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Article

Recovery of Manganese Dioxide (MnO_2) from Dry Cell Battery Waste via Microwave-Assisted Hydrometallurgy: A Mass Balance Study

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Abstract

The increasing accumulation of dry cell battery waste necessitates efficient recovery methods for valuable materials like manganese dioxide (MnO_2). This study investigates the mass balance and recovery efficiency of MnO_2 from dry cell battery waste using a microwave-assisted hydrometallurgical process. The procedure consisted of three primary stages: material preparation, microwave-assisted acid leaching, and oxidative precipitation. Leaching was conducted using 100 mL of 1.2 M H_2SO_4 and 2% H_2O_2 at 80°C for 50 minutes, achieving an MnO_2 leaching recovery yield of 96.76% by converting manganese and zinc into soluble manganese sulpahte ($MnSO_4$) and zinc sulphate ($ZnSO_4$). Subsequent oxidative precipitation utilizing 0.25 M potassium permanganate ($KMnO_4$) successfully converted dissolved Mn^{2+} into solid MnO_2 with purity 96.57%, while zinc remained in the filtrate as soluble salts. The comprehensive mass balance analysis across all stages demonstrated minimal material loss, confirming the high efficiency and selectivity of the process toward manganese recovery. These findings indicate that integrating microwave-assisted hydrometallurgy with oxidative precipitation is an effective and sustainable approach for recovering high-purity MnO_2 from dry cell battery waste.

Keywords: dry cell, hydrometallurgy, manganese dioxide, mass balance, oxidative precipitation

1. Introduction

Manganese(IV) oxide (MnO_2) is widely utilized in various industrial applications. In filtration processes, MnO_2 serves as an effective filter medium due to its ability to adsorb and oxidize iron (Fe) and manganese (Mn) ions present in wastewater [1]. In the steel industry MnO_2 serves as a protective coating for iron-based soft magnetic composite materials (FeSMCs) [2]. It is also an essential component in energy storage applications, particularly in lithium-ion and zinc–manganese batteries [3], [4]. According to data from the Central Statistics Agency, Indonesia continues to import approximately 24,531,206 kg of MnO_2 per year as of 2024 to meet industrial demand, which was an increase of 32.32% from the previous year [5]. MnO_2 compounds can be sourced from both natural mineral deposits and the recycling of dry cell battery waste. Notably, waste from dry cell batteries contains a high concentration of MnO_2, reaching 60.82% [6], as illustrated in Fig.1.

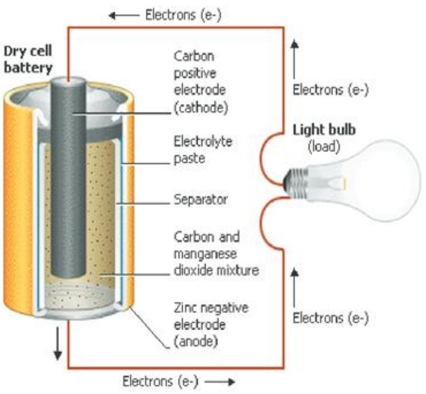

Fig. 1. Dry cell battery component.

The MnO_2 content in dry cell battery waste can be effectively separated from impurities through hydrometallurgical processing. This method involves a leaching process, which operates based on the solubility of materials in a selected solvent. During leaching, the dry cell materials are mixed with an acidic solution, allowing undesirable impurities to dissolve in the solvent, while insoluble components are separated [7], [8], [9], [10]. The hydrometallurgical process is considered the most efficient and practical technique for extracting MnO_2 compounds, as it does not require high operating temperatures or the involvement of microorganisms, both of which demand specific conditions to achieve optimal recovery [7], [11], [12], [13], [14]. Chang et al. found that microwave-assisted heating in the hydrometallurgical process achieved a MnO_2 leaching efficiency of 90% shows that this method enhanced the process efficiency [15].

