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REVIEW ARTICLE

Utilization pathways and risk management of biomass power plant ash and slag for ecological restoration

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Abstract

The rapid expansion of the biomass energy industry has led to a sharp increase in the production of ash and slag from biomass power plants. Traditional landfill disposal methods for these by-products pose high economic costs and potential environmental risks. However, biomass ash and slag are rich in essential plant nutrients such as calcium, potassium, phosphorus, and magnesium, and exhibit strong alkalinity, giving them considerable potential as soil amendments and ecological restoration materials. This offers a promising pathway for simultaneously promoting waste valorization and supporting the restoration of degraded ecosystems. A major constraint on their resource application is the potential presence of heavy metals (e.g., cadmium, chromium, lead) and other impurities, which, if not properly managed, can lead to secondary soil pollution. By integrating recent Chinese and international research with relevant policy documents, this review develops a practical framework for identifying suitable utilization scenarios, key environmental risks, and critical regulatory needs for biomass ash and slag. The paper systematically reviews the regulatory challenges involved in transitioning biomass ash from a "waste" to a "by-product" legal status, analyzes how its physicochemical properties are influenced by fuel source and combustion technology, and synthesizes resource utilization pathways in areas such as soil acidification amelioration, nutrient cycling, heavy metal passivation, and mine site restoration. While technical feasibility is supported by numerous studies, the establishment of unified quality standards, a scientific risk assessment framework, and a clear regulatory system—particularly for detecting and controlling impurities—is crucial for promoting the large-scale, high-value resource utilization of biomass ash and slag.

Keywords: Biomass power plant ash and slag; Resource utilization; Soil remediation; Ecological restoration; Regulatory framework

1. Introduction

Biomass energy, as a renewable energy source, plays a vital role in addressing climate change and ensuring energy security. Biomass is currently the world's fourth-largest energy source after coal, oil, and natural gas, accounting for 8–15% of the global primary energy supply. Projections suggest that by 2050, biomass could meet 33–50%

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of the global primary energy demand.[1] In China, aligned with the Blue Book for the Development of a New Power System, the target for non-fossil energy consumption is set to 25% by 2030, providing strong impetus for the development of the biomass power generation industry. By the end of 2024, the national cumulative installed capacity for biomass power generation had reached 45.99 million kilowatts, with an annual electricity generation of 208.3 billion kilowatt-hours.[2] Recent estimates indicate that biomass power plants in China generate approximately 40–49 million t of ash and slag annually, although this figure varies with biomass consumption, ash content, and reporting scope.[3] This substantial output underscores the urgency of developing safe and high-value utilization pathways beyond conventional disposal. Against this background, establishing a systematic recycling and ecological restoration model for bulk industrial solid wastes has become a critical research focus for enhancing resource utilization and implementing collaborative risk control. The "Earth Macrocycle" theory proposed by Chai *et al.*[4] provides a comprehensive framework for the multi-level recycling and ecological restoration of challenging industrial solid wastes.

The direct combustion of biomass for power generation yields significant amounts of ash, primarily comprising bottom ash (BBA) and fly ash (BFA). Many biomass power plants in China are located in less developed regions, where the resource utilization of BBA started relatively late and faces challenges such as complex composition, inefficient processing equipment, and inadequate sorting, leading to limited markets for derived products.[5,6] China's Environmental Protection Tax Law and its implementing regulations stipulate that enterprises discharging taxable solid waste directly into the environment must pay an environmental protection tax based on the discharge volume. Conversely, proper storage, disposal, or comprehensive resource utilization can qualify for tax exemptions or reductions.[7,8] This policy significantly incentivizes power generation enterprises to pursue ash resource utilization. Globally, the European Union (EU)'s revisions to the Waste Framework Directive (WFD) and the Fertilising Products Regulation (FPR) have established legal pathways for recognizing ash as a "by-product" and achieving "end-of-waste" status, aiming to integrate it into the circular economy.[6] While this review focuses on China and the EU due to their distinct and policy-relevant regulatory approaches, ash and slag utilization and disposal are pertinent issues worldwide. Practices from countries such as Finland, Sweden, Austria, and Canada offer valuable insights for forestry, agriculture, and ecological restoration, which are referenced in subsequent sections where appropriate.

Research shows that biomass ash is not a homogeneous waste; its physicochemical properties are highly dependent on fuel types (e.g., wood, straw) and combustion technologies (e.g., grate furnaces, circulating fluidized beds).[9-17] Typically rich in SiO_2, CaO, K_2O, MgO, alkaline in nature, and often possessing a porous structure, biomass ash holds broad application potential in agricultural soil improvement, environmental remediation, and building materials production.[18-20] This includes applications within China, where ash and slag have been investigated for use in cementitious materials, non-fired bricks, blocks, and fillers. However, compared to agricultural and ecological uses, large-scale application in construction materials remains constrained by ash heterogeneity, residual carbon content, chlorine/salt levels, and the need for stringent quality control.[14,16] The use of biomass ash for ecological restoration presents clear advantages, such as alkalinity, nutrient supply potential, and possible improvement of soil structure, but is also limited by significant heterogeneity, variable pollutant contents, uncertain leaching behavior, and a general lack of unified utilization standards in many regions.[6,21,22]

Given the large stockpiles of biomass ash and slag in China and the unsustainability of traditional disposal methods, systematic research into resource utilization pathways—particularly high-value applications in ecological restoration—is of great practical significance for promoting the sustainable development of the biomass power industry and advancing the "Zero-Waste City" initiative.[3,23] Accordingly, there is a need to systematically analyze the key issues faced in pollution reduction and carbon mitigation for China's biomass power generation, focusing on the coordination between technical pathways and policies, to provide a theoretical basis for future targeted research and management optimization.[23] As biomass energy expands globally under decarbonization and energy security pressures, the sustainable management of biomass combustion residues has become a universal challenge for transitioning to a circular economy, restoring soils, and governing environmental risks.

