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Original Research Article

Sustainable Recovery of SiO_2, Al_2O_3, and MgO from Slag, Aluminum Cans, and Bittern

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Abstract

This study investigates the utilization of solid waste from slag and aluminum cans as sources of valuable raw materials, along with bittern waste for magnesium oxide (MgO)cons production. Slag, a byproduct of industrial combustion in the palm oil industry, and aluminum cans, generated from human consumption in urban areas, were both subjected to leaching processes to recover silica (SiO_2) and alumina (Al_2O_3), respectively. The leaching of slag using 4 M NaOH yielded 85.68% SiO_2, while aluminum cans treated with 4 M HCl produced 85.90% Al_2O_3. Additionally, the study extracted MgO from bittern waste via precipitation, resulting in 76.98% MgO. X-ray fluorescence (XRF) analysis was employed used to determine the composition of the slag, aluminum can waste, and bittern, while X-ray diffraction (XRD) analysis confirmed the crystallinity of the recovered materials. The integration of recycled materials into the production of cordierite ceramics represents an innovative approach to waste valorization, offering potential for the development of advanced materials from industrial and urban waste. This research highlights the potential for valorizing industrial and municipal solid wastes through chemical processes, contributing to sustainable resource recovery and environmental conservation.

Keywords: Recyling of industrial waste; leaching; SiO_2; Al_2O_3; MgO; sustainable materials

1. Introduction

Waste is an inevitable by-product of production processes, posing presenting significant challenges releated to in terms of pollution and environmental degradation. damage. As global awareness of these issues increases grows, the urgency need to minimize waste generation has become more pronounced. increasingly urgent. The clean production paradigm has emerged as a global benchmark for sustanaible resource management. managing resources sustainably. This approach emphasizes the efficient use of materials and energy while minimizing waste through effective management strategies (Bui et al., 2022). Given the environmental impacts associated with waste, adopting sustainable waste management practices is essential for crucial to reducing pollution and conserving resources. Waste can be categorized into liquid, gas, and solid forms, with solid waste often being the greatest management challenges most challenging to manage due to its diverse and persistent nature (Wulandari et al., 2023).

Non-biodegradable solid waste, such as metal waste from cans and slag, represents a particularly pressing issue due to its resistance to difficulty in decomposition and potential environmental hazards.

In urban areas, the accumulation of discarded beverage and food cans has have become a significant concern. due to their large accumulation. These cans are primarily often made of aluminum, which accounts for constitutes up to 97% of their total weight (Abdelkader et al., 2021). This high aluminum content makes them a valuable source of aluminum oxide (Al_2O_3), which can be recovered and reused. Properly management managing and recycling of these cans can mitigate environmental impacts and conserve aluminum resources. Similarly, in Indonesia, a leading producer of major palm oil producer, the production process generates significant substantial amounts of slag. This by-product forms a hardened crust on the walls of furnace walls due to continuous high-temperature combustion. The accumulation of slag disrupts interferes with the combustion process and decreases reduces efficiency, highlighting the necessity need for effective management (Senthil Kumar et al., 2019). Palm oil slag, which is rich in silicon dioxide (SiO_2), can be collected and repurposed, providing an additional offering another opportunity for resource recovery (Aulia et al., 2018).

Effective waste management practices, such as leaching and precipitation are crucial for transforming waste into valuable resources. Leaching is a widely used technique in extractive metallurgy that facilitates allows for the extraction of valuable metals from materials such as slag and aluminum cans (Yin et al., 2018). This process is economically viable, environmentally friendly, and energy efficient energhy-efficient (Ramakokovhu et al., 2020). For aluminum cans, leaching can recover Al_2O_3, which is essential for various industrial applications (Roy et al., 2022). In the case of slag from the palm oil industry, leaching can extract SiO_2, which has numerous industrial uses (Chinnu et al., 2022). Additionally, bittern waste from the salt industry presents another opportunity for resource recovery. In Pulau Legundi Village, Lampung Province, salt production generates significant amounts of bittern waste, which has traditionally been left untreated in holding ponds. However, bittern waste, with its potential for high magnesium content, can be used as a utilized precursor for producing magnesium hydroxide ($Mg(OH)_2$) and magnesium oxide (MgO) through precipitation methods (Bagastyo et al., 2021). This approach helps to recover valuable compounds while minimizing environmental impact.

