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Utilization of Post-Coal Mining Reclaimed Land for Livestock Feed and Animal Husbandry Production: Challenges of Microbial Contamination, Heavy Metals, and Nutrient Deficiency

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ABSTRACT

Coal mining causes significant environmental degradation, transforming land from a stable ecosystem into a disturbed area with complex ecological and chemical challenges. This study aims to evaluate the feasibility of post-coal mining reclaimed land as an area for livestock feed and animal husbandry production, focusing on the main research question: Does the land meet specific criteria such as heavy metal thresholds (e.g., Pb <0.3 mg/kg, Cd <0.1 mg/kg according to FAO/WHO), microbial community recovery (enzyme activity >30% increase), and nutrient availability (N, P, K >1% total)? The systematic literature review method involved searching 94 empirical articles from Google Scholar (years 2016-2025), selected based on criteria: empirical research design, English or Indonesian language, complete text, and relevance to the theme of mine land reclamation. Data analysis used a thematic approach to identify main themes related to reclaimed land conditions. The results show that 80% of studies report heavy metal pollution with Pb concentrations ranging from 5-50 mg/kg, Cd 0.5-5 mg/kg, and Hg 0.1-2 mg/kg, which pose a risk of bioaccumulation in feed plants; post-reclamation soil quality improvement trends reach 20-50% for soil organic carbon (SOC) and 30-60% for microbial enzyme activity, although the main constraints are slow microbial community recovery and chronic nutrient deficiency. In conclusion, reclaimed land is conditionally suitable for livestock feed and animal husbandry production if integrated restoration strategies are implemented to address microbial contamination, heavy metals, and nutrients, as well as continuous monitoring to ensure feed safety and animal health.

1. INTRODUCTION

Coal mining is one of the main pillars of socio-economic development in many countries, as it provides a cheap and abundant source of energy. However, this activity causes severe ecological and environmental impacts, including pollution of water, soil, and the atmosphere, which can persist for years (Sun et al., 2025). Before mining, the land is generally characterized by fertile topsoil layers, stable soil structure, and diverse and active microbial communities. This natural ecosystem supports efficient nutrient cycles, rich biodiversity, and high

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plant productivity, which in turn contribute to overall ecosystem balance.

Mining operations, especially through open-pit methods which involve stripping topsoil and rock layers to access coal deposits drastically alter the landscape. This process removes topsoil layers, compacts the soil, and disrupts physical properties (such as porosity and drainage), chemical properties (such as pH and nutrient content), and biological properties (such as soil microbial communities) (Rouhani et al., 2023; Wang et al., 2021). As a result, degraded land is marked by low nutrient availability, loss of soil organic carbon, poor soil structure, and disturbed soil microbial communities, which reduce the soil's ability to support plant growth (Swab et al., 2020). In addition, mining releases toxic compounds, including heavy metals (such as lead and mercury), radioactive elements, and polycyclic aromatic hydrocarbons (PAHs), into the environment, which can accumulate in the soil and potentially enter the food chain (Rouhani et al., 2023).

Although reclamation laws require mining companies to restore the environmental function of post-mining land through techniques such as re-spreading fertile soil and erosion management (Wu et al., 2024), many sites still face long-term soil pollution issues. This pollution not only hinders the restoration of natural ecosystems but also poses health risks to humans and animals, especially if the land is used for agricultural or livestock activities. One potential use of post-mining reclaimed land is for livestock feed production and animal husbandry, which can provide additional economic value while supporting sustainable development. However, the feasibility of such utilization heavily depends on the successful mitigation of mining's environmental impacts, particularly in terms of livestock feed safety and land productivity.

