

Review

# Turning Waste into Greener Cementitious Building Material: Treatment Methods for Biomass Ashes—A Review

Fatih Bülbül \*  and Luc Courard 

Urban and Environmental Engineering, University of Liège, Quartier Polytech 1—Allée de la Découverte 9, B-4000 Liège, Belgium; luc.courard@uliege.be

\* Correspondence: fbulbul@uliege.be

**Abstract:** The production of biomass ash (BA) is expected to increase in the future, as biomass is generally considered a carbon-neutral fuel. BA potentially concentrates heavy metals and trace elements at high levels. With the growing production of BA, its disposal in landfills or recycling must be addressed through solid waste policies and within the framework of a circular economy. Utilizing BA as a cement substitute solves disposal issues while offering environmental benefits aligned with the circular economy. However, the varying physical and chemical properties of BA, influenced by factors such as biomass type and combustion technique, necessitate more effective utilization strategies. Consequently, researchers are developing various treatment methods to ensure that BA meet the necessary requirements and do not pose problems such as heavy metal or chlorine leaching. These treatments facilitate the production of concrete with higher compressive strength at greater cement replacement levels, supporting greener construction practices. This review consolidates existing BA data and treatment methods, focusing on their impacts and efficiency. It also explores combined treatments and potential new approaches. By providing a foundation for future research and practical applications, this study aims to improve treatment techniques, helping the industry mitigate environmental risks and advance carbon-neutral construction solutions.

**Keywords:** biomass ash; carbonation; cement; grinding; hydrothermal synthesis; leaching; micro-grinding; substitution



Academic Editor: Mohammad Saberian

Received: 6 January 2025

Revised: 10 February 2025

Accepted: 11 February 2025

Published: 14 February 2025

**Citation:** Bülbül, F.; Courard, L. Turning Waste into Greener Cementitious Building Material: Treatment Methods for Biomass Ashes—A Review. *Materials* **2025**, *18*, 834. <https://doi.org/10.3390/ma18040834>

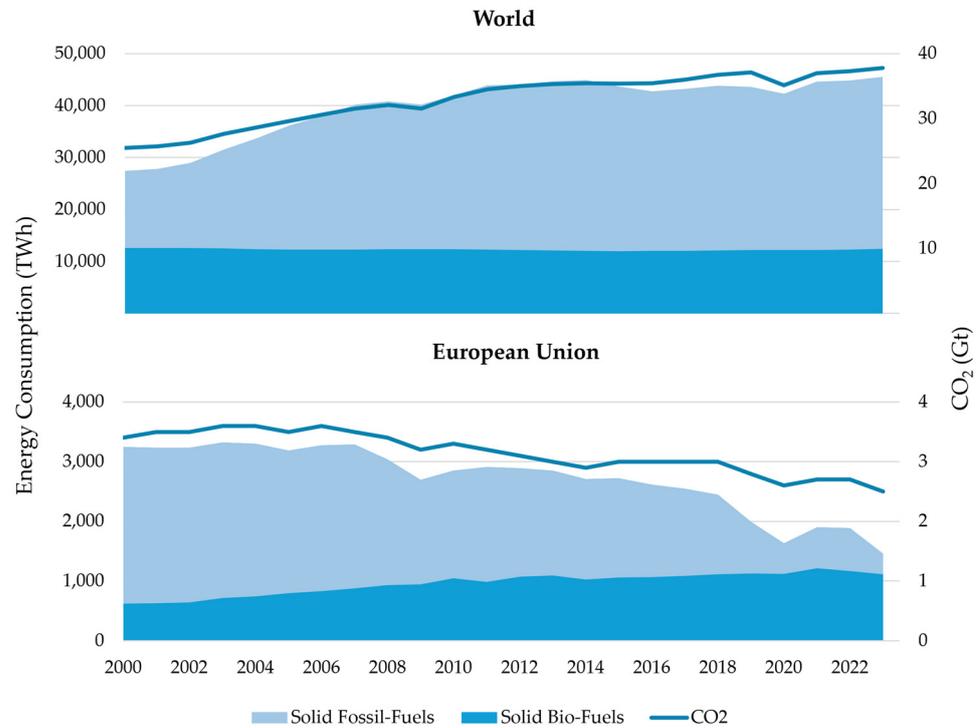
**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Anthropogenic emissions of CO<sub>2</sub> come from three main sources: burning of fossil fuels (coal, oil, and gas), large-scale deforestation, and carbonate decomposition [1]. Coal use in energy and power generation is the factor with the largest share in global CO<sub>2</sub> emissions, with a share of 41% in 2022 [2]. Cement is the largest source of emissions from the decomposition of carbonates [1]. Cement production leads to CO<sub>2</sub> emissions in two main ways. The first is through chemical reactions during clinker production (5% of total annual anthropogenic emissions), where carbonates (limestone, CaCO<sub>3</sub>) transform into oxides (lime and CaO) and CO<sub>2</sub> due to heat [1,3,4]. The second source is from fossil fuels or purchased electricity used to heat raw materials in clinker production. Energy-related emissions make up approximately 60% of process emissions [1,5].

Reducing dependence on fossil fuels is crucial for mitigating environmental issues associated with greenhouse gas (GHG) emissions (Figure 1) [6]. It is essential to address the resulting energy deficit by promoting the use of renewable resources in order to secure future energy needs and minimize environmental impacts [7–9]. There are various

renewable energy sources that can be utilized for energy production [8,10]. Biomass, in particular, garners significant attention due to its widespread availability worldwide and its ease of use in energy production [11]. By 2050, biomass could supply up to 33–50% of the world's current primary energy consumption [12]. In energy production, biomass is considered carbon neutral because the CO<sub>2</sub> emitted when burned is equivalent to the CO<sub>2</sub> absorbed during biomass growth. However, for this to be sustainable, the consumption rate must not exceed the growth rate [13].



**Figure 1.** Comparison of solid fossil fuel and solid bio-fuel consumption and CO<sub>2</sub> emission values for the European Union and the world [2,14–16].

Biomass can be defined as a complex heterogeneous mixture of organic and inorganic matter obtained from living or recently deceased organisms and primarily originates from wood sources, as well as from herbaceous agricultural residues like grasses, flowers, straw, husks, and pits [17,18]. Additionally, it encompasses various specific waste streams, including commercial and construction waste like demolition debris and paper pellets, along with household and industrial organic waste, animal and human biomass waste, and aquatic biomass, such as algae [19]. When biomass is mentioned as feedstock for power plants, some biomasses can be seen to be used more widely, such as forest residues, wood chips, agricultural residues, rice husk, wheat straw, municipal solid waste, sewage sludge, and industrial waste [20–22]. Additionally, specific to certain geographical locations, biomass types such as sugarcane bagasse, palm oil, olive residue, bamboo leaf, banana leaf, marabou weed, and corn cob can be utilized in energy production [23–33]. By utilizing industrial, municipal, agricultural, and forest waste for energy production, biomass contributes to waste management as well as carbon-neutral energy production.

There are several disadvantages to using biomass in energy production as well as advantages; one of the most important is the generation of solid waste [34]. It is estimated that, all around the world, around 480 million tons of ash are produced from biomass-fired power plants every year [12]. The waste produced by power plants is called biomass ash (BA). There are two types of ash produced in biomass-fueled power plants: fly ash, which consists of lightweight particles carried by exhaust gases, and bottom ash, which

consists of heavier unburned or partially burned particles found in the form of slurry or slag [17,34]. BA is a mixture containing complex organic and inorganic materials, including minerals and carbon-based substances in crystalline, semi-crystalline, or non-crystalline phases [8,18].

At present, BA is primarily disposed of in landfills, leading to environmental concerns such as pollution, land degradation, and the aesthetic deterioration of surrounding areas [35,36]. As the amount of ash produced increases, so do the costs of storage [8]. To mitigate these challenges and derive economic benefits, BA has been widely utilized across various industries, including construction, agriculture, environmental remediation, waste management, and the production of ceramics and glass [8,35,37]. Its high alkalinity and surface charge enable the effective adsorption of heavy metals from wastewater, while the presence of unburnt carbon enhances its capacity to capture organic pollutants and flue gas contaminants [38–40]. Furthermore, BA serves as a valuable raw material in the production of geopolymers, ceramics, and glass-ceramics, where its mineral composition improves thermal stability and mechanical properties [41–43]. Modified BA-based materials have also demonstrated significant potential in phosphate removal from wastewater and mercury capture from flue gases [42,44]. Additionally, the presence of iron oxides and other magnetic minerals expands its applications to metallurgy and ore processing [41,42]. Moreover, BA has been effectively incorporated as a cost-efficient and sustainable binder in backfill materials for mining applications, enhancing their mechanical strength and permeability. By reducing cement consumption in backfill formulations, BA not only improves material performance but also supports resource efficiency and lowers the environmental footprint of mining operations [45–47].

In the construction industry, BA is commonly used as a supplementary cementitious material (SCM) in cementitious composites. The high content of minerals such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{CaO}$  in BA imparts pozzolanic and hydraulic activity, making it a desirable material. Although numerous studies have demonstrated that BA can positively affect concrete's strength, durability, thermal conductivity, and acid resistance, it can also contain harmful substances that adversely impact its properties [48,49]. Various treatment methods are employed to reduce the harmful substances in BA and to enhance its reactivity, allowing for higher cement replacement ratios and the production of higher-performance concretes. This study aims to provide a thorough investigation of the treatment methods used for BA, as well as their influence on its characteristics and applications in ash-based concrete. The research presents and compares different treatment techniques, outlining how they modify specific properties and processes. Additionally, it will review the results from prior studies that have employed these methods, offering insights into the effectiveness and outcomes observed. Finally, the study will assess the combined impact of these methods by analyzing findings from earlier research, with a focus on optimizing the performance of BA in concrete applications.

## 2. Properties of Biomass Ash

BA refers to the solid waste produced as a result of the combustion of various types of biomass. Similar to coal ash, BA is composed of fly ash and bottom ash, depending on where the ash accumulates. Biomass fly ash (BFA) is a fine ash fraction that is carried by the flue gases from the biomass combustion chamber and captured by emission control devices such as electrostatic precipitators or bag filters, typically possessing an average particle size ranging from 4  $\mu\text{m}$  to 100  $\mu\text{m}$ , and biomass bottom ash (BBA) is a coarse ash fraction that is accumulated at the bottom of the combustion chamber [50,51].

It is well recognized that even within the same biomass type, factors such as growth conditions, plant maturity, pesticide application, harvest timing, soil characteristics, con-

tamination levels, and the specific plant part utilized can influence ash composition [51–55]. Table 1 presents the minimum, maximum, and average values of major oxides for woody and herbaceous biomasses, highlighting the chemical composition variations between different parts of the same biomass and the effects of filtration and treatment techniques on ash composition. Vassilev et al. [55] demonstrated that BA has the potential to contain elements from nearly the entire periodic table. However, the chemical composition of BA, while showing variability in relative concentrations, primarily consists of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, MgO, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, and SO<sub>3</sub> compounds [12,54,56,57].

The mineralogical composition of BA is characterized by the presence of various secondary mineral phases, including silicates, oxides and hydroxides, sulfates, phosphates, carbonates, chlorides, and nitrates [12,58,59]. The dominant crystalline phases commonly identified in BA include quartz, calcite, sylvite, arcanite, anhydrite, char, glass, lime, periclase, and hematite [12,60]. The mechanisms of silicate formation in BA are quite similar to those in coal ash [61]. Likewise, oxides and hydroxides in BA develop through mechanisms comparable to those in coal fly ash (CFA). These phases primarily emerge from the breakdown and oxidation of organic matter, as well as from the transformation of oxalates, carbonates, phosphates, sulfates, chlorides, and nitrates. Additionally, crystallization of molten material during combustion contributes to the formation of these mineral phases [18]. In contrast, iron compounds such as siderite and hematite have only been observed in forest residue ash [19,60]. Furthermore, some oxy-hydroxides remain unchanged during biomass combustion due to their high melting/decomposition temperatures, persisting as primary minerals in the ash [12].

**Table 1.** Chemical characteristics (main oxides) of BA depending on variables such as biomass type, biomass part, combustion technique, combustion stage, fuel mix, and treatment (forest r.: forest residue).

