https://doi.org/10.53360/2788-7995-2026-2(22)-69

IRSTI: 53.37.91; 87.53.13

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A MINI REVIEW ON LEACHING METHODS OF ASH AND SLAG WASTE USING AMORPHOUS GRAPHITE IN A MICROWAVE FURNACE

Abstract: *Currently, the recycling of ash-slag waste generated by thermal power plants and the efficient recovery of valuable metals such as aluminum from these materials represent one of the most important environmental and economic challenges. Traditional aluminum extraction methods, including acid and alkaline leaching, high-temperature thermal treatment, pyrometallurgical processes, and organic extraction techniques, are characterized by high energy consumption, significant environmental impact, and low economic efficiency.*

This review provides a comprehensive analysis of modern methods for extracting aluminum from industrial ash-slag waste, comparing their efficiency, energy consumption, and technological limitations. Special attention is given to microwave-assisted leaching technology using amorphous graphite, and its advantages over conventional methods are systematically evaluated.

The results of the literature review indicate that microwave-assisted leaching is a promising approach due to its energy efficiency, accelerated reaction kinetics, increased aluminum dissolution rate, and reduced environmental burden. Furthermore, this review highlights the scientific advantages of the proposed technology and identifies key areas for further development, including optimization of microwave penetration depth, power input, and temperature regimes.

Thus, this review systematizes the scientific basis for the application of microwave technologies in the processing of ash–slag waste and contributes to the development of new, environmentally friendly methods for the efficient recovery of aluminum from waste materials.

Key words: *ash-slag waste, aluminum oxide, graphite, electromagnetic technology, aluminum, microwave processing, leaching, chemical thermodynamics.*

1. Introduction

Currently, the efficient processing of industrial waste, along with the recovery of the various valuable metals it contains, represents one of the most important environmental and economic challenges. One of the main by-products of thermal power plants is ash-slag waste, which contains small amounts of aluminum along with iron, calcium, and mineral phases such as mullite and quartz. In this regard, the extraction of aluminum from ash-slag waste using traditional hydrometallurgical methods is inefficient due to high energy consumption and associated environmental impacts. Therefore, microwave-assisted leaching technology using amorphous graphite is being considered as an alternative, efficient, and environmentally friendly approach compared to conventional methods, offering reduced environmental impact and lower energy consumption [1-2].

At present, the development of an energy-efficient microwave-assisted leaching process for aluminum extraction from ash-slag waste using amorphous graphite remains a key research topic. This is because microwave leaching with amorphous graphite enables energy savings while reducing environmental impact and lowering overall process energy demand [3]. Various methods for aluminum recovery from ash-slag waste exist; however, most of them are economically and environmentally inefficient. Globally, coal accounts for approximately 30% of electricity generation, though this varies across regions [4]. In the context of waste recycling and depletion of bauxite reserves, the search for alternative sources of aluminum is one of the most urgent scientific and industrial challenges [5]. The main advantage of microwave-assisted leaching is the uniform volumetric heating, which significantly accelerates reaction rates, promotes rapid formation of active phases, increases leaching efficiency, and reduces energy consumption [6]. In aluminum leaching from ash-slag waste, the role of amorphous graphite is particularly important, as it strongly absorbs microwave radiation and ensures efficient heat transfer. Acting as a heating mediator in the microwave field, it also creates a partially reducing environment during the leaching process, enhances reaction kinetics, and improves the transfer of aluminum into solution.

Numerous studies indicate that optimizing process parameters-such as temperature, microwave power, graphite dosage, and leaching medium composition-is a key challenge for scaling the technology to an industrial level [7]. Conventional leaching processes typically use mineral acids (H_2SO_4, HCl, HNO_3) or alkalis (NaOH) and rely on convective heating. However, convective heating has several disadvantages, including high energy consumption, long processing time, and limited leaching efficiency. To address these limitations, microwave heating has been proposed as an alternative to leaching processes [8]. Tian and co-authors investigated microwave-assisted pressure leaching of converter vanadium slag and found that, compared to conventional electric heating, the microwave method achieved up to 96% vanadium leaching efficiency within only 20 minutes, whereas electric heating achieved only 46%. In addition, the activation energy decreased from 40.5 kJ/mol under conventional heating to 14.8 kJ/mol under microwave irradiation, clearly demonstrating that microwave irradiation significantly reduces the reaction's kinetic barrier. The acceleration of the leaching process under microwave energy can be explained by several mechanisms. First, microwaves interact directly with the material's internal structure, enabling volumetric heating that differs from conventional surface heating. Second, microwave irradiation induces rapid boiling of the solution, helping to overcome chemical and diffusion kinetic limitations [9]. Hamidi and co-authors further investigated microwave-assisted leaching using organic acids, including ascorbic, gluconic, citric, and acetic acids. They found that oxalic acid enabled complete vanadium recovery and full iron removal, and that microwave leaching was the most environmentally friendly and efficient process, as determined by life-cycle assessment [10]. Kurtulus and co-authors demonstrated that microwave irradiation applied to electric arc furnace slag, using different approaches including direct treatment and NaOH-assisted leaching, increased aluminum dissolution by up to 25% and calcium removal by up to 50% [11]. Kim and co-authors (2016) showed that amorphous carbon can be transformed into crystalline graphite within 5 minutes under microwave heating, confirming that carbon-based materials effectively absorb microwave energy [12]. Gao and co-authors studied waste carbon derived from coal gasification residues and found that partially graphitized carbon exhibits excellent microwave absorption properties due to dielectric loss and polarization relaxation mechanisms [13]. Thus, based on the reviewed studies, microwave-assisted leaching of valuable metals from ash-slag waste using amorphous graphite as a microwave absorber is a promising, environmentally efficient approach. Microwave processing accelerates leaching kinetics, reduces energy consumption, and increases metal recovery efficiency. The high microwave absorption capacity of amorphous graphite makes it an excellent additive and absorber in microwave heating systems. However, research in this area remains limited, particularly regarding the optimization of process parameters, kinetic mechanisms, and the industrial-scale applicability of amorphous graphite in ash-slag leaching systems.