Previous studies have explored the impacts of coal mining on soil separately, such as analyses of heavy metal contamination (Rouhani et al., 2023) or changes in microbial communities (Swab et al., 2020). However, there is a significant research gap: there is no comprehensive review that integrates soil microbial conditions, heavy metal contamination levels, and nutrient availability in the specific context of land use for livestock feed production. The linkage between soil degradation due to mining and its direct consequences on livestock productivity such as reduced feed quality, risks of toxin bioaccumulation in the animal food chain, and potential disruptions to livestock health has not been sufficiently emphasized in the literature. This is important because contaminated livestock feed can cause food safety issues, such as the transfer of heavy metals to meat or milk products, and reduce overall livestock production efficiency. Therefore, this review aims to advance knowledge by filling this gap through an integrative assessment.

2. METHODS

This study employs a systematic literature review method to integrate secondary data from relevant literature studies on coal mining, soil degradation, and land use for livestock feed. This review involves systematic searching, selection, and analysis of literature to answer research questions, focusing on original empirical research articles that include abstracts, introductions, methods, results, and discussions. Article searches were conducted through the Google Scholar and ResearchGate databases. The initial publication period was limited to 2016–2025 to include recent studies emerging after the initial period, such as research on long-term mining impacts, to avoid selection bias and ensure comprehensiveness. Inclusion criteria include original empirical research articles from primary sources, including experimental, observational, descriptive, or randomized controlled trial (RCT) studies, focusing on the impacts of coal mining on soil, microbes, heavy metals, nutrients, and utilization for livestock feed; full articles in English or Indonesian; and articles published between 2016 and 2025. Exclusion criteria include review articles, editorials, or conference abstracts without full empirical results; irrelevant articles; and articles with low methodological quality. The selection process followed three main steps: identification (1,250 potential articles), screening based on title and abstract (350 relevant articles), and eligibility through full reading (94 articles included). To ensure accuracy, each article was evaluated using the Critical Appraisal Skills Programme (CASP) quality assessment tool, covering methodological validity, risk of bias, relevance, and consistency, with scores of 1–4 per aspect (maximum total 16), and articles with scores below 10 were excluded; assessments were conducted by two researchers independently. Data analysis used a simplified qualitative-narrative synthesis approach, including simultaneous summarization and critical assessment of study strengths/weaknesses, identification of themes answering research objectives, synthesis of similar themes with discussion of finding strengths, evaluation of theme names and groupings, analysis of similarities/differences between themes, and final review to ensure themes answer research questions while considering bias risks.

3. RESULT AND DISCUSSION

A. Microbial Contamination in Reclaimed Land

Soil health and fertility largely depend on diverse and active microbial communities, which serve as key indicators of the feasibility of post-coal mining reclamation land for livestock feed production. A synthesis of findings from the literature shows that disturbances in microbial ecosystems not only alter community composition but also have significant functional implications for the soil–plant–livestock chain, including reduced feed biomass productivity, risks of heavy metal transfer to livestock products, and limitations on land carrying capacity. Although studies such as Swab et al. (2020), Mulyani et al. (2021), and Mao et al. (2024) provide comprehensive descriptions of microbial changes, critical analysis reveals gaps in integrating these factors with livestock feed safety standards, which may threaten the sustainability of farming on reclaimed land.

Post-mining microbial ecosystem disturbances are driven by several major factors closely linked to chemical contamination and nutrient deficiencies, such as the removal and replacement of topsoil layers that destroy natural microbial habitats, reducing biomass by 6–18 times and nutrient availability (e.g., nitrogen) by 30–50%; changes in soil physical and chemical properties that create toxic environments with microbial enzyme activity reduced by 40–60%; and heavy metal contamination such as Pb or Hg that causes direct toxicity, reducing species diversity by up to 70% and exacerbating nutrient deficiencies (Hamidović et al., 2020; Wang et al., 2021; Su et al., 2023).

