Fahim Muntasir Riyan

A Sustainable Hydrometallurgical Route for Zinc and Manganese Recovery from Spent Dry-Cell Batteries Using Gre...

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Chapter 1: INTRODUCTION

As more people buy electronics, household gadgets, and portable devices, the demand for dry-cell batteries around the world has been steadily rising. In Bangladesh, millions of these batteries are used every year, and most of them are thrown away without being properly treated or recycled. Used dry-cell batteries are a major source of valuable metals, especially manganese (Mn) and zinc (Zn), which together make up a large part of the black mass content (Almeida et al., 2006; Chowdhury et al., 2022). Even though they are useful, throwing them away the wrong way can cause serious problems for the environment, such as heavy metals leaching into soil and water, which can harm both ecosystems and human health (Mantuano et al., 2006).

Hydrometallurgical recycling has become a useful and scalable way to get metals back from old batteries. This method uses acid leaching, which is when metals are dissolved with chemicals like sulfuric acid. People are more worried about the environment now, so they are looking for greener alternatives to traditional leaching systems that use harsh chemicals and non-sustainable reductants. Recent research has indicated the utilization of organic compounds such as citric acid, glucose, and ascorbic acid as efficient "green reductants," which not only attain elevated recovery rates but also mitigate environmental impact (Amaral et al., 2014; Almeida et al., 2006).

In light of this context, this thesis examines the recovery of zinc and manganese from spent dry-cell batteries utilizing sulfuric acid in conjunction with glucose and ascorbic acid as environmentally friendly reductants. The study also seeks to examine the efficacy of these reductants under diverse operational conditions and to evaluate the prospective implementation of this process in Bangladesh.

1.1 Goals of the Study

The goals of this study are as follows:

8
- To extract zinc and manganese from the black mass of spent dry-cell batteries via hydrometallurgical leaching, employing sulfuric acid with glucose and ascorbic acid as reducing agents.

7
- To examine the influence of various parameters—such as reagent concentration, temperature, and reaction duration—on recovery efficiency.
- To assess the efficacy of green reductants against traditional methods documented in literature and ascertain the optimal conditions for metal recovery.
- To examine the environmental and economic viability of implementing green reductant-based recycling within the Bangladeshi context.

1.2 Structure of the Thesis

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There are six chapters in the thesis:

Chapter 1 gives an overview of the thesis's background, goals, and structure.

Chapter 2 reviews the literature on previous studies about getting metals back from used dry-cell batteries. It talks about the techniques that are already in use, their limits, and the areas where more research is needed.

Chapter 3 talks about the chemicals, materials, and experimental methods that were used in this study.

Chapter 4 talks about the computational and analytical methods, such as the governing equations and how to check them.

Chapter 5 shows the results of the experiments, how they were analyzed, and how they relate to other research.

Chapter 2: Literature Review

Recycling used dry-cell batteries has gotten a lot of attention lately because of both environmental concerns and the chance to get valuable metals back. Many studies have looked into hydrometallurgical leaching methods, how acids and reductants work, and how to use analytical techniques to describe black mass and materials that have been recovered. This chapter examines significant literature in these domains, concentrating on prior research pertinent to zinc (Zn) and manganese (Mn) recovery, the implementation of green reductants, and process optimization.

2.1 What Makes Up Spent Dry-Cell Batteries

Numerous studies have documented the elemental composition of dry-cell battery black mass.

Almeida et al. (2006) conducted XRF and chemical analyses, demonstrating that manganese (Mn) and zinc (Zn) are the predominant metals, constituting over 50% of the black mass.

Chowdhury et al. (2022) conducted XRF analysis on washed powder samples of spent zinc-carbon batteries in Bangladesh, verifying Mn at approximately 54% and Zn at approximately 21% as predominant components.

Mantuano et al. (2006) also looked at used batteries and talked about how dangerous it is to throw them away without any control, pointing out how heavy metals can get into the soil and water.

These studies show that Mn and Zn are the main things that need to be recovered, and they also show how important it is to recycle properly for the environment.

2.2 Traditional Hydrometallurgical Methods

Strong acids are a big part of traditional hydrometallurgical recovery.