Ash Type	Main Oxides (%wt)												
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	MgO	SO <sub>3</sub>	MnO	Na <sub>2</sub> O	Cl	TiO <sub>2</sub>	LoI
Woody biomasses (minimum) [53]	1.86	0.12	0.37	5.79	0.66	2.19	1.10	0.36	-	0.22	-	0.06	-
Woody biomasses (average) [53]	22.22	5.09	3.44	43.03	3.48	10.75	6.07	2.78	-	2.85	-	0.29	-
Woody biomasses (maximum) [53]	68.18	15.12	9.54	83.46	13.01	31.99	14.57	11.66	-	29.82	-	1.20	-
Herbaceous and agricultural biomasses (minimum) [53]	2.01	0.10	0.22	0.97	0.54	2.29	0.19	0.01	-	0.09	-	0.01	-
Herbaceous and agricultural biomasses (average) [53]	33.39	3.66	3.26	14.86	6.48	26.65	4.02	3.61	-	2.29	-	0.18	-
Herbaceous and agricultural biomasses (maximum) [53]	94.48	14.60	36.27	44.32	31.06	63.90	16.21	14.74	-	26.20	-	2.02	-
Wood pellets (spruce) [62]	24.70	5.30	3.20	25.80	4.90	7.90	9.30	-	1.00	2.30	-	0.40	9.70
Pine bark [53]	9.20	7.20	2.79	56.83	5.02	7.78	6.19	2.83	-	1.97	-	0.19	-
Pine chips [53]	68.18	7.04	5.45	7.89	1.56	4.51	2.43	1.19	-	1.20	-	0.55	-
Pine prunings [53]	7.76	2.75	1.25	44.10	5.73	22.32	11.33	4.18	-	0.42	-	0.17	-
Pine sawdust [53]	9.71	2.34	2.10	48.88	6.08	14.38	13.80	2.22	-	0.35	-	0.14	-
Rice straw [53]	77.20	0.55	0.50	2.46	0.98	12.59	2.71	1.18	-	1.79	-	0.04	-
Rice husk [53]	94.48	0.21	0.22	0.97	0.54	2.29	0.19	0.92	-	0.16	-	0.02	-
70% forest r. and 30% peat [63]	52.20	11.00	4.80	16.00	1.70	2.90	3.50	1.70	-	2.10	0.10	-	3.20
60% forest r., 30% recycling waste, and 10% paper sludge [63]	39.40	12.10	4.90	23.00	1.30	2.40	3.10	6.90	-	2.90	0.40	-	0.70
50% forest r. 40% peat, and 10% recycled wood waste [63]	43.80	7.40	2.60	21.10	3.00	6.50	3.40	6.30	-	2.10	0.30	-	5.40
70% forest r. and 30% peat (air-classified) [63]	53.70	11.10	4.70	15.10	1.60	2.90	3.30	1.40	-	2.10	0.10	-	2.90
60% forest r. 30% recycling waste, and 10% paper sludge (air-classified) [63]	49.70	13.60	5.30	14.50	0.90	2.60	2.20	2.40	-	2.90	0.10	-	3.90
50% forest r., 40% peat, and 10% recycled wood waste (air-classified) [63]	56.50	8.80	2.80	13.80	1.80	5.90	2.30	2.20	-	2.20	0.10	-	3.30
Pine sawdust and chips (from wood burning) [64]	9.51	2.67	2.65	5.87	0.89	1.42	1.69	-	0.71	-	-	0.28	74.31
Pine sawdust and chips (from generated ash) [64]	25.06	12.28	8.05	9.90	1.60	3.99	2.60	-	0.69	1.33	-	3.00	31.50
Pine sawdust and chips (from ash disposal) [64]	21.56	10.73	7.82	4.60	0.85	3.03	1.36	-	0.46	0.12	-	1.61	58.59
Wood pellet [65]	3.22	1.07	1.31	42.38	3.23	4.57	4.87	0.59	4.73	0.11	0.07	0.07	-
Wood pellet (calcining and milling) [65]	3.97	1.18	1.44	53.33	5.01	4.19	8.67	0.52	7.20	0.09	0.06	0.09	-
Wood chips (bottom ash) [66]	25.10	4.51	2.28	44.60	4.96	10.20	4.73	-	0.83	0.58	-	0.19	5.40
Wood chips (electrostatic precipitator) [66]	13.50	3.18	1.64	30.90	4.13	18.20	3.70	-	0.41	0.70	-	0.17	21.1
Wood chips (bottom ash) [66]	35.80	0.98	0.79	51.10	3.51	7.31	1.48	-	0.35	0.43	-	0.07	3.51
Wood chips (cyclone filter) [66]	17.90	1.31	8.98	55.00	1.92	1.18	1.27	-	0.31	0.47	-	0.10	30.20

Table 1. Cont.

Ash Type	Main Oxides (%wt)												
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	MgO	SO <sub>3</sub>	MnO	Na <sub>2</sub> O	Cl	TiO <sub>2</sub>	LoI
Woody (grate combustion) [67]	11.00	2.40	2.90	53.60	2.90	14.60	4.20	5.40	-	1.00	0.80	-	15.00
Woody (grate combustion—washed) [67]	12.70	3.00	3.20	65.00	3.80	4.40	5.80	1.30	-	1.00	0.00	-	19.60
Woody (circulating fluidized bed) [67]	23.80	5.60	3.10	44.70	3.80	7.60	4.10	6.10	-	0.80	0.40	-	16.20
Woody (circulating fluidized bed—washed) [67]	26.50	6.30	3.30	45.00	4.20	5.70	4.40	3.70	-	0.90	0.00	-	19.70
Wood and peat [68]	41.80	13.10	13.60	16.30	3.50	2.30	2.50	2.10	-	2.10	0.10	0.50	0.30
Wood and peat [68]	30.80	15.10	26.70	12.00	4.90	1.60	2.50	3.50	-	1.10	0.10	0.40	1.50

Sulfates also play a significant role in the mineralogical composition of BA, formed through interactions between acidic gases and oxides produced during combustion [12]. Additionally, sulfates can form through the interaction of newly generated phosphates with oxides during combustion. Carbonates and amorphous materials (glass) are the final major phases present in BA. Minerals rich in calcium, particularly calcite, anhydrite, and dolomite, are prevalent in BA, which is largely attributed to the naturally high calcium content found in woody biomass [60]. In addition, the formation of an amorphous glassy phase occurs as inorganic components melt during combustion and subsequently solidify upon rapid cooling [12,69,70].

The composition and properties of BA, including its chemical and mineralogical makeup, glass content, unburned carbon levels, elemental distribution, and particle density, are shaped mainly by combustion parameters such as temperature, duration, air-to-fuel ratio, fuel particle size, and combustion rate [12,56,57,59,70]. A study published by Baxter et al. [71] described the properties of BA and its combustion behavior for various biomass fuels. Their study analyzed ash samples from various boiler sections, identifying key inorganic elements like Si, K, Ca, Na, Al, Mg, Fe, S, P, and Cl. Biomass ash formation temperatures vary more widely and are generally lower than coal's, yet the mechanisms of fundamental phase-mineral transformation show similarities [61]. High Ca, Al, and Ti, along with low contents of K, Si, P, S, Fe, Na, and Mg, contribute to an increased biomass combustion temperature (around 1100 °C). The ash formation process in biomass follows a series of phase-mineral transformations, starting with the generation of intermediate and less-stable compounds such as chlorides, hydroxides, carbonates, sulfates, and phosphates, along with amorphous inorganic materials. This is followed by the development of silicates and glass phases incorporating various salts, eventually leading to the carbonation of newly formed mineral structures. The formation pathways of glass, amorphous phases, char, organic minerals, and other inorganic components are linked to rising combustion temperatures [18]. Specifically, organic material combustion occurs between 200–850 °C, particle fragmentation initiates at 500 °C, particle agglomeration occurs between 700–1300 °C, and mineral fusion progresses in stages: initial melting at 700 °C, extensive fusion between 900 and 1100 °C, complete fusion at 1100–1500 °C, new phase crystallization between 500 and 1500 °C, and molten glass formation between 700 and 1500 °C [18].

During biomass combustion, certain heavy metals volatilize and later condense into the finer fractions of BFA as the material cools [12,72]. This process facilitates the incorporation of elements such as Cd, As, Pb, Ni, Hg, Cr, Cu, Mn, and Zn into the ash matrix, making their presence a significant concern in terms of environmental impact [55]. These potentially hazardous elements typically accumulate in biomass from external sources like soil, pesticides, and fertilizers. Upon combustion, they become mobilized, forming water-soluble compounds in the final BFA. Additionally, combustion conditions influence the unburned carbon content in BFA, the proportion of residual organic material to inorganic matter, and the overall nutrient composition of the ash [52,69].

The physical properties of BA, like its chemical characteristics, vary depending on the type of biomass. The average particle size of BA can range from 0 to 10 mm [49].

Particle size affects the reactivity and workability of the ash. BA also exhibits variations in properties such as density and water absorption. However, it generally tends to have a lower density and higher water absorption compared to inorganic materials like sand and cement. The combustion time and temperature also influence the morphology, texture, and porosity of the ash [73].

### 3. Expectation of Biomass Ash as a Supplementary Cementitious Material

In Europe, the determination of whether BA (non-reactive, non-hazardous, or hazardous) is disposed of in a landfill depends on the leaching concentrations of trace elements [74,75]. BA should be treated as controlled waste in commercial–industrial environments both in the EU and globally [76]. Moreover, contemporary management schemes prefer the recycling of industrial solid waste rather than its disposal [75,76]. Many different articles mention that BA reduces costs for cementitious composites, decrease carbon emissions, provide lower thermal conductivity, and lead to the production of more durable and lightweight elements. This makes BA desirable for SCMs.

BA is utilized as cement substitution, depending on its physical and chemical properties [11,77–81]. The positive effects of using BA as cement substitution on the various properties of cementitious mixtures have been demonstrated in numerous studies [81,82]. However, not all forms of BA exhibit strong pozzolanic reactivity due to their specific chemical and physical characteristics, and some may contain compounds that could be detrimental to cementitious mixtures.

There are currently no established standards for the use of ashes derived from biomass combustion in cementitious mixtures. Due to this lack of specific guidelines, the most practical approach is to apply the standards used for coal ash and natural pozzolans when incorporating biomass ashes into cementitious mixtures. These include standards such as ASTM C618-23 and EN 450-1 [83,84].

Classifying BA according to European and American standards is a complex task, as the two standards have similar yet distinct limitations as shown in Table 2. While some forms of BA, typically classified as Class F, meet the required physical and chemical properties for compliance with these standards, variations in oxide and calcium content often prevent classification in a broad context. These compositional differences pose challenges in aligning different forms of BA with established standards. Based on the 86 types of biomasses identified by Vassilev et al. [53], Figure 2 comparing oxide and calcium contents for woody biomasses, herbaceous and agricultural biomasses, contaminated biomasses, and solid fossil fuels reveals that woody forms of BA generally do not meet the standards. While agricultural forms of BA include more types that align with the standards, a significant portion still fails to comply. For instance, biomass ashes derived from land-clearing wood, pine chips, reed canary grass, sorghastrum grass, rice straw, coconut shells, rice husks, sugarcane bagasse, and mixed wastepaper are considered suitable according to both European and American standards. In contrast, ashes from alder–fir sawdust, Christmas trees, oak wood, miscanthus grass, sweet sorghum grass, switchgrass, wheat straw, and demolition wood meet only the oxide content requirements specified in the American standards.

**Table 2.** Characteristics of ashes to be used in concrete applications according to EN 450-1 and ASTM C 618-23 [83,84].

Characteristics	EN 450-1 (%wt)	ASTM C618-23 (%wt)
LOI	$A \leq 5 - B \leq 7 - C \leq 9$	$\leq 6$
$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	$\geq 70$	$\geq 50$
Chloride	$\leq 0.1$	-

Table 2. Cont.

Characteristics	EN 450-1 (%wt)	ASTM C618-23 (%wt)
Sulfate (SO <sub>3</sub> )	≤3	≤5
Free CaO	≤1.5	-
Reactive CaO	≤10	F≤18-C>18
Reactive SiO <sub>2</sub>	≥25	-
Moisture Content	-	≤3
Total Alkalis (Na + K)	≤5	-
MgO	≤4	-
P <sub>2</sub> O <sub>5</sub>	≤5	-
Fineness (45 μm)	S ≤ 12-N ≤ 40	≤34
Activity Index (7 day)	-	≥75
Activity Index (28 day)	≥75	≥75
Activity Index (90 day)	≥85	-

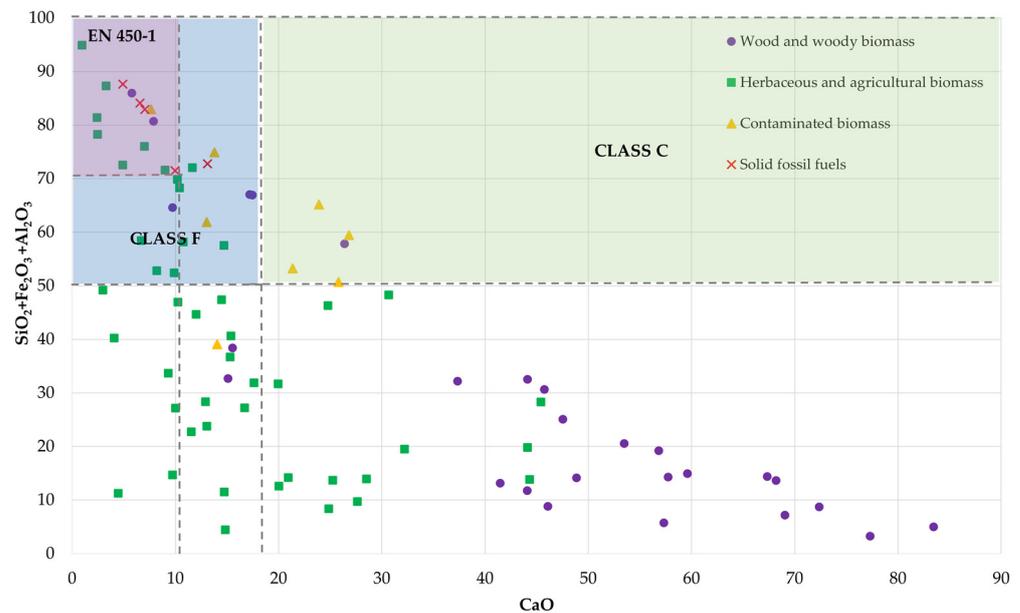


Figure 2. CaO and oxide contents to determine the pozzolanic category of BA [58,85–109].

The use of ashes as SCMs is not only cost-effective and environmentally friendly in terms of the reutilization of ashes and the reduction of clinker production but also contributes to the mechanical and physical properties of products [110]. Research indicates that moderate replacement levels (typically up to 20%) can enhance long-term strength due to pozzolanic reactions, while higher replacement ratios often result in strength reductions due to excessive silica content acting primarily as a filler rather than a reactive component [81]. Studies have shown that compressive strength can be maintained or slightly improved with controlled biomass ash replacement, whereas splitting tensile and flexural strength generally follow similar trends, with moderate reductions at higher replacement levels [111]. However, the contaminants present in the ashes and their varying chemical compositions they possess depend on the type of biomass and combustion process, and their physical properties such as particle size, shape, texture, and surface area must be refined to suit the intended purpose of the cementitious composite. While rearranging these properties through different treatments, limiting factors such as the amount of energy required, the waste produced, time, and cost must be considered to choose the most efficient method.