Microbiological conditions before mining are generally healthy, with complex communities dominated by phyla such as Proteobacteria, Acidobacteriota, and Actinobacteriota, supporting efficient nutrient cycling (Thavamani et al., 2017; Kong et al., 2024). However, after mining, these changes have critical implications for the soil–plant–livestock chain, including a decline in microbial diversity and biomass abundance of up to 70%, reducing livestock feed biomass productivity by 40–60% per hectare and limiting land carrying capacity to 2–3 cattle per hectare; shifts in community composition with dominance of Actinomycetes and Gram-positive bacteria, while Gram-negative bacteria decline, functionally reducing nitrogen content in forage crops and animal protein by 15–25%, increasing deficiency risks; loss of key functional groups such as sucrase and phosphatase enzyme activity reduced by 50%, disrupting carbohydrate and phosphorus availability, combined with heavy metals causing Pb transfer from soil to forage crops up to 10–20 mg/kg, exceeding FAO/WHO thresholds (50 mg/kg for livestock feed) and Codex Alimentarius limits (maximum 10 mg/kg in animal products), thereby increasing risks of chronic toxicity in livestock such as anemia or kidney damage; and slow recovery, requiring 10–20 years to restore 50–70% of microbial diversity, with ecosystem functions such as nutrient cycling only becoming optimal after 15–30 years. Without interventions such as microbial inoculation, land may not achieve safe feed productivity, with risks of Hg in beef >0.5 mg/kg exceeding EU standards (maximum 0.05 mg/kg) (Hou et al., 2018; Singh et al., 2024; Wang et al., 2020).

Overall, the integration of microbial, chemical, and nutritional factors within the soil–plant–livestock framework shows that microbial degradation is not merely a matter of composition but also a functional barrier to land feasibility. Studies such as Mao et al. (2024) emphasize the need for quantitative indicators such as functional microbial ratios (e.g., nitrogen-fixing bacteria >10^6 CFU/g soil) to assess risks. However, these findings require further synthesis with field data for practical recommendations, such as the use of biofertilizers to accelerate recovery and minimize toxin transfer (Arcila-Galvis et al., 2022).

B. Heavy Metals in Reclaimed Land

Coal mining activities inherently release various heavy metals into the environment, posing serious threats to ecosystems and the health of living organisms through bioaccumulation in the food chain, which critically affects the feasibility of reclaimed land for livestock feed production. A synthesis of findings from the literature, such as Afzal & Mahreen (2024) and Su et al. (2023), shows that heavy metals including As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn not only increase concentrations in post-mining soils by 202–533% compared to control soils (Maiti & Rana, 2016), but also disrupt soil microbial functions, reducing species diversity by up to 70% and nutrient enzyme activity by 50%, thereby exacerbating nitrogen and phosphorus deficiencies required for forage crop growth (Haghighizadeh et al., 2024; Su et al., 2023).

Before mining, natural soils had background concentrations of heavy metals below toxicity thresholds, with neutral pH and complex microbial populations supporting feed biomass productivity up to 60% per hectare and land carrying capacity for 5–7 cattle per hectare. However, after mining, sources such as mine spoils and tailings increase the mobility of heavy metals through dissolved fractions (e.g., Pb^{2+} and $HgSO_4$), with risk indices such as Igeo and PLI indicating moderate to high pollution (Zhang et al., 2024). Functionally, this reduces protein content in livestock feed by 15–25% and increases the risk of nutritional deficiencies in animals (Atanassova et al., 2019).

The risk of heavy metal transfer from soil to forage crops and livestock products becomes a critical issue within the soil–plant–livestock framework, where accumulation of As, Cd, Hg, and Pb (Maiti & Rana, 2016) in plant biomass can reach 10–20 mg/kg, exceeding FAO/WHO thresholds (50 mg/kg for livestock feed) and Codex Alimentarius limits (maximum 10 mg/kg in animal products). This raises chronic toxicity risks such as anemia or kidney damage in livestock, with significant carcinogenic risks especially for children (Li et al., 2018; Wang et al., 2022; Sharafi & Salehi, 2025).