The objective of this review is to compare existing aluminum extraction methods in terms of energy consumption, economic feasibility, and environmental impact, and to systematically evaluate the advantages and industrial potential of microwave-assisted leaching technology. The aim of this work is to provide a scientific justification for improving the efficiency of valuable component extraction from ash-slag waste using amorphous graphite as a microwave absorber.

2. Physicochemical and Chemical Properties of Ash-slag

2.1. Physical Properties of Ash-slag

The physicochemical properties of ash depend directly on the composition of the initial raw material, the combustion temperature, and the technological operating conditions. Recent literature has identified the main components of ash as oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO, and their relative contents determine the ash's reactivity and structural properties [14]. The most important physical properties of ash include density, bulk density, specific surface area, and moisture content. For example, the density of ash from different thermal power plants is approximately 2140-2210 kg/m³, while the bulk density ranges from 750-780 kg/m³, indicating a porous structure. Such high porosity enhances ash's adsorption properties, making it suitable for use in construction materials and composites [15].

Table 1 presents the physical properties of ash, indicating that its morphology varies significantly. Physicochemical studies indicate that ash is not merely an inert waste material but rather an active structural component. Its high specific surface area increases the reaction surface, thereby enhancing hydration and bonding processes.

Table 1 – Physical properties and quantitative characteristics of ash.

Description of Physical Properties of Ash	Values of Physico-Chemical Properties of Ash	Reference
Particle size distribution	Fly ash particle size ranges from 1 μm to 300 μm, with an average particle size of 10-20 μm	[16]
Morphological shapes	Predominantly spherical, angular, and irregular particle forms	[16]
Density	Average density is 2.0 g/cm³, varying between 1-3 g/cm³ depending on composition	[16]
Composition and density of cenospheres	Cenospheres make up approximately 1% of the total mass; average density 600-800 kg/m³	[16]
pH value	pH ranges from 8 to 12	[16]
Unburned carbon content (LOI)	Loss on Ignition (LOI) varies between 1% and 15%	[16]
Relation between radioactivity and chemical composition	Increased CaO and SO_3 content reduces the concentration of radionuclides from the natural uranium series; increased P_2O_5, K_2O, and Na_2O increases radionuclide content	[17]
Heavy metals and toxic components	Contains Pb, Cr, As, Se, Zn, Cu, Ni; concentration of radioactive heavy metals depends on the type of fuel used	[17]
Specific surface area	Ranges from 1-50 m²/g; mechanically activated samples may exceed 10 m²/g	[18]
Pozzolanic activity	Fine amorphous ash samples show high reactivity; higher CaO content accelerates the hydration reaction with water	[19]

2.2 Chemical Properties

The chemical composition of ash waste directly influences its pozzolanic activity. Given their chemical composition, amorphous SiO_2 and Al_2O_3 phases can react with calcium hydroxide, forming calcium silicate hydrate compounds and thereby increasing the material's strength. In addition, the presence of iron and calcium oxides in the ash determines its melting temperature, thermal stability, and reactivity [20]. Mizerova and co-authors investigated the compounds present in ash and their respective contents. As a result, the data presented in Table 2 were obtained [21]. The quantitative data in Table 2 show that ash-slag waste contains various oxides and both amorphous and crystalline phases, which makes the extraction of active components from ash more difficult. Therefore, the complex and heterogeneous nature of ash composition, as well as the variability of its physicochemical properties, indicates the inefficiency of the extraction process. This is mainly due to the presence of inert mineral impurities with low reactivity, in particular quartz and mullite, which reduce overall extraction efficiency [21-22].

Table 2 – Chemical composition of ash [21]

	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	S	K_2O
(%)	49.82	24.67	7.5	3.91	0.7	2.68	0.91	2.78

The high porosity and heterogeneous granular structure of ash hinder the uniform penetration of reagents into all particles, resulting in incomplete reaction progress. In addition, the strong bonding of certain elements, such as aluminum and silicon compounds, within a stable crystalline lattice makes their chemical extraction more difficult.

All these factors increase the complexity of recovering valuable components from ash and reduce the overall efficiency of the extraction process. Therefore, to improve this process, it is necessary to apply pre-treatment methods such as grinding, thermal treatment, and activation techniques [23].

2.3 Review of Different Methods for Leaching and Recovery of Aluminum from Ash–Slag Waste

According to scientific studies, a review of the physical and chemical properties, temperature dependence, and composition of ash-slag waste investigated by international researchers shows that Wang and co-authors reported amorphous graphite effectively absorbs microwave radiation and acts as a heating medium. It disrupts aluminosilicate phases in ash-slag waste, thereby increasing the leaching degree of aluminum, while the catalytic effect of graphite facilitates the transfer of aluminum into solution [24]. However, Wang and co-authors did not provide detailed information regarding the economic efficiency and technological parameters required for industrial-scale application of this method. Zhou and co-authors reported that microwave-assisted leaching technology is considered an alternative, efficient, and environmentally friendly method [25]. In addition, Li and co-authors demonstrated that microwave leaching methods reduce energy consumption, increase reaction rates, enhance the extraction degree of valuable metals such as aluminum, and improve the environmental safety of the process [26-28].