Furthermore, the addition of a reducing agent, such as H_2O_2 (hydrogen peroxide), in the hydrometallurgical process under conventional heating conditions, was shown to increase the MnO_2 leaching yield to 99.04% [10], [16]. The hydrometallurgical process for MnO_2 recovery requires mass balance calculation to properly account for the input and output of materials, based on the principle that the mass entering the system equals the mass leaving it [17]. Despite previous studies exploring various leaching methods, there is a lack of research specifically addressing the integration of microwave-assisted leaching and mass balance analysis. To overcome these limitations, this study aims to comprehensively analyze the mass balance in the recovery of MnO_2 from dry cell battery waste via microwave-assisted hydrometallurgy. By evaluating the efficiency, product yield, and mass loss at each stage, this research provides essential data to determine the overall viability and scalability of the process.

2. Materials and Methods

This study was conducted at the Biomass and Energy Laboratory, Faculty of Engineering, Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya, Indonesia. The experimental work and data analysis were carried out from January to June 2025. Materials used in this study include "ABC" dry cell batteries collected from household waste in the city of Surabaya, sulfuric acid (H_2SO_4 >98%, extra pure for analysis), hydrogen peroxide (H_2O_2 50%, extra pure for analysis), potassium permanganate ($KMnO_4$ 99%, extra pure for analysis), and dihydrated oxalic acid ($H_2C_2O_4 \cdot 2H_2O$ >98%, extra pure), all supplied by CV. Chemical Indonesia Multi Sentosa, Surabaya. Demineralized water (H_2O) used in this study was obtained from UD. Nirwana Abadi, Surabaya. The instruments used in this study are categorized as follows:

a. Heating and Mixing Equipment : A modified Electrolux Microwave Model EMG23K22B (equipped with a magnetic stirrer operating at 240 W and 300 rpm, as shown in Fig. 2), an oven, a mortar and pestle, a stirring glass rod, and a spatula.
b. Measurement Tools : A thermometer, a pH meter, and an analytical balance.
c. Glassware and General Apparatus : A 500 mL two-neck flat-bottom flask, a 40 cm Allihn condenser, a 500 mL beaker glass, a 250 mL volumetric flask, 10 mL and 100 mL measuring cups, a 50 mL burette, a watch glass, a 75 mm glass funnel, and a dropper.
d. Other Supporting Equipment : Filter paper, a water tank, a stand and clamp, a hose, a pump, and aluminum foil.

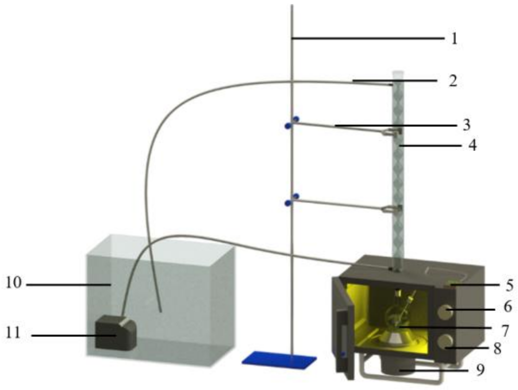

Fig. 2. Microwave-assisted instrumentation.

Remark:

1. Stand
2. Hose
3. Clamp
4. Condenser
5. Thermocouple
6. Power set
7. 500 mL two neck flat bottom flask
8. Time set
9. Magnetic stirrer
10. Water tank
11. Water pump

The mass balance was calculated by comparing the total mass of inputs and outputs in each process stage, including material preparation, microwave-assisted leaching, and oxidative precipitation. Through this analysis, the efficiency of MnO_2 recovery and the proportion of material losses during processing were quantitatively evaluated. A mass balance is a quantitative analysis that accounts for the total amount of materials entering, leaving, accumulating, or being discarded in a production process. In principle, a mass balance describes that during any process, materials may undergo physical, chemical, or combined transformations, while maintaining the fundamental rule that the total mass entering the system equals the total mass leaving the system. Thus, in any processing operation, the input mass must be equal to the output mass, consistent with the law of conservation of mass [18].