The integration of microbial, chemical, and nutritional factors shows that microbial degradation due to heavy metals not only alters community composition but also hampers nutrient cycling, reducing feed biomass productivity by 40–60% and limiting land carrying capacity to 2–3 cattle per hectare, thereby threatening farming sustainability. Therefore, remediation strategies such as the addition of biochar and compost (Antonangelo et al., 2023; Chafik et al., 2025; Acosta-Luque et al., 2023; Ippolito et al., 2024; Majewska et al., 2025; Meng et al., 2025), as well as phytoremediation (Koornneef et al., 2025), are necessary to reduce heavy metal bioavailability, restore microbial functions, and ensure safe feed quality. Nevertheless, studies such as Mao et al. (2024) emphasize the need for quantitative indicators such as functional microbial ratios (>10^6 CFU/g soil) for more accurate risk evaluation.

Table 1. Differences in Soil Conditions Before and After Mining

Before Mining	After Mining
Complex microbial population (5,7 x 10^8)	Complex microbial population (1,1 x 10^4)
Black soil color	Reddish-brown soil color
pH (6,8-7)	pH (7,46-0,08)
Heavy metal concentration:	Heavy metal concentration:
As (20 μg/g)	As (5-35 μg/g)
Co (50 μg/g)	Co (10-45 μg/g)
Cu (100 μg/g)	Cu (20-80 μg/g)
Pb (85 μg/g)	Pb (15-120μg/g)
Zn (200 μg/g)	Zn (50-150 μg/g)
Cd (2 μg/g)	Cd (0,5-3,5 μg/g)
Hg (0,5 μg/g)	Hg (0,1-1,2 μg/g)

Source: (Zhang et al., 2024; Wang et al., 2025).

C. Nutrient Deficiency in Reclaimed Land

The availability of nutrients is a major limiting factor for ecological restoration and vegetation growth in post-coal mining reclaimed land, critically affecting the soil–plant–livestock chain through severe nutrient deficiencies and integration with heavy metal contamination. A synthesis of findings from the literature, such as Ma et al. (2019), Qu et al. (2017), and Wang et al. (2021), shows that the loss of topsoil reduces SOM, TN, and AP to half of natural levels within eight years of reclamation (Chen & Zhang, 2019), while soil microbial disturbances reduce nutrient mineralization by up to 50%. This decreases livestock feed biomass productivity by 40–60% per hectare and limits land carrying capacity to 2–3 cattle per hectare.

Nutrient deficiencies not only hinder plant growth with symptoms such as leaf yellowing or stunted growth but also reduce protein content in forage by 15–25%, increasing the risk of nutritional deficiencies in animals and threatening farming sustainability. Integration with heavy metals worsens the situation, where Pb or Hg accumulation in forage crops can reach 10–20 mg/kg, exceeding FAO/WHO thresholds (50 mg/kg for livestock feed) and Codex Alimentarius limits (maximum 10 mg/kg in animal products), thereby increasing chronic toxicity risks such as anemia in livestock, with significant carcinogenic risks in plants (Ma et al., 2019; Wang et al., 2021; Sopialena et al., 2024).

Based on findings by Daru et al. (2020) and Andini et al. (2019), remediation strategies such as the addition of compost, biochar, and organic fertilizers (Chafik et al., 2025; Nogués et al., 2023; Haigh et al., 2021), straw (Xu et al., 2025; Bo et al., 2024), and microbial inoculation (Li et al., 2024; Shang et al., 2023; Qu et al., 2017) show potential to increase SOM by 20–30%, nutrient enzyme activity by 40%, and bacterial diversity by 70%. Functionally, these measures restore nutrient cycling and reduce heavy metal bioavailability. However, critical analysis reveals gaps in integrating these factors, where studies such as Mao et al. (2024) emphasize the need for quantitative indicators such as functional microbial ratios (>10^6 CFU/g soil) to assess heavy metal transfer risks, ensuring that reclaimed land not only restores nutrients but also remains safe for sustainable livestock feed production (Ahirwal et al., 2020; Banda et al., 2024; Song et al., 2025).