Although plasma-based waste treatment methods are widely used, they remain underdeveloped [29]. One of their main drawbacks is high electricity consumption during waste processing [30], which results in additional waste generation during the fuel production, enrichment, and processing stages. Li, Doucet, and co-authors studied the roasting of ash with ammonium sulfate ($(NH_4)_2SO_4$) at high temperature, where aluminosilicates were activated, and subsequent acid washing enabled the transfer of Al^{3+} ions into solution. However, this method has significant disadvantages, including high energy demand for the roasting stage (700-900 °C), high reagent consumption, and the release of gases such as ammonia and SO_2, which require continuous gas treatment systems [31]. Zhao and co-authors removed SiO_2 from ash using NaOH solution, followed by acid treatment to extract aluminum. However, this method has drawbacks, such as high NaOH consumption, formation of Na_2SiO_3 in solution requiring separation, and corrosion risks to equipment [32]. Rahul and co-authors studied pyrometallurgical methods involving flux melting with salts (Na_2CO_3, NaOH) or complex mixtures followed by water leaching for aluminum recovery from ash. The disadvantages of this method include high temperature requirements, environmental risks associated with salts, and the need for multi-stage washing processes [33]. Gökelma and co-authors investigated the separation of metallic aluminum from primary production residues using mechanical/physical separation methods. However, this method is limited because it is only applicable to metallic aluminum fractions, not oxides, and fine ash particles are difficult to process, requiring large-scale mechanical treatment [34]. Amani Shilla and co-authors reviewed the extraction of metal ions from ash in liquid phase systems. However, the main disadvantage of these methods is that organic solvents are environmentally hazardous, difficult to regenerate, and economically inefficient [35].

In acid-leaching processes, energy consumption is moderate; however, environmental issues arise from acidic waste and corrosion. Due to high acid consumption, spent solutions must be neutralized. Alkaline leaching processes are relatively efficient, but they also involve medium energy consumption and potential environmental corrosion risks. Their main limitations include high NaOH consumption and the formation of Na_2SiO_3. Thermal treatment methods, although efficient, require very high temperatures (700-900 °C) and generate CO_2 and SO_2 emissions. Pyrometallurgical salt fusion processes also suffer from high energy demand, low economic feasibility, and the generation of salt waste requiring multi-stage washing. Mechanochemical activation methods have moderate efficiency, but their high energy demand limits their applicability. DES/organic extraction methods have moderate energy consumption but involve toxic solvents and complex recycling processes.

In contrast, bioleaching and microwave-assisted leaching methods demonstrate low energy consumption and relatively low environmental impact. Considering the above limitations, microwave-assisted leaching using amorphous graphite has been actively studied as an alternative, energy-efficient method for aluminum extraction from ash–slag waste. The main advantage of this method is the uniform volumetric heating induced by microwave radiation, which significantly increases reaction rates, promotes rapid formation of active phases, and reduces overall energy consumption.

Amorphous graphite effectively absorbs microwave radiation, acting as a rapid-heating mediator and promoting the structural degradation of ash in the microwave field. In addition, its presence accelerates the decomposition of aluminosilicate phases and creates a reducing environment, thereby enhancing the transfer of aluminum into solution. This makes microwave-assisted leaching more environmentally friendly and energy-efficient compared to conventional hydrometallurgical and pyrometallurgical methods.

Currently, coal fly ash (CFA), despite its complex mineral composition, has attracted significant interest as a valuable metal resource. The aluminum oxide (Al_2O_3) content in CFA can reach 20-30%, but most of it is bound in stable inert phases such as mullite ($3Al_2O_3 \cdot 2SiO_2$) and quartz, which hinder efficient aluminum recovery [36]. Therefore, various strategies for aluminum extraction have been extensively studied. In general, aluminum recovery methods can be classified into four categories:

1. Conventional chemical leaching (acid/alkaline),
2. Pre-treatment methods (thermal, mechanochemical, microwave),
3. Biohydrometallurgical methods,
4. Deep eutectic solvents (DES) – a promising emerging approach.

In conventional leaching methods, many studies have focused on optimizing aluminum extraction using NaOH, H_2SO_4, and HNO_3 [36]. The formation of sodium aluminate ($NaAlO_2$) via NaOH is considered one of the most efficient mechanisms; however, due to mullite's stability, high temperatures (150-250°C) or long processing times are required.

Many studies in the literature have also investigated the use of NaOH, H_2SO_4, and HNO_3 individually or in combination for aluminosilicate dissolution in CFA. However, due to the high acid resistance of aluminosilicate phases in ash–slag waste, aluminum recovery remains limited [37]. Therefore, acid leaching is more effective when applied to pre-activated or calcined ash materials.

2.4 Acid Leaching (H_2SO_4, HCl, HNO_3)

Efficiency of acid leaching methods: Acid leaching is highly efficient, with direct leaching with acids enabling recovery of 68-87% Al from the amorphous phase, while autoclave conditions (180-220°C under pressure) can achieve 90-95%. In the studies of Sangita Panda and co-authors, sulfuric acid (H_2SO_4) was identified as the most effective leaching agent, achieving an Al yield of 68.68% at 220°C, while under high-pressure leaching conditions, the recovery reached 94.16%. When hydrochloric acid (HCl) is used, autoclave conditions can achieve Al recovery of 90–95%, though the process causes significant equipment corrosion [38].

Economic aspects of acid leaching: Acid leaching is technologically simple and uses relatively inexpensive reagents (H_2SO_4 is the most affordable mineral acid). However, high-temperature (180-220°C) and high-pressure conditions require autoclave equipment, which increases capital costs [39]. Aphane and co-authors noted that when silica (SiO_2) and mullite phases are not fully decomposed, the process results in high operational costs [40].

Environmental aspects of acid leaching: The use of fluoride additives (NaF) can increase yield, but poses a risk of fluoride pollution. Liquid wastes contain acids and heavy metals, requiring additional neutralization steps. If acid regeneration is incomplete, the process becomes environmentally unfavorable. The main limitations include: mullite-phase Al is not directly decomposed (it requires thermal/mechanical activation); high-temperature and high-pressure requirements; need for corrosion-resistant equipment; and toxicity of fluoride-based additives [41].