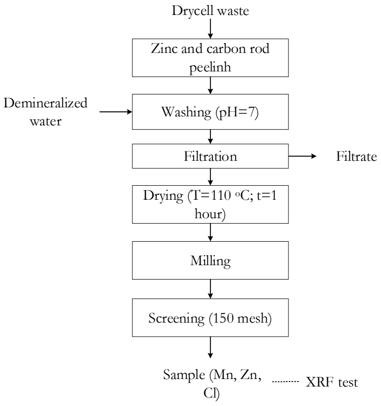

Fig. 3. Flow Diagram of Material Preparation Process.

This study consists of three main stages, which are material preparation, microwave-assisted leaching, and oxidative precipitation followed by drying, with a mass balance analysis conducted for both inputs and outputs of component mass at each stage. The process begins with the material preparation stage. Dry cell batteries are first disassembled to separate the zinc casing from the internal components. The section containing the manganese mixture, as shown in Fig. 3, is collected for use as the raw material. The black mixture is then thoroughly washed with demineralized water until the filtrate reaches a neutral pH (pH 7) to remove residual electrolytes. Following the washing step, the material is dried in an oven at 110°C for one hour and subsequently ground to a particle size of 150 mesh to facilitate better extraction efficiency in the subsequent stage.

Table 1. Element analysis of prepared “ABC” dry cell sample

Composition	Mn	Zn	Cl
%weight	58.78	40.46	0.76

Based on table 1, the chemical compound composition can calculate using Eq. (1-4).

$$\mathrm{m_{MnO_2}} = \frac{\mathrm{m_{Mn}}}{\mathrm{MW_{Mn}}} \times \mathrm{MW_{MnO_2}} \tag{1}$$

$$\mathrm{m_{ZnCl_2}} = \frac{\mathrm{m_{Cl}}}{2\times\mathrm{MW_{Cl}}} \times \mathrm{MW_{ZnCl_2}} \tag{2}$$

$$\mathrm{m_{ZnO}} = \left(\frac{\mathrm{m_{Zn}}}{\mathrm{MW_{Zn}}} - \frac{\mathrm{m_{Cl}}}{2\times\mathrm{MW_{Cl}}}\right) \times \mathrm{MW_{ZnO}} \tag{3}$$

$$\%weight_i = \frac{m_i}{m_{total}} \times 100\% \tag{4}$$

Where is, $\mathrm{m_{Mn}}$ is mass of mangan element (g), $\mathrm{m_{Cl}}$ is mass of chlor element (g), $\mathrm{m_{Zn}}$ is mass of zinc element, $\mathrm{m_{MnO_2}}$ is mass of manganese dioxide compound (g), $\mathrm{m_{ZnO}}$ is of mass zinc oxide compound (g), $\mathrm{m_{ZnCl_2}}$ is mass of zinc chloride compound (g), $\mathrm{MW_{Mn}}$ is molecular weight of mangan element (g/gmol), $\mathrm{MW_{Cl}}$ molecular weight of chlor element (g/gmol), MW_{Zn} is molecular weight of zinc element (g/gmol), MW_{MnO_2} is molecular weight of manganese dioxide compound (g/gmol), MW_{ZnO} is of molecular weight of zinc oxide compound (g/mol), MW_{ZnCl_2} is molecular weight of zinc chloride compound (g/mol)), $\%weight_i$ is mass percentage of compound i, m_i is mass of compound i, and m_{total} is total mass of all compounds. Result of calculation by Eq. (1-4) are shown in table 2.

Table 2. Chemical compound of prepared "ABC" dry cell sample

Composition	MnO_2	ZnO	$ZnCl_2$
%weight	64.61	34.37	1.02

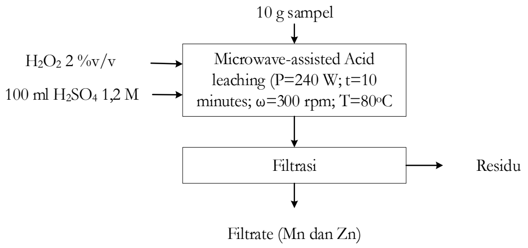

Fig. 4. Flow Diagram of microwave- assisted acid leaching process.