## 4. Treatments

There are various characteristics of BA that may prevent it from functioning effectively as an SCM. To achieve the desired chemical composition or physical characteristics for their use, certain treatments may be necessary. These treatments can range from low-energy, resource-efficient processes to more complex procedures that require substantial energy and resources. From an environmental perspective, efforts should focus on minimizing additional processing or meeting the desired characteristics through minimal interventions such as screening. High-energy and resource-intensive methods, such as vitrification, chemical washing, or electro-dialytic remediation, which may also lead to extra waste generation, should be carefully evaluated for their performance benefits and economic feasibility. The combination of different improvement techniques has been observed in numerous studies [34,112,113]. In this section, current improvement technologies and cutting-edge processes for utilizing ashes as SCMs will be reviewed.

### 4.1. Grinding

Ensuring that the materials used in concrete have a specific particle size distribution (PSD) is crucial for its overall performance. Therefore, screening aggregates, fillers, or pozzolans to achieve the desired PSD is a common practice. However, the use of materials that do not possess the ideal PSD is also important from the perspective of recycling and the circular economy. Adjusting their particle size for SCMs can significantly enhance pozzolanic reactivity [114]. For ashes that possess suitable chemical properties but contain larger particle fractions, grinding into finer particles can make them more suitable for use [75]. Maschio et al. [115] demonstrated that by grinding and screening BBA, a PSD similar to that of fly ash and cement can be achieved. In a broader context, grinding increases the fineness and surface area of the material, which enhances pozzolanic reactivity and packing density, thereby leading to higher compressive strength [116]. Grinding treatment is particularly effective for agricultural BA, converting highly large porous particles into denser particles [117]. According to the study by Cordeiro et al. [118] on sugarcane bagasse ash, grinding also positively affects concrete resistance to chloride-ion penetration and rheology due to pore refinement resulting from pozzolanic reaction and reduction of the particle interlocking and internal friction, respectively.

According to ASTM C618-23 [83], a good SCM should leave a maximum residue of 34% on a 45  $\mu\text{m}$  (No. 325) sieve. By applying grinding, not only can the actual pozzolanic reactivity of the ashes be enhanced, but compliance with these standards can also be achieved (according to EN 450-1 [84], the maximum ratio is 40%). The duration of the grinding process is also crucial for achieving desired results. Longer grinding times have been observed in various studies to lead to an enhanced surface area and, consequently, higher compressive strength [114,116]. The outcomes of the grinding process are influenced not only by the grinding duration but also by factors such as the type of process, the grinding mechanism, and the speed. These variables can significantly affect the efficiency of treatment. In a study investigating grinding process efficiency, a comparison between vibratory and tumbling mills showed that the vibratory mill produced better results in a shorter time and with less energy consumption [118].

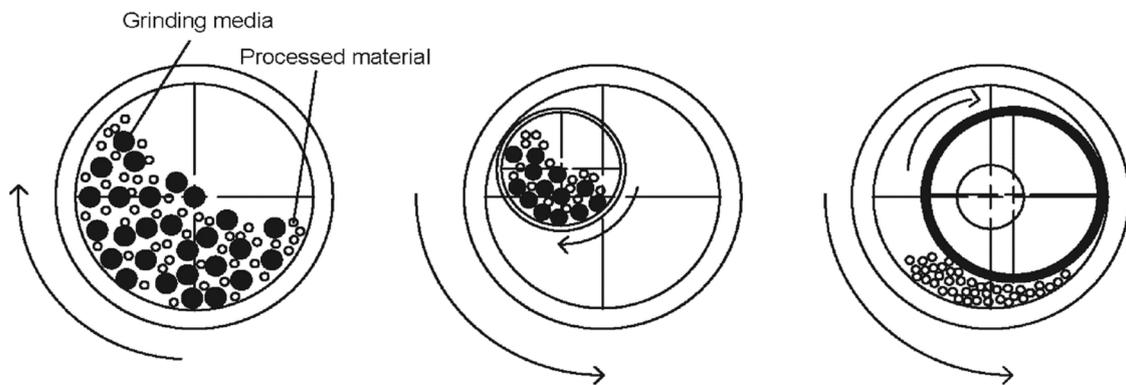
### 4.2. Mechano-Chemical Activation (MCA)

Mechano-chemistry is an extended branch of the grinding process used not only for construction materials but also for processing minerals, food, pharmaceuticals, and chemicals [119]. It is an environmentally friendly process that enables the production of new compounds through solid-state reactions without the use of heat or solvents [120]. Mechano-chemical reactions rely on changes in Gibbs free energy and require mechanical

functions such as shearing, compression, and grinding to accumulate the stress energy needed to initiate the reaction [121].

Mechano-chemical reactions are based on milling, a process that not only reduces particle size but also promotes the formation of reactive surfaces (Figure 3). When precursor materials are crushed between two balls, a significant amount of potential energy is stored, causing bonds to break and leading to the formation of defects and active sites on the surface. The reaction occurs at the interfaces between phases, which makes the creation of fresh and active surfaces essential. Therefore, factors such as the amount of substrate, the size and material of the milling vessel, the number, diameter, and density of the balls, the rotation speed, and the milling time are critical for achieving MCA and ensuring efficiency in ball milling [121]. Depending on these factors, mechano-chemical reactions may not be observed in every grinding process.

MCA, fundamentally a grinding process, results in processed ashes with improved fineness and surface area, leading to similar outcomes in concrete. Grinding reduces particle size and creates new surfaces that serve as precipitation sites for cement hydration products, enhancing the filling effect [122–125]. The increased pozzolanic reactivity leads to a higher formation of reaction products such as calcium–silicate–hydrate (C-S-H) and calcium–aluminate–hydrate (C-A-H) within the cement matrix. This contributes to a denser microstructure, thereby improving compressive strength [126,127]. MCA can increase the substitution value of non-reactive solid waste, such as BBA without compromising strength by improving their reactivity [112]. This phenomenon was observed in the study of [128]: using untreated fly ash resulted in higher strength compared to the reference mix at a substitution rate of only 10%, whereas milled fly ash allowed for a substitution rate of up to 30%. The factors contributing to this increase include relatively higher contents of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ , lower LOI, and an increase in fineness.



**Figure 3.** Types of milling equipment processes: **left**—ball mill, **middle**—planetary ball mill, and **right**—ring mill [129].

Moreover, MCA can also facilitate the stabilization of heavy metals present in the ash. Chen et al. [130] observed that MCA of municipal solid waste ash (MSWA) resulted in the stabilization of heavy metals such as Cd, Cu, Mo, Pb, Sb, and Zn. When the ash is subjected to prolonged grinding, its microstructure deteriorates, crystallinity decreases, and the structure transforms into amorphous phases resembling a melt-like state, as evidenced by X-ray diffraction (XRD) [128,130]. It is believed that heavy metals are stabilized through absorption by these amorphous phases [124,130,131]. The stabilization of heavy metals suggests that ashes treated with MCA may be suitable for use as SCMs, remaining safe even after weathering and not posing adverse environmental impacts.

The grinding duration and method significantly impact the outcome. As observed in the study by Wu et al. [128], longer grinding increases reactivity and alters the mineralogical

structure. MCA reduces the degree of silicate polymerization, and this effect becomes more pronounced as the treatment time extends. The characteristics of BA also vary depending on the grinding method. Due to differences in grinding methods, materials with the same PSD can exhibit different specific surface areas, impacting reactivity and compressive strength. For instance, Wu et al. [128] found that vibration milling resulted in a greater increase in reactivity compared to ball milling.

#### 4.3. High-Temperature Treatment (HTT)

HTT of ashes has been observed in various studies, often through processes like re-combustion to eliminate organic matter or vitrification. HTT reduces the LOI and enhances pozzolanic activity [132–134]. The feasibility of this treatment depends on the amount of energy consumed and the type of energy source. In a study conducted by [34], HTT was applied by heating BBA to 800 °C and maintaining that temperature for 18 h. Considering the compressive strength improvement achieved, the authors concluded that this treatment was feasible. Other studies have also shown that heating up to 800 °C increases the relative amount of amorphous silica in the ash, enhancing pozzolanic oxides and reactivity [135,136]. This improvement is also due to the removal of volatile compounds and organic matter at around 600 °C [137]. However, beyond 800 °C, pozzolanic reactivity decreases due to the transformation of amorphous silica into crystalline cristobalite [135,136].

In another study, the vitrification process was used to transform ashes into non-crystalline materials with high latent hydraulic reactivity. A mixture of fly and bottom ash obtained from power plants burning both woodchips and straw was used as the ash source. The vitrification process was completed at a temperature of 1500 °C in one hour. The effects of vitrified ash on compressive strength were evaluated against SCMs like limestone, fumed silica, and pozzolan. The results showed that the vitrified ash mortar (at 28 days and 30% replacement) performed better than other SCMs and untreated ash. Performance at 90, 180, and 360 days increased further due to the filler effect, hydration acceleration, and pozzolanic or hydraulic reactions. Additionally, to investigate the effect of vitrification temperature, a second set of samples was heated up to 1300 °C. However, at the lower vitrification temperature, the final product contained crystalline particles, resulting in a glass–ceramic structure and lower performance compared to fully vitrified ash [138].

Vitrification separates harmful organic compounds and stabilizes heavy metals within a glassy matrix [139,140]. It is considered one of the safest methods for processing hazardous waste and transforming it into leach-resistant materials [140]. However, the most prominent disadvantage of vitrification is the high energy consumption required for the melting process [140]. The glassy product obtained through post-vitrification can be used as an SCM, as demonstrated in the study by [138], or as a colored vitreous product, as shown in the works of Ribeiro and Monteiro [139,140].

#### 4.4. Hydrothermal Synthesis (HTS)

HTS is a process that uses water under high temperatures and pressure to induce specific chemical and physical changes in various materials. It is commonly employed in waste management, biomass recycling, material synthesis, and mineral processing. HTS is considered as an eco-efficient process due to the fact that it employs low temperatures to activate BA, implying no emission of CO<sub>2</sub> to the atmosphere, and is increasingly used in the recycling and reuse of industrial waste [141]. Studies on the synthesis of tobermorite from ashes using HTS have a history of about a quarter century, with conducted subtopics including improving process efficiency, temperature and pressure values, starting materials, and the stabilization of harmful elements [142].

Kaminskas et al. [143] investigated the potential use of HTS for synthesizing C-S-H products from BFA and explored the properties of the synthesized material for use as an SCM. In their study, synthesis was carried out at 200 °C for 2 to 24 h. Tobermorite formation was already observed after 2 h of synthesis. The final product contained only quartz, calcite, and tobermorite. Extending the synthesis time to 24 h resulted in an increase in C-S-H products, but this increase was not sufficient relative to the energy expended. According to the results, replacement of up to 10% can be achieved without reducing the compressive strength.

HTS, while utilized for the enhancement of ashes, is also a commonly employed method in the synthesis of zeolites. Although zeolites exhibit a range of mineralogical variations, they can be broadly described as hydrated aluminum-silicate crystals. Depending on their mineralogical variety, zeolites are employed for various applications including water treatment [144,145], the remediation of polluted soils [146], chemical catalysis [147], and as SCMs [148]. Zeolites used as SCMs are typically synthesized from waste products resulting from the production of  $AlF_3$  [149,150]. When used as SCMs, zeolites generally improve the freeze–thaw resistance and compressive strength of concrete, although they can reduce workability [149–151].

Jiménez et al. [141] synthesized tobermorite along with zeolitic phases such as analcime and cancrinite, from a 4 h synthesis process at 200 °C. In their study, NaOH solution was used as the synthesis medium to enable the formation of zeolite and the more efficient dissolution of silica crystals. The reactivity of the treated ash was assessed based on its lime-fixing capacity, showing better performance compared to SCMs like silica fume and metakaolin, as well as untreated ash. Additionally, the absence of chloride ions in the processed ash after HTS is promising for its use as an SCM.

It can be observed from the literature that there is limited research on the use of zeolites obtained from BA through HTS [19]. The study by Pimraksa et al. [148] demonstrated that zeolites produced from CFA can be used as SCMs, showing good performance in both strength and heavy metal stabilization. Fukasawa et al. [152] showed that BA can be employed in the synthesis of zeolites via HTS, suggesting the potential use of these synthesized zeolites as SCMs.

In another study, a BA composite was developed using treated sewage sludge ash (SSA) as a filler, which demonstrated potential for application as a robust material for packaging and insulation purposes. In this composite, straw powder and waste sawdust were utilized as the biomass matrix, with treated SSA serving as the filler. The HTS resulted in the formation of C-S-H products, which enhanced the cohesion performance of the ash as a filler. This improvement enhanced the overall structural integrity and effectiveness of the composite [153].

#### 4.5. Washing Treatment

Washing treatment is an easy-to-apply method for improving ashes, involving the washing of ashes with water, solvents, or acids. Washing is an effective method for removing salts such as chlorides, sulfates, and alkaline compounds, as well as heavy metals [154,155]. Since chlorides and sulfates are known to harmfully influence the strength and durability properties of concrete, this treatment could be beneficial for using ash as an SCM.

##### 4.5.1. Water Washing (WW)

WW can be carried out in a single step or in several sequential steps. Several studies have demonstrated that chlorides can be effectively removed in the initial step of washing [156]. According to these studies, WW is a viable method for chloride removal.

However, the authors of [156] noted that the efficiency of removal decreases in subsequent steps. Phua et al. [157] reported that WW can achieve up to 90–95% removal of chlorides from the ash, improving the quality of the final product for further utilization. Nevertheless, Yang et al. [158] have raised concerns about the potential risk of heavy metal leaching in discharge waters. According to Zhu et al. [159], the use of chemical additives and pH adjustment could address this issue.