This review aims to systematically synthesize current knowledge on the physicochemical characteristics, regulatory status, ecological restoration pathways, and risk management strategies related to biomass power plant ash and slag. Specifically, it focuses on: (i) how fuel type and combustion technology determine ash properties; (ii) how regulatory frameworks influence the transition of biomass ash from waste to resource; (iii) the main utilization pathways of biomass ash in ecological restoration; and (iv) the key environmental risks, technical barriers, and future research priorities for its safe and large-scale application.

The practical utility of this review lies in integrating material characteristics, regulatory requirements, application pathways, and risk-control strategies into a single analytical framework, thereby providing a reference for researchers, regulators, and biomass power plant operators to promote the safe and high-value utilization of biomass ash and slag.

The article is structured as follows: Section 2 describes the literature search and selection methodology; Section 3 summarizes the characteristics of biomass ash and explains the necessity of classified management; Section 4 reviews the regulatory and policy background for the waste-to-resource transition; Section 5 discusses the major utilization pathways of biomass ash in ecological restoration; Section 6 analyzes the associated risks, challenges, and future research directions; finally, Section 7 presents the main conclusions.

2. Methodology

2.1. Search strategy

This review was conducted as a structured literature analysis. Relevant studies were collected from both international and Chinese academic databases, including Web of Science Core Collection, Scopus, ScienceDirect, and China National Knowledge Infrastructure (CNKI), to ensure broad coverage of the scientific and technical literature on biomass power plant ash and slag. Additionally, official policy documents, laws, regulations, and technical reports were consulted to support the analysis of the regulatory and institutional context.

The literature search encompassed publications available up to 2025, with emphasis on recent studies. The main search terms included combinations of "biomass ash," "biomass bottom ash," "biomass fly ash," "ash and slag," "resource utilization," "ecological restoration," "soil amendment," "acid soil improvement," "heavy metal immobilization," "risk assessment," and "regulatory framework." Chinese equivalents of these terms were also used in CNKI to identify relevant domestic studies.

2.2. Literature screening and thematic analysis

Retrieved literature was screened according to the following criteria: (i) direct relevance to biomass power plant ash or slag; (ii) content pertinent to at least one of the core topics: physicochemical characteristics, classified management, regulatory/policy context, ecological restoration pathways, environmental risks, or control strategies; and (iii) source type being peer-reviewed journal articles, reviews, dissertations, or relevant official policy/regulatory documents. Duplicates and publications with weak relevance were excluded.

Following screening, the selected literature was analyzed and synthesized according to four thematic categories: (i) ash characteristics and classified management necessity; (ii) regulatory and policy background for resource utilization; (iii) ecological restoration utilization pathways; and (iv) risks, challenges, and future perspectives. This thematic structure forms the organizational basis for the review. Data were organized using Excel (Microsoft, United States of America [USA]), and figures were prepared using Excel and Origin 2022 (OriginLab Corporation, USA). The literature retrieval, screening, and synthesis process is illustrated in Figure 1.

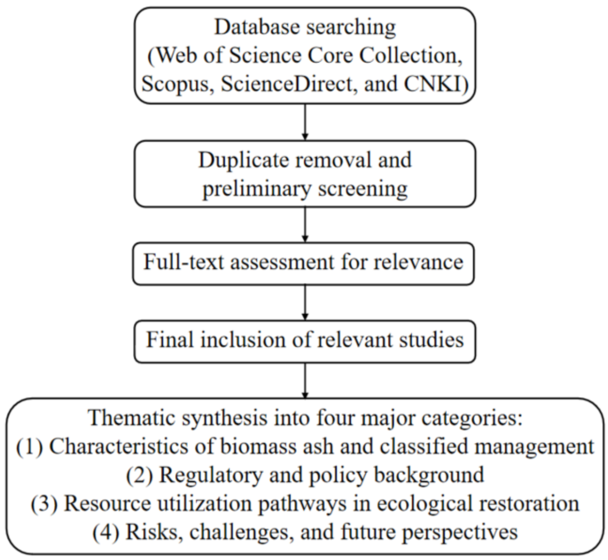

Figure 1. Flowchart illustrating the literature retrieval, screening, and thematic synthesis process adopted in this review.

3. Characteristics of biomass ash and the necessity of classified management

The physicochemical properties of biomass ash fundamentally determine its resource utilization, application directions, and associated risks. Precise classification and detailed characterization are essential prerequisites for achieving high-value utilization.

3.1. Effects of fuel sources and combustion processes on ash characteristics

Biomass ash composition is complex and variable, with fuel source being the primary influencing factor. Ash from woody biomass typically has high calcium and magnesium, with relatively low concentrations of potentially toxic elements such as cadmium (Cd) and lead (Pb), resulting in lower environmental risk and making it preferable for ecological restoration.[24] In contrast, ash from crop straw is rich in potassium and phosphorus but often contains significantly high levels of chlorine (Cl) and silicon (Si), posing a potential risk of soil salinization if over-applied.[25] Ash derived from waste wood or contaminated mixed fuels may contain heavy metals and persistent organic pollutants from coatings and preservatives, necessitating strict prohibition of its use on agricultural or ecological land.[6]

The combustion process also profoundly affects ash characteristics. Widely used grate furnace technology produces BBA, accounting for 65–90% of total ash. BBA is characterized by coarse particles, high carbon content, a developed pore structure, and a large specific surface area, indicating potential as an adsorbent material.[9-11,25] Conversely, circulating fluidized bed boilers achieve more complete combustion, yielding a higher proportion of BFA. BFA consists of fine particles rich in soluble salts like potassium and sodium, resulting in rapid alkalinity and nutrient release, but also presents challenges such as high-dust generation and salt loading.[12-17]

Systematic analysis shows that fuel type significantly affects ash yield. Straw-based fuels generally produce more BBA, whereas woody fuels yield relatively less. Overall, BBA constitutes the majority, underscoring the importance of focusing on its reduction and resource utilization in practical recycling efforts.[26] Regarding combustion technology, the loss on ignition for BBA from a grate furnace is typically high (15–30%), while loss on ignition from circulating fluidized beds can be as low as 2.8%.[26]

