

Innovations in Environmental Remediation and Sustainable Resource Utilisation

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1. Introduction

Environmental sustainability remains a critical global concern, particularly considering the increasing scale of industrialisation, urbanisation, and resource exploitation. Challenges such as acid mine drainage (AMD), food and agricultural waste (FAW), and industrial byproducts necessitate innovative, cost-effective, and ecologically sound remediation strategies [1,2]. This editorial showcases emerging advancements in environmental remediation and sustainable resource utilisation, as exemplified by recent articles in *Applied Sciences* (MDPI, 2076-3417). Collectively, these studies underscore the integration of ecological engineering, biotechnological innovation, and phytoremediation in addressing complex environmental issues. The key approaches explored include anaerobic co-digestion, ecological engineering, phytoremediation, and industrial waste stabilisation.

The quantity of FAW, a major component of municipal solid waste, is increasing rapidly, posing both environmental risks and resource recovery opportunities [3]. Anaerobic digestion (AD) is an effective method for converting FAW into bioenergy; however, mono-digestion faces limitations such as volatile fatty acid accumulation and nutrient imbalances [4]. Co-digestion with complementary substrates—such as sludge, garden waste, and manure—has been shown to enhance process stability and sustainability [5]. Microalgae (MA), rich in organic matter and non-competitive with food crops, offer a promising co-substrate, though their low carbon-to-nitrogen ratio and resilient cell walls constrain mono-digestion efficacy [6]. While AD supports sustainable development goals and complies with EU directives, challenges persist in digestate management, as untreated by-products may pose environmental and health risks [7]. Indeed, advancements in digestate processing and valorisation are essential for integrating AD within circular bioeconomy initiatives, necessitating further research into current technologies, regulatory alignment, and environmental benefits [8].

Since the 1970s, natural and constructed wetlands have also served as passive treatment systems for AMD, leveraging ecological processes to filter and transform pollutants. These systems facilitate complex biological and chemical interactions that promote metal sequestration and water quality improvement [9]. However, AMD remains a persistent issue due to its high acidity and metal content, posing threats to ecosystems and public health. Passive treatment systems, especially ecologically engineered wetlands, provide sustainable and cost-effective alternatives to chemically intensive active treatments [10,11]. Ecological engineering emphasises ecosystem self-design, enabling adaptive functioning with minimal intervention. Nevertheless, the mechanisms and long-term efficacy of such



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systems require further elucidation, underscoring the need for performance evaluations and process-level investigations to guide future remediation [12].

Environmental pollution, particularly from mining activities, poses severe risks to ecosystems and public health. Conventional remediation methods are often costly and environmentally unfriendly, prompting a shift toward sustainable, nature-based solutions such as phytoremediation [13]. In this approach, plants are employed to extract, stabilise, degrade, or volatilise contaminants in soil and water, offering a low-impact, in situ alternative. In many countries, mining has resulted in extensive environmental contamination by heavy metals and radioactive elements, particularly in regions such as Johannesburg and the Witwatersrand [14]. Despite these countries' rich biodiversity and policy alignment with sustainable development, phytoremediation remains underutilised. Recent studies [15] highlight the potential of indigenous plant species in rehabilitating degraded landscapes, though research trends and collaborative networks require further exploration.

Phosphogypsum (PG), a byproduct of phosphoric acid production, is generated in substantial quantities worldwide, with much of it stockpiled or disposed of inadequately, leading to environmental contamination. Although PG has potential applications in construction and agriculture, impurities including heavy metals, acids, and radionuclides present significant risks [16]. Cemented paste backfill (PCPB) offers a promising large-scale disposal route, though fluoride leaching remains a challenge, particularly at low cement ratios. Various pretreatment methods—including chemical additives and solid-waste blending—have shown potential but often entail high costs [16]. Water washing represents a cost-effective alternative yet requires careful optimisation to balance environmental safety and mechanical performance. It is thus imperative to examine how the initial fluoride content of PG influences PCPB behaviour. In this vein, laboratory simulations and advanced material analyses can be employed to establish standardised pretreatment protocols for industrial application [17].

Together, these studies reflect a multidisciplinary approach to environmental remediation, integrating biochemical, ecological, and engineering principles. They emphasise the importance of contextual adaptation, community involvement, and policy support in implementing effective and sustainable solutions. As societies worldwide contend with environmental degradation, such research contributions provide a foundation for resilience, innovation, and ecological stewardship.