Almeida et al. (2006) studied sulfuric acid leaching and showed that it could dissolve a lot of Zn at moderate temperatures.

Mantuano et al. (2006) investigated the application of hydrochloric acid and sulfuric acid, documenting effective recovery while acknowledging the corrosive and environmentally detrimental characteristics of these reagents.

Shin et al. (2009) investigated the kinetics of manganese leaching, demonstrating that temperature and acid molarity substantially affect recovery rates.

These processes work well, but they are bad for the environment and safety because they use harsh chemicals.

2.3 Using Green Reductants for Leaching

People are now looking at green and eco-friendly reductants as possible substitutes for regular chemicals.

Amaral et al. (2014) presented citric acid as a leaching agent, indicating moderate zinc recovery and a diminished environmental impact in comparison to strong acids.

Gharabaghi et al. (2016) assessed ascorbic acid (Vitamin C) as a reductant in sulfuric acid leaching, demonstrating substantial enhancement in manganese dissolution attributable to its potent reducing characteristics.

Sarma et al. (2019) examined glucose as a reductant and found that it offered sustainable recovery efficiencies while being cost-effective and biodegradable.

Chowdhury et al. (2022) built on this research in Bangladesh by comparing ascorbic acid and glucose in a lab setting. They found that ascorbic acid was better at extracting Mn, but glucose was cheaper.

These studies indicate that green reductants offer a more environmentally friendly option without compromising efficiency.

2.4 Factors that affect recovery in the process

Several factors have a big effect on how well leaching works:

Shin et al. (2009) found that higher temperatures led to better Mn recovery, but the gains started to level off after 80 °C.

Acid Concentration: Almeida et al. (2006) determined that elevating sulfuric acid concentration enhanced Zn recovery up to 1.0 M, after which the effect stabilized.

Gharabaghi et al. (2016) said that the right amount of ascorbic acid to black mass is very important. Too much of either one wastes reagents without adding any benefits.

Reaction Time: Sarma et al. (2019) noted that extended leaching enhances recovery while escalating operational expenses, thereby necessitating time optimization.

2.5 Methods for Characterization Analysis

It is very important to analyze raw materials and products correctly.

XRF Analysis: Almeida et al. (2006) and Chowdhury et al. (2022) utilized XRF to ascertain the metal composition in battery powder.

Shin et al. (2009) and Chowdhury et al. (2022) used AAS (Atomic Absorption Spectroscopy) to measure the amounts of Mn and Zn in leachates, which made it possible to figure out how well the recovery worked.

Amaral et al. (2014) employed scanning electron microscopy to examine alterations in surface morphology post-leaching, thereby validating dissolution behavior.

These methods make sure that the recycling process is being watched correctly.

2.6 Important Results and Areas for Further Research

Important Results:

Mn and Zn are always found to be the main metals that can be recovered from used dry-cell batteries.

Sulfuric acid leaching works well, but it needs to be better for the environment.

Citric acid, glucose, and ascorbic acid are examples of green reductants that could be very useful for long-term recycling.

The best way to recover depends on finding the right balance between the amount of acid, the amount of reductant, the temperature, and the time it takes for the reaction to happen.

Gaps in Research:

There have been few studies done in Bangladesh, where battery use is growing quickly.

There are still not many comparative studies of different green reductants under the same conditions.

There are not many studies that look at how practical it is to use glucose and ascorbic acid, even though they cost and work differently.

Scaling laboratory processes to industrial applications remains predominantly unexamined.

Chapter 3: The Model/System's Description

3.1 Materials and Blackmass Preperation

We got used zinc-carbon dry-cell batteries from trash cans in homes. The outer casing was taken apart by hand, and the black mass inside was taken out. The main ingredients in this black mass are manganese dioxide (MnO_2), zinc oxide (ZnO), graphite, and a few other things.