3.2. Characteristics and resource utilization potential of ash and slag

Both BBA and BFA are alkaline, with BBA typically having a slightly higher pH. Their chemical composition is dominated by Si, aluminum (Al), iron (Fe), calcium (Ca), magnesium (Mg), and potassium (K). The combined mass fraction of SiO_2, Al_2O_3, and Fe_2O_3 often exceeds 50%, with many samples meeting criteria for Class C pozzolanic materials. The mineral phases in BBA primarily consist of quartz, calcite, and anhydrite, while amorphous silica- and aluminosilicate-bearing phases may contribute to pozzolanic reactivity. While BFA and BBA share similar mineral composition, X-ray diffraction (XRD) analysis of BFA often shows broad diffuse scattering features, indicating a higher proportion of amorphous phases and consequently stronger pozzolanic reactivity. As shown in Figure 2, the XRD patterns further confirm both the similarity in major mineral phases between BBA and BFA and the higher amorphous content in BFA.[13,26]

Despite these variations, biomass ash commonly exhibits several key characteristics that underpin its resource value:

(i) Alkalinity: While pH typically ranges between 10 and 12, it can serve as a low-cost amendment for acidic soils, potentially replacing traditional lime[27];
(ii) Nutrient value: It contains microelements, secondary nutrients, and micronutrients essential for plant growth (e.g., K, phosphorus [P], Ca, Mg), showing promise as a soil nutrient supplement.[28] (iii) Structural property: Rich in amorphous SiO_2 and Al_2O_3, it exhibits pozzolanic activity, and its particle characteristics can help improve soil aggregate structure.[29,30] These properties enable the graded and classified resource utilization of different ash types. For instance, low-risk, high-nutrient ash can be used for farmland improvement, while ash with specific particle sizes may be developed into water treatment media or eco-friendly building materials.[9]

As summarized in Table 1, straw-based biomass ash tends to be richer in Si, K, and P, whereas woody biomass ash contains more Ca and Mg and is more alkaline. Mixed-fuel ash usually exhibits a more balanced but less predictable composition.

The significant variation in ash composition with feedstock and combustion conditions leads to diverse resource utilization pathways and management strategies, highlighting that high-value utilization should be pursued based on source classification and quality grading.[21]

Because these compositional differences directly influence both resource value and environmental risk, biomass ash utilization should be guided by source classification and quality grading. The following sections therefore summarize the major differences associated with fuel source, combustion process, and ash type, and explain how these differences affect potential utilization pathways and risk-control requirements.

(i) Differences in fuel sources

Biomass ash from different feedstocks exhibits substantial differences, necessitating identification and differentiation during resource utilization.

- Forestry residues/woody biomass ash: Generally considered a high-quality resource, with relatively low

Table 1. Comparison of the chemical composition of biomass ash from different fuel types

Fuel type	SiO_2	CaO	MgO	K_2O	P_2O_5	Main characteristics
Straw-based	High	Low	Low	High	High	Rich in silicon, potassium, and phosphorus
Woody	Medium	High	High	Low	Low	Rich in calcium and magnesium, highly alkaline
Mixed fuel	Relatively high	Relatively high	Medium	Medium	Medium	Well-balanced composition

Note: The entries represent relative compositional trends summarized from Refs.[1,20,26], rather than fixed thresholds, because ash composition varies with feedstock and combustion conditions.

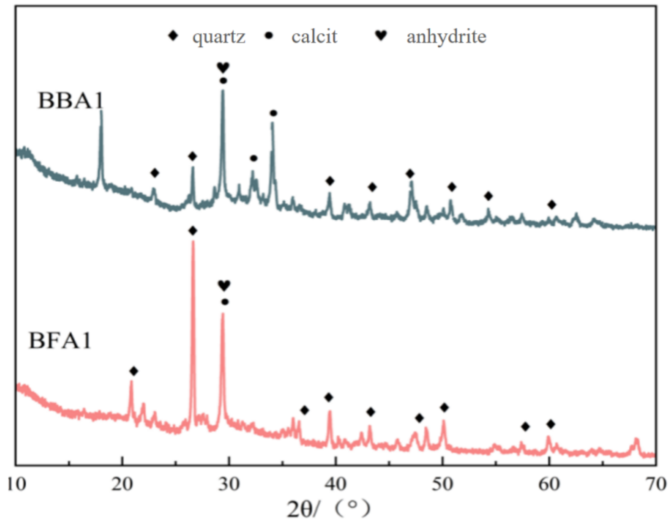

Figure 2. Comparison of representative X-ray diffraction patterns for bottom ash (BBA) and fly ash (BFA)

contents of heavy metals (e.g., Cd, Pb, Hg) and organic pollutants such as polycyclic aromatic hydrocarbons, while being rich in nutrients such as potassium and calcium. This makes it the preferred material for soil remediation.

- Agricultural waste ash (e.g., straw): Often has higher nutrient contents, especially potassium, but may also contain elevated concentrations of Cl and Si, posing a salinization risk. Some studies also reported concerns regarding heavy metals, particularly arsenic (As).[22]
- Mixed or contaminated fuel ash (e.g., waste wood): Carries a relatively high risk, potentially containing heavy metals (chromium [Cr], copper [Cu]) and organic pollutants (polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins and dibenzofurans) from paints and preservatives.[31] Its application in soil remediation, especially agricultural soil, requires extreme caution.

(ii) Differences in combustion process and ash type

Bottom ash is generally coarse-grained and has higher alkalinity, but has relatively low nutrient content and high silicon content. Its slow-release properties make it suitable as a long-acting soil conditioner. In contrast, BFA is fine-grained with a large specific surface area, rich in readily soluble nutrients like potassium and sodium, and exhibits a rapid liming reaction. However, it poses dust emission risks and often requires stabilization (e.g., granulation) before application. Therefore, source classification and detailed characterization of BFA are prerequisites for its safe resource utilization. Overall, the heterogeneity of biomass ash properties confirms that source-oriented classification is essential for determining appropriate utilization pathways and risk-control measures.