The next stage of the process is microwave-assisted leaching as shown in Fig. 4. A total of 10 grams of sample was dissolved in 100 mL of 1.2 M H_2SO_4 solution with the addition of a 2%vol. of H_2O_2. The resulting mixture was then placed in a microwave-assisted heater and heated for a designated duration for 50 minutes under controlled conditions of 240 W power, 300 rpm stirring speed, and a temperature of 80°C. Upon completion of the leaching process, the solution was filtered to separate the carbon residue, while the resulting filtrate was used in the subsequent oxidative precipitation stage for the purification of MnO_2 compounds.

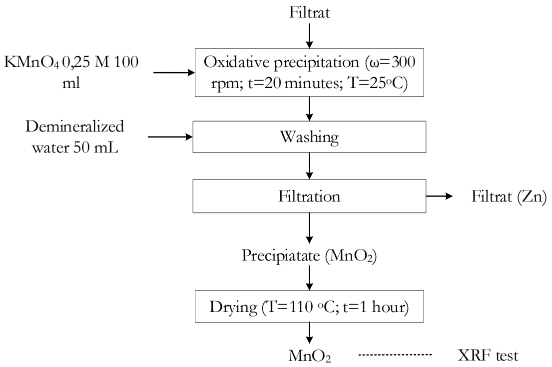

Fig. 5. Flow diagram of oxidative precipitation process.

The oxidative precipitation process was carried out by adding 100 mL of 0.25 M $KMnO_4$ solution to the filtrate and stirring for 20 minutes at a temperature of 25°C with a stirring speed of 300 rpm as shown in fig. 5. After precipitation, the mixture was filtered, and the obtained residue was washed with demineralized water until the filtrate became clear, indicating the complete removal of excessed $KMnO_4$. The MnO_2-containing precipitate was then dried in an oven at 110°C for one hour, yielding the final MnO_2 product recovered through the hydrometallurgical process.

Table 3. Element analysis of prepared "ABC" dry cell sample

Composition	Mn	Zn	Cl
%weight	97.47	2.26	0.27

Based on table 1, the chemical compound composition can calculate using Eq. (1-4).

$$m_{MnO_2} = \frac{m_{Mn}}{MW_{Mn}} \times MW_{MnO_2} \tag{5}$$

$$m_{ZnCl_2} = \frac{m_{Cl}}{2\times MW_{Cl}} \times MW_{ZnCl_2} \tag{6}$$

$$m_{ZnSO_4} = \left(\frac{m_{Zn}}{MW_{Zn}} - \frac{m_{Cl}}{2\times MW_{Cl}}\right) \times MW_{ZnSO_4} \tag{7}$$

$$\%weight_i = \frac{m_i}{m_{total}} \times 100\% \tag{8}$$

Where is, m_{Mn} is mass of mangan element (g), m_{Cl} is mass of chlor element (g), m_{Zn} is mass of zinc element, m_{MnO_2} is mass of manganese dioxide compound (g), m_{ZnSO_4} is of mass zinc sulphate compound (g), m_{ZnCl_2} is mass of zinc chloride compound (g), MW_{Mn} is molecular weight of mangan element (g/gmol), MW_{Cl} molecular weight of chlor element (g/gmol), MW_{Zn} is molecular weight of zinc element (g/gmol), MW_{MnO_2} is molecular weight of manganese dioxide compound (g/gmol), MW_{ZnSO_4} is of molecular weight of zinc sulphate compound (g/mol), MW_{ZnCl_2} is molecular weight of zinc chloride compound (g/mol), $\%weight_i$ is mass percentage of compound i, m_i is mass of compound i, and m_{total} is total mass of all compounds. Result of calculation by Eq. (1-4) are shown in table 2.