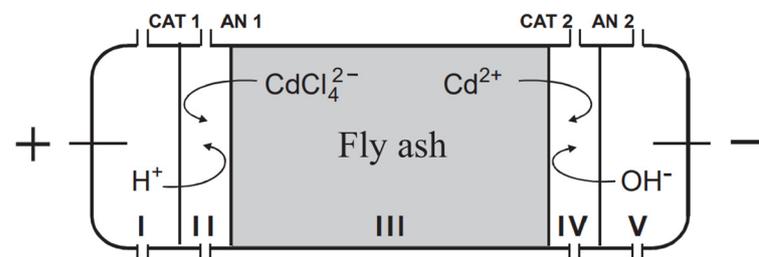
#### 4.5.2. Chemical Washing (CW)

There is limited research on washing ashes with solvents or acids. CW is generally applied for the removal of heavy metals [160]. Washings with sulfuric acid and phosphoric acid have shown good results in the removal of heavy metals such as Pb, Zn, and Cu [159]. In the study by Ma and Zhang [161], phosphoric acid was found to be more effective than sulfuric acid. Washing treatment with HCl is also quite effective in removing Pb, Cd, Cu, and Zn [160]. Pöykiö et al. [162] investigated the leaching behavior of residues in ashes using a three-step washing process with water, ammonium acetate ( $\text{CH}_3\text{COONH}_4$ ), and HCl solutions, respectively. They found that water extraction was effective for S, ammonium acetate extraction was effective for Cu and S, and HCl extraction was effective for the removal of Ti and Al concentrations.

In washing processes aimed at reducing the chlorine content of ashes, factors such as the liquid-to-solid ratio, stirring speed, temperature, and time play a significant role [161,163]. For instance, a higher liquid-to-solid ratio yields better results. However, there is currently no standard or general consensus on washing parameters [164]. The washing process also has some drawbacks, including the large volumes of water required and the necessity to treat process waters for contamination before discharge [154,155,159,161,163].

#### 4.6. Electro-Dialytic Remediation (EDR)

EDR is a method that combines electro-dialysis with the electro-migration of ions to remove the mobile fraction of heavy metals from ash, thereby reducing heavy metal and salt leaching. The fundamental principle of the EDR involves placing a solution containing an ash suspension into electro-dialytic cells. An electric current is applied across the cells, facilitating the transport of metal ions to the electrodes according to their charges. Ion-exchange membranes placed between the cells enable the collection of metal ions before they reach the electrodes and subsequently their removal from the solution as shown in Figure 4 [164]. In EDR, the ion transfer medium can be deionized water,  $\text{NH}_3$  solution, citric acid solution, or ammonium citrate solution [165–168].



**Figure 4.** The principle of EDR (CAT: cation exchange membrane, AN: anion exchange membrane) [169].

According to the study by [165], the EDR technique is not very efficient in the removal of heavy metals. Ebbers et al. [166] suggest that efficiency can be improved by using certain ancillary agents to optimize heavy metal removal. However, this can result in the production of a more challenging liquid waste that requires further treatment before

reuse or disposal [170]. Additionally, EDR is a method that requires continuous energy consumption and is quite time-consuming [164].

Although EDR has been used in several studies for the removal of Cd from BA, these studies did not aim to use the treated ash as an SCM [169,171]. According to the study conducted by [169], EDR was able to remove 70% of the Cd present in the ash. In another study conducted by Chen et al. [171], EDR reduced the leachability of heavy metals such as Se, As, Ba, Pb, Cu, Zn, Cd, Cr, and Mn (except Ni). Researchers noted that the reduction in K content during the process also decreased the fertilizer value of the ash. However, the ash can still be used as an SCM or as a clay substitute in bricks [172,173]

In the study conducted by Kirkelund et al. [174], which is one of the few studies investigating the use of EDR-treated ash as an SCM, it was found that the heavy metal leaching of MSWA mortars was similar to that of the reference mortars without any additives. The compressive strengths were also comparable to those of CFA mortars (at 28 days with 15% replacement, achieving 40 MPa). However, it was observed that the initial setting time of treated ash mortars increased up to 16 h and workability decreased. According to Kirkelund et al. [174], due to its high salt content, treated ash should only be considered for unreinforced concrete.

#### 4.7. Carbonation—Accelerated Carbonation (AC)

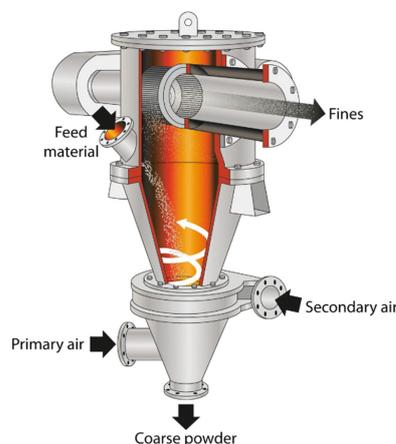
Under specific conditions, CO<sub>2</sub> can be absorbed and stabilized in alkaline solid waste, such as BA, in the form of carbonate minerals or dissolved carbonate ions, depending on the alkalinity and reactivity of the waste [112,175,176]. AC is used to reduce the environmental impact of waste materials and improve their structural properties [177]. The primary goal of this treatment is to facilitate the binding of CO<sub>2</sub> by reactive components within the ash, thereby reducing the amount of carbon in the atmosphere. AC of ashes represents a sustainable and environmentally friendly approach to CO<sub>2</sub> sequestration. During AC, CO<sub>2</sub> reacts with compounds like calcium silicate and aluminate to form calcium carbonate (CaCO<sub>3</sub>). The presence of phases such as lime, free CaO, and portlandite in the material facilitates CO<sub>2</sub> binding, while carbonation of silicate phases like gehlenite and akermanite is more challenging [178]. Additionally, a finer particle size enhances carbonation [179]. Carbonation also stabilizes the chemical structure of the ash and reduces leaching risks.

The use of carbonated ashes in mortars has been investigated by various researchers. While carbonated ashes may lead to reduced compressive strength due to their larger particle size, they can produce more durable products resistant to dissolution and chemical degradation, thanks to their more stable chemical structure [112]. Previous studies have shown that carbonated waste, when used as SCMs, provides higher strength compared to untreated waste and reduces Ca leaching [180–182].

#### 4.8. Air-Classification Treatment (ACT)

ACT is a method used to analyze the ash in a dry state based on particle size and to remove detrimental materials such as sulfates, chlorides, heavy metals, or unburnt carbon found in fine fractions [72,183]. ACT essentially involves exposing the ash to airflow at a specific speed, where the finer ash fractions are captured and separated by the airflow while the coarser ash fractions pass through the airstream and are deposited separately (Figure 5). The process is highly dependent on airflow and requires different speeds for different materials. In the study conducted by Ohenoja et al. [183], after ACT, it was found that the SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> fractions remained in the coarser ash fraction, while harmful substances such as sulfates, chlorides, and heavy metals (Cd, Cu, Zn, and Pb), along with the CaO fraction, were retained in the finer ash fraction. By separating the finer fraction from the ash, a material that met standards for sulfate and chloride content was obtained.

Similarly, De La Grée et al. [113] found that ACT was highly effective in removing fine carbon particles and the chlorides and sulfates attached to these particles.



**Figure 5.** Working principle and classification procedure of the air-jet classifier [183].

Zhang et al. [184] observed in their study that the fine fraction obtained after ACT was rich in amorphous phases, as well as chlorides, sulfates, and unburnt carbon, while the coarse fraction was abundant in crystalline phases. Through pozzolanic activity and compressive strength tests, they found that fractions with particle size below 8  $\mu\text{m}$  exhibited higher reactivity and were deemed more suitable for use as SCMs. Another study by Ohenoja et al. [63] provided data consistent with these findings. The ash subjected to ACT showed lower reactivity compared to their previous studies. The researchers attributed this to the removal of Ca and S content along with the fine fractions during the ACT process.

#### 4.9. Combined Treatments

There are various treatment processes applied to improve the properties of BA for its use as an SCM. In the literature, it is often observed that these treatment methods are combined. By using different thermal, chemical, and mechanical treatments together, the adverse effects of one treatment can be mitigated by another, ash quality can be improved, and more eco-efficient and cost-effective processes can be developed.

Rosales et al. [34] aimed to determine the optimal treatment process for BA by applying three different treatment methods and their combinations to mitigate the adverse effects of organic matter on the durability and mechanical properties of cementitious mixtures. The methods used in the study include combustion (800  $^{\circ}\text{C}$  for 18 h), flotation, and grinding (to a particle size finer than 125  $\mu\text{m}$ ), as well as their combinations. All treatments successfully reduced organic matter content; however, combustion demonstrated the greatest efficiency, while grinding showed the lowest efficiency. The lowest organic matter content was achieved with the combination of all treatments, while the contribution of flotation and grinding treatments to combustion was only 3%. The lowest porosity and water absorption values were also obtained with the triple-combined treatment. For both porosity and water absorption, grinding proved to be the most effective treatment. Similarly, for compressive and flexural strength results, the triple-combined treatment yielded values closest to those of mortar without ash, with grinding being the most effective treatment. Table 3 presents the compressive strength values from studies investigating different treatment methods for biomass ashes from various sources. The grinding-combustion combination achieved 75% and 100% increases in strength at 20% and 38.5% replacement ratios, respectively. However, the final strength at the 38.5% replacement remained lower compared to the 20% replacement. According to the researchers, grinding and combustion processes are

considered feasible for using BA as an SCM. However, flotation is theoretically applicable but considered a challenging and expensive process.

De La Grée et al. [113] conducted a study aimed at reducing the leaching of contaminants from BA. To achieve this, the researchers examined the effectiveness of various treatment techniques, both individually and in combination, for ashes with different physical and chemical properties, and designed a combined treatment approach. The methodology involved initially removing carbon particles from the ashes. Subsequently, the ashes were washed to reduce the content of soluble salts (such as chloride and sulfate), heavy metals, and aluminum and finally ground to achieve a suitable PSD to enhance reactivity. The study authors found that washing alone was insufficient for chloride removal in some ashes. The researchers hypothesized that soluble chlorides were bound to the surface of carbon particles and thus did not dissolve in water. To address this issue, they proposed two pre-treatments to remove carbon particles before washing: First, re-heating the ashes to 750 °C to burn off the carbon particles, and second, applying air-filtration to physically separate fine carbon particles from the ash mixture. Following these pre-treatments, the chlorine content in the ashes decreased by 70% and 75%, respectively, supporting the researchers' hypothesis. With the removal of carbon content, the total reduction in chlorine content for ashes subjected to re-washing was 93% and 82%, respectively. Sieving the ashes also improved chlorine reduction in some cases. In experiments with ashes containing large carbon particles, washing without sieving achieved a chlorine removal rate of 71%, while sieving through a 500 µm sieve before washing increased this rate to 91%. Air-filtering and re-heating processes, which removed fine carbon particles, led to changes in the PSD of the ashes. Ashes with increased average particle size were ground to meet the standard PSD. Based on experimental data, the researchers developed a pilot process for scaling up the washing procedure to an industrial scale, incorporating cycloning, flotation, and rinsing stages. According to the results of the study, an industrial-scale treatment method was developed that is both cost-effective and eco-efficient compared to ash storage.

In a study aimed at developing waste-derived SCMs, Skevi et al. [112] applied a combination of MCA and carbonation treatment to BA. The study authors found that with a 40% replacement ratio, the compressive strength of mortar with BA was only 17% of that achieved without any ash addition, whereas mortar with mechano-chemically activated biomass ash (MBA) reached 63% of the reference strength. The 28-day compressive strength of mortar with 40% MBA (23.17 MPa) was nearly identical to that of mortar with 20% untreated BA (25.01 MPa), which is promising for more economical and eco-efficient concrete. MCA led to a decrease in the intensity of akermanite and the formation of the carbonate phase baylissite ( $K_2Mg(CO_3)_2 \cdot 4H_2O$ ), with new carbonates forming due to surface defects and atmospheric  $CO_2$ . Other observed changes included the amorphization of calcites and an increase in amorphous silica content in the ash. Replacing 40% of cement with carbonated MBA resulted in a 28.5% increase in 28-day compressive strength compared to the reference, which was significantly lower than the values for MBA mortars but nearly twice that of mortars containing untreated ash. The carbonation process led to the formation of stable carbonate phases in the MBA. Consequently, the active Si-O bonds on the surface of the carbonated MBA likely bonded with  $CO_2$  during the carbonation process, leaving fewer active sites compared to MBA. The formation of carbonates may have also contributed to the larger particle sizes of carbonated MBA, which could reduce the filling effect compared to MBA. Although the carbonation of BA before incorporation into cementitious composites adversely affected compressive strength, the potential to reduce the carbon footprint to near zero is a significant outcome. Therefore, it is recommended to maintain relatively low replacement levels in applications involving carbonation to avoid substantial reductions in strength.

**Table 3.** Effects of treatments methods on the strength properties of different ashes [34,63,67,112,185].

Ash Type	Source	Treatment	Substitution Ratio (%)	Reference Strength (MPa)	Untreated Strength (MPa)	Treated Strength (MPa)	Effect of Treatment
BBA	Wood and timber combustion	Mechano-Chemical Activation	40%	36.80	6.24	23.17	+271.31%
		Mineral Carbonation and MCA	40%	36.80	6.24	10.48	+67.95%
BBA	Wood (whole tress and primarily pine)	Sieving-Washing	20%	69.90	51.10	59.30	+16.05%
BFA	70% forest residues and 30% peat	Classification	20%	49.40	25.80	29.00	+12.40%
		Classification + Grinding	20%	49.40	25.80	36.60	+41.86%
BFA	60% forest residues, 30% recycling waste, and 10% paper sludge	Classification	20%	49.40	27.80	29.20	+5.04%
		Classification + Grinding	20%	49.40	27.80	34.20	+23.02%
BFA	40% peat, 50% forest residues, and 10% recycled wood waste	Classification	20%	49.40	31.40	36.60	+16.56%
		Classification + Grinding	20%	49.40	31.40	38.40	+22.29%
BBA	Olive tree prunings	Washing	20%	58.03	25.12	27.61	+9.91%
		Heat Treatment	20%	58.03	25.12	29.12	+15.92%
		Grinding	20%	58.03	25.12	36.18	+44.03%
		Washing + Heat Treatment	20%	58.03	25.12	33.21	+32.21%
		Washing + Grinding	20%	58.03	25.12	38.92	+54.94%
		Heat Treatment + Grinding	20%	58.03	25.12	44.17	+75.84%
		Washing + Heat Treatment + Grinding	20%	58.03	25.12	51.96	+106.85%
BFA	Wood chips	Washing	15%	46.50	40.00	38.00	-5.00%
		Washing	30%	46.50	38.20	39.00	+2.00%

ACT is an effective method for removing harmful substances from the fine fraction of ash. However, as demonstrated in several studies, the method yields better results when combined with grinding [183,184]. In the study of Ohenoja et al. [183], prior to ACT, ash was subjected to grinding solely to eliminate agglomerations formed during storage and transportation, which facilitated the separation of the fine fraction and its associated contaminants. A drawback of the ACT is that it can adversely affect the PSD of the ash. In their study, De La Grée et al. [113] used combined treatments, whereby they re-ground the ash after ACT, achieving the desired PSD in ash containing fewer detrimental materials. A similar result was obtained in the research by Ohenoja et al. [63], where ACT significantly reduced the levels of  $\text{SO}_3$  and Cl in the ash, while the content of " $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ " relatively increased. Additionally, the median particle size increased from approximately 45  $\mu\text{m}$  to 200  $\mu\text{m}$ , and to rectify this, grinding was employed, reducing the median particle size to 30  $\mu\text{m}$ . This resulted in an improvement in both flexural and compressive strength.