D. Feasibility Testing of Reclaimed Land for Forage and Livestock

Utilizing post-mining reclaimed land for forage and livestock farming offers significant potential for ecosystem rehabilitation and local economic development (Daru et al., 2020; Ariansyah et al., 2020). However, feasibility depends heavily on successful mitigation of microbial contamination, heavy metals, and nutrient deficiencies, which are interconnected within the soil–plant–livestock framework.

Critically, soil microbial changes—such as reduced diversity and activity of nitrogen-fixing bacteria and P- and S-cycling bacteria (Sopialena et al., 2024; Mao et al., 2024)—not only disrupt community composition but also functionally hinder organic matter decomposition and nutrient mineralization, reducing N, P, and S availability by 30–50% compared to natural soils (Ma et al., 2019; Wang et al., 2021). This directly impacts forage biomass production, which declines by up to 40% in reclaimed land, and lowers forage nutrient content such as crude protein (from 15–20% to 10–12%), requiring supplementation to maintain livestock productivity (Daru et al., 2020).

The loss of rhizosphere microbes such as PGPR and mycorrhizal fungi (Thavamani et al., 2017; Mao et al., 2024) weakens plant resilience to stress, including heavy metal immobilization, which in turn worsens bioaccumulation in the soil–plant–livestock food chain. Heavy metal contamination poses a major threat, with bioaccumulation risks exceeding international safety standards such as FAO/WHO (2005) for Pb (0.3 mg/kg) and Cd (0.1 mg/kg) in livestock feed. Studies show that forage crops in reclaimed land can accumulate Pb up to 5–10 mg/kg and Cd up to 1–2 mg/kg, even at moderate soil concentrations (Maiti & Rana, 2016; Song et al., 2025; Castro-Bedriñana et al., 2021).

Although quantitative levels of Pb, Cd, Cu, and Zn in forage often remain below maximum limits (e.g., Pb <10 mg/kg under EU Regulation 2002/32/EC), strict monitoring is required since bioaccumulation in livestock tissues can increase chronic toxicity risks such as oxidative stress and reproductive disorders (Afzal & Mahreen, 2024; Umeobi et al., 2025). These risks are compounded by heavy metal phytotoxicity, which inhibits plant growth by 25–35% and reduces forage biomass (Haghighizadeh et al., 2024; Acosta-Luque et al., 2023), with potential transfer to animal products such as meat and milk, posing human health threats if Codex Alimentarius standards are exceeded (Afzal & Mahreen, 2024).

Nutrient deficiencies further exacerbate challenges, where low N, P, and K levels (often <0.5% N and <10 ppm P) in reclaimed land (Ramadha et al., 2019; Qu et al., 2017) limit forage biomass production to 50–70% compared to productive land, reducing land carrying capacity to only 2–5 livestock per hectare per year (Daru et al., 2020; Andini et al., 2019). Forage nutritional quality also degrades, with protein and energy content declining by up to 20%, requiring supplementation to prevent deficiencies in livestock (Umeobi et al., 2025). Overall, the integration of microbial, chemical, and nutritional factors indicates that reclamation requires a holistic approach, such as biofertilizer application to enhance microbial activity and reduce heavy metal bioaccumulation, in order to achieve minimum forage biomass productivity of 5–8 tons/ha/year and ensure food chain safety according to international standards.

E. Feasibility, Potential, and Challenges

The potential of post-mining reclaimed land as forage and livestock farming areas can be realized through rehabilitation that synthesizes soil quality improvement with contamination risk mitigation in a cohesive soil–plant–livestock framework. Effective reclamation programs such as the application of biochar, compost, straw, and microbial inoculation significantly improve soil physical, chemical, and biological properties, including increases in soil organic carbon (SOC) by 20–50%, N, P, and K concentrations by 2–3 times, and enzyme activities such as urease and phosphatase by 30–60% within 2–5 years (Arifin et al., 2025; Umeobi et al., 2025; Yu et al., 2025; Kang et al., 2025; Li et al., 2024).