Additionally, the study aims to provide insights into the environmental and economic benefits of these waste management practices. By quantifying the reduction in waste volumes and the conservation of raw materials, the research will highlight the broader implications for sustainability and resource efficiency. The ultimate goal is to contribute to the development of a more sustainable and circular economy by demonstrating how industrial waste can be effectively transformed into valuable resources. Through this research, it is hoped that practical solutions will be offered to provided for industries seeking to enhance their improve waste management practices. and reduce their environmental footprint.

2. Methods

2.1 Preparation of The Palm Oil Slag, Bitter Waste, and Aluminum Cans

The slag waste was collected from a the palm oil processing facility operated by industry of a salt company in Lampung, while the and Bitter waste was sourced from the salt industry in was collected from Pulau Legundi Village, Punduh Pedada District, Pesawaran Regency, Lampung.

2.2 Leaching Palm Oil Slag to Produce SiO_2 Powder

Mix 50 g of palm oil slag with 4 M NaOH and heat the mixture at 100°C for 120 minutes using a hotplate and an overhead stirrer. After heating, add 250 mL of distilled water to produce sodium silicate silikat (Na_2SiO_3), as shown in presented Reaction 1. Gradually Add 8 M HCl while stirring at 100°C until the pH reaches 7. Allow the solution to stand, then neutralize the gel with 300 mL of distilled water. Separate the sediment using filter paper, dry it an oven at 100°C, in an oven, and grind it to obtain SiO_2

powder, as indicated in Reactions 2 (Shrotri et al., 2017). The resulting SiO2 powder is amorphous, with high surface area and porosity, useful for applications such as adsorbents or fillers (Ulum et al., 2023).

$SiO_{2(s)} + NaOH_{(l)} \rightarrow Na2SiO_{3(aq)}$ (1)

$Na2SiO_{3(aq)} + HCl_{(l)} \rightarrow H_2SO_{3(s)} + NaCl_{(aq)}$ (2)

$H_2SO_{3(s)} \rightarrow SiO_{2(s)} + H_2O_{(aq)}$ (3)

The slag waste, both before and after the leaching process, was analyzed using X-ray fluorescence (XRF) with an Olympus Delta Type analyzer and X-ray diffraction (XRD) with a Pan-Analytical X'Pert powder diffractometer to determine its composition and structural changes.

2.3 Leaching Bittern Waste to Produce MgO

Add 50 g of CaCl2 to 500 mL of bittern waste and stir at 70°C for 1 hour at 500 rpm to produce MgCl2 (Reaction 4). Then, mix 50 g of CaO with 16 mL of water to form Ca(OH)2. Combine the Ca(OH)2 with MgCl2 to precipitate Mg(OH)2 (Reaction 5). Separate the Mg(OH)2, add distilled water, stir until more precipitate forms, and then separate and dry the Mg(OH)2 at 800°C for 2 hours to obtain MgO. The resulting MgO produced is a white, powdery substance characterized by high purity and thermal stability, and it is utilized in refractory materials, fertilizers, and as a desiccant (Mustafa & Abdallah, 2013).

$MgSO4_{(s)} + CaCl2_{(aq)} \rightarrow MgCl2_{(aq)} + CaSO4_{(aq)}$ (3)

$CaO_{(s)} + H2O_{(l)} + MgCl2_{(aq)} \rightarrow CaCl2_{(aq)} + Mg(OH)2_{(aq)}$ (4)

The bittern waste, both before and after the precipitation process, was analyzed using X-ray fluorescence (XRF) with an Olympus Delta Type analyzer. The precipitated magnesium oxide (MgO) was examined using X-ray diffraction (XRD) with a Pan-Analytical X'Pert powder diffractometer to evaluate its composition and crystal structure.

2.4 Leaching Alumunium Cans to Produce Al2O3

Cut 50 g of alumunium cans waste into small pieces and dissolve it in 120 mL of 4 M HCl while stirring at 200 rpm for 120 mins (Reaction 6). Filter the solution and add sodium bicarbonate to precipitate Al2O3 (Reaction 7). Separate the sediment, wash with distilled water, and dry it at 150°C in an oven to obtain Al2O3. The resulting Al2O3 is a white, crystalline powder with high purity, known for its hardness and used as an abrasive, in ceramics, and as a catalyst support (Ghulam et al., 2020; How et al., 2017).

$Al_{(s)} + HCl_{(l)} \rightarrow AlCl3_{(aq)} + H2_{(g)}$ (6)

$AlCl3_{(aq)} + NaHCO3_{(aq)} \rightarrow Al(OH)3_{(aq)} + NaCl_{(aq)}$ (7)

$Al(OH)3_{(aq)} \rightarrow Al2O3_{(s)} + H2O_{(l)}$ (8)

The composition of the aluminum cans was initially analyzed using a portable XRF Sci-Aps analyzer directly on the cans. The leaching results were subsequently examined using XRF with an Olympus Delta Type analyzer and XRD with a Pan-Analytical X-pert powder diffractometer to determine the composition and structural properties of the final Al2O3.

