Biosolids as a Sustainable Approach to Mine Site Rehabilitation in Brazil

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Abstract. Global environmental concerns and the rising number of abandoned mine sites in Brazil need the development of cost-effective and sustainable rehabilitation strategies. These sites pose a significant challenge due to severe soil contamination, limited nutrient availability, and harsh biophysicochemical conditions. Traditional rehabilitation methods are often expensive and time-consuming, highlighting the need for innovative approaches.

Biosolids hold the potential to address those environmental concerns while repurposing wastewater treatment by-products. Biosolids can enhance soil fertility by increasing organic matter content and promoting beneficial microbial activity, which is crucial for nutrient cycling and decomposition. Additionally, they can contribute to balancing soil pH and potentially aid in immobilizing or detoxifying certain contaminants. These improvements in soil properties can further help establishing diverse plant communities, fostering ecological succession and promoting long-term ecological stability.

This study explored the feasibility of incorporating biosolids into mine site rehabilitation in Brazil. Through a comprehensive evaluation of relevant studies, their findings and existing environmental regulations, the research investigated the potential benefits and potential limitations associated with biosolids application in this context. The successful integration of biosolids, with careful management practices to address potential concerns like heavy metal accumulation, offers a practical pathway towards achieving environmental restoration and promoting long-term ecological stability in these degraded landscapes.

Keywords. circular economy, organic fertilizer, environmental sustainability.

1. Introduction

While mining operations provide essential raw materials for industries worldwide, they've come at a significant environmental cost [4]. The environmental impacts are multifaceted, going from terrestrial to aquatic and even atmospheric [4]. These include habitat destruction, soil contamination and water pollution. The formation of acid mine drainage leads to high toxicity and heavy metal levels in the soil and water [11,31,33,35]. The repercussions extend beyond direct effects to encompass indirect consequences such as erosion, mobilization of mine tailings and loss of biodiversity [35]. These impacts include direct effects, like chemicals, and indirect effects, such as building and cumulative biodiversity loss [31,33]. The dispersion of mine tailings by wind and water exacerbates ecosystem contamination, posing risks to animals, plants, soil and water bodies, while the release of atmospheric dust containing sulfur and other substances poses health hazards to both mine workers and nearby residents [11].

The scars of extraction persisted for generations due to the level of disruption. The sites exhibit low capacity for self-recovery due to aggressive mining practices, nutrient depletion and unfavorable post-mining environments [3,27,35]. The need for effective environmental management strategies to mitigate adverse effects and ensure sustainable mining practices is key [3, 27, 35].

In Brazil, mining companies are oblied by law to rehabilitate mine sites, reflecting the significant ecological footprint of mining activities. The impacts include barren landscapes, soil degradation, erosion, loss of biodiversity and contamination of soil and water [17]. Reclamation efforts are essential for restoring disturbed areas and promoting sustainable development [30]. However, these endeavors are often restricted by their high costs, lengthy timelines and complexity, leading to the abandonment of many sites [11].

Addressing the challenges of mine site rehabilitation in Brazil is essential, particularly in states like Minas Gerais, which face significant issues related to abandoned mine sites [30]. The catastrophic collapse of the Vale dam, "Fundão," in Mariana/MG in 2015 resulted in the release of millions of cubic meters of iron ore tailings, devastating ecosystems and communities along the Doce River Basin [9]. This event prompted a reevaluation of mine site safety, leading to a 30% increase in paralyzed or abandoned mines in Minas Gerais [17]. According to data from the Minas Gerais Development Company (Codemge), there are 1,425 mines in the state, including active, inactive and exhausted sites [Fig 1, 17]. Despite the extensive rehabilitation efforts required, most of these sites remain untreated due to various constraints, including inadequate planning, regulatory oversight and financial resources [17].

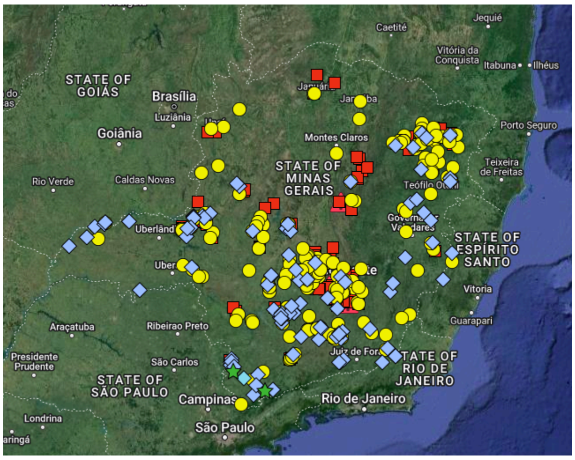

Fig. 1 - Map of the abandoned mines of Minas Gerais (Fundação Estadual de Meio Ambiente e A Pública, 2016 [17])

The introduction of biosolids into the final steps of the rehabilitating degraded mine sites holds promise. Biosolids, byproducts of wastewater treatment, offer a sustainable approach to revitalizing nutrient-depleted soils and supporting plant growth [23, 29, 34]. Their application could provide a cost-effective and environmentally sustainable alternative to traditional fertilizer sources [29].