4. Regulatory and policy background for the resource utilization of biomass ash

The primary challenge in utilizing biomass ash as a resource lies in defining its legal status. Regulations and policies are key drivers for transforming biomass ash from "waste" to "resource," with active legislative exploration underway both in China and internationally. Among international frameworks, the EU provides a leading reference due to its integrated system combining the WFD, circular-economy legislation, and the FPR. The EU has developed influential legal pathways for determining "by-product" and "end-of-waste" status, creating a structured basis for moving certain ash-based materials from waste management to regulated product use. While other regions have also explored ash utilization (e.g., in agriculture, forestry, and construction), the EU offers one of the most systematic and legally transparent models linking waste governance to resource recovery. Consequently, this review uses the EU as the principal benchmark for in-depth policy analysis, with practices from other regions mentioned for context where relevant.

4.1. Current regulations and taxation policies in China

China employs economic instruments for solid waste management primarily through the Ecological and Environmental Code of the People's Republic of China. The law mandates that enterprises discharging taxable solid waste (including BFA and slag) directly into the environment must pay an environmental protection tax based on discharge volume. Conversely, tax exemptions are available for storage, disposal, and comprehensive resource utilization that comply with national and local environmental protection standards. This policy explicitly links economic costs to environmental responsibilities, strongly incentivizing power generation enterprises to pursue ash utilization. A representative case from Guigang, Guangxi Province in China, involves a biomass cogeneration project in the Qintang Industrial Park using agricultural and forestry residues (e.g., sugarcane leaves, straw, eucalyptus branches) to supply green electricity and centralized heat. According to local tax authority reports, the project has established a circular biomass-energy model at the park level. The enterprise received value-added tax refunds of approximately RMB 11.5 million and total tax relief (covering value-added tax, corporate income tax, and environmental protection tax) exceeding RMB 15 million.[7] Although public data does not isolate the environmental protection tax reduction solely attributable to ash utilization, this case demonstrates how China's green tax policies and resource-utilization incentives can support circular industrial development, consistent with the Ecological and Environmental Code.[8]

At the national level, the State Council's 2025 Action Plan for the Comprehensive Management of Solid Waste provides a systematic framework for solid waste governance in China. Adhering to the principles of reduction, resource utilization, and harmless treatment, the plan emphasizes whole-process management from generation to disposal. It calls for targeted remediation in key sectors and guides the enhancement of comprehensive management capacity through improved laws/standards, strengthened supervision, and better economic policies.[32] To clarify how regulatory instruments support different biomass ash utilization pathways, the policy-support framework is summarized in Figure 3.

Considering current policy and technological trends, promoting large-scale and industrialized on-site ash treatment is considered the most effective approach.

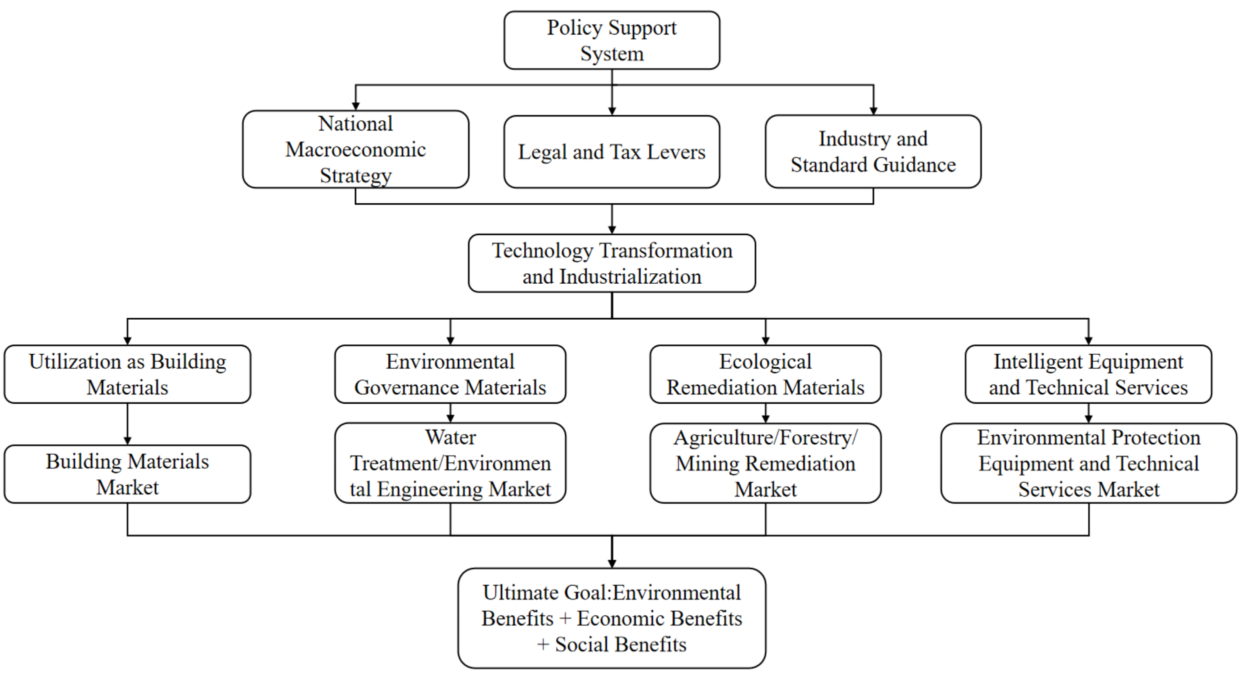

Figure 3. Policy support framework and different utilization pathways for biomass ash resource utilization

Advances in modification technologies for different BBA particle sizes could enhance its value as an environmental functional material. Developing integrated systems for intelligent collection, automatic screening, and resource utilization is crucial for supporting multi-objective utilization pathways.