2.5 Alkaline Leaching (NaOH, $Ca(OH)_2$)

Efficiency: Alkaline leaching is typically carried out after pre-calcination at 600-900°C. Kumar and co-authors reported 80% Al dissolution in a muffle furnace and 89.4% under microwave heating conditions [42]. However, below 400°C, hydroxycancrinite forms, leading to Al loss. According to Tenza and Aphane, alkaline leaching and alkali fusion are effective for silicate recovery, but high reagent consumption reduces aluminum selectivity [43].

Economic aspects: NaOH is an expensive reagent and must be regenerated for large-scale applications. Sibanda and co-authors identified the high cost and difficulty in recycling as key barriers to commercialization [44]. In lime-soda sintering processes, reagents are cheaper, but very high temperatures (~1200°C) are required, leading to high energy consumption.

Environmental aspects: When Na_2CO_3 is used, CO_2 is released. Su reported that Na_2CO_3 sintering is more resource- and energy-efficient than $CaCO_3$ sintering [45]. However, large amounts of secondary solid waste are generated, requiring additional treatment.

Main limitations: high energy demand (600-1200°C); expensive reagents (NaOH); formation of hydroxycancrinite at low temperatures (~400°C), causing Al loss; CO_2 emissions and secondary solid waste generation.

2.6 Thermal Treatment with Sodium Carbonate Sintering

Efficiency: Na_2CO_3 sintering is one of the most efficient methods, achieving 91-95% Al recovery. Conventional sintering requires 800-900°C and 60+ minutes. Microwave-assisted sintering reduces these conditions to 700°C and 20-30 minutes. Gao and co-authors proposed the most promising approach as "desilication → Na_2CO_3 activation → acid leaching" [46].

Economic aspects: Conventional sintering operates at 800-1200°C, resulting in high energy costs. The Na_2CO_3 dosage is typically 0.8-1.2 times the stoichiometric amount relative to Al_2O_3. Microwave sintering reduces energy consumption by 30-50%, but it increases equipment costs. Bakirov and co-authors demonstrated 83-90% Al recovery from Almaty CHP-2 ash-slag waste using a CaO + Na_2CO_3 system, showing economic feasibility for Kazakhstan [47].

Environmental aspects: CO_2 emissions result from Na_2CO_3 decomposition, and large amounts of solid residues ($CaSiO_3$, SiO_2) are produced. Microwave technology helps reduce CO_2 emissions.

Limitations: high energy consumption (800-1200°C); CO_2 emissions; large amounts of solid waste; high reagent use.

2.7 Mechanochemical Activation (Ball Milling)

Efficiency: Mechanochemical activation breaks mullite and quartz phases, increasing acid solubility. Xu reported 91.15% Al recovery after 6 hours of milling followed by acid leaching [48]. Gao showed that mechanochemical activation reduced the calcination temperature by 100°C, the processing time by 20 minutes, and the Na_2CO_3/Al_2O_3 ratio to 0.1 [48]. Fang achieved 95.58% Al recovery using $Na_2S_2O_7$ activation combined with $Na_2S_2O_8$ pressure leaching [49].

Economic aspects: Ball milling equipment is relatively inexpensive, but grinding for 1-6 hours consumes significant electricity. However, reduced calcination temperature improves overall energy efficiency. Gao described mechanochemical activation as an «energy-efficient pre-treatment method» [50].

Environmental aspects: Low chemical consumption and relatively low-temperature processing make it environmentally favorable. However, noise, dust formation, and equipment wear are disadvantages.

Limitations: long grinding time (1-6 hours); high mechanical energy consumption; scaling difficulties; particle agglomeration requiring extended milling.

Traditional leaching methods primarily aim to determine optimal leaching conditions and evaluate alternative aluminum recovery routes using chemical reagents.

Pre-treatment methods

a) Calcination (thermal treatment):

At 1000-1200°C, mullite structure is destroyed and transformed into more reactive phases, significantly increasing Al recovery during NaOH leaching [51].

b) Mechanochemical activation:

High-energy ball milling disrupts CFA crystalline structure and increases surface area, improving leaching efficiency by 30-40% [52].

c) Microwave pre-treatment:

Microwaves (2.45 GHz) alter dielectric properties of Fe_2O_3, TiO_2, and Al_2O_3–SiO_2 systems. Internal heating weakens the mullite structure and accelerates leaching 3-5 times. Agus Mirwan et al. reported 67% Al recovery using 4 M HCl at 40°C for 15 minutes under 100 W microwave power, compared to 46.6% at 80 W, showing that higher microwave power improves dissolution kinetics [53].

2.8 Deep Eutectic Solvents (DES)

In recent years, deep eutectic solvents (DES) have attracted significant research interest for the recovery of aluminum and rare earth elements (REEs) from coal fly ash (CFA), sludge, and bauxite residues. DES are similar to ionic liquids but are considered more cost-effective and environmentally friendly. These solvents are characterized by low toxicity, high thermal stability, and the ability to tune their acidic or alkaline properties by changing component ratios. In addition, they exhibit strong selectivity for metal ion complexation and can efficiently absorb microwave radiation, providing additional advantages for process intensification [54].

DES are typically formed from choline chloride (ChCl) combined with hydrogen bond donors such as lactic acid (LA), p-toluenesulfonic acid (pTSA), glycerol, and urea. The main role of DES systems in aluminum leaching has been demonstrated using ChCl:LA (1:2) acidic DES, which enables the recovery of 30-60% of aluminum and REEs from CFA residues [55]. ChCl:pTSA is considered a highly effective solvent for aluminum dissolution due to the strong acidity of both chloride and pTSA, which facilitates the breaking of Al–O bonds in solution [56].