3. Result and Discussion

3.1 Leaching of Palm Oil Industry Slag Waste

Palm oil slag waste appears as is in the form of hard, gray rocks. and is gray in color. XRF and XRD tests were conducted to determine the composition and phases of the compounds present contained in the slag.

Table 1. Results of XRF Test of Slag waste, Leaching of slag and SiO2 from factory

No	*Compounds*	*Conc. unit*		
		Palm oil slag waste	**Leaching of palm oil slag waste**	**SiO_2 from factory**
1	SiO_2	56.60%	85.68%	95.81%
2	P_2O_5	5.57%	0.62%	2.14%

No	Compounds	Conc. unit		
		Palm oil slag waste	Leaching of palm oil slag waste	SiO_2 from factory
3	K_2O	0.139	0.63%	397.9 ppm
4	CaO	17.15%	0.24%	0.21%
5	TiO_2	0.54%	0.14%	0.19%
6	MnO	0.31%	-	-
7	Fe_2O_3	4.43%	-	-
8	CuO	0.11%	15.5 ppm	-
9	V_2O_5	4.43%	29.6 ppm	-
10	Cr_2O_3	289.6 ppm	-	-
11	NiO	39.4 ppm	-	-
12	Cl	-	11.03%	-
13	SO_3	-	1.25%	0.65%

Therefore, XRD testing was conducted to analyze the phases of compounds in the slag, as shown in (Figure 1).

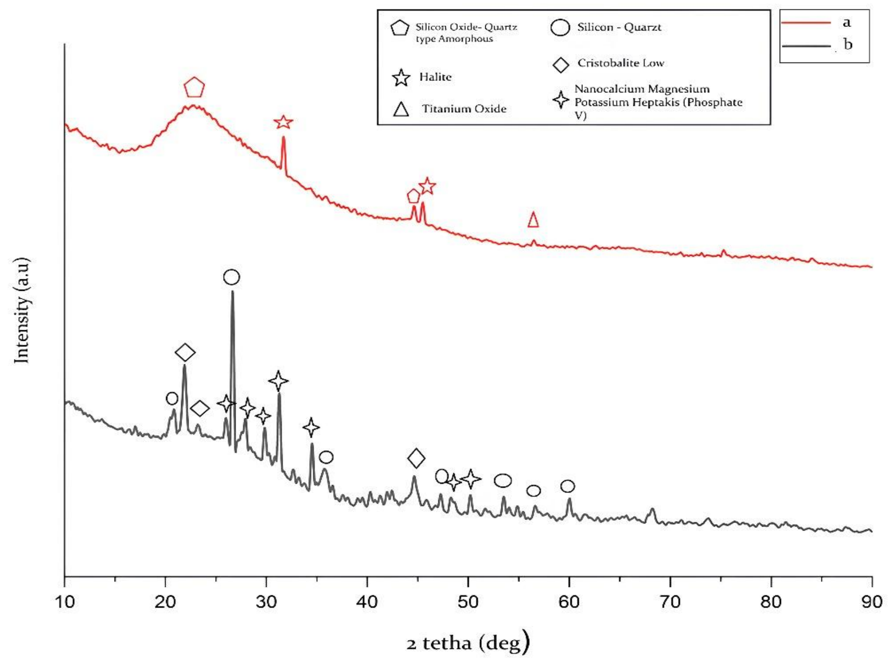

Figure 1. XRD spectra of palm oil slag, where (a) after leaching process (red line) and (b) before the leaching process (black line)

The results of the XRF analysis, presented are shown in (Table 1), indicating that the slag has a SiO2 content of 56.60%, making it the most abundant component, while element, with other compounds are below 1%. The highest component in slag is SiO2 . The slag, shaped like coral, contains SiO2 (46.12%), Al2O3 (9.21%), Fe2O3 (1.25%), CaO (36.14%), MgO (5.23%), Na2O (0.21%), and K2O (1.24%).