2. Overview of Published Articles

The study conducted by Pan et al. [18] represents a significant contribution to anaerobic co-digestion, examining the integration of food waste (FW) and microalgae (MA) as co-substrates. Their research elucidates synergistic microbial interactions that enhance biogas production and process stability. Among the five FW/MA mixing ratios tested, the 1:1 ratio proved most effective, yielding a 9.03% increase in biogas potential and the highest microbial diversity. These findings align with circular bioeconomy strategies by demonstrating the valorisation of organic waste streams through optimised co-digestion. Microbial community analysis revealed enrichment of *Methanospirillum* and *Methanomethylovorans*, key methanogens associated with improved methane production. Kinetic modelling using the Cone model provided an excellent fit ($R^2 = 0.99$), corroborating the experimental results. This work offers insights into system optimisation for organic waste management and renewable energy generation, highlighting how FW-MA integration improves biodegradability and supports microbial synergy. This study is significant; thus, numerous other authors [19–21] have recently conducted substantial research in the field of anaerobic co-digestion.

In a related contribution, Jansen van Vuuren et al. [22] evaluate the application of ecological engineering for AMD remediation in South Africa. Their case study of the Zaalklapspruit wetland demonstrates how engineered structures—concrete berms and weirs—significantly improved surface water quality: pH increased from 3.9 to 7.18, and aluminium concentrations decreased by 99.38%. Using a source–pathway–receptor framework, the authors trace the transformation and transport of metals and sulphur compounds within the wetland system. Macrophytes, periphyton, and microbial communities are shown to contribute substantially to contaminant adsorption, sequestration, and biotransformation, enhancing ecological resilience. This study underscores the importance of long-term monitoring and community engagement in sustaining restoration efforts, offering a scalable model for similar contexts in the Global South. Nonetheless, assessing ecological engineering for acid mine drainage restoration is of worldwide interest, as multinational contributions [23–25] in this field are already developing.

Akinpelu and Nchu [26] provide a bibliometric analysis of phytoremediation research in South Africa from 1997 to 2022. Despite a modest annual growth rate of 4.49%, their analysis of 39 publications identifies key contributors, influential journals, and collaborative networks that have shaped the field. The study documents growing interest in phytoremediation for rehabilitating mining-affected regions, highlighting successful applications of indigenous species, including *Berkheya coddii*, *Phragmites australis*, *Vetiveria zizanioides*, and *Eichhornia crassipes*. These species demonstrated notable efficacy in removing heavy metals, nutrients, and organic pollutants; for example, *Eichhornia crassipes* achieved a 93.8% reduction in phosphate, while *Vetiveria zizanioides* effectively removed Cr (VI) under hydroponic conditions. The authors advocate for increased investment, institutional collaboration, and integration of phytoremediation into national environmental strategies to fully leverage its potential. The growing body of this research [27–29] underscores the strategic importance of phytoremediation, prompting other scholars to explore its applications in mining rehabilitation and environmental restoration.

Zhang et al. [30] investigate the effect of fluoride content in PG on the performance of phosphogypsum-based cemented paste backfill (PCPB). Their research establishes a pretreatment threshold of 0.0093 wt.% fluoride to meet environmental safety standards. Through strength and leaching tests supplemented by SEM and XRD analyses, the authors demonstrate that elevated fluoride levels inhibit cement hydration, compromising structural integrity. Calcium fluoride (CaF₂) formation and its adsorption onto hydration products were identified as primary immobilisation mechanisms. This study provides practical guidance for industrial PG pretreatment, supporting safer, more sustainable mining practices by aligning waste reuse with circular-economy objectives. Furthermore, the study of fluoride thresholds and immobilisation mechanisms has sparked broader interest [31–33] in optimising PCPB formulations for both structural performance and environmental compliance.

The review by Dincă et al. [34] examines sustainable strategies for valorising anaerobic digestate, a byproduct of biogas production. As anaerobic digestion gains prominence under EU waste treatment legislation, digestate management has become critical for achieving circular economy and carbon neutrality targets. The authors note that untreated digestate poses environmental risks via greenhouse gas emissions, pathogens, heavy metals, and antibiotic resistance genes. Like in previous work [35–37], the authors explored various processing technologies, including pyrolysis, gasification, hydrothermal carbonisation, ammonia stripping, and struvite recovery, which can mitigate environmental impacts and transform digestate into valuable products such as biofertilisers. This review contributes to broader circular bioeconomy discourse and identifies priorities for future research and policy development.

Collectively, these studies advance our understanding of sustainable environmental technologies, emphasising the need for interdisciplinary methodologies, robust analytics, and policy integration to achieve long-term ecological resilience.

3. Conclusions

The articles in this editorial reflect a growing emphasis on interdisciplinary approaches within environmental science. From microbial synergies in waste digestion to ecological engineering in wetland restoration and from bibliometric analysis of phytoremediation to advances in industrial waste management, these studies provide practical solutions to urgent environmental challenges. As South Africa and the global community confront ongoing pollution and resource degradation, such research offers a roadmap for sustainable development grounded in innovation, collaboration, and ecological integrity.

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