Microwave-assisted DES systems temporarily reduce viscosity and enhance heat transfer, significantly accelerating leaching kinetics. This process can increase leaching rates by 3-10 times, reduce energy consumption, and improve aluminum recovery. The journal Green Chemistry (2021) reported that MW–DES combinations significantly enhance metal extraction efficiency [54].

Efficiency of DES: DES are a new generation of "green" solvents composed of organic acids and hydrogen bond donor/acceptor mixtures. Studies by Söldner et al. demonstrated their ability to selectively leach metal salts and oxides [55]. Bond et al. tested 11 DES and 6 green solvents on CFA and found performance comparable to that of mineral acids [55]. Huntington et al. reported that ChCl–EG (choline chloride-ethylene glycol) DES showed comparable extraction efficiencies for Fe, Cu, Al, and Ni relative to EDTA [56].

According to Moradi and Karimi, the main advantages of DES include selectivity, biodegradability, recyclability, and low wastewater generation [57]. The main limitations are high viscosity, slow reaction kinetics, and the lack of validated large-scale applications.

Economic aspects: DES components (choline chloride, urea, organic acids) are relatively inexpensive; however, their high viscosity limits mass transfer, leading to longer processing times. An industrial-scale application has not yet been demonstrated, and most studies remain at the laboratory scale.

Environmental aspects: DES are among the most environmentally friendly leaching agents due to their biodegradability, low toxicity, and minimal wastewater generation. They can also be regenerated. However, key limitations include high viscosity, which leads to poor mass transfer; lack of industrial-scale validation; limited interaction with CFA mullite phases; and limited quantitative performance data.

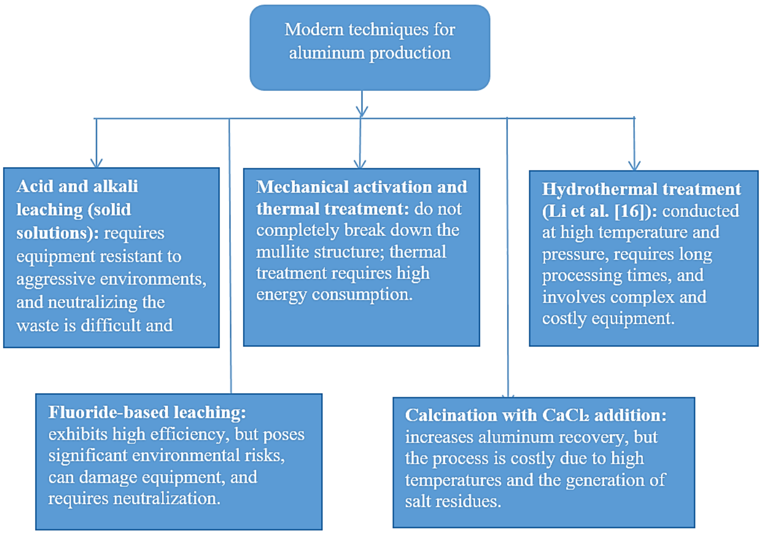
Based on the comparative data presented in Table 3, the thermal treatment method enables recovery of aluminum ions up to 95%. However, this process requires high temperatures, which results in significant energy consumption. Therefore, to achieve efficient aluminum ion extraction from ash-slag waste in a shorter processing time while saving energy, microwave-assisted leaching using amorphous graphite in a microwave furnace is a promising alternative.

Table 3 – Comparison of main aluminum leaching methods, reagents used, advantages, and disadvantages of each method

Aluminum leaching methods	Main reagents used	Aluminum recovery efficiency	Advantages of the method	Disadvantages o f the method	References
1	*2*	*3*	*4*	*5*	*6*
Acid leaching	H_2SO_4, HNO_3, HCl	68-84%	Simple process	Mullite in ash-slag waste is not completely decomposed; high temperature is required	[39-40]
Alkaline leaching	NaOH, Na_2CO_3	48-93%	High selectivity	May require multistage processing to carry out the process	[41-42]
Roasting and leaching	Na_2CO_3/$CaCl_2$ + acid/alkali	80-90%+	Breaks down the mullite structure; high efficiency.	High energy consumption.	[43]
Cascade approaches	Alkali → calcination → acid leaching	90%+	Multiple products; near-zero waste generation; economically efficient	Requires a complex technological scheme	[44-45]
Water leaching	H_2O	>92% Salt production	Simple; environmentally friendly	Designed only for extracting salts from compounds	[46]
Thermal treatment (Na_2CO_3 + sintering)	In the conventional method: 800-900°C In a microwave furnace: 700°C	91-95%	High yield; completely destroys the mullite structure	The process is carried out at high temperatures; high reagent consumption	[47]

1	2	3	4	5	6
Mechanochemical activation (ball milling)	1-6 hours of grinding + acid leaching	74-95%	Reduces the calcination temperature by 100°C; decreases reagent consumption	Long grinding time; significant energy consumption	[50]
DES (Deep eutectic solvents)	Can be carried out at room temperature	Limited quantitative data available	Environmentally friendly; selective; reusable	Industrial-scale application has not yet been demonstrated; the process is expensive	[54]

Based on Scheme 1, the methods for leaching aluminum from ash-slag waste can be categorized into five groups. However, it should be noted that, for cost-effectiveness and low energy consumption, each of these methods has its own limitations [58].



Scheme 1 – Modern methods currently used for aluminum recovery

Zhao and co-workers reported that desilicated fly ash was calcined with calcium carbonate, transforming the mullite phase into nepheline. This increased the leachability of Al_2O_3 and Fe_2O_3 during acid leaching to 90.4% and 92.3%, respectively. They also stated that during acid leaching, silicon compounds in the activated fly ash were converted into silicic acid with a purity of 93.9%, while sequential precipitation allowed the recovery of $Fe(OH)_3$ and $Al(OH)_3$ with purities of 70.6% and 90.8%, respectively [59].