Table 1 presents the results of X-ray fluorescence (XRF) analysis of slag waste, the outcomes of slag leaching, and the SiO2 content from the factory. The slag waste column indicates a SiO2 concentration of 56.60%, accompanied by impurities of CaO (17.15%), SO3 (15.27%), P2O5 (5.57%), and Fe2O3 (4.43%). Following the leaching process, the slag leaching column shows a reduction in several impurities and an increase in SiO2 content to 85.68%. The leaching process, which utilized NaOH in this study, effectively reduced other minerals in addition to SiO2. Notably, the compounds MnO, Fe2O3,

Cr_2O_3, and NiO were eliminated after leaching. However, the leaching results did detect the presence of Cl and SO_3. The Cl compound originated from the addition of hydrochloric acid (HCl) during the neutralization process. In comparison, the SiO_2 content from the factory remains higher than the leaching results obtained from the slag.

The XRD spectra of slag waste (black line), identifying silicon dioxide – quartz (SiO_2), low cristobalite (SiO_2), and potassium heptakis (phosphate (V)) non-calcium magnesium ($Ca_9MgK(PO_4)_7$). The slag is dominated by silicon dioxide - quartz and non-calcium magnesium potassium heptakis (phosphate (V)). The composition of slag waste contains many impurities, as many peaks are formed; thus, leaching was conducted to increase the SiO_2 content. The slag was leached to separate impurities from the SiO_2. Leaching with 4M NaOH resulted in a clear yellow solution (Figure 2a). The yellow color of the leaching solution is due to the presence of iron oxide (Wang et al., 2020) . After adding HCl to adjust the pH to 8, a white silica sol precipitate formed (Figure 2b). The sol was then rinsed with distilled water to remove Cl, dried at 110°C, and ground to a size of 200 mesh. The leaching process, equilibrium of materials and solutions, and pH value are critical factors. The equilibrium concentration is calculated using the law of mass action, where solubility requirements must be adjusted for materials with multiple compounds. Solid compounds form after dissolution when pH approaches neutral or during salt formation

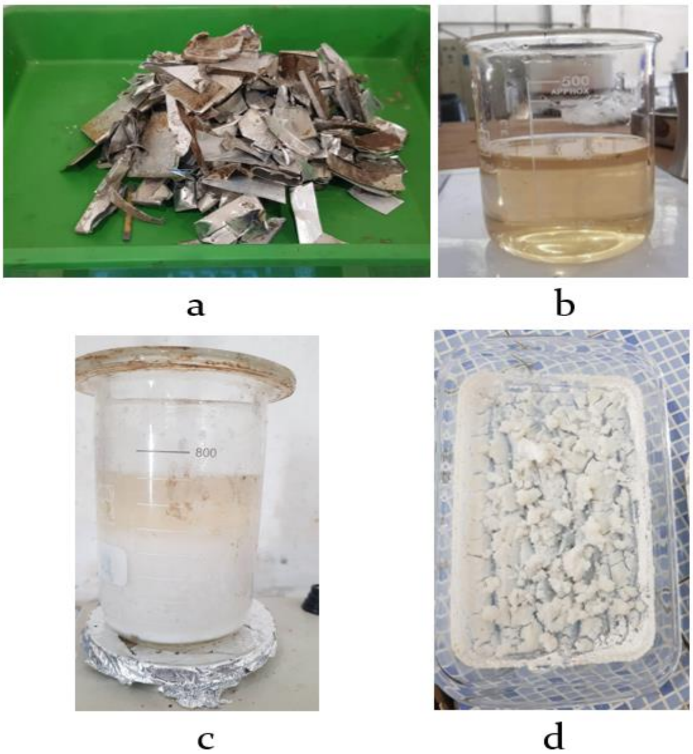

Figure 2. Leaching slag: (a) silica sol solution, (b) silica precipitate, (c) silica drying, (d) SiO_2 synthesis result

The red line in Figure 1 (a) shows the SiO_2 compounds after leaching, identified as Quartz-type SiO_2, Amorphous SiO_2, Sodium chloride (NaCl), and Titanium Oxide (TiO_2). The wide reflection peak corresponds to the crystalline silica phase likely due to the small size and internal structure of impurity compounds. Cl content is caused by base and acid reactions in the leaching process, identified as NaCl by XRD analysis. The Cl content can be reduced by thermal treatment After leaching, the SiO_2 content increased from 56.60% to 85.68% but remains lower than SiO_2 from the factory (95.81%). Impurities include Cl (11.03%), SO_3 (1.25%), and other compounds below 1%. The process of drying produces silica in a white powder form, helping remove organic matter from the slag waste Inadequate washing with distilled water leaves Cl residues. Meanwhile, XRF analysis of SiO_2 from the factory shows 95.81% purity, with P_2O_5 as the main impurity (2.14%).