## 5. Conclusions

The production of biomass ash as a residue of biomass combustion is increasing worldwide. The chemical and mineral composition of biomass ash is extremely varied, and a general evaluation of its utilization cannot truly be made. The integration of biomass ash into concrete has demonstrated significant potential in contributing to both improved material performance and more sustainable construction practices. Biomass ash contains beneficial components such as silica, alumina, and iron oxides, which contribute to its reactivity. Depending on its chemical composition and fineness, untreated biomass ash can sometimes be directly used as a supplementary cementitious material, though its performance may vary considerably. Nevertheless, the effectiveness of biomass ash as a supplementary cementitious material is highly dependent on the treatments applied to enhance its properties, such as particle size distribution, reactivity, and contaminant content.

It is important to note that certain properties can be improved depending on the treatment methods used, while others may be adversely affected. Heavy metal and chlorine content may decrease, but particle size distribution may deteriorate, reducing the filler effect. Alternatively, while reactivity and fineness may increase, some contaminants might remain in the system, reducing the durability of the mixture. Therefore, careful optimization of these treatments is necessary to balance the beneficial and adverse impacts specific to the chemical and physical properties of the ashes, ensuring that the overall performance of the concrete is enhanced. Moreover, the environmental advantages of using biomass ash are considerable, as its inclusion in concrete production can reduce the reliance on traditional cement, thereby lowering greenhouse gas emissions and conserving natural resources.

Considering these findings, the effective treatment and use of biomass ash should be further explored to maximize its potential as a key component in sustainable construction. In line with this goal, future research conducted by our team will focus on examining the effects of the mechano-chemical activation method on biomass ashes obtained from different sources, as this review identifies mechano-chemical activation as one of the most effective treatment methods. This approach could provide valuable insights into enhancing the sustainability and durability of concrete structures.

**Funding:** This work was supported by the Republic of Türkiye Ministry of National Education (Study Abroad Programme).

**Data Availability Statement:** No new data were created in this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

BA	Biomass Ash
BFA	Biomass Fly Ash
BBA	Biomass Bottom Ash
SCM	Supplementary Cementitious Material
GHG	Greenhouse Gas
PSD	Particle Size Distribution
CFA	Coal Fly Ash
MCA	Mechano-Chemical Activation
C-S-H	Calcium–Silicate–Hydrate
C-A-H	Calcium–Aluminate–Hydrate
HTS	Hydrothermal Synthesis
SSA	Sewage Sludge Ash
WW	Water Washing
CW	Chemical Washing
EDR	Electro-Dialytic Remediation
ACT	Air-Classification Treatment
AC	Accelerated Carbonation
LoI	Loss on Ignition
ASTM	American Society for Testing and Materials
EN	European Norm

## References

- Andrew, R.M. Global CO<sub>2</sub> Emissions from Cement Production. *Earth Syst. Sci. Data* **2018**, *10*, 195–217. [CrossRef]
- Ritchie, H.; Rosado, P.; Roser, M. CO<sub>2</sub> Emissions by Fuel. *Our World in Data*. 2024. Available online: <https://ourworldindata.org/emissions-by-fuel> (accessed on 20 September 2024).
- Boden, T.A.; Marland, G.; Andres, R.J. *Estimates of Global, Regional, and National Annual CO<sub>2</sub> Emissions from Fossil-Fuel Burning, Hydraulic Cement Production, and Gas Flaring: 1950–1992*; ORNL/CDIAC-90, NDP-030/R6, 207068; USDOE: Washington, DC, USA, December 1995.
- Ritchie, H.; Roser, M.; Rosado, P. Energy. *Our World in Data*. 2022. Available online: <https://ourworldindata.org/energy> (accessed on 20 September 2024).
- International Energy Agency. *Energy Technology Perspectives 2023*; International Energy Agency: Paris, France; OECD: Paris, France, 2023; ISBN 978-92-64-80416-6.
- Lim, J.S.; Abdul Manan, Z.; Wan Alwi, S.R.; Hashim, H. A Review on Utilisation of Biomass from Rice Industry as a Source of Renewable Energy. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3084–3094. [CrossRef]
- Ashik, U.P.M.; Wan Daud, W.M.A.; Abbas, H.F. Production of Greenhouse Gas Free Hydrogen by Thermocatalytic Decomposition of Methane—A Review. *Renew. Sustain. Energy Rev.* **2015**, *44*, 221–256. [CrossRef]
- Munawar, M.A.; Khoja, A.H.; Naqvi, S.R.; Mehran, M.T.; Hassan, M.; Liaquat, R.; Dawood, U.F. Challenges and Opportunities in Biomass Ash Management and Its Utilization in Novel Applications. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111451. [CrossRef]
- Vassilev, S.V.; Vassileva, C.G. Water-Soluble Fractions of Biomass and Biomass Ash and Their Significance for Biofuel Application. *Energy Fuels* **2019**, *33*, 2763–2777. [CrossRef]
- Motghare, K.A.; Rathod, A.P.; Wasewar, K.L.; Labhsetwar, N.K. Comparative Study of Different Waste Biomass for Energy Application. *Waste Manag.* **2016**, *47*, 40–45. [CrossRef]
- Wang, L.; Hustad, J.E.; Skreiberg, Ø.; Skjevrak, G.; Grønli, M. A Critical Review on Additives to Reduce Ash Related Operation Problems in Biomass Combustion Applications. *Energy Procedia* **2012**, *20*, 20–29. [CrossRef]
- Vassilev, S.V.; Baxter, D.; Andersen, L.K.; Vassileva, C.G. An Overview of the Composition and Application of Biomass Ash. Part 1. Phase–Mineral and Chemical Composition and Classification. *Fuel* **2013**, *105*, 40–76. [CrossRef]
- Rajamma, R.; Ball, R.J.; Tarelho, L.A.C.; Allen, G.C.; Labrincha, J.A.; Ferreira, V.M. Characterisation and Use of Biomass Fly Ash in Cement-Based Materials. *J. Hazard. Mater.* **2009**, *172*, 1049–1060. [CrossRef]
- Energy Institute Statistical Review of World Energy; Smil (2017)—with Major Processing by Our World in Data. 2024. Available online: <https://ourworldindata.org/grapher/global-energy-substitution?time=2000..latest&facet=None> (accessed on 20 September 2024).

15. European Commission: Eurostat. *Energy, Transport and Environment Statistics: 2020 Edition*; Publications Office: Luxemburg, 2020; ISBN 978-92-76-20736-8.
16. IEA CO<sub>2</sub> Total Emissions by Region, 2000-2023—Charts—Data & Statistics. Available online: <https://www.iea.org/data-and-statistics/charts/co2-total-emissions-by-region-2000-2023> (accessed on 20 September 2024).
17. Agrela, F.; Cabrera, M.; Morales, M.M.; Zamorano, M.; Alshaaer, M. Biomass Fly Ash and Biomass Bottom Ash. In *New Trends in Eco-Efficient and Recycled Concrete*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 23–58, ISBN 978-0-08-102480-5.
18. Vassilev, S.V.; Baxter, D.; Vassileva, C.G. An Overview of the Behaviour of Biomass during Combustion: Part I. Phase-Mineral Transformations of Organic and Inorganic Matter. *Fuel* **2013**, *112*, 391–449. [[CrossRef](#)]
19. Belviso, C. State-of-the-Art Applications of Fly Ash from Coal and Biomass: A Focus on Zeolite Synthesis Processes and Issues. *Prog. Energy Combust. Sci.* **2018**, *65*, 109–135. [[CrossRef](#)]
20. Aprianti, E.; Shafiqh, P.; Bahri, S.; Farahani, J.N. Supplementary Cementitious Materials Origin from Agricultural Wastes—A Review. *Constr. Build. Mater.* **2015**, *74*, 176–187. [[CrossRef](#)]
21. Chen, L.; Liao, Y.; Xia, Y.; Ma, X. Combustion Characteristics of Co-Combusted Municipal Solid Wastes and Sewage Sludge. *Energy Sources Part Recovery Util. Environ. Eff.* **2020**, *46*, 5730–5742. [[CrossRef](#)]
22. Tursi, A. A Review on Biomass: Importance, Chemistry, Classification, and Conversion. *Biofuel Res. J.* **2019**, *6*, 962–979. [[CrossRef](#)]
23. Tun, M.M.; Juchelkova, D.; Win, M.M.; Thu, A.M.; Puchor, T. Biomass Energy: An Overview of Biomass Sources, Energy Potential, and Management in Southeast Asian Countries. *Resources* **2019**, *8*, 81. [[CrossRef](#)]
24. Chinnici, G.; D’Amico, M.; Rizzo, M.; Pecorino, B. Analysis of Biomass Availability for Energy Use in Sicily. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1025–1030. [[CrossRef](#)]
25. Kumar, A.; Adamopoulos, S.; Jones, D.; Amiamdamhen, S.O. Forest Biomass Availability and Utilization Potential in Sweden: A Review. *Waste Biomass Valorization* **2021**, *12*, 65–80. [[CrossRef](#)]
26. Barreiro, S.; Schelhaas, M.-J.; Kändler, G.; Antón-Fernández, C.; Colin, A.; Bontemps, J.-D.; Alberdi, I.; Condés, S.; Dumitru, M.; Ferezliev, A.; et al. Overview of Methods and Tools for Evaluating Future Woody Biomass Availability in European Countries. *Ann. For. Sci.* **2016**, *73*, 823–837. [[CrossRef](#)]
27. Ferreira-Leitão, V.; Gottschalk, L.M.F.; Ferrara, M.A.; Nepomuceno, A.L.; Molinari, H.B.C.; Bon, E.P.S. Biomass Residues in Brazil: Availability and Potential Uses. *Waste Biomass Valorization* **2010**, *1*, 65–76. [[CrossRef](#)]
28. Lozano-García, D.F.; Santibañez-Aguilar, J.E.; Lozano, F.J.; Flores-Tlacuahuac, A. GIS-Based Modeling of Residual Biomass Availability for Energy and Production in Mexico. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109610. [[CrossRef](#)]
29. Balat, M. Use of Biomass Sources for Energy in Turkey and a View to Biomass Potential. *Biomass Bioenergy* **2005**, *29*, 32–41. [[CrossRef](#)]
30. Brosowski, A.; Thrän, D.; Mantau, U.; Mahro, B.; Erdmann, G.; Adler, P.; Stinner, W.; Reinhold, G.; Hering, T.; Blanke, C. A Review of Biomass Potential and Current Utilisation—Status Quo for 93 Biogenic Wastes and Residues in Germany. *Biomass Bioenergy* **2016**, *95*, 257–272. [[CrossRef](#)]
31. Galik, C.S.; Abt, R.; Wu, Y. Forest Biomass Supply in the Southeastern United States—Implications for Industrial Roundwood and Bioenergy Production. *J. For.* **2009**, *107*, 69–77. [[CrossRef](#)]
32. Okafor, C.C.; Nzekwe, C.A.; Ajaero, C.C.; Ibekwe, J.C.; Otunomo, F.A. Biomass Utilization for Energy Production in Nigeria: A Review. *Clean. Energy Syst.* **2022**, *3*, 100043. [[CrossRef](#)]
33. Frías, M.; Moreno De Los Reyes, A.M.; Villar-Cociña, E.; García, R.; Vigil De La Villa, R.; Vasić, M.V. New Eco-Cements Made with Marabou Weed Biomass Ash. *Materials* **2024**, *17*, 5012. [[CrossRef](#)]
34. Rosales, J.; Cabrera, M.; Beltrán, M.G.; López, M.; Agrela, F. Effects of Treatments on Biomass Bottom Ash Applied to the Manufacture of Cement Mortars. *J. Clean. Prod.* **2017**, *154*, 424–435. [[CrossRef](#)]
35. Chang, C.-Y.; Wang, C.-F.; Mui, D.T.; Chiang, H.-L. Application of Methods (Sequential Extraction Procedures and High-Pressure Digestion Method) to Fly Ash Particles to Determine the Element Constituents: A Case Study for BCR 176. *J. Hazard. Mater.* **2009**, *163*, 578–587. [[CrossRef](#)]
36. Karpis, O.; Aboltins, A.; Palabinskis, J. Biomass Ash Utilization Opportunities in Agriculture. In Proceedings of the International Scientific Conference “RURAL DEVELOPMENT 2017”, Kaunas, Lithuania, 15 February 2018.
37. James, A.; Thring, R.; Helle, S.; Ghuman, H. Ash Management Review—Applications of Biomass Bottom Ash. *Energies* **2012**, *5*, 3856–3873. [[CrossRef](#)]
38. Lu, G.Q.; Do, D.D. Adsorption Properties of Fly Ash Particles for NO<sub>x</sub> Removal from Flue Gases. *Fuel Process. Technol.* **1991**, *27*, 95–107. [[CrossRef](#)]
39. Cho, H.; Oh, D.; Kim, K. A Study on Removal Characteristics of Heavy Metals from Aqueous Solution by Fly Ash. *J. Hazard. Mater.* **2005**, *127*, 187–195. [[CrossRef](#)]
40. Polat, H.; Vengosh, A.; Pankratov, I.; Polat, M. A New Methodology for Removal of Boron from Water by Coal and Fly Ash. *Desalination* **2004**, *164*, 173–188. [[CrossRef](#)]

