary perspective may provide an incomplete understanding of treatment-system behavior.

The proposed framework addresses this challenge by positioning constructed wetlands as interdisciplinary learning environments. Students can investigate the relationship between hydraulic retention time and treatment performance, examine chemical conditions affecting metal precipitation, evaluate microbial contributions to geochemical transformations, and analyze the role of substrates and vegetation in contaminant retention.

This interdisciplinary organization also creates opportunities for collaborative learning. Environmental engineering students may work with specialists in chemistry to interpret metal speciation, with microbiologists to investigate microbial communities, and with ecologists to evaluate vegetation and ecosystem interactions.

The importance of this integration extends beyond technical knowledge. Engineering professionals must also communicate findings to environmental authorities, mining companies, communities, and other stakeholders. The ability to translate complex scientific information into understandable technical recommendations is therefore an essential component of professional preparation.

Pehkonen et al. (2026) provide a relevant perspective on the social and cognitive dimensions of engineering students' learning in Living Labs, emphasizing the relationship between theoretical knowledge and practical engagement. In the proposed framework, these dimensions are reflected in collaborative activities, stakeholder interaction, and the development of communication and problem-solving competencies.

Nevertheless, interdisciplinary learning requires deliberate academic coordination. Without clear learning objectives, roles, and assessment criteria, collaboration may become fragmented or result in the superficial participation of different disciplines. Universities should therefore define shared project objectives and establish mechanisms for integrating disciplinary contributions into a coherent engineering solution.

7.5. The Complementarity Between Environmental Performance and Educational Performance

A central feature of the proposed framework is the distinction between environmental performance and educational performance. Although these dimensions are interconnected, they represent different outcomes and require different assessment methods.

Environmental performance concerns the capacity of the wetland to treat mining-affected water under specified operating conditions. Its assessment requires appropriate water-quality measurements, hydraulic information, characterization of accumulated metals, and consideration of system stability over time.

Educational performance, in contrast, concerns the development of students' knowledge, technical abilities, critical reasoning, and professional competencies. It requires learning-outcome assessments, technical reports, design portfolios, project evaluations, and other educational instruments.

This distinction prevents an important methodological problem: assuming that successful operation of a wetland automatically demonstrates the effectiveness of the educational model. A system may achieve a reduction in selected metal concentrations while students demonstrate limited understanding of the underlying processes. Conversely, students may develop substantial engineering competencies while the wetland experiences technical difficulties that provide valuable opportunities for diagnosis and learning.

The framework therefore proposes that both outcomes should be monitored independently and interpreted together. This approach allows universities to identify whether the infrastructure is functioning as intended and whether the educational activities are producing the expected learning outcomes.

Future empirical studies could examine the relationship between these two dimensions. For example, researchers could investigate whether participation in sustained monitoring activities improves students' ability to interpret environmental data, or whether involvement in design optimization strengthens systems-thinking competencies.

Such investigations would help determine the extent to which environmental infrastructure can serve as an effective educational resource without compromising its primary environmental responsibilities.

7.6. Institutional Feasibility and Challenges in Mining Regions

Although the proposed framework offers potential educational and environmental benefits, its implementation requires institutional and operational conditions that may not be available in all universities.

The first challenge concerns infrastructure and financial resources. Constructed wetlands require appropriate site selection, engineering design, materials, monitoring equipment, and maintenance. Even when their operational requirements may be lower than those of some conventional treatment technologies, they are not maintenance-free systems. Universities must account for long-term monitoring, substrate management, vegetation maintenance, and the safe handling of accumulated contaminants.

The second challenge involves access to representative mining-affected water. Direct access to operational mining sites may require agreements with companies, environmental authorities, and other responsible organizations. In the absence of such agreements, universities may use pilot-scale systems, controlled experimental solutions, or appropriately documented historical datasets.

The third challenge concerns student and staff safety. Mining-affected water and contaminated sediments may contain potentially toxic substances. Therefore, educational activities must incorporate risk assessments, personal protective equipment, sampling protocols, laboratory controls, and procedures for the management of contaminated materials.

The fourth challenge involves institutional continuity. Living Laboratory projects may lose operational capacity when academic courses end, research funding expires, or responsible personnel change. Long-term agreements, technical documentation, shared responsibilities, and institutional support are necessary to maintain the infrastructure and preserve the accumulated information.

Finally, the participation of communities and external stakeholders requires transparent communication. Universities should explain the purpose of the infrastructure, the limitations of the treatment process, and the meaning of environmental monitoring results. They should avoid presenting pilot systems as definitive solutions to complex mining-related contamination problems.

These challenges indicate that implementation should be approached as an institutional process rather than as an isolated teaching activity. The feasibility of the framework depends on the interaction between technical capacity, educational planning, safety governance, and stakeholder collaboration.