3.2 The Precipitation Results of Bittern Waste to Produce MgO

The bittern waste produced is brown in color and has a viscosity of 26 baume. Bittern waste was subjected to XRF analysis to determine the composition content, which can be seen in the **Table 2.**

Table 2. XRF results of bittern waste

Compounds	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO2	Fe_2O_3	Br
Conc. unit	17.76 %	19.24 %	0.79 %	0.14 %	0.17 %	5.51 %	50.38 %	3.98 %	0.51 %	75.9 ppm	221.8 ppm	1.39 %

The XRF analysis results indicate that the highest compound content is Cl at 50.51%, followed by MgO at 19.24%, and Na2O at 17.76%. Based on the research conducted by the MgO content of bittern was 15.80%, and after processing, it reached 90.00%. The bittern waste was collected from the holding pond and filtered. It was then heated to 30 Baume. In the next stage, $CaCl_2$ was added in a 1:1 ratio to form $MgCl_2$. A CaO solution was then introduced, leading to a reaction between CaO and $MgCl_2$ to produce insoluble Magnesium Hydroxide ($Mg(OH)_2$) and soluble Calcium Chloride ($CaCl_2$). The $Mg(OH)_2$ precipitate was heated at 150°C to remove water, followed by a calcination process at 800°C to obtain MgO (Gravogl et al., 2018). The final MgO product was tested using XRF, and the results are shown in Table 3.

Table 3. Comparison of XRF test results of MgO and MgO from the factory

No	Compounds	Conc. Unit	
		MgO (from Bittern)	MgO from Factory
1	MgO	76.98%	83.70 %
2	SO_3	0.13%	0.35 %
3	SiO_2	1.90%	5.78 %
4	Al_2O_3	0.96%	0.97 %
5	CaO	18.99%	4.76 %
6	TiO_2	460.8ppm	930.2 ppm
7	Fe_2O_3	0.62%	3.53 %
8	CuO	122.8ppm	-

The XRF analysis results of the MgO obtained from bittern waste show a composition of 76.98% MgO, with CaO being the second most abundant compound at 18.99%. MgO from bittern waste still contains several impurities compared to the factory MgO, because the reaction between $Ca(OH)_2$ and $MgCl_2$ is not perfect (Kastiukas et al., 2019) resulting in incomplete formation of $CaCl_2$ and $Mg(OH)_2$. This can cause residual unbound Ca^{2+} to remain in the final product resulting in excess CaOH which contributes to high CaO levels in the final product. Meanwhile, the purity of MgO from the factory reaches 83.70%, with SiO_2 and CaO impurities of 5.78% and 4.76%, respectively. The XRD analysis of MgO from bittern waste is illustrated in (Figure 3).

The XRD analysis results of the synthesized MgO show identified compound phases such as Calcite ($CaCO_3$), Magnesium Oxide (MgO), and Dolomite ($CaMg(CO_3)_2$). The compound phase with the dominant diffraction peak is MgO because it shows the highest peak in the Rietveld HSP analysis, this is also related to the XRF results which show the highest MgO content. The compound phase with the dominant diffraction peak is MgO. However, the image shows that the highest detected diffraction peak corresponds to the compound phase $CaCO_3$, which is caused by the use of CaO for precipitation during MgO synthesis from the reaction between Ca^{2+} and CO_3^{2-} ions present in bittern waste According to bittern waste from the salt industry was processed to obtain $MgCl_2$, then $Mg(OH)_2$, followed by heat treatment to produce high-purity MgO crystals from bittern waste, reaching a purity of 83.4%. Bittern waste contains various ions such as Ca^{2+}, K^+, Na^+, with a relatively high content of Mg^{2+}. The compounds $MgCl_2$, NaCl, and KCl are the three main components found in bittern.