41. Izquierdo, M.T.; Rubio, B. Carbon-Enriched Coal Fly Ash as a Precursor of Activated Carbons for SO<sub>2</sub> Removal. *J. Hazard. Mater.* **2008**, *155*, 199–205. [[CrossRef](#)] [[PubMed](#)]
42. Wang, P.; Guo, Y.; Zhao, C.; Yan, J.; Lu, P. Biomass Derived Wood Ash with Amine Modification for Post-Combustion CO<sub>2</sub> Capture. *Appl. Energy* **2017**, *201*, 34–44. [[CrossRef](#)]
43. Muñoz, P.; Letelier, V.; Muñoz, L.; Gencel, O.; Sutcu, M.; Vasic, M. Assessing Technological Properties and Environmental Impact of Fired Bricks Made by Partially Adding Bottom Ash from an Industrial Approach. *Constr. Build. Mater.* **2023**, *396*, 132338. [[CrossRef](#)]
44. Sarmah, M.; Baruah, B.P.; Khare, P. A Comparison between CO<sub>2</sub> Capturing Capacities of Fly Ash Based Composites of MEA/DMA and DEA/DMA. *Fuel Process. Technol.* **2013**, *106*, 490–497. [[CrossRef](#)]
45. Wang, S.; Song, X.; Wei, M.; Liu, W.; Wang, X.; Ke, Y.; Tao, T. Strength Characteristics and Microstructure Evolution of Cemented Tailings Backfill with Rice Straw Ash as an Alternative Binder. *Constr. Build. Mater.* **2021**, *297*, 123780. [[CrossRef](#)]
46. Qi, T.; Gao, X.; Feng, G.; Bai, J.; Wang, Z.; Chen, Q.; Wang, H.; Du, X. Effect of Biomass Power Plant Ash on Fresh Properties of Cemented Coal Gangue Backfill. *Constr. Build. Mater.* **2022**, *340*, 127853. [[CrossRef](#)]
47. Qin, Z.; Jin, J.; Liu, L.; Zhang, Y.; Du, Y.; Yang, Y.; Zuo, S. Reuse of Soil-like Material Solidified by a Biomass Fly Ash-Based Binder as Engineering Backfill Material and Its Performance Evaluation. *J. Clean. Prod.* **2023**, *402*, 136824. [[CrossRef](#)]
48. Carrasco, B.; Cruz, N.; Terrados, J.; Corpas, F.A.; Pérez, L. An Evaluation of Bottom Ash from Plant Biomass as a Replacement for Cement in Building Blocks. *Fuel* **2014**, *118*, 272–280. [[CrossRef](#)]
49. Olatoyan, O.J.; Kareem, M.A.; Adebajo, A.U.; Olawale, S.O.A.; Alao, K.T. Potential Use of Biomass Ash as a Sustainable Alternative for Fly Ash in Concrete Production: A Review. *Hybrid Adv.* **2023**, *4*, 100076. [[CrossRef](#)]
50. Cabrera, M.; Galvin, A.P.; Agrela, F.; Carvajal, M.D.; Ayuso, J. Characterisation and Technical Feasibility of Using Biomass Bottom Ash for Civil Infrastructures. *Constr. Build. Mater.* **2014**, *58*, 234–244. [[CrossRef](#)]
51. Niu, Y.; Tan, H.; Hui, S. Ash-Related Issues during Biomass Combustion: Alkali-Induced Slagging, Silicate Melt-Induced Slagging (Ash Fusion), Agglomeration, Corrosion, Ash Utilization, and Related Countermeasures. *Prog. Energy Combust. Sci.* **2016**, *52*, 1–61. [[CrossRef](#)]
52. Pitman, R.M. Wood Ash Use in Forestry—a Review of the Environmental Impacts. *Forestry* **2006**, *79*, 563–588. [[CrossRef](#)]
53. Vassilev, S.V.; Baxter, D.; Andersen, L.K.; Vassileva, C.G. An Overview of the Chemical Composition of Biomass. *Fuel* **2010**, *89*, 913–933. [[CrossRef](#)]
54. Vassilev, S.V.; Baxter, D.; Andersen, L.K.; Vassileva, C.G.; Morgan, T.J. An Overview of the Organic and Inorganic Phase Composition of Biomass. *Fuel* **2012**, *94*, 1–33. [[CrossRef](#)]
55. Vassilev, S.V.; Vassileva, C.G.; Vassilev, V.S. Advantages and Disadvantages of Composition and Properties of Biomass in Comparison with Coal: An Overview. *Fuel* **2015**, *158*, 330–350. [[CrossRef](#)]
56. Vassilev, S.V.; Baxter, D.; Vassileva, C.G. An Overview of the Behaviour of Biomass during Combustion: Part II. Ash Fusion and Ash Formation Mechanisms of Biomass Types. *Fuel* **2014**, *117*, 152–183. [[CrossRef](#)]
57. Girón, R.P.; Ruiz, B.; Fuente, E.; Gil, R.R.; Suárez-Ruiz, I. Properties of Fly Ash from Forest Biomass Combustion. *Fuel* **2013**, *114*, 71–77. [[CrossRef](#)]
58. Tortosa Masiá, A.A.; Buhre, B.J.P.; Gupta, R.P.; Wall, T.F. Characterising Ash of Biomass and Waste. *Fuel Process. Technol.* **2007**, *88*, 1071–1081. [[CrossRef](#)]
59. Suarez-Garcia, F.; Martinez-Alonso, A.; Fernandez-Llorente, M.; Tascon, J. Inorganic Matter Characterization in Vegetable Biomass Feedstocks. *Fuel* **2002**, *81*, 1161–1169. [[CrossRef](#)]
60. Vamvuka, D.; Kakaras, E. Ash Properties and Environmental Impact of Various Biomass and Coal Fuels and Their Blends. *Fuel Process. Technol.* **2011**, *92*, 570–581. [[CrossRef](#)]
61. Vassileva, C.G.; Vassilev, S.V. Behaviour of Inorganic Matter during Heating of Bulgarian Coals. *Fuel Process. Technol.* **2006**, *87*, 1095–1116. [[CrossRef](#)]
62. Hubert, J.; Grigoletto, S.; Michel, F.; Zhao, Z.; Courard, L. Development and Properties of Recycled Biomass Fly Ashes Modified Mortars. *Recycling* **2024**, *9*, 46. [[CrossRef](#)]
63. Ohenoja, K.; Wigren, V.; Österbacka, J.; Illikainen, M. Mechanically Treated Fly Ash from Fluidized Bed Combustion of Peat, Wood, and Wastes in Concrete. *Waste Biomass Valorization* **2020**, *11*, 3071–3079. [[CrossRef](#)]
64. Silvestro, L.; Sclaro, T.P.; Ruviano, A.S.; Santos Lima, G.T.D.; Gleize, P.J.P.; Pelisser, F. Use of Biomass Wood Ash to Produce Sustainable Geopolymeric Pastes. *Constr. Build. Mater.* **2023**, *370*, 130641. [[CrossRef](#)]
65. Ates, F.; Park, K.T.; Kim, K.W.; Woo, B.-H.; Kim, H.G. Effects of Treated Biomass Wood Fly Ash as a Partial Substitute for Fly Ash in a Geopolymer Mortar System. *Constr. Build. Mater.* **2023**, *376*, 131063. [[CrossRef](#)]
66. Maschowski, C.; Kruspan, P.; Garra, P.; Talib Arif, A.; Trouvé, G.; Gieré, R. Physicochemical and Mineralogical Characterization of Biomass Ash from Different Power Plants in the Upper Rhine Region. *Fuel* **2019**, *258*, 116020. [[CrossRef](#)]
67. Sigvardsen, N.M.; Geiker, M.R.; Ottosen, L.M. Phase Development and Mechanical Response of Low-Level Cement Replacements with Wood Ash and Washed Wood Ash. *Constr. Build. Mater.* **2021**, *269*, 121234. [[CrossRef](#)]

68. Rissanen, J.; Giosué, C.; Ohenoja, K.; Kinnunen, P.; Marcellini, M.; Letizia Ruello, M.; Tittarelli, F.; Illikainen, M. The Effect of Peat and Wood Fly Ash on the Porosity of Mortar. *Constr. Build. Mater.* **2019**, *223*, 421–430. [[CrossRef](#)]
69. Wang, G.; Shen, L.; Sheng, C. Characterization of Biomass Ashes from Power Plants Firing Agricultural Residues. *Energy Fuels* **2012**, *26*, 102–111. [[CrossRef](#)]
70. Boström, D.; Skoglund, N.; Grimm, A.; Boman, C.; Öhman, M.; Broström, M.; Backman, R. Ash Transformation Chemistry during Combustion of Biomass. *Energy Fuels* **2012**, *26*, 85–93. [[CrossRef](#)]
71. Baxter, L.L.; Miles, T.R.; Miles, T.R.; Jenkins, B.M.; Milne, T.; Dayton, D.; Bryers, R.W.; Oden, L.L. The Behavior of Inorganic Material in Biomass-Fired Power Boilers: Field and Laboratory Experiences. *Fuel Process. Technol.* **1998**, *54*, 47–78. [[CrossRef](#)]
72. Lanzerstorfer, C. Cyclone Fly Ash from a Grate-Fired Biomass Combustion Plant: Dependence of the Concentration of Various Components on the Particle Size. *Fuel Process. Technol.* **2015**, *131*, 382–388. [[CrossRef](#)]
73. Trivedi, N.S.; Mandavgane, S.A.; Mehetre, S.; Kulkarni, B.D. Characterization and Valorization of Biomass Ashes. *Environ. Sci. Pollut. Res.* **2016**, *23*, 20243–20256. [[CrossRef](#)]
74. Vassilev, S.V.; Baxter, D.; Andersen, L.K.; Vassileva, C.G. An Overview of the Composition and Application of Biomass Ash. Part 2. Potential Utilisation, Technological and Ecological Advantages and Challenges. *Fuel* **2013**, *105*, 19–39. [[CrossRef](#)]
75. Voshell, S.; Mäkelä, M.; Dahl, O. A Review of Biomass Ash Properties towards Treatment and Recycling. *Renew. Sustain. Energy Rev.* **2018**, *96*, 479–486. [[CrossRef](#)]
76. van Loo, S.; Koppejan, J. *The Handbook of Biomass Combustion and Co-Firing*; Earthscan: London, UK, 2008; ISBN 978-1-84407-249-1.
77. Barbosa, R.; Lapa, N.; Dias, D.; Mendes, B. Concretes Containing Biomass Ashes: Mechanical, Chemical, and Ecotoxic Performances. *Constr. Build. Mater.* **2013**, *48*, 457–463. [[CrossRef](#)]
78. Horsakulthai, V.; Phiuvanna, S.; Kaenbud, W. Investigation on the Corrosion Resistance of Bagasse-Rice Husk-Wood Ash Blended Cement Concrete by Impressed Voltage. *Constr. Build. Mater.* **2011**, *25*, 54–60. [[CrossRef](#)]
79. Omran, A.; Soliman, N.; Xie, A.; Davidenko, T.; Tagnit-Hamou, A. Field Trials with Concrete Incorporating Biomass-Fly Ash. *Constr. Build. Mater.* **2018**, *186*, 660–669. [[CrossRef](#)]
80. Sata, V.; Jaturapitakkul, C.; Kiattikomol, K. Influence of Pozzolan from Various By-Product Materials on Mechanical Properties of High-Strength Concrete. *Constr. Build. Mater.* **2007**, *21*, 1589–1598. [[CrossRef](#)]
81. Siddique, R. Utilization of Wood Ash in Concrete Manufacturing. *Resour. Conserv. Recycl.* **2012**, *67*, 27–33. [[CrossRef](#)]
82. Cheah, C.B.; Ramli, M. The Implementation of Wood Waste Ash as a Partial Cement Replacement Material in the Production of Structural Grade Concrete and Mortar: An Overview. *Resour. Conserv. Recycl.* **2011**, *55*, 669–685. [[CrossRef](#)]
83. *ASTM C618-23*; Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2023. [[CrossRef](#)]
84. *EN-450-1*; Fly Ash for Concrete—Part 1: Definition, Specifications and Conformity Criteria. CEN: Brussels, Belgium, 2012.
85. Vamvuka, D.; Zografos, D. Predicting the Behaviour of Ash from Agricultural Wastes during Combustion. *Fuel* **2004**, *83*, 2051–2057. [[CrossRef](#)]
86. Vassilev, S.V.; Vassileva, C.G. A New Approach for the Classification of Coal Fly Ashes Based on Their Origin, Composition, Properties, and Behaviour. *Fuel* **2007**, *86*, 1490–1512. [[CrossRef](#)]
87. Vassilev, S.V.; Vassileva, C.G. A New Approach for the Combined Chemical and Mineral Classification of the Inorganic Matter in Coal. 1. Chemical and Mineral Classification Systems. *Fuel* **2009**, *88*, 235–245. [[CrossRef](#)]
88. Etiégni, L.; Campbell, A.G. Physical and Chemical Characteristics of Wood Ash. *Bioresour. Technol.* **1991**, *37*, 173–178. [[CrossRef](#)]
89. Misra, M.K.; Ragland, K.W.; Baker, A.J. Wood Ash Composition as a Function of Furnace Temperature. *Biomass Bioenergy* **1993**, *4*, 103–116. [[CrossRef](#)]
90. Demirbas, A. Potential Applications of Renewable Energy Sources, Biomass Combustion Problems in Boiler Power Systems and Combustion Related Environmental Issues. *Prog. Energy Combust. Sci.* **2005**, *31*, 171–192. [[CrossRef](#)]
91. Demirbas, A. Combustion Characteristics of Different Biomass Fuels. *Prog. Energy Combust. Sci.* **2004**, *30*, 219–230. [[CrossRef](#)]
92. Wigley, F.; Williamson, J.; Malmgren, A.; Riley, G. Ash Deposition at Higher Levels of Coal Replacement by Biomass. *Fuel Process. Technol.* **2007**, *88*, 1148–1154. [[CrossRef](#)]
93. Tite, M.S.; Shortland, A.; Maniatis, Y.; Kavoussanaki, D.; Harris, S.A. The Composition of the Soda-Rich and Mixed Alkali Plant Ashes Used in the Production of Glass. *J. Archaeol. Sci.* **2006**, *33*, 1284–1292. [[CrossRef](#)]
94. Nutalapati, D.; Gupta, R.; Moghtaderi, B.; Wall, T.F. Assessing Slagging and Fouling during Biomass Combustion: A Thermodynamic Approach Allowing for Alkali/Ash Reactions. *Fuel Process. Technol.* **2007**, *88*, 1044–1052. [[CrossRef](#)]
95. Lapuerta, M.; Hernández, J.J.; Pazo, A.; López, J. Gasification and Co-Gasification of Biomass Wastes: Effect of the Biomass Origin and the Gasifier Operating Conditions. *Fuel Process. Technol.* **2008**, *89*, 828–837. [[CrossRef](#)]
96. Umamaheswaran, K.; Batra, V.S. Physico-Chemical Characterisation of Indian Biomass Ashes. *Fuel* **2008**, *87*, 628–638. [[CrossRef](#)]
97. Madhiyanon, T.; Sathitruangsak, P.; Soponronnarit, S. Co-Combustion of Rice Husk with Coal in a Cyclonic Fluidized-Bed Combustor ( $\psi$ -FBC). *Fuel* **2009**, *88*, 132–138. [[CrossRef](#)]