The obtained $CaSiO_3$, silica gel, $Fe(OH)_3$, and $Al(OH)_3$ can be reused as flame-retardant materials. In addition, $Al(OH)_3$ can be converted to $NaAlO_2$ to remove chlorides from saline wastewater. It has been noted that this cascade recovery approach is economically efficient, environmentally friendly, and does not generate solid waste during fly ash utilization in Figure 1 [59].

Mullite is an aluminosilicate solid solution composed of aluminum oxide and silicon oxide, and it is more stable than corundum at very high temperatures [59]. Mullite exists in two stoichiometric forms: 3:2 and 2:1 [59]. Due to its low thermal expansion coefficient and high resistance to deformation, it exhibits low thermal expansion, making phase transformations difficult. Since aluminum and silicon in fly ash are present as mullite, their separation is challenging.

Yanghui and co-workers reported that as the number of aluminum atoms in tetrahedral units increases, the absorption peaks shift to lower wavenumbers. This indicates an increase in aluminum content within the structure under microwave irradiation, which in turn accelerates the polycondensation reaction rate. These findings were clearly demonstrated in their study Fig. 2 [59].

The dielectric loss factors of solid carbon, calculated using microwave polarization (MWS, 300 MWS), are located in the low-absorption region, indicating they fall within the microwave-transparent materials range. Tewon and co-workers compared the dielectric loss and its corresponding coefficients, and presented the results in Figure 3 [60].

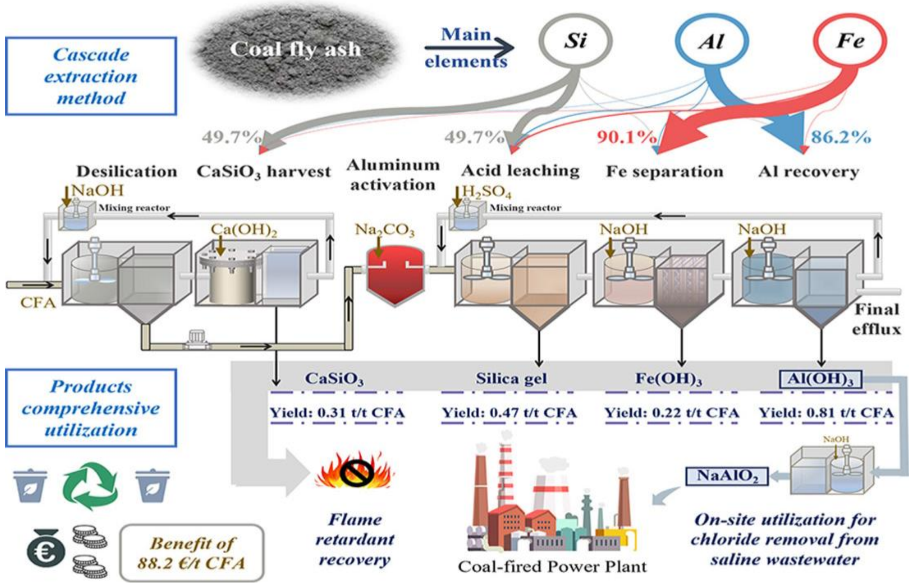


Figure 1 – Schematic of aluminum leaching from ash-slag waste in acidic and alkaline media [59]

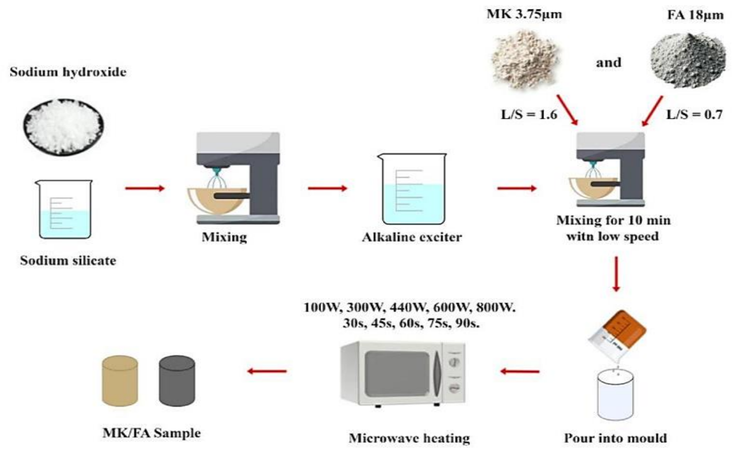


Figure 2 – Experimental block diagram of ash-slag waste treatment showing parameters such as microwave power and irradiation time [59]

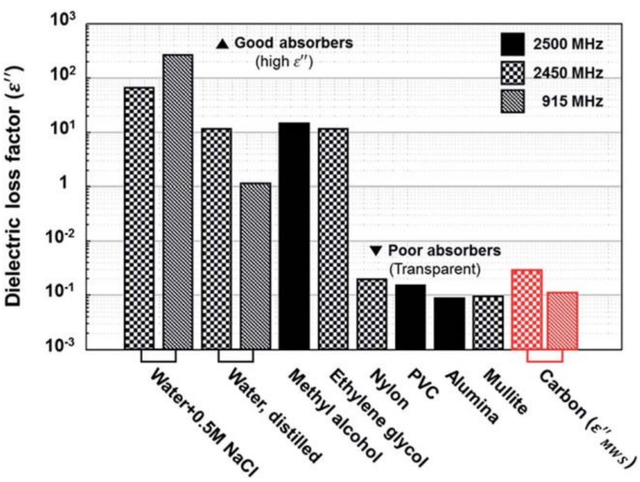


Figure 3 – Comparison of dielectric loss factor

The dielectric loss factors of solid carbon calculated based on microwave polarization (MWS, 300 MWS) are located in the low absorption region, meaning they fall within the area of microwave-transparent materials. Tewon and co-workers compared the dielectric loss and its corresponding coefficients, and presented the results in Figure 3 [60].