7.7. Implications for Engineering Curricula and Professional Formation

The integration of bioengineered wetlands into engineering education has implications for curriculum design. Environmental engineering programs may use the proposed framework to connect courses that are frequently taught as separate subjects, including fluid mechanics, hydrology, environmental chemistry, microbiology, water treatment, environmental management, and engineering design.

For example, a wetland-based educational project could require students to calculate hydraulic retention time, evaluate the relationship between flow and treatment area, characterize water chemistry, investigate substrate properties, and interpret changes in contaminant concentrations. These activities would allow students to recognize how different areas of engineering knowledge contribute to the performance of a single environmental system.

The framework may also support project-based learning and interdisciplinary capstone projects. Rather than assigning isolated exercises, instructors could organize semester-long projects in which student teams investigate a specific treatment challenge and develop technically justified recommendations.

At the institutional level, this approach could strengthen the connection between teaching, research, and community engagement. Monitoring information generated through educational activities may contribute to research datasets, provided that appropriate quality-control procedures are followed. Similarly, research findings may be incorporated into teaching materials and used to update engineering design exercises.

However, universities should avoid transforming student participation into a substitute for qualified technical personnel. Environmental infrastructure must remain under appropriate professional supervision, and educational activities should not compromise treatment performance, safety, or environmental compliance.

The broader implication is that engineering education can become more closely connected to the environmental challenges of the regions in which universities operate. This connection may contribute to the formation of professionals who understand not only how to design treatment systems but also how to evaluate their long-term implications and interact responsibly with affected communities.

7.8. Limitations of the Proposed Framework

Several limitations should be acknowledged when interpreting the contribution of the proposed framework.

First, the framework is conceptual and has not yet been validated through implementation in a university or mining-region context. Its six dimensions and operational stages represent an integrated proposal derived from the conceptual relationship between constructed wetlands, Living Laboratories, and sustainability-oriented engineering education. Their practical effectiveness remains to be established.

Second, the performance of constructed wetlands is highly dependent on local environmental conditions. Differences in contaminant composition, pH, climate, hydrology, substrate availability, and vegetation may influence the feasibility and effectiveness of specific configurations. Consequently, the framework cannot be interpreted as a universal technical design for mining effluents.

Third, educational outcomes may vary according to students' previous knowledge, curriculum structure, instructor experience, institutional resources, and the duration of participation. The framework does not establish standardized effect sizes or quantify improvements in student competencies.

Fourth, the proposed environmental and educational indicators require further operationalization. Future studies should develop validated assessment instruments, establish appropriate monitoring frequencies, and define criteria for comparing different implementation contexts.

Fifth, the integration of environmental treatment and education may introduce competing operational priorities. For example, student experimentation may require additional sampling or controlled modifications, whereas the treatment system may require stable operating conditions. Appropriate supervision and operational protocols are therefore necessary.

Finally, the proposed model should be evaluated in relation to institutional costs and long-term sustainability. Its educational value may be substantial, but implementation requires resources for infrastructure, laboratory analysis, personnel, maintenance, and safety management.

These limitations do not invalidate the conceptual contribution. Instead, they define the conditions under which future research should examine its applicability and identify the modifications required for different educational and environmental contexts.

7.9. Future Research Agenda

The discussion identifies several priorities for future empirical research.

First, pilot implementations should be developed in universities located in mining regions. These projects could evaluate whether constructed wetlands can function simultaneously as treatment systems and structured learning environments under local environmental and institutional conditions.

Second, longitudinal educational studies should investigate changes in engineering competencies before and after student participation. Such studies could examine systems thinking, technical problem-solving, environmental data interpretation, interdisciplinary collaboration, and the ability to formulate evidence-based engineering recommendations.

Third, comparative research should evaluate different educational configurations. For example, studies could compare conventional classroom instruction, laboratory-based activities, and participation in a wetland-based Living Laboratory to identify differences in learning outcomes.

Fourth, environmental monitoring studies should examine the long-term behavior of metals retained in substrates, sediments, and biomass. Particular attention should be given to the possibility of remobilization, substrate saturation, and changes in treatment performance under variable environmental conditions.

Fifth, research should investigate the institutional feasibility of university–industry–community partnerships. Relevant variables include access to environmental information, funding continuity, stakeholder participation, technical supervision, and the governance of contaminated materials.

Finally, future studies should examine whether the proposed framework can be adapted to other environmental engineering applications, including mine drainage management, wastewater treatment, contaminated soil remediation, and nature-based infrastructure for climate adaptation.

Together, these research directions would provide the empirical foundation necessary to assess the educational, technological, and institutional contribution of the Integrated Educational-Technological Framework.

7.10. Overall Interpretation of the Findings

The discussion suggests that the main contribution of integrating bioengineered wetlands into engineering education is not limited to introducing a nature-based treatment technology into university curricula. Rather, it involves establishing a structured relationship between environmental problem-solving, technological investigation, experiential learning, and professional competency development.