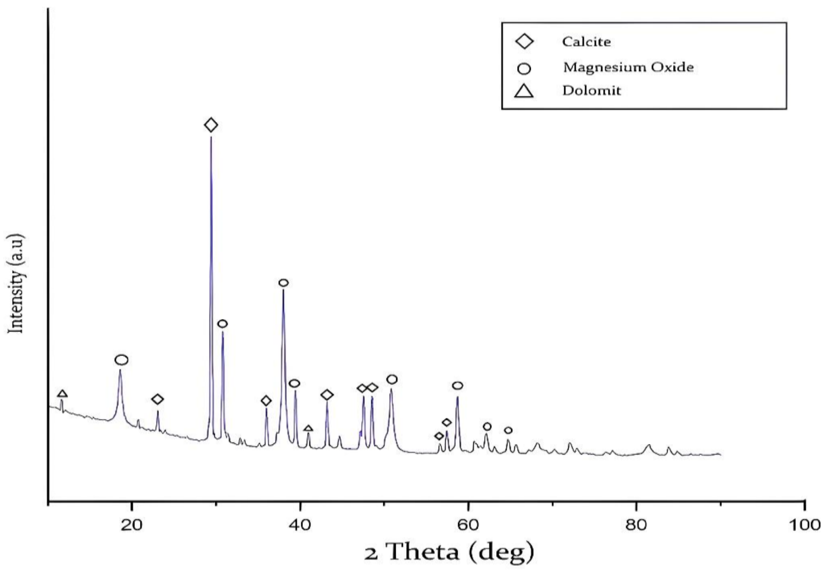

Figure 3. XRD spectra of MgO from bittern waste

3.3 Leaching of Alumunium Cans to Production Al2O3

Aluminum beverage cans were used as raw material for producing alumina oxide (Al_2O_3). The composition of the aluminum cans was determined using a portable XRF Sci-Aps device by direct analysis. The results of the analysis for three different brands of cans are shown in **Table 4**.

Table 4. Average results of XRF analysis of aluminum cans waste

Element	**Al**	**Mn**	**Fe**	**Cu**	**Zn**	**Mg**	**Zr**
(%)	97.33	1.34	0.68	0.38	0.08	0.04	0.01

The aluminum content (Al) in the cans was found to be the highest at 97.33%, followed by manganese (Mn) at 1.34%, and iron (Fe) at 0.68%. Given the high aluminum content, these cans have strong potential for alumina oxide (Al_2O_3) production. To begin the process, the aluminum cans were cut into small pieces to facilitate leaching. 50 grams of the aluminum can pieces were weighed and dissolved in 120 ml of 4M HCl with continuous stirring. The resulting solution was filtered, producing a clear yellow aluminum chloride ($AlCl_3$) solution. During the leaching process, aluminum can be oxidized, producing various compounds. This oxidation can change the color of the aluminum surface, especially if there are contaminants or other elements that react with aluminum, such as iron ions (Fe) where Fe^{2+} ions can be oxidized to Fe^{3+}, producing yellow compounds (Palacio & Arranz, 2001)..Sodium bicarbonate ($NaHCO_3$) was then added to the solution to form a white aluminum hydroxide ($Al(OH)_3$) gel precipitate. The precipitate was filtered, washed three times, and then dried at 120°C to removed water content (Kasraee et al., 2023). The progression of this process is illustrated in (Figure 5).

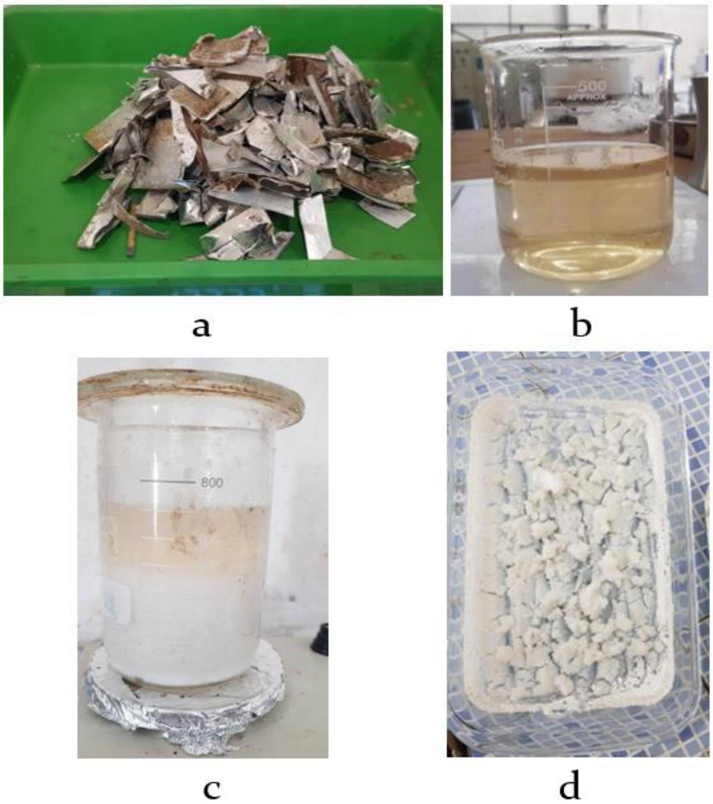

Figure 5. Leaching of aluminum can waste (a) pieces of aluminum cans waste, (b) $AlCl_3$ solution, (c) $Al(OH)_3$ gel precipitate, (d) Al_2O_3

The Al_2O_3 obtained from the leaching process was subjected to XRF analysis, and the results were compared with factory-produced alumina, as shown in (Table 5). The XRF analysis of leached aluminum cans showed that the Al_2O_3 content was 85.90%, which is lower than the factory-produced alumina at 99%. The presence of impurities such as chlorine (Cl) at 11.20% and titanium oxide (TiO) at 1.02% can be attributed to the use of HCl during the dissolution process and $NaHCO_3$ during precipitation Other impurities such as CaO (0.50%) and MnO (846.6 ppm) were also detected (Kaußen & Friedrich, 2016).