3. Microwave leaching: the effect of power and time on yield

The efficiency of microwave-assisted leaching (MAL) mainly depends on two key factors: microwave power and irradiation time. The effect of microwave power was studied by Mirwan and co-workers during aluminum leaching from beneficial clay using HCl solution. At 100 W, an aluminum yield of 67% was achieved, while at 80 W the yield decreased to 46.6% [61]. In the study of Hamidi et al., vanadium and nickel in oil ash were completely (100%) leached using 700 W microwave irradiation in H_2SO_4 solution without any additional oxidizing agent. This result is achievable only in conventional leaching with 10% H_2O_2 [62].

Regarding time effects, Liu and co-workers activated ash–slag waste with Na_2CO_3 under microwave heating at 700 °C for 20 minutes, achieving an aluminum recovery of 95.52%, whereas conventional heating required more than 1 hour to reach similar results [63]. Similarly, Hu et al. reported that in a comparable system (Na_2CO_3 activation at 700 °C), microwave treatment achieved ~93% yield in 30 minutes, while conventional heating required more than 50 minutes [10].

Ma et al. used a H_2SO_4 + NH_4HSO_4 system under microwave-assisted roasting (280 °C, 60 min) and achieved 82.4% aluminum recovery, while significantly reducing energy consumption and gas emissions compared to conventional acid sintering [64].

Khan et al. compared microwave-assisted leaching with conventional heating for municipal waste ash and found that MAL significantly reduces processing costs, making it a more energy-efficient and promising method [65].

Based on the literature data presented in Table 4, it can be concluded that the use of amorphous graphite in microwave-assisted leaching of aluminum from ash–slag waste significantly reduces processing time and enables operation at lower temperature and power conditions.

Table 4 – Comparison of the effect of time and power in microwave-assisted leaching processes

Power/Temperature	Time	Al/metal yield	Comparison with conventional method	References
100 watts	15 min	67% Al	The value is 46.6% at W	[61]
700 watts	30 min	100% V, 100% Ni	No H_2O_2 is required.	[10]
700°C (MWH)	20 min	95,52% Al	The time is reduced threefold.	[62]
280°C (MWH)	60 min	82,4% Al	Gas emissions were reduced.	[63]
700°C (MWH)	30 min	~93% Al	Lower temperature and shorter time	[64]
MAE	40 min	48,4% Al	5M HCl is optimal	[65]

Amorphous graphite possesses a high specific surface area, a defective structure, good electrical conductivity, and strong dielectric absorption properties, which enable it to effectively absorb microwave radiation and convert it into thermal energy. These characteristics make it suitable for use in leaching systems as a catalyst or energy transformer [66].

During microwave heating, amorphous graphite particles absorb microwave energy, generating localized «hot spots» within the reaction mixture. As a result, the interaction rate with leaching agents increases, leading to enhanced solubility and higher aluminum recovery yield. Therefore, current research considers incorporating amorphous graphite into microwave-assisted leaching processes as a promising direction [67].

During microwave-assisted leaching, complex physicochemical interactions occur between graphite and aluminosilicate phases. Graphite absorbs microwave energy and can generate localized surface temperatures of 500-700°C on ash particles. This effect weakens the aluminosilicate structure and intensifies leaching reactions. As a result of electron transfer and redox reactions, graphite can act as a reducing agent, facilitating the conversion of aluminum oxide species into more reactive forms and enhancing their dissolution in solution. Due to surface adsorption and complexation processes, oxygen-containing functional groups on the graphite surface (–OH, –COOH) promote hydrogen bonding or coordination interactions with aluminum ions, thereby catalyzing leaching [68].

Based on the studies mentioned above, X-ray phase analysis was performed on the initial ash–slag waste composition obtained from Thermal Power Plant No. 2 in Almaty. The obtained sample was mixed with amorphous graphite and milled in a ball mill for 30 minutes, then treated with a 1-6 M NaOH solution. Analytical tests were then carried out to determine the concentration of aluminum ions in the solution. The results demonstrate that, in microwave-assisted leaching of aluminum from ash-slag waste using amorphous graphite, the processing time is significantly reduced and energy consumption is minimized. It was also confirmed that phase structures are effectively disrupted under these conditions, providing a scientifically validated basis for this approach.

Conclusion

In conclusion, the conducted literature review demonstrates that the technologies used for extracting aluminum from ash–slag waste vary significantly, and their efficiency largely depends on the balance between energy consumption, environmental safety, and industrial applicability. Acidic and alkaline leaching methods provide relatively high aluminum recovery; however, they are associated with high reagent consumption and environmental issues such as corrosion and secondary pollution. High-temperature thermal and pyrometallurgical processes are technologically effective but require substantial energy input, thereby increasing environmental burdens.

At the same time, the review highlights microwave-assisted leaching using amorphous graphite as a promising alternative approach for aluminum recovery. The literature indicates that this method efficiently utilizes microwave energy, accelerates reaction kinetics, and rapidly disrupts aluminosilicate phases, thereby enhancing the dissolution of aluminum into solution. The reduction in processing temperature and reaction time under microwave conditions contributes to overall energy savings.

However, the reviewed studies also reveal several unresolved challenges in microwave leaching. In particular, the penetration depth of microwaves into dense ash-graphite mixtures, the energy efficiency of high-power режимдер, the consumption and recyclability of graphite, as well as the feasibility of continuous and large-scale operation, remain insufficiently studied. These factors represent key limitations for industrial-scale application of the technology.

In conclusion, microwave-assisted leaching using amorphous graphite is a promising, energy-efficient, and environmentally friendly alternative for aluminum recovery from ash-slag waste. Nevertheless, its industrial implementation requires systematic studies to optimize the relationship between microwave power and temperature, evaluate overall process economics, and address scale-up challenges. Such research could significantly contribute to the development of alternative aluminum sources and advanced technologies for comprehensive industrial waste utilization.