To get the feedstock ready:

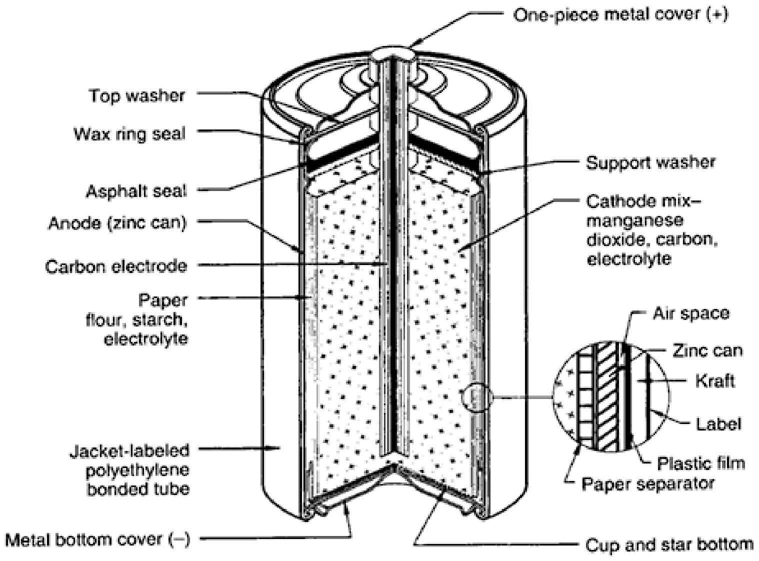
1.To get rid of soluble salts like ammonium chloride (NH_4Cl) and zinc chloride ($ZnCl_2$), the black mass was washed with distilled water over and over again.

2.To get rid of any leftover moisture, the washed material was dried in an oven at 80 °C for 6 to 8 hours.

We ground and sieved the dried powder (with particles smaller than 150 µm) so that it would be the same size for the next leaching experiments.

3.2 Black Mass Analysis

Characterizing the black mass is crucial for identifying the target metals and their concentrations.

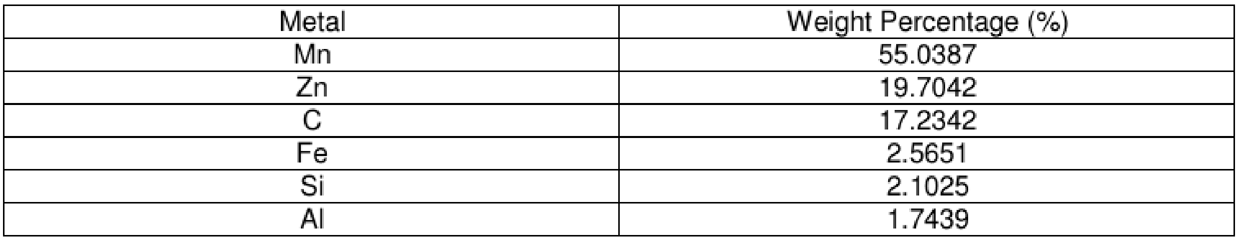


Referance: Mahbub, Hasib & Deb, Nandini & Abedin, Muhammad & Abedin, Shamsul & Khan, Mohidus Samad. (2015). Metal Recovery from Waste Dry Cell Batteries. 10.13140/RG.2.1.2890.4806

XRF Analysis: Earlier research (Almeida et al., 2006; Chowdhury et al., 2022) indicated that Mn comprised approximately 50–55% and Zn about 20–25% of the primary components, alongside trace amounts of Fe, K, and C.

AAS Baseline Analysis: The first AAS tests of the dissolved black mass showed that Mn^{2+} and Zn^{2+} were still in the solution after leaching.

Physical Properties: The black mass looked like a fine black powder with a bulk density of about 1.8 g/cm³.



Metal	Weight Percentage (%)
Mn	55.0387
Zn	19.7042
C	17.2342
Fe	2.5651
Si	2.1025
Al	1.7439

Reference: Mahbub, Hasib & Deb, Nandini & Abedin, Muhammad & Abedin, Shamsul & Khan, Mohidus Samad. (2015). Metal Recovery from Waste Dry Cell Batteries. 10.13140/RG.2.1.2890.4806

3.3 Reagents Used

The following chemicals were used:

Sulfuric Acid (H_2SO_4, 1.0 M): Main leaching agent.

Ascorbic Acid ($C_6H_8O_6$): A green reductant that helps change Mn^{4+}/Mn^{3+} into soluble Mn^{2+}.