4.2. Advanced European Union practices and legislative frameworks

Under the EU's WFD, BFA is typically classified as waste (codes 100101 and 100103), restricting its free circulation and resource application. The EU has established a mature legislative framework for waste valorization, introducing the concepts of "by-products" and "end-of-waste" status.[6] A substance can be deemed a by-product (exempt from strict waste rules) if it meets four cumulative criteria: certainty of further use, direct usability without further processing, integration into a production process, and compliance with environmental/health requirements. Furthermore, waste that undergoes recovery and meets specific standards can achieve "end-of-waste" status, allowing free circulation as a product. Revisions to the *EU's* FPR aim to include compliant ash-based materials into "Component Material Categories," enabling their marketing as "European Community fertilizers" within the EU internal market, thus providing a policy pathway for bio-based soil inputs, including ash.[33,34]

A concrete example comes from Finland. Under its fertilizer product framework, ash fertilizers intended for forest use must meet minimum nutrient requirements and maximum heavy metal limits. Using waste ash in forests generally requires a separate environmental permit. Recent guidance indicates that the Finnish Food Authority decides whether an end-of-waste fertilizing product can be used in forest fertilization. In practice, this means that only ash materials transitioning from waste status to a regulated fertilizing product can be applied in forestry. Finnish case studies show wood-ash fertilization can improve growth in peatland forests, demonstrating how regulated ash products can be used under a controlled national framework.[35,36]

A similar practice-oriented approach exists in Sweden. Guidance from the Swedish Forest Agency recommends compensatory fertilization after forest fuel extraction, prioritizing ash recycling, while specifying quality requirements, environmental precautions, and documentation for ash applied to forest land. This shows that practical ash reuse in forestry depends not only on EU-level concepts like by-product status, but also on detailed national guidance governing ash quality and application conditions.[37]

4.3. Regulatory challenges and prospects

Despite clear policy directions, practical challenges persist. China currently lacks mandatory national standards for the agricultural or ecological use of biomass ash, including pollutant limits and application guidelines tailored to different soil types and scenarios. Consequently, enterprises lack operational guidance, and regulators lack enforcement bases. Future efforts should leverage EU experience to accelerate the formulation of *Technical Specifications for Ecological Utilization of Biomass Ash*, clarifying transformation pathways, quality thresholds, and risk assessment methods.[5]

These regulatory and policy conditions define the institutional boundary for biomass ash valorization and provide the basis for evaluating its specific ecological restoration pathways, discussed next. Table 2 compares the

Table 2. Comparison of regulatory and policy frameworks for biomass ash utilization in China and the European Union (EU)

Aspect	China	EU	Key difference	Implication for biomass ash utilization
Legal status	Managed mainly under solid waste governance and utilization policy guidance	Waste classification may be modified through by-product or end-of-waste routes	The EU has more explicit legal transition pathways	Legal clarity determines whether ash can enter practical resource-use channels
Policy basis	Ecological and Environmental Code; Action Plan for Comprehensive Management of Solid Waste	WFD; FPR	The EU framework is more product- and status-oriented	China needs more detailed operational criteria
Application control	Limited scenario-specific standards	More explicit qualification logic	EU provides clearer market-entry pathways	Standardized application criteria are crucial for large-scale use
Main challenge	Lack of mandatory technical standards	Compliance complexity	China lacks standards; the EU has higher regulatory specificity	Both require better alignment of regulation and technical feasibility

Note: The EU is selected as the principal international benchmark due to its comparatively mature legal framework for by-product recognition, end-of-waste determination, and fertilizer market access.

main regulatory frameworks for biomass ash utilization in China and the EU, highlighting differences in regulatory logic, practical implications, and remaining limitations.

5. Resource utilization pathways of biomass ash in ecological restoration

Owing to its unique physicochemical properties, biomass ash exhibits diverse application prospects in ecological restoration, representing a significant pathway for high-value utilization.

5.1. Acidic soil amendment and fertility enhancement

Soil acidification, particularly in southern China's red and yellow soils, is a growing concern.[38] The alkalinity of biomass ash can effectively neutralize soil acidity at a lower cost than traditional lime, while simultaneously supplying nutrients.[39,40] In particular, BFA may have potential as a phosphorus fertilizer source, although its effects on soil microbiota and crop response depend on ash properties and application conditions.[41] Studies have shown that biomass ash and related alkaline amendments can increase soil pH, reduce acidity-related constraints, and improve soil nutrient availability in acid soils.[42-44] Field-scale evidence further indicates that biomass ash can partly substitute for conventional lime and improve soil properties, plant growth, forage production, or soil biological responses under appropriate application rates.[45-47] Baloch *et al.*[48] systematically summarized the mechanisms and application potential of woody biomass ash in crop production, soil acidity amelioration, and contaminated-environment remediation, highlighting its sustainability when application rate and pollutant risks are properly controlled. For instance, Shi *et al.*[49] confirmed the effectiveness of biomass ash in ameliorating red soil acidity. Silicon in ash can promote soil aggregate formation, improving water and nutrient retention as well as soil physical structure.[50,51]

International studies corroborate the agricultural potential of biomass ash. Żołnowski *et al.*[52] reported significant yield increases and improved nutrient quality of maize silage following BFA application. Szostek *et al.*[53] further showed that BFA from biomass combustion could influence spring rape growth, nutrient and trace element accumulation, and soil properties, indicating its agronomic potential under controlled application conditions. Biochar, another biomass-derived material, has also improved soil physicochemical properties and nutrient retention, though its mechanisms and application differ from biomass ash, and it is mentioned here for comparative context only.[54,55]

Typical application case: An eight-year Austrian grassland field trial applied biomass ash at 500 kg ha^{-1} $year^{-1}$ (the legal maximum for grassland), either alone or with cattle slurry. Results showed biomass ash performed comparably to carbonated lime, and the ash-slurry combination maintained higher forage yields than the unfertilized control. This case indicates that low-dose, repeated ash application can serve as a practical amendment for acidic grassland soils under managed agriculture.[45] Overall, biomass ash is most suitable for acidic soil amendment when its alkalinity and nutrient content are high, and pollutant levels are controlled.[40]