1.2 Biosolids, a history

During the late 19th and early 20th centuries, the rise of densely populated urban areas came with a major challenge: sanitation. Epidemics of typhoid and cholera emphasized the urgent need for effective wastewater management systems. Initially, the "flush and forget" approach emerged [6], fueled by the belief that simply flushing would eliminate the threat of disease [33].

Over time, the improved wastewater treatment starts to protect public health and the environment. However, the "culture of flushing" [6] leads to a disconnect from the realities of waste management. And with the growing global population, the volume of waste is increasing proportionally. It is no longer viable to simply accumulate waste. We need to prioritize resource recovery and responsible waste use. Today, we stand at a critical juncture. We celebrate sanitation advancement but, we must acknowledge their limits and the need for sustainable solutions.

During the wastewater treatment process, biosolids are separated from the liquid. Dating back to the 19th century, scientists recognized that biosolids contain valuable nutrients that can improve soil fertility [1]. In the 1920s, growers started to use sewage sludge from wastewater treatment as a soil conditioner [13]. Still, before being used or disposed of safely, biosolids may undergo treatments to ensure the health and safety of their use [34]. Strict guidelines regulate the food production sector, minimizing risks to human health [7].

The literature highlights numerous benefits of biosolids land application, including availability of nutrients to soil and crops, enhanced crop yields and carbon sequestration [19, 29]. The organic matter is the main content of the biosolids. It improves soil structure, prevents erosion, enhances water infiltration and retention, and supports soil biodiversity [11]. Careful risk assessments and long-term studies have shown that biosolids, when managed and applied well avoid harm to soil, groundwater and surface water [2, 23].

Federal and state regulations ensure the responsible management of biosolids. They also prevent environmental contamination and promote continuous initiatives aiming for better management and environmental stewardship among wastewater treatment facilities [27].

Finally, biosolids offer a solution to current and future environmental challenges, making them an alluring choice as soil conditioners. The increase in urban population and proportional generation of biosolids requires better waste management [33]. By utilizing biosolids as soil conditioners, we address this problem effectively, repurposing what would otherwise be a burdensome waste stream [33]. Additionally, biosolids offer a sustainable alternative to chemical conditioners, mitigating the environmental impact of their production and use[33]. Their organic composition enriches soil fertility, providing a healthier ecosystem and enhancing soil structure [29]. In the context of abandoned mine site rehabilitation, biosolids ease the recovery process, providing essential nutrients and promoting vegetation establishment[1, 2, 34]. By evaluating the potential of biosolids, we address waste management issues and contribute to environmental sustainability and ecosystem restoration efforts, aligning with broader goals of resource efficiency and conservation.

This article explores the potential of biosolids in helping restore mine sites, focusing on soil, vegetation, and ecosystems. By analyzing the benefits and policy implications, it aims to show how integrating biosolids can lead to sustainable mine site rehabilitation. The study evaluates the practicality of using biosolids in Brazil, considering economic, environmental and regulatory aspects. Research and investigation, it highlight biosolids' potential as a sustainable solution for restoring degraded mine sites, deepening our understanding of human impact on the environment.

2. Literature Review

2.1 The regulations about the use of biosolids

Strong regulatory frameworks are crucial to ensure the responsible use of biosolids. This section evaluates the current situation in Brazil. It compares the rules for biosolids used in mine rehabilitation in other countries, shedding light on their strengths, weaknesses and what Brazil can learn from them.

Although there is a regulatory framework in Brazil, it is complex, fragmented and filled with inconsistencies and limitations [27]. CONAMA Resolution No. 412/2009 sets national quality standards for biosolids used in land application. These standards provide maximum limits allowed of heavy metals, pathogens, and organic matter and top application rates. It safeguards certain places including public parks, water sources, and protected areas. Furthermore, it ensures that procedures are correctly and safely monitored [7].

The National Policy on Solid Waste (Política Nacional de Resíduos Sólidos) established by Law No. 12.305/2010, provides guidelines for managing various waste types, including sludge from sewage treatment plants. It emphasizes recycling and sustainable reuse, prioritizing environmental protection and public health. Following these laws is vital, since they ensure that biosolids help restore mines without harm and keep biosolids from endangering people or the environment.