Functionally, these measures restore microbial activity, such as nitrogen-fixing bacteria that enhance nutrient mineralization by 40%, thereby supporting forage biomass production up to 5–8 tons/ha/year and reducing heavy metal bioaccumulation in the food chain, with Pb and Cd levels in forage remaining below FAO/WHO thresholds (0.3 mg/kg Pb and 0.1 mg/kg Cd) for livestock feed safety. Successful revegetation is achieved through the selection of tolerant forage species such as hybrid grasses with phytoremediation capacity, stabilizing vegetation cover up to 80–90% within 3–5 years and reducing soil heavy metal concentrations by 20–40%. This produces high-quality forage with crude protein content of 12–18%, preferred by livestock such as elk and deer, thereby increasing productivity by up to 25% (Song et al., 2025; Koornneef et al., 2025; Beale & Boyce, 2020).

Continuous monitoring, with routine evaluation of indicators such as soil pH (target 6–7), heavy metal concentrations (Cd <1 mg/kg), and livestock health (Pb bioaccumulation in blood <0.1 mg/kg), conducted every 6–12 months, ensures land carrying capacity reaches 5–10 livestock/ha/year while assessing higher trophic levels such as animal product safety according to Codex Alimentarius standards (Umeobi et al., 2025; Beale & Boyce, 2020).

Overall, post-coal mining reclaimed land can be utilized as forage and livestock farming areas if supported by planned, integrated, and sustainable reclamation efforts that address microbiological, heavy metal, and nutrient issues, while considering food safety and livestock health

4. CONCLUSION

Coal mining fundamentally alters land ecosystems, creating serious challenges for post-mining utilization, particularly for forage and livestock farming areas. These changes include drastic declines in soil microbial diversity and activity, accumulation of toxic heavy metals that may contaminate the food chain, and deficiencies in essential nutrients. Collectively, these conditions restrict forage growth, reduce its nutritional quality, and pose health risks to livestock as well as humans as consumers.

Comprehensive and sustainable reclamation strategies can improve soil quality, reduce heavy metal mobility, and enhance forage productivity. Integrated approaches involving the addition of organic amendments (biochar, compost, straw), inoculation with functional microbes, and revegetation with suitable plant species have proven effective in restoring soil properties and supporting vegetation growth. However, soil ecosystem recovery particularly in terms of microbial functions and heavy metal stabilization requires long timeframes and careful monitoring.

Recommendations

Based on the literature review, improving the feasibility of post-coal mining land for forage and livestock farming requires an integrated and sustainable reclamation approach. This effort includes soil improvement with biochar, compost, straw, and appropriate fertilizers, as well as the use of functional microbial inoculants to accelerate nutrient cycling recovery. Selecting tolerant forage species with phytoremediation potential is crucial to reduce heavy metal mobility, while routine monitoring of metal concentrations in soil, plants, and livestock products must be conducted in reference to international safety standards.

In addition, sustainable farming practices such as legume cultivation and organic management can enhance soil fertility and support forage productivity. Reclamation evaluation should be conducted holistically using the Soil Quality Index (SQI), which incorporates physical, chemical, and biological indicators, while also assessing success at higher trophic levels, including livestock health. Long-term research is needed to understand soil–plant–livestock system dynamics under diverse climatic conditions, while exploring microbial biotechnology to address acid mine drainage problems. Economic analysis is also essential to assess the financial feasibility of livestock farming on reclaimed land.

With integrated strategies and strict monitoring, post-coal mining land has the potential to be transformed into productive landscapes that support sustainable agriculture and food security.

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