5.2. Immobilization of heavy metals in contaminated soils

Biomass ash also shows potential in remediating heavy metal-contaminated soils.[56] Its mechanisms include: (i) pH elevation, promoting precipitation of heavy metals as hydroxides or carbonates; and (ii) adsorption and co-precipitation, facilitated by porous structures and components such as SiO_2, Al_2O_3, and Fe_2O_3. Liang *et al.*[57] found reduced Cd bioavailability in red soils amended with biomass ash, while Song *et al.*[58] enhanced Cd immobilization using modified ash. Rolka *et al.*[59] demonstrated significant reductions in Cd, Pb, and Zn bioavailability using woody biomass ash. Zhao *et al.*[60] showed synergistic effects of ash and phosphate in immobilizing Cu and Pb. Studies suggest BFA, with higher amorphous content and pozzolanic activity, may perform better in immobilization.[26] Ash can also neutralize acidic mine drainage, immobilize metals, and support vegetation restoration, making it suitable for mine subsidence areas and tailings ponds. Reviews indicate soil amendments reduce heavy metal bioavailability through multiple pathways, though effectiveness depends on contamination type, soil properties, and amendment characteristics.[61] Similarly, amendment-based remediation studies have shown that appropriate soil amendments can reduce Cd bioavailability and influence soil enzyme activity, further supporting the need to match amendment type with soil conditions and contamination characteristics.[62]

A representative field-scale application was reported in a Cd-contaminated paddy field in Xiangtan, China, where a novel ash–biochar biocomposite (90% BBA, 5% animal-derived biochar, 5% bentonite) was applied at 1, 5, and 10 kg m^{-2}. At application rates of ≥ 5 kg m^{-2}, soil pH increased from 4.11 to >6.0, available silicon content rose markedly, and Cd accumulation in rice was effectively reduced. This demonstrates the practical potential of ash-based composites for *in situ* Cd immobilization in acidic paddy soils.[63] Thus, the effectiveness of biomass ash depends not only on its alkalinity and reactive minerals but also on pretreatment, contamination type, and site-specific soil properties.[64,65]

5.3. Integrated restoration of mined lands, degraded forest lands, and other disturbed sites

In degraded ecosystems such as mined lands, degraded forest lands (e.g., affected by acid deposition or nutrient depletion from intensive harvesting), and other disturbed sites, biomass ash can offer multiple benefits. These environments often suffer from soil acidification, nutrient depletion, and poor substrate quality, limiting vegetation establishment. Ash application can help neutralize acidity, supply base cations and essential nutrients, and improve substrate chemical conditions.[66,67] Specifically, certain forest ecosystems degraded by long-term acid deposition, excessive biomass removal, fire, or pests may benefit from the targeted application of clean woody ash, aiding recovery by restoring removed nutrients and alleviating soil acidity. This practice, reported in northern European countries, exemplifies a circular approach to nutrient return in forest management.[6,36,37] Returning ash from harvested wood to forest soils compensates for nutrient removal and maintains long-term productivity.[36] Studies indicate woody biomass ash influences soil physicochemical properties and microbial communities, affecting forest soil ecological processes.[46,48] This practice is well-established in Sweden and Finland[6,37], illustrating circular economy principles in ecosystem management. Industrialized on-site ash treatment and integrated equipment systems are key for scaling up ecological restoration applications.[68]

Given these functions, biomass ash has been tested in several field-scale restoration contexts, including mine-tailings revegetation and forest-soil nutrient restoration. The following representative cases illustrate how application rate, site conditions, and ash quality influence restoration outcomes.

(i) Mine-site restoration: A multi-year trial on historic gold mine tailings in Northern Ontario, Canada, evaluated high-carbon wood ash biochar (0–30 t ha^{-1}) after planting native jack pine. Sapling survival and growth peaked at 3–6 t ha^{-1}, while the highest rate (30 t ha^{-1}) increased the risk of contaminant accumulation in some plant tissues, suggesting low-to-moderate application rates are preferable for tailings revegetation.[69]

(ii) Forestry restoration: In northern Finland, wood ash (5 Mg ha^{-1}) applied to former peat-based agricultural land afforested with Scots pine increased stand volume by 35 m^3 ha^{-1} over 21 years. Combining ash with weed control increased volume by 55 m^3 ha^{-1}, demonstrating long-term restoration potential in nutrient-deficient peat soils.[36]

Together, these findings suggest that biomass ash is particularly promising in degraded ecosystems requiring simultaneous pH adjustment and nutrient supplementation. The major ecological restoration pathways are summarized in Figure 4. Table 3 compares these pathways, summarizing mechanisms, benefits, risks, and control measures.

As shown, the ecological restoration use of biomass ash is technically promising across multiple scenarios, but practical feasibility depends on proper source classification, necessary pretreatment/stabilization, scenario-specific application, and post-application monitoring.

6. Major risks and control strategies

While recognizing the utilization potential of biomass ash, associated risks and challenges must be addressed.

6.1. Environmental risks associated with biomass ash application

6.1.1. Toxic elements: Cd, Pb, and other priority pollutants

Environmental safety risks are primary constraints. Among hazardous components, Cd and Pb are priority toxic elements because of their toxicity, mobility, and potential for food-chain transfer. Elements like As and Cr may also require attention depending on fuel and combustion conditions. Leaching behavior is highly pH-dependent, with Cd-, Pb-, and As-related risks being particularly concerning in some ash fractions.[65,70,71] Therefore, systematic pollutant detection, source classification, and risk grading are essential before field application.

6.1.2. Dual-role elements: Cu and Zn

Unlike Cd and Pb, Cu and Zn are essential micronutrients but can become toxic at excessive or mobile concentrations.[59,65] Their risk assessment cannot rely solely on total concentration; it must consider chemical speciation, leachability, soil pH, and background nutrient status. Thus, Cu and Zn should be managed separately from strictly toxic elements, with application thresholds linked to land-use type and amendment rate.