The proposed framework brings together six dimensions that are frequently addressed separately: infrastructure, treatment processes, experiential learning, sustainability competencies, performance assessment, and institutional integration. Their articulation

provides a conceptual basis for understanding how environmental treatment systems may also support engineering education.

At the same time, the discussion highlights the need for scientific rigor. Constructed wetlands should not be presented as universally effective solutions for all mining effluents, and their treatment performance should not be inferred from isolated concentration reductions. Similarly, the educational effectiveness of a Living Laboratory must be demonstrated through explicit learning outcomes and appropriate assessment instruments.

The proposed framework should therefore be understood as a foundation for future applied research rather than as a validated implementation model. Its potential contribution lies in creating a coherent structure through which universities can connect environmental engineering knowledge with authentic regional challenges and prepare graduates to develop technically sound, environmentally responsible, and socially relevant solutions.

8. Conclusions and Recommendations

8.1. Conclusions

This article examined the potential integration of bioengineered constructed wetlands into engineering education, proposing an Integrated Educational-Technological Framework that connects environmental treatment infrastructure with experiential learning and sustainability-oriented competency development. The conceptual analysis highlights the possibility of transforming constructed wetlands from exclusively environmental treatment systems into multifunctional Living Laboratories that support both applied research and professional engineering education.

The first conclusion is that bioengineered constructed wetlands offer relevant technological and educational opportunities for addressing mining-related water contamination. Their combination of physical, chemical, and biological processes provides an authentic context for understanding complex environmental engineering problems. Through the investigation of hydraulic behavior, substrate properties, vegetation, microbial interactions, and metal retention mechanisms, students can connect theoretical principles with practical environmental challenges.

The second conclusion is that the educational contribution of these systems depends on the deliberate integration of experiential learning activities into engineering curricula. Environmental infrastructure alone does not guarantee competency development. Its educational potential must be supported by structured activities involving environmental diagnosis, technological design, monitoring, data interpretation, optimization, and technical communication. These activities can create opportunities to strengthen systems thinking, interdisciplinary problem-solving, analytical reasoning, and environmental responsibility.

The third conclusion concerns the importance of distinguishing contaminant concentration reduction from permanent metal removal. Constructed wetlands may retain or immobilize metals in substrates, sediments, and plant biomass, but such accumulation does not necessarily eliminate long-term environmental risks. Changes in environmental conditions may influence metal mobility and remobilization. Consequently, engineering education should emphasize contaminant fate, mass-balance considerations, and long-term monitoring rather than relying exclusively on apparent removal-efficiency percentages.

The fourth conclusion is that environmental and educational performance must be evaluated through separate but complementary assessment systems. Treatment performance requires water-quality measurements, hydraulic indicators, and characterization of accumulated metals. Educational performance requires evidence of students' knowledge, technical abilities, problem-solving capacity, and sustainability competencies. The simultaneous consideration of these dimensions provides a more comprehensive basis for evaluating the contribution of a wetland-based Living Laboratory.

The fifth conclusion is that institutional collaboration is essential for the long-term feasibility of the proposed framework. Universities, mining stakeholders, environmental authorities, research institutions, and local communities can contribute to the technical, educational, and organizational conditions required for implementation. However, successful collaboration requires clear responsibilities, safety protocols, adequate resources, and continuity beyond individual academic projects.

Overall, the proposed framework contributes a conceptual structure for integrating nature-based environmental treatment technologies into engineering education. Its principal innovation is the articulation of environmental infrastructure, bioengineered treatment processes, experiential learning, sustainability competencies, performance assessment, and institutional collaboration within a single model. Nevertheless, its practical effectiveness remains to be demonstrated through empirical implementation and systematic evaluation.

8.2. Recommendations for Higher Education Institutions

Based on the proposed framework, several recommendations can be established for universities seeking to strengthen environmental engineering education in mining regions.

First, integrate constructed wetlands into engineering curricula. Universities should consider incorporating wetland-based projects into courses related to environmental engineering, water treatment, hydrology, environmental chemistry, microbiology, and sustainable infrastructure. These activities should be aligned with explicit learning outcomes and competency assessment criteria.

Second, establish pilot-scale Living Laboratories. Institutions with limited infrastructure or restricted access to mining sites may begin with small-scale constructed wetlands using appropriately characterized water or controlled experimental solutions. Pilot systems can provide opportunities for design, monitoring, and experimentation while reducing the risks associated with uncontrolled environmental exposure.

Third, strengthen interdisciplinary teaching. Wetland-based educational projects should encourage collaboration among engineering, chemistry, biology, environmental sciences, and management disciplines. This approach can improve students' understanding of the multiple processes influencing treatment performance and environmental sustainability.