Table 4. Chemical compound of prepared "ABC" dry cell sample

Composition	MnO_2	$ZnSO_4$	$ZnCl_2$
%weight	96.57	3.11	0.32

3. Results and Discussion

This study focuses on mass balance analysis to determine the recovery yield of MnO_2 and to identify the mass losses that occur at each stage of the hydrometallurgical process. The mass balance was calculated by comparing the total mass of inputs and outputs in each process stage, including material preparation, microwave-assisted leaching, and oxidative precipitation. Through this analysis, the efficiency of MnO_2 recovery and the proportion of material losses during processing were quantitatively evaluated. A mass balance is a quantitative analysis that accounts for the total amount of materials entering, leaving, accumulating, or being discarded in a production process [18]. Mass Balance in each process shows in table 5.

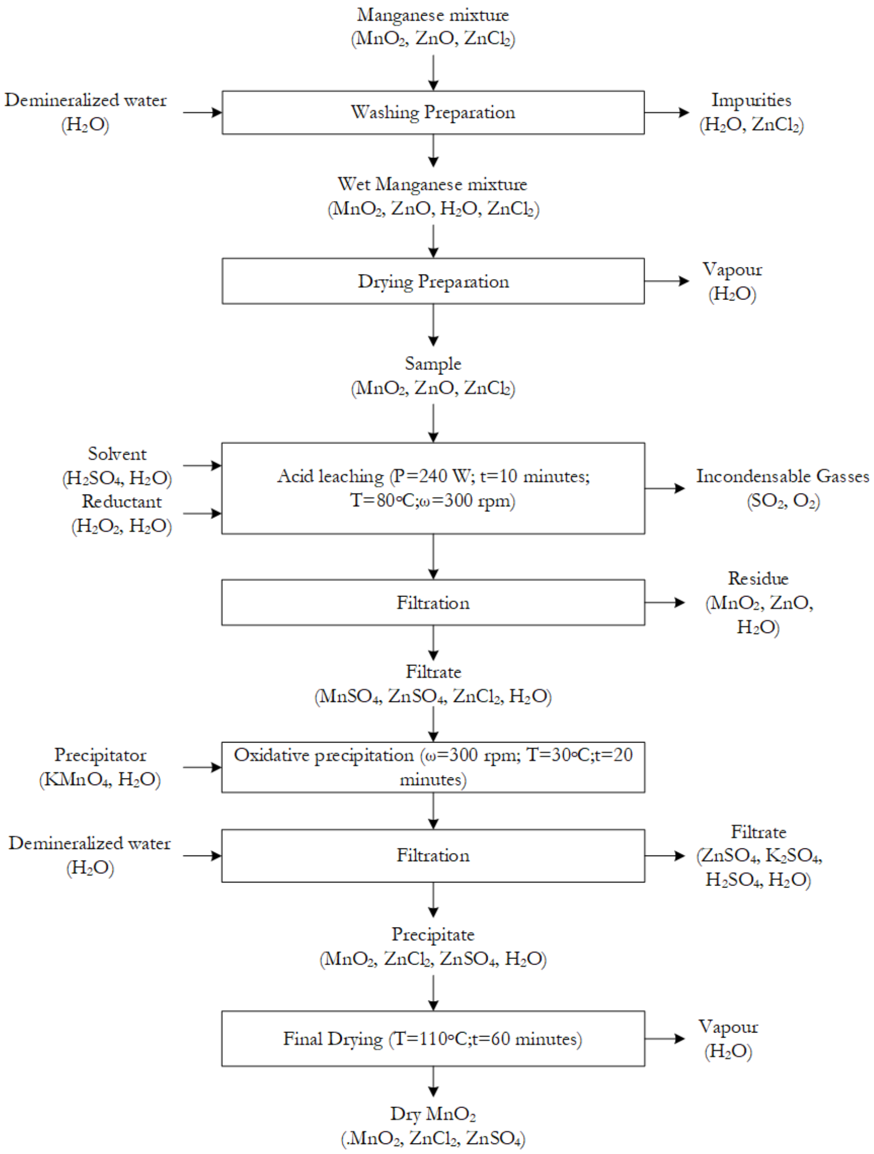

Fig. 6. flow diagram of components distribution each process

Table 5. Mass balance in each process

Washing Preparation Process					
Mass inlet			Mass outlet		
component	mass (g)	mass fraction	component	mass (g)	mass fraction
Dry Cell			Wet manganese mixture		
MnO_2	3041.0000	0.6082	MnO_2	3041.0000	0.6123
ZnO	1617.6934	0.3235	ZnO	1617.6934	0.3257
$ZnCl_2$	341.3066	0.0683	$ZnCl_2$	48.0084	0.0097
Subtotal	5000.0000	1.0000	H_2O	260.0000	0.0523
Demineralized water			Subtotal	4966.7017	1.0000
H_2O	1000	1.0000	Filtrate (impurities)		
Subtotal	1000	1.0000	H_2O	740.0000	0.7162
			$ZnCl_2$	293.2983	0.2838
			Subtotal	1033.2983	1.0000
Total	**6000.0000**		**Total**	**6000.0000**	
Drying Preparation Process					
Mass inlet			Mass outlet		
component	mass (g)	mass fraction	component	mass (g)	mass fraction
Wet manganese mixture			Sample		
MnO_2	3041.0000	0.6123	MnO_2	3041.0000	0.6461
ZnO	1617.6934	0.3257	ZnO	1617.6934	0.3437
$ZnCl_2$	48.0084	0.0097	$ZnCl_2$	48.0084	0.0102
H_2O	260.0000	0.0523	Subtotal	4706.7017	1.0000
Subtotal	4966.7017	1.0000	Vapour		
			H_2O	260.0000	1.0000