6.1.3. Short-term leaching risk of soluble salts

An often-underemphasized risk is the short-term release of soluble salts, particularly chloride- and potassium salts (e.g., KCl). Ash can contain elevated soluble K, Na, Mg, and Cl, increasing soil electrical conductivity and potentially causing transient salinity or osmotic stress, especially with fresh BFA, fine fractions, or poorly buffering soils.[21,70,71] Granulation, carbonation, and stabilization can reduce electrical conductivity and soluble chloride hazards, indicating that pretreatment is a crucial control step.[21,60,70]

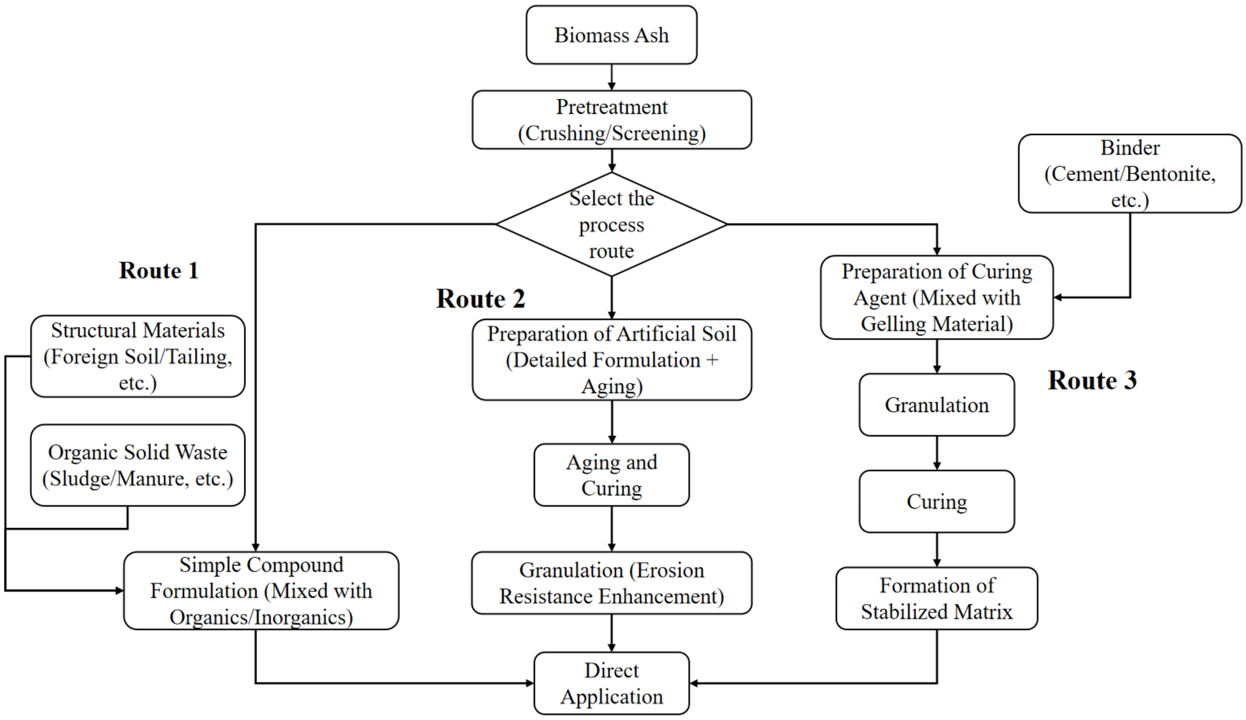

Figure 4. Schematic diagram of pathways for using biomass ash in ecological restoration.

6.1.4. Long-term nutrient accumulation and potential eutrophication risk

Beyond short-term salt release, long-term accumulation of nutrients like P and K must be considered. While biomass ash can improve nutrient supply, repeated or excessive application may increase plant-available P and exchangeable K, raising the risk of runoff losses.[40,72,73] As phosphorus enrichment drives eutrophication, long-term ash utilization should be assessed for catchment-scale nutrient export risk, particularly in drained soils, coarse-textured, or sloping soils near ditches, streams, or reservoirs. Scenario-specific application rates and long-term soil-water monitoring are essential.[66,74]

A practical risk-control framework should integrate source classification, pollutant detection, pretreatment/stabilization, scenario-specific application, and post-application monitoring of both soil and water quality. These differentiated risks indicate that future development should not rely on a single control strategy, but rather on a staged combination of standards, technology, and long-term ecological governance.

6.2. Future research and development directions

6.2.1. Near-term priorities: standards and rapid detection

The most urgent task is improving the regulatory and technical basis for safe use. This involves establishing source-oriented quality standards, land-use-specific application criteria, and clear pollutant thresholds for different ash types and scenarios. Simultaneously, rapid screening tools such as portable X-ray fluorescence should be promoted for routine quality control, supporting efficient pre-application ash assessment.[3,75]

6.2.2. Mid-term priorities: Intelligent equipment and composite products

Medium-term efforts should focus on engineering integration and product upgrading. This includes creating intelligent systems for collection, classification, screening, granulation, and dosing, and designing composite ash-based products tailored to specific restoration needs. Combining ash with organic materials, binders, or other additives can improve nutrient-release profiles, reduce salt-related risks, and enhance field operability.[21,66,68] Optimizing stabilized, granulated products is key for large-scale use in acidic soils, contaminated lands, and mining areas.

6.2.3. Long-term priorities: Life-cycle ecological assessment and carbon accounting

Long-term research should progress beyond proof-of-concept to full life-cycle ecological benefit assessment.