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Funding: *This work has been supported by Ministry of Science and Higher Education of the Republic of Kazakhstan (grant number: AP26101069).*

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АМОРФТЫ ГРАФИТТІ ҚОЛДАНА ОТЫРЫП, КҮЛ-КОЖ ҚАЛДЫҚТАРЫН МИКРОТОЛҚЫНДЫ ПЕШТЕ ШАЙМАЛАУ ӘДІСТЕРІНЕ ШАҒЫН ШОЛУ

Қазіргі уақытта жылу электр станцияларынан түзілетін күл-қож қалдықтарын қайта өңдеу және олардың құрамындағы алюминий сияқты бағалы металдарды тиімді алу экологиялық және экономикалық тұрғыдан маңызды мәселелердің бірі болып табылады. Дәстүрлі түрде алюминий алу әдістері – қышқылды және сілтілі шаймалау, жоғары температуралы термиялық өңдеу, пирометаллургиялық және органикалық экстракция әдістері – энергия шығынының жоғары болуымен, экологиялық тұрғыдан қоршаға ортаға тигізетін зияны мен қатар экономикалық тұрғыдан тиімсіз болуымен сипатталады.

Осы шолу жұмысында өнеркәсіптік күл-қож қалдықтарынан алюминийді алудың қолданыстағы заманауи әдістеріне кешенді талдау жүргізіліп, олардың тиімділігі, энергетикалық шығындары мен технологиялық тұрғыдан алғандағы шектеулері салыстырмалы түрде қарастырылды. Әсіресе аморфты графитті қолдана отырып микротолқынды пеште шаймалау технологиясына ерекше назар аударылып, оның дәстүрлі әдістермен салыстырғандағы артықшылықтары жүйеленді.

Жүргізілген әдеби шолулар нәтижесінде микротолқынды пеште шаймалау әдісінің энергия үнемділігі, реакцияның жылдамдығын арттыруы, алюминийдің ерітіндіге өту дәрежесін жоғарылатуы және экологиялық жүктемені азайтуы тұрғысынан перспективалы бағыт екендігі анықталды. Сонымен қатар, бұл шолу аталған технологияның ғылыми тұрғыдан артықшылықтарын нақтылап, және оны дамытуға қажетті негізгі бағыттарды – микротолқындардың ену тереңдігін, қуат пен температура режимдерін оңтайландыруды – айқындайды.

Осылайша, берілген шолу жұмысы күл-қож қалдықтарын қайта өңдеу саласында микротолқынды технологияларды қолданудың ғылыми негіздерін жүйелеп, қалдықтың құрамындағы алюминийді тиімді алудың жаңа, экологиялық қауіпсіз әдістерін дамытуға үлес қосады.

Түйін сөздер: *күлшлак, алюминий оксиді, графит, электромагниттік технология, алюминий, микротолқынды өңдеу, сілтілеу, химиялық термодинамика.*

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КРАТКИЙ ОБЗОР МЕТОДОВ МИКРОВОЛНОВОГО ВЫЩЕЛАЧИВАНИЯ ЗОЛО-ШЛАКОВЫХ ОТХОДОВ С ИСПОЛЬЗОВАНИЕМ АМОРФНОГО ГРАФИТА

В настоящее время переработка золошлаковых отходов, образующихся на тепловых электростанциях, и эффективное извлечение из них ценных металлов, таких как алюминий, является одной из важных экологических и экономических задач. Традиционные методы извлечения алюминия – кислотное и щелочное выщелачивание, высокотемпературная термическая обработка, пирометаллургические процессы и методы органической экстракции – характеризуются высоким энергопотреблением, негативным воздействием на окружающую среду и низкой экономической эффективностью.

В данном обзорном исследовании проведён комплексный анализ современных технологий извлечения алюминия из промышленных золошлаковых отходов с сравнительной оценкой их эффективности, энергетических затрат и технологических ограничений. Особое внимание уделено технологии микроволнового выщелачивания с использованием аморфного графита, а также систематизированы её преимущества по сравнению с традиционными методами.

Результаты литературного обзора показывают, что микроволновое выщелачивание является перспективным направлением благодаря энергоэффективности, ускорению кинетики реакций, повышению степени перехода алюминия в раствор и снижению экологической нагрузки. Кроме того, в работе определены основные научные преимущества данной технологии и ключевые направления её дальнейшего развития, включая глубину проникновения микроволн и оптимизацию режимов мощности и температуры.

Таким образом, данная обзорная работа систематизирует научные основы применения микроволновых технологий в переработке золошлаковых отходов и способствует разработке новых экологически безопасных методов эффективного извлечения алюминия из отходов.

Ключевые слова: *золошлаковые отходы, оксид алюминия, графит, электромагнитные технологии, алюминий, микроволновая обработка, выщелачивание, химическая термодинамика.*

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Received 06.01.2026
Revised 30.04.2026
Accepted 30.04.2026

https://doi.org/10.53360/2788-7995-2026-2(22)-70

IRSTI: 61.59.29

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RESEARCH OF THE EFFECT OF UV-IRRADIATION ON UNSATURATED POLYESTER RESINS OBTAINED IN THE PROCESS OF «COLD» CURING WITH ACRYLIC ACID

Annotation: *The investigation of the influence of UV irradiation on polymers represents an important and relevant area of science and technology, as it enables the development of new approaches for designing more durable and efficient materials. This work examines the changes occurring in polymers based on unsaturated polyesters under prolonged exposure to ultraviolet radiation. The objective of the study was to evaluate the effect of long-term UV irradiation on the thermal stability of polymeric materials based on polyethylene glycol maleate and polypropylene glycol maleate copolymerized with acrylic acid at a component*