98. Miles, T.R.; Miles, T.R.; Baxter, L.L.; Bryers, R.W.; Jenkins, B.M.; Oden, L.L. Boiler Deposits from Firing Biomass Fuels. *Biomass Bioenergy* **1996**, *10*, 125–138. [[CrossRef](#)]
99. Bryers, R.W. Fireside Slagging, Fouling, and High-Temperature Corrosion of Heat-Transfer Surface Due to Impurities in Steam-Raising Fuels. *Prog. Energy Combust. Sci.* **1996**, *22*, 29–120. [[CrossRef](#)]
100. Tillman, D.A. Biomass Cofiring: The Technology, the Experience, the Combustion Consequences. *Biomass Bioenergy* **2000**, *19*, 365–384. [[CrossRef](#)]
101. Werther, J.; Saenger, M.; Hartge, E.-U.; Ogada, T.; Siagi, Z. Combustion of Agricultural Residues. *Prog. Energy Combust. Sci.* **2000**, *26*, 1–27. [[CrossRef](#)]
102. Scurlock, J.M.O.; Dayton, D.C.; Hames, B. Bamboo: An Overlooked Biomass Resource? *Biomass Bioenergy* **2000**, *19*, 229–244. [[CrossRef](#)]
103. Thy, P.; Lesher, C.E.; Jenkins, B.M. Experimental Determination of High-Temperature Elemental Losses from Biomass Slag. *Fuel* **2000**, *79*, 693–700. [[CrossRef](#)]
104. Zevenhoven-Onderwater, M.; Blomquist, J.-P.; Skrifvars, B.-J.; Backman, R.; Hupa, M. The Prediction of Behaviour of Ashes from Five Different Solid Fuels in Fluidised Bed Combustion. *Fuel* **2000**, *79*, 1353–1361. [[CrossRef](#)]
105. Risnes, H.; Fjellerup, J.; Henriksen, U.; Moilanen, A.; Norby, P.; Papadakis, K.; Posselt, D.; Sørensen, L.H. Calcium Addition in Straw Gasification. *Fuel* **2003**, *82*, 641–651. [[CrossRef](#)]
106. Feng, Q.; Lin, Q.; Gong, F.; Sugita, S.; Shoya, M. Adsorption of Lead and Mercury by Rice Husk Ash. *J. Colloid Interface Sci.* **2004**, *278*, 1–8. [[CrossRef](#)]
107. Wei, X.; Schnell, U.; Hein, K. Behaviour of Gaseous Chlorine and Alkali Metals during Biomass Thermal Utilisation. *Fuel* **2005**, *84*, 841–848. [[CrossRef](#)]
108. Theis, M.; Skrifvars, B.-J.; Zevenhoven, M.; Hupa, M.; Tran, H. Fouling Tendency of Ash Resulting from Burning Mixtures of Biofuels. Part 2: Deposit Chemistry. *Fuel* **2006**, *85*, 1992–2001. [[CrossRef](#)]
109. Ross, A.; Jones, J.; Kubacki, M.; Bridgeman, T. Classification of Macroalgae as Fuel and Its Thermochemical Behaviour. *Bioresour. Technol.* **2008**, *99*, 6494–6504. [[CrossRef](#)]
110. Ro, J.W.; Cunningham, P.R.; Miller, S.A.; Kendall, A.; Harvey, J. Technical, Economic, and Environmental Feasibility of Rice Hull Ash from Electricity Generation as a Mineral Additive to Concrete. *Sci. Rep.* **2024**, *14*, 9158. [[CrossRef](#)]
111. Udoeyo, F.F.; Inyang, H.; Young, D.T.; Oparadu, E.E. Potential of Wood Waste Ash as an Additive in Concrete. *J. Mater. Civ. Eng.* **2006**, *18*, 605–611. [[CrossRef](#)]
112. Skevi, L.; Baki, V.A.; Feng, Y.; Valderrabano, M.; Ke, X. Biomass Bottom Ash as Supplementary Cementitious Material: The Effect of Mechanochemical Pre-Treatment and Mineral Carbonation. *Materials* **2022**, *15*, 8357. [[CrossRef](#)]
113. Doudart De La Grée, G.C.H.; Florea, M.V.A.; Keulen, A.; Brouwers, H.J.H. Contaminated Biomass Fly Ashes—Characterization and Treatment Optimization for Reuse as Building Materials. *Waste Manag.* **2016**, *49*, 96–109. [[CrossRef](#)] [[PubMed](#)]
114. Memon, S.A.; Khan, M.K. Ash Blended Cement Composites: Eco-Friendly and Sustainable Option for Utilization of Corncob Ash. *J. Clean. Prod.* **2018**, *175*, 442–455. [[CrossRef](#)]
115. Maschio, S.; Tonello, G.; Piani, L.; Furlani, E. Fly and Bottom Ashes from Biomass Combustion as Cement Replacing Components in Mortars Production: Rheological Behaviour of the Pastes and Materials Compression Strength. *Chemosphere* **2011**, *85*, 666–671. [[CrossRef](#)] [[PubMed](#)]
116. Cordeiro, G.C.; Toledo Filho, R.D.; Tavares, L.M.; Fairbairn, E.M.R. Pozzolanic Activity and Filler Effect of Sugar Cane Bagasse Ash in Portland Cement and Lime Mortars. *Cem. Concr. Compos.* **2008**, *30*, 410–418. [[CrossRef](#)]
117. Chusilp, N.; Jaturapitakkul, C.; Kiattikomol, K. Effects of LOI of Ground Bagasse Ash on the Compressive Strength and Sulfate Resistance of Mortars. *Constr. Build. Mater.* **2009**, *23*, 3523–3531. [[CrossRef](#)]
118. Cordeiro, G.C.; Toledo Filho, R.D.; Tavares, L.M.; Fairbairn, E.D.M.R. Ultrafine Grinding of Sugar Cane Bagasse Ash for Application as Pozzolanic Admixture in Concrete. *Cem. Concr. Res.* **2009**, *39*, 110–115. [[CrossRef](#)]
119. Zhang, Q.; Saito, F. A Review on Mechanochemical Syntheses of Functional Materials. *Adv. Powder Technol.* **2012**, *23*, 523–531. [[CrossRef](#)]
120. Jones, W.; Eddleston, M.D. Introductory Lecture: Mechanochemistry, a Versatile Synthesis Strategy for New Materials. *Faraday Discuss* **2014**, *170*, 9–34. [[CrossRef](#)]
121. Szczeńniak, B.; Borysiuk, S.; Choma, J.; Jaroniec, M. Mechanochemical Synthesis of Highly Porous Materials. *Mater. Horiz.* **2020**, *7*, 1457–1473. [[CrossRef](#)]
122. Weerdt, K.D.; Sellevold, E.; Kjellsen, K.O.; Justnes, H. Fly Ash–Limestone Ternary Cements: Effect of Component Fineness. *Adv. Cem. Res.* **2011**, *23*, 203–214. [[CrossRef](#)]
123. Moghaddam, F.; Sirivivatnanon, V.; Vessalas, K. The Effect of Fly Ash Fineness on Heat of Hydration, Microstructure, Flow and Compressive Strength of Blended Cement Pastes. *Case Stud. Constr. Mater.* **2019**, *10*, e00218. [[CrossRef](#)]
124. Li, M.-G.; Sun, C.-J.; Gau, S.-H.; Chuang, C.-J. Effects of Wet Ball Milling on Lead Stabilization and Particle Size Variation in Municipal Solid Waste Incinerator Fly Ash. *J. Hazard. Mater.* **2010**, *174*, 586–591. [[CrossRef](#)]

125. Cho, Y.K.; Jung, S.H.; Choi, Y.C. Effects of Chemical Composition of Fly Ash on Compressive Strength of Fly Ash Cement Mortar. *Constr. Build. Mater.* **2019**, *204*, 255–264. [[CrossRef](#)]
126. Hsu, S.; Chi, M.; Huang, R. Effect of Fineness and Replacement Ratio of Ground Fly Ash on Properties of Blended Cement Mortar. *Constr. Build. Mater.* **2018**, *176*, 250–258. [[CrossRef](#)]
127. Haha, M.B.; De Weerd, K.; Lothenbach, B. Quantification of the Degree of Reaction of Fly Ash. *Cem. Concr. Res.* **2010**, *40*, 1620–1629. [[CrossRef](#)]
128. Wu, F.; Li, H.; Yang, K. Effects of Mechanical Activation on Physical and Chemical Characteristics of Coal-Gasification Slag. *Coatings* **2021**, *11*, 902. [[CrossRef](#)]
129. Tole, I.; Habermehl-Cwirzen, K.; Cwirzen, A. Mechanochemical Activation of Natural Clay Minerals: An Alternative to Produce Sustainable Cementitious Binders—Review. *Mineral. Petrol.* **2019**, *113*, 449–462. [[CrossRef](#)]
130. Chen, C.-G.; Sun, C.-J.; Gau, S.-H.; Wu, C.-W.; Chen, Y.-L. The Effects of the Mechanical–Chemical Stabilization Process for Municipal Solid Waste Incinerator Fly Ash on the Chemical Reactions in Cement Paste. *Waste Manag.* **2013**, *33*, 858–865. [[CrossRef](#)]
131. Nomura, Y.; Fujiwara, K.; Takada, M.; Nakai, S.; Hosomi, M. Lead Immobilization in Mechanochemical Fly Ash Recycling. *J. Mater. Cycles Waste Manag.* **2008**, *10*, 14–18. [[CrossRef](#)]
132. Morales, E.V.; Villar-Cociña, E.; Frías, M.; Santos, S.F.; Savastano, H. Effects of Calcining Conditions on the Microstructure of Sugar Cane Waste Ashes (SCWA): Influence in the Pozzolanic Activation. *Cem. Concr. Compos.* **2009**, *31*, 22–28. [[CrossRef](#)]
133. Frías, M.; Villar, E.; Savastano, H. Brazilian Sugar Cane Bagasse Ashes from the Cogeneration Industry as Active Pozzolans for Cement Manufacture. *Cem. Concr. Compos.* **2011**, *33*, 490–496. [[CrossRef](#)]
134. Cordeiro, G.C.; Barroso, T.R.; Toledo Filho, R.D. Enhancement the Properties of Sugar Cane Bagasse Ash with High Carbon Content by a Controlled Re-Calcination Process. *KSCE J. Civ. Eng.* **2018**, *22*, 1250–1257. [[CrossRef](#)]
135. Bahurudeen, A.; Santhanam, M. Influence of Different Processing Methods on the Pozzolanic Performance of Sugarcane Bagasse Ash. *Cem. Concr. Compos.* **2015**, *56*, 32–45. [[CrossRef](#)]
136. Joshaghani, A.; Moeini, M.A. Evaluating the Effects of Sugar Cane Bagasse Ash (SCBA) and Nanosilica on the Mechanical and Durability Properties of Mortar. *Constr. Build. Mater.* **2017**, *152*, 818–831. [[CrossRef](#)]
137. Cordeiro, G.C.; Toledo Filho, R.D.; Fairbairn, E.M.R. Effect of Calcination Temperature on the Pozzolanic Activity of Sugar Cane Bagasse Ash. *Constr. Build. Mater.* **2009**, *23*, 3301–3303. [[CrossRef](#)]
138. Salvo, M.; Rizzo, S.; Caldirola, M.; Novajra, G.; Canonico, F.; Bianchi, M.; Ferraris, M. Biomass Ash as Supplementary Cementitious Material (SCM). *Adv. Appl. Ceram.* **2015**, *114*, S3–S10. [[CrossRef](#)]
139. Monteiro, R.C.C.; Alendouro, S.J.G.; Figueiredo, F.M.L.; Ferro, M.C.; Fernandes, M.H.V. Development and Properties of a Glass Made from MSWI Bottom Ash. *J. Non-Cryst. Solids* **2006**, *352*, 130–135. [[CrossRef](#)]
140. Ribeiro, A.S.M.; Monteiro, R.C.C.; Davim, E.J.R.; Fernandes, M.H.V. Ash from a Pulp Mill Boiler—Characterisation and Vitrification. *J. Hazard. Mater.* **2010**, *179*, 303–308. [[CrossRef](#)]
141. Jiménez, I.; Pérez, G.; Guerrero, A.; Ruiz, B. Mineral Phases Synthesized by Hydrothermal Treatment from Biomass Ashes. *Int. J. Miner. Process.* **2017**, *158*, 8–12. [[CrossRef](#)]
142. Byrappa, K.; Yoshimura, M. *Handbook of Hydrothermal Technology*, 2nd ed.; William Andrew: Oxford, UK; Waltham, MA, USA, 2013; ISBN 978-0-12-375090-7.
143. Kaminskis, R.; Eisinas, A.; Barauskas, I.; Gaivenis, M. Hydrothermally Treated Biomass Fly Ash as an Additive for Portland Cement. *Sustainability* **2024**, *16*, 2754. [[CrossRef](#)]
144. Ríos, C.A.; Williams, C.D.; Roberts, C.L. Removal of Heavy Metals from Acid Mine Drainage (AMD) Using Coal Fly Ash, Natural Clinker and Synthetic Zeolites. *J. Hazard. Mater.* **2008**, *156*, 23–35. [[CrossRef](#)] [[PubMed](#)]
145. Vadapalli, V.R.K.; Gitari, W.M.; Ellendt, A.; Petrik, L.F.; Balfour, G. Synthesis of Zeolite-P from Coal Fly Ash Derivative and Its Utilisation in Mine-Water Remediation. *S. Afr. J. Sci.* **2010**, *106*, 1–7. [[CrossRef](#)]
146. Querol, X.; Alastuey, A.; Moreno, N.; Alvarez-Ayuso, E.; García-Sánchez, A.; Cama, J.; Ayora, C.; Simón, M. Immobilization of Heavy Metals in Polluted Soils by the Addition of Zeolitic Material Synthesized from Coal Fly Ash. *Chemosphere* **2006**, *62*, 171–180. [[CrossRef](#)] [[PubMed](#)]
147. Ríos, R.C.A.; Oviedo, V.J.A.; Henao, M.J.A.; Macías, L.M.A. A NaY Zeolite Synthesized from Colombian Industrial Coal By-Products: Potential Catalytic Applications. *Catal. Today* **2012**, *190*, 61–67. [[CrossRef](#)]
148. Pimraksa, K.; Chindaprasit, P.; Huanjit, T.; Tang, C.; Sato, T. Cement Mortars Hybridized with Zeolite and Zeolite-like Materials Made of Lignite Bottom Ash for Heavy Metal Encapsulation. *J. Clean. Prod.* **2013**, *41*, 31–41. [[CrossRef](#)]
149. Girskas, G.; Skripkiūnas, G.; Šahmenko, G.; Korjakins, A. Durability of Concrete Containing Synthetic Zeolite from Aluminum Fluoride Production Waste as a Supplementary Cementitious Material. *Constr. Build. Mater.* **2016**, *117*, 99–106. [[CrossRef](#)]
150. Vaitkevičius, V.; Vaičiukynienė, D.; Kantautas, A.; Kartovickis, A.; Rudžionis, Ž. Blended Cements Produced With Synthetic Zeolite Made from Industrial By-Product. *Mater. Sci.* **2015**, *21*, 136–142. [[CrossRef](#)]
151. Hassan, E.M.; Abdul-Wahab, S.A.; Abdo, J.; Yetilmezsoy, K. Production of Environmentally Friendly Cements Using Synthetic Zeolite Catalyst as the Pozzolanic Material. *Clean Technol. Environ. Policy* **2019**, *21*, 1829–1839. [[CrossRef](#)]