Fourth, implement systematic environmental monitoring. Universities should establish protocols for measuring influent and effluent quality, hydraulic conditions, and metal accumulation in treatment media. Monitoring should be designed to generate reliable information while protecting students, staff, and the surrounding environment.

Fifth, develop competency-based assessment instruments. Educational activities should be evaluated using technical reports, design portfolios, project presentations, laboratory records, and structured assessment rubrics. These instruments should assess both technical competencies and broader sustainability-related capacities.

Sixth, establish long-term institutional partnerships. Collaboration with mining companies, local governments, environmental authorities, and communities may facilitate access to environmental information, technical expertise, and opportunities for applied research. Such partnerships should operate under transparent agreements that define responsibilities and environmental safeguards.

Seventh, incorporate long-term risk management. Universities should establish procedures for the management of contaminated sediments, substrates, and biomass. The potential for metal remobilization should be considered when designing monitoring and maintenance strategies.

8.3. Recommendations for Mining Regions

In mining regions, the proposed framework may provide a context-sensitive approach to connecting environmental challenges with higher education and applied research.

Universities should prioritize environmental problems that are relevant to their geographical and socioeconomic context. The selection of target contaminants and treatment configurations should be based on the actual characteristics of affected water, rather than assuming that a single wetland design can address all types of mining effluents.

Regional research initiatives should also encourage the development and evaluation of locally available substrates and plant species. However, their suitability must be established through scientific characterization and controlled testing, particularly when materials or biomass may accumulate potentially toxic metals.

Mining stakeholders should be encouraged to participate in collaborative research and educational initiatives, provided that environmental information is communicated transparently and institutional independence is maintained. Universities should retain responsibility for scientific integrity, educational quality, and the objective interpretation of environmental evidence.

Finally, environmental authorities and local institutions may benefit from university-generated research and monitoring information. Nevertheless, pilot-scale educational systems should not be presented as substitutes for legally required industrial wastewater treatment or environmental compliance measures.

8.4. Future Research Directions

The conceptual nature of this article establishes the need for further research to evaluate the feasibility and effectiveness of the proposed framework.

Future studies should prioritize the following areas:

1. Empirical validation: implement pilot-scale wetland-based Living Laboratories and evaluate their technical and educational performance under defined environmental conditions.
2. Comparative educational assessment: compare student learning outcomes in conventional instruction, laboratory-based learning, and wetland-based experiential learning environments.
3. Longitudinal competency evaluation: examine whether sustained participation in Living Laboratory activities contributes to the development of systems thinking, interdisciplinary collaboration, technical problem-solving, and environmental responsibility.
4. Long-term metal behavior: investigate the accumulation, stability, and potential remobilization of metals in substrates, sediments, and plant biomass under different operating and environmental conditions.
5. Technological optimization: evaluate alternative substrate combinations, vegetation configurations, hydraulic conditions, and treatment arrangements according to the characteristics of specific mining effluents.
6. Institutional feasibility: examine the financial, organizational, regulatory, and operational conditions required to maintain Living Laboratories within higher education institutions.
7. Stakeholder participation: investigate how collaboration among universities, mining companies, environmental authorities, and local communities influences research relevance, knowledge exchange, and institutional continuity.
8. Assessment instrument development: design and validate instruments that measure environmental treatment performance and student competency development as separate but interconnected outcomes.

These research directions would help move the proposed framework from conceptual development toward evidence-based implementation and evaluation.

8.5. Final Considerations

The environmental challenges associated with mining require engineers who can integrate scientific knowledge, technological innovation, environmental responsibility, and interdisciplinary collaboration. Engineering education must therefore create opportunities for students to engage with authentic environmental problems and understand the consequences of engineering decisions over time.

Bioengineered constructed wetlands provide a relevant context for this transformation because they combine environmental processes that can be investigated, measured, and interpreted through engineering practice. Their integration into Living Laboratory environments may strengthen the relationship between university education and the environmental priorities of mining regions.

The proposed Integrated Educational-Technological Framework offers a conceptual pathway for achieving this integration. By connecting environmental infrastructure with structured experiential learning and independent performance assessment, it establishes a basis for developing engineering education models that are more closely connected to sustainability challenges.

Ultimately, the value of this approach will depend on its capacity to generate reliable environmental information, meaningful learning outcomes, and sustained institutional collaboration. Its contribution should therefore be assessed not only by the treatment performance of constructed wetlands but also by the quality of the engineering competencies and environmental decision-making processes that emerge from their educational use.

The integration of bioengineered wetlands into engineering education should not be viewed simply as the incorporation of an additional treatment technology into university curricula. Rather, it represents an opportunity to redefine how engineering knowledge is developed, applied, and evaluated in response to complex environmental challenges. In this sense, Living Laboratories based on nature-based treatment systems may become valuable platforms for connecting environmental innovation with the formation of future engineers.

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