Every state, however, needs more specific rules that consider the unique situations and problems of their area. Consequently, some states, like Minas Gerais, have made stricter rules for their areas. The COPAM Deliberation No. 151/2009 supplements Resolution No. 412/2009 by requiring an Environmental Impact Assessment (EIA/RIMA) based on project scale and potential environmental impact. It emphasizes public participation by consulting local communities throughout project planning and implementation [8].

Brazilian laws rely on regulations from other countries but lack adjustments for Brazil's unique conditions. For example, the CONAMA Resolution uses US and Australian rules for some heavy metals. But for Chromium, Barium and Molybdenum, CETESB sets the limits without clear reasoning or research basis [27].

Strict CONAMA levels may hinder biosolid reuse [5]. Australia allows up to Class D biosolids for reuse, unlike Brazil's Class A restriction. This calls for a comprehensive Resolution review to ensure consistency and alignment with best practices. Brazil's regulations needs refining to enhance sustainable use of biosolids. Moreover, the absence of specific mine rehabilitation regulations poses risks of irresponsible use, environmental harm and disasters.

Furthermore, when CONAMA categorizes biosolids into Class A, restrictions for their use still apply, while the US and Australia deem Class A safe for any use [19, 27]. This leads to farmers avoiding biosolids due to monitoring complexities, limiting sustainable farming benefits. Aligning regulations with global standards is crucial for wider biosolid use in Brazil [6].

Establishing national guidelines for biosolids use in mine site rehabilitation is crucial for environmental security and responsible application. In addition, incentivizing states to adopt complementary regulations tailored to their specific contexts and collaborating across government levels could simplify legislation and facilitate collaborative development.

Biosolids offer promising environmental and economic benefits for mine site rehabilitation in Brazil. However, the current regulatory framework lacks specific guidelines. Given their shared interests in environmental preservation and mining activities, Australia's framework can guide Brazil in developing clearer and more specific regulations to encourage responsible and effective biosolids use.

2.2 Mine site rehabilitation

Due to significant environmental issues from mine closures, urgent rehabilitation is needed. The Recovery Work Plan is the step on mine reclamation that directs the plan of action per se. It includes a remedial work plan and a morphological recovery plan. The first deals with contaminated tailings, waters, sediments, and soils. The second focuses on site morphological and scenic aspects [11]. There are several approaches for each part and the technique for remediation of contaminated soil, or water, needs to be individually tailored.

2.2.1. Phytoremediation, a remedial decontamination approach

In Brazil, the current approach to land recovery of ex-mine sites is often filled with challenges, including poor planning by the responsible companies and inadequate regulatory enforcement [8]. As a result, many mine sites remain abandoned or poorly rehabilitated, posing ongoing environmental and social risks [17].

Traditional remedial technologies for mining sites, such as leaching, vitrification and excavation, are costly and technically limited, often deteriorating soil fertility and causing negative ecosystem impacts. Phytoremediation uses plants to reduce, remove and degrade toxins. It offers a cheaper and environmentally friendly approach with long-term applicability [19, 23]. As a bonus, it avoids the use of harsh chemicals, promotes the establishment of diverse plant communities, improves the site's aesthetic and offers continuous removal and control of contaminants over time [25] .

From all phytoremediation processes,

phytostabilization and phytoextraction are particularly effective when dealing with mine site rehabilitation [21] . For instance, Vetiveria zizanioides (*Vetiver grass*) as a phytostabilizer, immobilizes metals, then uptakes and sequesters them with their roots, avoiding their migration to air, surface, groundwater and downwards the soil [18]. Phytoextraction is the use of metallophytes that absorb and metabolize those highly concentrated contaminants, reducing soil contamination [16, 32].

While phytoremediation offers a compelling solution for mine rehabilitation, it can take years for plants to significantly reduce contamination levels [26] . Adding biosolids to mine rehabilitation projects could accelerate and enhance the final result [35]. Biosolids act as natural fertilizers, enriching the soil with essential nutrients and promoting accelerated plant growth and biomass production [13]. This facilitates quicker contaminant uptake and soil stabilization [29].

Indian mustard (*Brassica juncea*), a hyperaccumulator, exhibits enhanced heavy metal removal when paired with biosolids. This symbiotic relationship results in a 40% increase in lead removal compared to standalone plant application [14,24,25]. Biosolids act as natural fertilizers, enriching the soil with essential nutrients like N, P, and K, thereby promoting accelerated plant growth and biomass production. Consequently, this facilitates quicker contaminant uptake and soil stabilization [25]. The untreated site, at times, results in the death of even the remedial plants [1]. However, the treatments promoted healthy plant development. Additionally, they also lifted the extremely acidic pH, which is more favorable for the plant species.