Table 3. Main ecological restoration pathways for biomass ash: mechanisms, benefits, associated risks, and control measures

Utilization pathway	Main mechanism	Expected benefits	Associated risks	Recommended control measures	Suitable application scenarios
Acidic soil amendment and fertility enhancement	Neutralization of soil acidity through alkaline components; supply of nutrients such as Ca, K, P, and Mg; improvement of soil aggregation and physicochemical properties	Increased soil pH; reduced exchangeable Al toxicity; improved nutrient availability, cation exchange capacity, and soil structure; enhanced crop productivity and soil fertility	Excessive application may lead to salinization, alkalization, or accumulation of undesirable elements; performance varies with ash type and fuel source	Source classification; control of application rate; pretreatment and quality testing before use; land-use-specific standards and monitoring of soil chemical properties	Acidified agricultural soils, red and yellow soils, nutrient-deficient soils
Immobilization of heavy metals in contaminated soils	Increase in soil pH promotes precipitation of metals; adsorption and co-precipitation by porous ash particles and reactive mineral phases; possible synergistic effects after modification or co-application with other amendments	Reduced bioavailability and mobility of Cd, Pb, Zn, Cu, and other metals; improved soil conditions for plant establishment; support for contaminated land remediation	Biomass ash itself may contain trace metals or leachable contaminants; inappropriate application may increase environmental risk instead of reducing it	Pollutant detection and risk classification before use; stabilization or modification treatments; matching ash properties with contamination type and soil characteristics; post-application monitoring of leaching behavior	Heavy metal-contaminated farmland, mine-affected soils, tailings areas, acidic contaminated soils
Integrated restoration of degraded ecosystems	Simultaneous pH adjustment, nutrient supplementation, and improvement of substrate conditions for vegetation establishment; possible recycling of nutrients removed during biomass harvesting	Enhanced vegetation establishment; improved substrate fertility; partial restoration of nutrient cycles; support for ecological rehabilitation and circular use of biomass residues	Uncertain long-term ecological effects; variable field performance; possible pollutant migration under site-specific conditions; lack of unified operational standards	Scenario-specific application strategies; pretreatment and granulation where necessary; long-term field monitoring; integration with restoration engineering and vegetation management	Mined lands, mine tailings, subsidence areas, degraded forest soils, severely nutrient-poor sites

Note: Compiled by the authors based on the literature reviewed in Sections 5 and 6.

Studies should evaluate long-term changes in runoff water quality, biodiversity recovery, ecosystem function, soil microbial community structure, and potential off-site nutrient transport. Long-term amendment studies have shown that repeated application of alkaline or organic amendments can reshape soil microbial communities, highlighting the need to include microbial indicators in long-term ecological assessment.[76] Incorporating carbon-benefit and carbon-sink accounting is crucial, especially where ash application aids vegetation restoration, forest productivity, or reduced reliance on conventional lime and fertilizers.[36,68,77] A scenario-oriented, long-term assessment framework is vital for determining ecological and climate co-benefits.[66,74,77]

Future research should evolve from fragmented validation toward a standardized, intelligent, and life-cycle-oriented system. Figure 5 proposes a conceptual framework integrating differentiated risk control with staged development priorities.

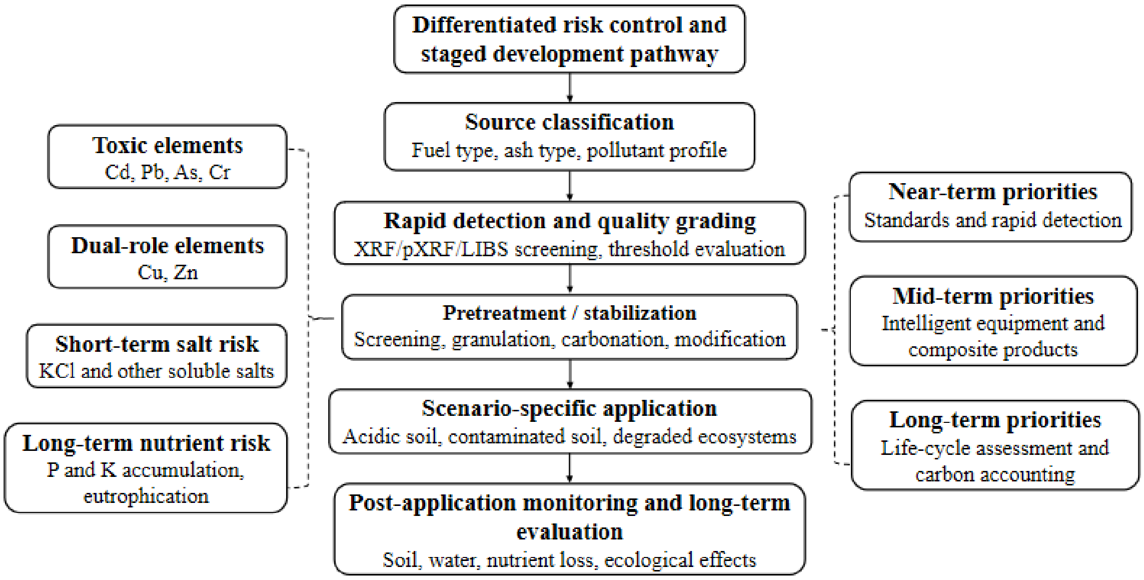

Figure 5. Conceptual framework for differentiated risk control and staged development of biomass ash utilization in ecological restoration.

7. Conclusion

Biomass power plant ash and slag possess significant potential for ecological restoration due to their alkalinity, nutrient content, and soil-conditioning properties. Evidence indicates these materials can contribute to acidic soil amelioration, nutrient supplementation, heavy metal immobilization, and the restoration of degraded ecosystems, representing a promising pathway for coupling waste valorization with ecological rehabilitation.

However, large-scale applications face major challenges, including the absence of unified standards and clear regulatory frameworks, uncertainties regarding pollutant behavior and long-term environmental risks, and techno-economic limitations related to source heterogeneity, pretreatment, transport, and field application. Consequently, transitioning biomass ash from waste to resource requires not only technical feasibility but also robust governance and risk-control systems.

Future efforts should emphasize cross-disciplinary collaboration, full-chain management, and intelligent, precision-based utilization. Priorities include source-oriented classification, rapid detection, pretreatment/stabilization, scenario-specific application, long-term monitoring, life-cycle ecological assessment, and carbon accounting. Through these advances, biomass ash utilization can evolve into a standardized, efficient, and high-value strategy for ecological restoration.

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Conflict of interest

The authors declare that they have no competing interests.

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