			Subtotal	260.0000	1.0000
Total	**4966.7017**		**Total**	**4966.7017**	
Acid Leaching Process Using Microwave-assisted heating					
Mass inlet			Mass outlet		
component	mass (g)	mass fraction	component	mass (g)	mass fraction
Sample			Residue		
MnO_2	6.4610	0.6461	MnO_2	0.2093	0.1162
ZnO	3.4370	0.3437	ZnO	1.4873	0.8256
$ZnCl_2$	0.1020	0.0102	H_2O	0.1048	0.0582
Subtotal	10.0000	1.0000	Subtotal	1.8014	1.0000
Solvent			Filtrate		
H_2SO_4	11.7600	0.1109	$MnSO_4$	10.8507	0.0947
H_2O	94.2400	0.8891	$ZnSO_4$	3.8754	0.0338
Subtotal	106.0000	1.0000	$ZnCl_2$	0.1020	0.0009
Reductant			H_2O	99.7211	0.8706
H_2O_2	2.2400	0.5000	Subtotal	114.5491	1.0000
H_2O	2.2400	0.5000	Incondensable gasses		
Subtotal	4.4800	1.0000	SO_2	1.5405	0.3731
			O_2	2.5890	0.6269
			Subtotal	4.1295	1.0000
Total	**120.4800**		**Total**	**120.4800**	
Oxidative Precipitation Process					
Mass inlet			Mass outlet		
component	mass (g)	mass fraction	component	mass (g)	mass fraction
Filtrate			Precipitate		

$MnSO_4$	10.8507	0.0947	MnO_2	10.4195	0.9178
$ZnSO_4$	3.8754	0.0338	$ZnCl_2$	0.0310	0.0027
$ZnCl_2$	0.1020	0.0009	$ZnSO_4$	0.3395	0.0299
H_2O	99.7211	0.8706	H_2O	0.5632	0.0496
Subtotal	114.5491	1.0000	Subtotal	11.3532	1.0000
Precipitator			Filtrate		
$KMnO_4$	7.8399	0.0727	$ZnCl_2$	0.0710	0.0003
H_2O	100.0000	0.9273	$ZnSO_4$	3.5359	0.0135
Subtotal	107.8399	1.0000	H_2O	248.5665	0.9522
Demineralized water			K_2SO_4	4.1678	0.01597
H_2O	50.0000	1.0000	H_2SO_4	4.6948	0.0180
Subtotal	50.0000	1.0000	Subtotal	261.0359	1.0000
Total	**272.3891**		**Total**	**272.3891**	
Final Drying Process					
Mass inlet			Mass outlet		
component	mass (g)	mass fraction	component	mass (g)	mass fraction
Precipitate			Dry MnO_2		
MnO_2	10.4195	0.9178	MnO_2	10.4195	0.9657
$ZnCl_2$	0.0310	0.0027	$ZnSO_4$	0.3395	0.0311
$ZnSO_4$	0.3395	0.0299	$ZnCl_2$	0.0310	0.0032
H_2O	0.5632	0.0496	Subtotal	10.7900	1.0000
Subtotal	11.3532	1.0000	Vapour		
			H_2O	0.5632	1.0000
			Subtotal	0.5632	1.0000
Total	**11.3532**		**Total**	**11.3532**	