152. Fukasawa, T.; Horigome, A.; Tsu, T.; Karisma, A.D.; Maeda, N.; Huang, A.-N.; Fukui, K. Utilization of Incineration Fly Ash from Biomass Power Plants for Zeolite Synthesis from Coal Fly Ash by Hydrothermal Treatment. *Fuel Process. Technol.* **2017**, *167*, 92–98. [[CrossRef](#)]
153. Shi, Y.; Wei, L.; Sun, H.; Li, Y.; Cui, J.; Zhang, W. Preparation and Characterization of Biomass-Ash Composites Derived from Incinerated Sewage Sludge Fly Ash after Hydrothermal Treatment. *Proc. Inst. Mech. Eng. Part J Mater. Des. Appl.* **2024**, *238*, 1778–1790. [[CrossRef](#)]
154. Lam, C.H.K.; Ip, A.W.M.; Barford, J.P.; McKay, G. Use of Incineration MSW Ash: A Review. *Sustainability* **2010**, *2*, 1943–1968. [[CrossRef](#)]
155. Margallo, M.; Taddei, M.B.M.; Hernández-Pellón, A.; Aldaco, R.; Irabien, Á. Environmental Sustainability Assessment of the Management of Municipal Solid Waste Incineration Residues: A Review of the Current Situation. *Clean Technol. Environ. Policy* **2015**, *17*, 1333–1353. [[CrossRef](#)]
156. Wang, L.; Li, R.D.; Li, Y.L.; Wei, L.H. Release of Soluble Salts and Heavy Metals during the Short-Time Washing Process of MSWI Fly Ash. *Adv. Mater. Res.* **2012**, *518–523*, 3247–3251. [[CrossRef](#)]
157. Phua, Z.; Giannis, A.; Dong, Z.-L.; Lisak, G.; Ng, W.J. Characteristics of Incineration Ash for Sustainable Treatment and Reutilization. *Environ. Sci. Pollut. Res.* **2019**, *26*, 16974–16997. [[CrossRef](#)] [[PubMed](#)]
158. Yang, R.; Liao, W.-P.; Wu, P.-H. Basic Characteristics of Leachate Produced by Various Washing Processes for MSWI Ashes in Taiwan. *J. Environ. Manag.* **2012**, *104*, 67–76. [[CrossRef](#)] [[PubMed](#)]
159. Zhu, F.; Takaoka, M.; Oshita, K.; Kitajima, Y.; Inada, Y.; Morisawa, S.; Tsuno, H. Chlorides Behavior in Raw Fly Ash Washing Experiments. *J. Hazard. Mater.* **2010**, *178*, 547–552. [[CrossRef](#)]
160. Weibel, G.; Eggenberger, U.; Kulik, D.A.; Hummel, W.; Schlumberger, S.; Klink, W.; Fisch, M.; Mäder, U.K. Extraction of Heavy Metals from MSWI Fly Ash Using Hydrochloric Acid and Sodium Chloride Solution. *Waste Manag.* **2018**, *76*, 457–471. [[CrossRef](#)]
161. Ma, G.X.; Zhang, H.Y. Washing of the Ash from One Shanghai Plant Using Phosphoric Acid. *Adv. Mater. Res.* **2013**, *664*, 228–231. [[CrossRef](#)]
162. Pöykiö, R.; Nurmesniemi, H.; Dahl, O.; Mäkelä, M. Chemical Fractionation Method for Characterization of Biomass-Based Bottom and Fly Ash Fractions from Large-Sized Power Plant of an Integrated Pulp and Paper Mill Complex. *Trans. Nonferrous Met. Soc. China* **2014**, *24*, 588–596. [[CrossRef](#)]
163. Chen, W.-S.; Chang, F.-C.; Shen, Y.-H.; Tsai, M.-S.; Ko, C.-H. Removal of Chloride from MSWI Fly Ash. *J. Hazard. Mater.* **2012**, *237–238*, 116–120. [[CrossRef](#)]
164. Kanhar, A.H.; Chen, S.; Wang, F. Incineration Fly Ash and Its Treatment to Possible Utilization: A Review. *Energies* **2020**, *13*, 6681. [[CrossRef](#)]
165. Ottosen, L.M.; Jensen, P.E.; Kirkelund, G.M. Phosphorous Recovery from Sewage Sludge Ash Suspended in Water in a Two-Compartment Electrodialytic Cell. *Waste Manag.* **2016**, *51*, 142–148. [[CrossRef](#)] [[PubMed](#)]
166. Ebbers, B.; Ottosen, L.M.; Jensen, P.E. Comparison of Two Different Electrodialytic Cells for Separation of Phosphorus and Heavy Metals from Sewage Sludge Ash. *Chemosphere* **2015**, *125*, 122–129. [[CrossRef](#)] [[PubMed](#)]
167. Ebbers, B.; Ottosen, L.M.; Jensen, P.E. Electrodialytic Treatment of Municipal Wastewater and Sludge for the Removal of Heavy Metals and Recovery of Phosphorus. *Electrochim. Acta* **2015**, *181*, 90–99. [[CrossRef](#)]
168. Guedes, P.; Couto, N.; Ottosen, L.M.; Ribeiro, A.B. Phosphorus Recovery from Sewage Sludge Ash through an Electrodialytic Process. *Waste Manag.* **2014**, *34*, 886–892. [[CrossRef](#)]
169. Pedersen, A.J. Characterization and Electrodialytic Treatment of Wood Combustion Fly Ash for the Removal of Cadmium. *Biomass Bioenergy* **2003**, *25*, 447–458. [[CrossRef](#)]
170. Ferreira, C.D.; Jensen, P.; Ottosen, L.; Ribeiro, A. Preliminary Treatment of MSW Fly Ash as a Way of Improving Electrodialytic Remediation. *J. Environ. Sci. Health Part A* **2008**, *43*, 837–843. [[CrossRef](#)]
171. Chen, W.; Jensen, P.E.; Ottosen, L.M.; Kirkelund, G.M. Electrodialytic Remediation of Fly Ash from Co-Combustion of Wood and Straw. *Electrochim. Acta* **2015**, *181*, 208–216. [[CrossRef](#)]
172. Chen, W.; Ottosen, L.M.; Jensen, P.; Kirkelund, G.M.; Schmidt, J.W. A Comparative Study on Electrodialytically Treated Bio-Ash and MSWI APC-Residue for Use in Bricks. In Proceedings of the 5th International Conference on Engineering for Waste and Biomass Valorization (WasteEng2014), Rio de Janeiro, Brazil, 25 August 2014; pp. 648–662.
173. Lima, A.T.; Ottosen, L.M.; Ribeiro, A.B. Assessing Fly Ash Treatment: Remediation and Stabilization of Heavy Metals. *J. Environ. Manag.* **2010**, *95*, S110–S115. [[CrossRef](#)]
174. Kirkelund, G.M.; Geiker, M.R.; Jensen, P.E. Electrodialytically Treated MSWI APC Residue as Substitute for Cement in Mortar. *Nord. Concr. Res.* **2014**, *49*, 1–16.
175. Renforth, P. The Negative Emission Potential of Alkaline Materials. *Nat. Commun.* **2019**, *10*, 1401. [[CrossRef](#)] [[PubMed](#)]
176. Vassilev, S.V.; Vassileva, C.G. Extra CO<sub>2</sub> Capture and Storage by Carbonation of Biomass Ashes. *Energy Convers. Manag.* **2020**, *204*, 112331. [[CrossRef](#)]

177. Pan, S.-Y.; Chen, Y.-H.; Fan, L.-S.; Kim, H.; Gao, X.; Ling, T.-C.; Chiang, P.-C.; Pei, S.-L.; Gu, G. CO<sub>2</sub> Mineralization and Utilization by Alkaline Solid Wastes for Potential Carbon Reduction. *Nat. Sustain.* **2020**, *3*, 399–405. [[CrossRef](#)]
178. Liu, W.; Teng, L.; Rohani, S.; Qin, Z.; Zhao, B.; Xu, C.C.; Ren, S.; Liu, Q.; Liang, B. CO<sub>2</sub> Mineral Carbonation Using Industrial Solid Wastes: A Review of Recent Developments. *Chem. Eng. J.* **2021**, *416*, 129093. [[CrossRef](#)]
179. Kim, J.; Azimi, G. The CO<sub>2</sub> Sequestration by Supercritical Carbonation of Electric Arc Furnace Slag. *J. CO<sub>2</sub> Util.* **2021**, *52*, 101667. [[CrossRef](#)]
180. Carević, I.; Štirmer, N.; Serdar, M.; Ukrainczyk, N. Effect of Wood Biomass Ash Storage on the Properties of Cement Composites. *Materials* **2021**, *14*, 1632. [[CrossRef](#)]
181. Chen, T.-L.; Jiang, W.; Shen, A.-L.; Chen, Y.-H.; Pan, S.-Y.; Chiang, P.-C. CO<sub>2</sub> Mineralization and Utilization Using Various Calcium-Containing Wastewater and Refining Slag via a High-Gravity Carbonation Process. *Ind. Eng. Chem. Res.* **2020**, *59*, 7140–7150. [[CrossRef](#)]
182. Polettini, A.; Pomi, R. The Leaching Behavior of Incinerator Bottom Ash as Affected by Accelerated Ageing. *J. Hazard. Mater.* **2004**, *113*, 209–215. [[CrossRef](#)]
183. Ohenoja, K.; Körkkö, M.; Wigren, V.; Österbacka, J.; Illikainen, M. Increasing the Utilization Potential of Fly Ashes from Fluidized Bed Combustion by Mechanical Treatments. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 1839–1846. [[CrossRef](#)]
184. Zhang, T.; Yu, Q.; Wei, J.; Zhang, P. Effect of Size Fraction on Composition and Pozzolanic Activity of High Calcium Fly Ash. *Adv. Cem. Res.* **2011**, *23*, 299–307. [[CrossRef](#)]
185. Berra, M.; Mangialardi, T.; Paolini, A.E. Reuse of Woody Biomass Fly Ash in Cement-Based Materials. *Constr. Build. Mater.* **2015**, *76*, 286–296. [[CrossRef](#)]

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.