Table 5. Comparison of XRF leaching results of aluminum can waste and aluminum from the factory

No	Compound	Conc Unit	
		Leaching results of aluminum cans	**Aluminum from the factory**
1	Al_2O_3	85.90%	99%
2	P_2O_5	0.92%	0.90%
3	TiO	1.02%	103.4 ppm
4	Cl	11.20%	-
5	CaO	0.50%	0.09%
6	MnO	846.6 pmm	-
7	Fe_2O_3	0.18%	-
8	NiO	75ppm	-
9	CuO	154 ppm	-

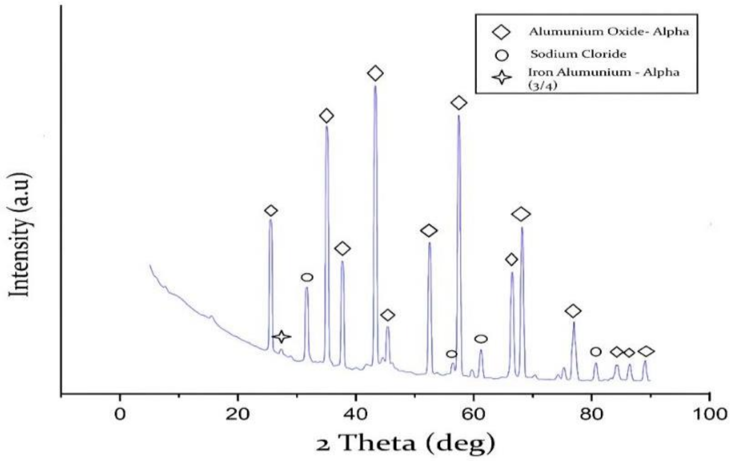

Figure 6. XRD spectrum of allumunium cans waste leaching results

MnO is produced from the content before the leaching process of aluminum can waste containing Mn, so in the leaching reaction it creates these impurities, while the presence of CaO in the leaching process using (Na2CO3), it can react with calcium to form soluble calcium species, which can then precipitate as CaO when changes in pH and temperature occur. The X-ray diffraction (XRD) pattern of alumina produced from the leaching process is shown in **Figure 6**.

The XRD analysis identified several phases, including aluminum oxide-alpha (Al_2O_3), sodium chloride (Na_1Cl_1), and iron-aluminum ($Al_{13}Fe_4$) compounds. The dominant phase was aluminum oxide-alpha (Al_2O_3), consistent with previous studies The XRD peaks also confirmed the presence of NaCl and $Al_{13}Fe_4$ as secondary phases in the process of dissolving aluminum using HCl which produces high temperatures, diffusion of aluminum and iron occurs to form $Al_{13}Fe_4$ and also Cl^- ions are formed in acidic conditions, then there is the addition of Na_2CO_3 which functions as a neutralizing agent, there are Na+ ions which then react to form NaCl (Gozan et al., 2021). These findings indicate that the leaching process effectively yielded Al_2O_3, but further refinement is needed to improve purity.

3.4 Future Prospect and Challenges

The recycling and valorization of industrial waste, such as palm oil slag, bittern waste, and aluminum cans, hold significant promise for advancing sustainability and resource efficiency. As global attention shifts toward more sustainable industrial practices, these waste materials present opportunities for innovation and improvement in recycling technologies. However, several challenges need to be addressed to fully realize their potential and integrate them effectively into circular economy practices (Rakesh et al., 2023).