The mass balance in the sample preparation process, as shown on Tables 5 and Fig. 6, indicates that there was no significant change in mass during this stage. A total of 5000 g of manganese mixture from dry cell battery waste was washed with 1 L of demineralized water to dissolve impurities such as residual. Dry cell contains ammonium chloride (NH_4Cl) as electrolytes [19]. Dry cell works through a reduction–oxidation reaction, one of which is the reaction between zinc and ammonium chloride that converts zinc into zinc chloride ($ZnCl_2$). The mixture was then filtered to separate the solid residue from the liquid filtrate. After drying, the solid mass remained nearly constant, showing only a minimal reduction due to the removal of soluble substances and fine particles. This result suggests that the washing process effectively removed impurities without causing significant material loss, maintaining the integrity of the manganese mixture for subsequent recovery steps.

Table 5 and Fig. 6 show that the hydrometallurgical process was carried out using 100 mL of 1.2 M sulfuric acid (H_2SO_4) to leach manganese (Mn) from 10 g of sample, which contained 64.61% MnO_2, 34.37% ZnO, and 1,02% $ZnCl_2$. Then, filatre which contain manganese will precipate using 0.25 M $KMnO_4$. During this process, several chemical reactions occur between the metal oxides and the acid solution, facilitating the dissolution of manganese and zinc into their soluble sulfate forms in Eq. (9-11) and manganese precipitation in Eq. (12) [20].

$$MnO_2(s) + H_2O_2(aq) + H_2SO_4(aq) \rightarrow MnSO_4(aq) + 2H_2O(l) + O_2(g) \quad (9)$$

$$2MnO_2(s) + 2H_2SO_4(aq) \rightarrow 2MnSO_4(aq) + 2H_2O(l) + O_2(g) \quad (10)$$

$$ZnO(s) + 2H_2SO_4(aq) \rightarrow ZnSO_4(aq) + 2H_2O(l) + SO_2(g+ 0.5O_2(g) \quad (11)$$

$$3MnSO_4\,(aq) + 2KMnO_4\,(aq) + 2H_2O\,(l) \rightarrow 5MnO_2\,(s) + 2H_2SO_4\,(l) + K_2SO_4\,(aq) \quad (12)$$

As shown by table 5 and Eq. (9-12), recovery of MnO_2 calculate using Eq. (13).

$$\%\text{Recovery} = \frac{\frac{3}{5} \times m_{\text{MnO}_2\,\text{final}}}{m_{\text{MnO}_2\,\text{sample}}} \times 100\% \quad (13)$$

Where %Recovery is recovery percentage of MnO_2, $m_{\text{MnO}_2\,\text{final}}$ is mass of MnO_2 after final drying (g), and $m_{\text{MnO}_2\,\text{sample}}$ is mass of MnO_2 in prepared sample.

The addition of hydrogen peroxide (H_2O_2) as a reducing agent effectively supports the acid leaching process, while microwave-assisted heating contributes to improved manganese extraction under the studied conditions. Only a small amount of MnO_2 loss occurs, which cannot be recovered from the dry cell waste. During the reaction, several chemical transformations take place, resulting in the formation of manganese sulfate ($MnSO_4$), zinc sulfate ($ZnSO_4$), water (H_2O), sulfur dioxide (SO_2), and oxygen (O_2) gases. Previous studies have reported that microwave-assisted heating and the use of H_2O_2 can enhance manganese leaching efficiency [15], [21], [22]. However, this study specifically focuses on evaluating the mass balance of the process under microwave-assisted conditions. Based on the results shown in Table 5, the method achieved a MnO_2 recovery of 96.76% of the manganese dioxide content by weight in the sample within 50 minutes using 2% vol. H_2O_2, reflecting the effectiveness of the process within the defined experimental scope.