Research suggests that biosolids can improve soil quality and microbial activity in contaminated environments [12,15,16,23,30]. They enhance soil structure, aeration and water retention, creating a more hospitable environment for the microorganisms and plants and enhancing their ability to remediate the contaminated soil [15, 22]. Moreover, they significantly increase the bacterial population, leading to higher chances of long-term ecosystem stability [23].

Populations of microbial groups crucial for nutrient cycling and organic matter decomposition also showed growth compared to chemical fertilizers in mine tailing restoration [12]. This improves plant growth and soil properties like increased water-holding and cation exchange capacities [28].

With that, it is possible to conclude that on several occasions, the biosolids added into the biological treatment make the environment more suitable for the plants to grow, the microorganisms to act and the soil to recover. However, it's needed to determine how the biosolids affect those aspects in Brazilian conditions. The perspectives are, even so, optimistic.

2.2.2. Vegetation establishment, a morphological approach

The end goal of the restoration plan is to bring back the aesthetics, topography and vegetation of the environment [11]. This process follows remedial work plans that address soil contamination. That way, the plants have more chances of long-term success [11].

The revegetation stabilizes soil with its root system, increases soil organic matter, lowers soil bulk density, moderates the pH levels and brings mineral nutrients to the surface [30]. It involves soil amendment, proper stockpiling and handling of topsoil and the introduction of suitable vegetation to restore soil fertility and accelerate ecological succession [11, 30].

However, revegetation can be challenging, expensive and time-consuming [17]. The erosion, compact soil, and lack of important nutrients inhibit soil-forming processes and plant growth [17]. It also affects microorganisms' diversity, decomposition of organic matter, fixation of nitrogen and the cycle of other nutrients [12,15,16,23,30].

Biosolids can help improve overall soil structure and aeration, minimizing the bulky aspect of compact and eroded soil [12]. That is due to the increases in pore space and developing soil texture, created by the biosolids addition[12]. There is an increase in field capacity, the soil's capacity to hold water and prevention of rapid runoff and erosion[13]. By enriching topsoil with biosolids, rehabilitation efforts become more efficient, promoting faster plant establishment and growth [28].

Mine rehabilitation projects like the Minas-Rio (Brazil) mine complex combine physical, revegetation and replanting [4]. Incorporating biosolids into it would create an ideal foundation for plant establishment. The topsoil can be enriched with biosolids, creating a potent growth medium for later revegetation efforts. Biosolids can be directly applied, during the revegetation phase, to promote faster plant establishment and growth. Finally, the monitoring phase becomes more efficient as biosolids contribute to a healthier, more resilient ecosystem, requiring less intervention for long-term success. This holistic approach creates a thriving ecosystem that supports diverse plant communities, accelerating the rehabilitation process.

3. Conclusion and Discussion

In conclusion, the exploration of biosolids in mine site rehabilitation presents an opportunity to deal with the environmental impact of the industry and, simultaneously, dialogue with the principles of the circular economy and resource recycling. As we, a world society, realize the urge for sustainable practices, the reuse of waste and the recovery of destroyed sites. Besides that, the escalating volume of biosolids, mirroring the rise in global population, underscores the urgency of finding more suitable solutions that maximize their potential while mitigating the associated risks of accumulated landfills.

Moreover, the application of biosolids in mine site rehabilitation opens the path for other uses, like a sustainable alternative for fertilizers in agricultural production. Yet, this potential must be managed with rigorous evaluation and mitigation of heavy metal contamination risks, emphasizing the importance of phytostabilization and alkaline stabilization techniques.

The need for a direct, uncomplicated and personalized regulation, made for the Brazilian conditions, is key for responsible management and use of biosolids. By developing a regulatory framework and fostering collaboration across sectors and nations, the course towards a more resilient and regenerative future can be reached.

Educational initiatives and public engagement efforts will be crucial for the ethos of collective acceptance. It will, additionally, encourage research, which is the answer to the lack of knowledge and safer use of the biosolids. Innovative technologies such as thermal processing [22], can aid and minimize the potential environmental impacts of biosolids. The detection of microplastics highlights the demand for initiative-taking mitigation strategies to safeguard soil health and ecosystem integrity.

In conclusion, the journey towards unlocking the full potential of biosolids in mine site rehabilitation is not only technical but a philosophical shift towards seeing waste as a resource and redefining our relationship with the environment. Through concerted action and knowledge, we can use biosolids to shift the prejudged understanding of waste into a more sustainable and prosperous future for all.

4. References

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