Palm oil slag, primarily composed of SiO2, CaO, and other minor elements, presents a valuable resource for the production of high-purity silica (Sayehi et al., 2020). The future prospects for palm oil slag recycling include improving leaching techniques to enhance SiO2 recovery and reduce impurities (Ulum et al., 2023).The current leaching process, which involves the use of 4M NaOH followed by acid precipitation, has shown an increase in SiO2 content from 56.60% to 85.68%. However, this is still below the 95.81% purity found in commercial SiO2. The use of 4M NaOH helps to dissolve non-silica components, such as aluminum oxides, iron oxides, and organic impurities, leaving behind a higher concentration of silica. The acid precipitation step then neutralizes the solution and precipitates soluble silicates as SiO_2, further enhancing the silica purity. Together, these steps effectively increase the concentration of SiO_2 in the final material. Future research could focus on optimizing the leaching conditions, such as adjusting the concentration of leaching agents, temperature, and reaction time, to achieve higher purity levels. By adjusting the concentration of the leaching agents, unwanted components can be dissolved more effectively. Changing the temperature can speed up chemical reactions, making the process faster. Optimizing reaction time reduces both energy consumption and reagent use. This helps to prevent the loss of silica, ensuring high purity without reducing the yield. Finding the best conditions also makes the process more consistent for industrial production. Finally, optimization balances cost and effectiveness, making the process more economical and sustainable. Additionally, advancements in filtration and purification technologies could further improve the quality of the recovered SiO_2. The challenge lies in balancing the cost-effectiveness of these processes with their environmental impact, ensuring that the benefits of recycling outweigh the associated costs.

Bittern, a by-product of salt production, contains significant amounts of MgO and Cl, with MgO being a valuable resource for various industrial applications. The current method of extracting MgO from bittern involves chemical reactions with CaCl2 and subsequent heating to produce high-purity MgO. The results show a recovery of MgO with 76.98% purity, compared to 83.70% for commercial MgO. Adding $CaCl_2$ to bittern causes magnesium to precipitate as magnesium hydroxide or carbonate, separating it from impurities. After precipitation, the magnesium compound is heated, converting it into magnesium oxide (MgO). The heating step removes water and produces high-purity MgO. This process effectively separates and purifies magnesium from other dissolved minerals in bittern (Bagastyo et al., 2021). Future advancements could focus on improving the efficiency of this process, such as optimizing the reaction conditions, enhancing the separation of impurities like CaO, and increasing the overall yield of MgO. Additionally, reducing the Cl content, which is a major impurity, through better washing and thermal treatment processes will be crucial. The challenge in this area includes managing large volumes of waste and ensuring that the processes are economically viable and environmentally friendly.

Recycling aluminum cans to produce Al_2O_3 involves a multi-step process that includes leaching with HCl, precipitation with $NaHCO_3$, and drying. The leaching results in an Al_2O_3 purity of 85.90%, which is lower than the 99% purity found in commercial alumina. Future research could focus on refining the leaching process to reduce impurities such as Cl and TiO, which result from the use of HCl and $NaHCO_3$. Improving the efficiency of these processes will require advancements in chemical engineering and materials science. Additionally, enhancing the recovery and reuse of by-products from the leaching process can contribute to overall sustainability. The challenge here involves optimizing the leaching conditions to maximize the purity of Al_2O_3 while minimizing environmental impacts and costs (Ghulam et al., 2020). The integration of recycled materials into the production of cordierite ceramics represents an innovative approach to waste valorization (Sadek et al., 2021). Cordierite, a ceramic material used in various industrial applications, requires precise ratios of alumina (Al_2O_3), silica (SiO_2), and magnesia (MgO) (Harrati et al., 2022). Using recycled waste materials to supply these components can reduce reliance on raw materials and lower production costs. Future research should explore the feasibility of using recycled SiO_2, MgO, and Al_2O_3 to produce high-quality cordierite, including assessing the impact of impurities on the final product's properties. The challenge in this area includes ensuring the consistency and quality of the recycled materials to meet industry standards and optimizing the production process to accommodate varying compositions of recycled inputs.

4. Conclusions

This study successfully demonstrated the potential for sustainable resource recovery from waste by repurposing solid industrial and urban waste, specifically slag and aluminum cans, into valuable raw materials through leaching processes. Slag waste from the palm oil industry was effectively used to recover 85.68% SiO_2, while aluminum can waste yielded 85.90% Al_2O_3, proving the efficiency of the leaching methods applied. Additionally, the recovery of 76.98% MgO from bittern waste via precipitation further highlights the versatility of industrial byproducts for material production. XRF and XRD analyses confirmed the composition and crystallinity of the extracted materials, indicating that these waste streams can serve as alternative sources for industrial compounds. The findings of this study offer a sustainable approach to waste management by converting solid waste into useful materials, promoting circular economy practices, and reducing the environmental burden of waste disposal. Further research may focus on optimizing these processes for industrial-scale applications to maximize resource recovery and minimize waste. Optimization is carried out by applying variations in temperature and reaction time during the leaching process and the use of advanced technology such as membrane filtration.

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