As shown on Table 5 and Fig. 6**,** the oxidative precipitation stage successfully converted dissolved manganese in the leachate into solid MnO_2 with a recovery yield of 99.9%. The leachate obtained from the microwave-assisted leaching process primarily contained $MnSO_4$, $ZnSO_4$, and $ZnCl_2$. During oxidative precipitation, the addition of 0.25 M $KMnO_4$ acted as a strong oxidizing agent, facilitating the oxidation of Mn^{2+} ions in solution to Mn^{4+}, which subsequently precipitated as manganese dioxide (MnO_2). The reaction proceeded efficiently under mild conditions at 25°C and a stirring rate of 300 rpm, resulting in nearly complete conversion of manganese from its soluble form into an insoluble oxide. The high precipitation efficiency indicates that $KMnO_4$ effectively oxidized Mn^{2+} without significant interference from Zn^{2+} and Cl^{-} ions, which remained in the filtrate as soluble salts. This finding confirms that the oxidative precipitation method is not only selective for manganese but also highly efficient for purifying MnO_2 from mixed metal solutions derived from dry cell waste. Study by Vieceli et al. also shows that $KMnO_4$ can precipitate manganese solution up to 99.5% yield [23].

The mass balance data in Table 5 indicates that the oxidative precipitation and drying stages proceeded efficiently, with no significant mass loss observed between the input and output streams. The precipitate initially contained 91.78% MnO_2, 2.99% $ZnSO_4$, 0.27% $ZnCl_2$, and 4.96% H_2O, totaling 11.3532 g. After the drying process, the total mass of dry MnO_2 product was 10.79 g, while 0.5632 g of water was released as vapor. The mass fraction of MnO_2 increased to 96.57%, confirming that the removal of moisture effectively concentrated the manganese content in the solid phase. Based on the mass balance calculation, the MnO_2 precipitation yield reached up to 99.9%. Vieceli et al. study shows that $KMnO_4$ can precipitate manganese solution up to 99.5% yield [23]. Freitas et al study also show that $KMnO_4$ can precipitate a $KMnO_4$ can precipitate manganese solution up to 99.9% yield in to mangan dioxide [24]. This is indicating that nearly all manganese was successfully precipitated and retained in solid form. This high recovery also suggests that the oxidative precipitation process using $KMnO_4$ was highly selective toward manganese, with minimal interference from zinc compounds (ZnO and $ZnCl_2$), which remained largely in the filtrate. Therefore, the process demonstrates excellent efficiency and selectivity for MnO_2 recovery from leach solutions derived from dry cell waste.

4. Conclusions

The results of this study show that the microwave-assisted hydrometallurgical method is highly effective for recovering MnO_2 from dry cell battery waste. Mass balance analysis across washing, leaching, and precipitation confirms high process efficiency. The acid leaching stage using H_2SO_4 and H_2O_2 achieved a MnO_2 recovery yield of 96.76%, efficiently dissolving manganese and zinc into soluble forms. This performance is enhanced by microwave heating, which provides rapid and uniform volumetric heating, improving heat transfer and accelerating reaction kinetics compared to conventional methods, thereby increasing leaching efficiency in a shorter time. The subsequent oxidative precipitation using $KMnO_4$ yielded 99.9% MnO_2 recovery, with 96.57% purity of MnO_2, zinc remaining in solution, indicating high selectivity. Overall, this method offers a simple, efficient, and environmentally friendly approach for producing high-purity MnO_2 from dry cell battery waste, highlighting its potential for further optimization of microwave power, reaction time, and reagent concentrations to further improve efficiency, reduce energy consumption and application at a larger processing scale.

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