Glucose ($C_6H_{12}O_6$): a different green reductant that is cheap and breaks down naturally.

Used in all reagent preparations and washing: **distilled water.**

All of the reagents were of **high quality** for analysis.

3.4 Specifications and Operating Parameters

We used a heating-stirring system that worked as the laboratory "boiler" to do leaching experiments.

Type: Magnetic stirrer with a hot plate

Glass reactor vessel with a capacity of 500 mL

Temperature range: 0 °C to 120 °C

Speed of stirring: 0–800 rpm

Power: 220 volts AC

Parameters for operation:

Temperature of the reaction: 80 °C (always)

Time for the reaction: 30 to 120 minutes (varied)

Volume of solution: 150 mL per batch

The ratio of solid to liquid is 15 g of black mass to 150 mL of acid solution.

Speed of stirring: 600 rpm

3.5 Experimental setup

The setup for the experiment was:

A **magnetic stirrer** with a **heating plate** holds a **250 mL** glass beaker (reactor).

Thermometer probe that lets you check the temperature in real time.

Magnetic stir bar to make sure the agitation is even.

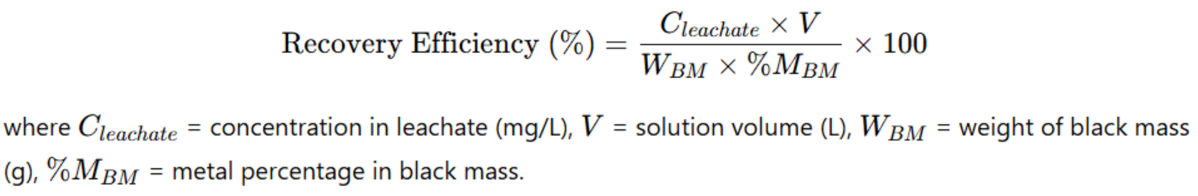
Filtration unit (**Whatman filter paper and funnel)** to get rid of **solid waste.**

Flasks for collecting leachate before testing.

3.6 Analytical Methods

Different characterization and quantification methods were used:

- **XRF (X-ray Fluorescence):** To determine elemental composition of the black mass.
- **AAS (Atomic Absorption Spectroscopy):** To measure Mn and Zn concentration in filtrates and calculate recovery efficiency:



$$\text{Recovery Efficiency } (\%) = \frac{C_{leachate} \times V}{W_{BM} \times \%M_{BM}} \times 100$$

where $C_{leachate}$ = concentration in leachate (mg/L), V = solution volume (L), W_{BM} = weight of black mass (g), $\%M_{BM}$ = metal percentage in black mass.

Gravimetric Analysis: To quantify solid residues left after leaching.

3.7 Environmental Impact Analysis

When old batteries are thrown away in the wrong way, they release Mn, Zn, and other heavy metals into the soil and water, which can harm the environment and people's health. Using strong acids and synthetic reductants in traditional ways makes the problem worse.

This study's approach helps the environment by:

Using glucose and ascorbic acid as green reductants because they are safer and better for the environment than chemical ones.

Allowing the recovery of Mn and Zn, which makes it less necessary to mine new minerals.

Helping Bangladesh's growing battery use have less of an impact on the environment and encouraging circular economy practices.

3.8 System Relevance to Bangladesh

Bangladesh doesn't have any official battery recycling plants. Most used batteries end up in landfills or informal scrapyards. The process that was created here is meant to be:

1.Low-cost because glucose is cheap and easy to find in the area.

2.Scalable because industrial reactors can handle the moderate temperature and mild acid needs.

3.Eco-friendly, which fits with Bangladesh's need for long-term solutions for dealing with waste.

This model can help build a national system for recycling dry-cell batteries.

Chapter 4: Methodology

This study followed a structured methodological framework to establish a sustainable hydrometallurgical route for the recovery of zinc (Zn) and manganese (Mn) from spent dry-cell batteries. The process was designed to align with environmental sustainability, material efficiency, and economic feasibility. The methodology is divided into four principal stages:

1. Collection and Pre-treatment of Spent Batteries
2. Reductive Acid Leaching
3. Selective Precipitation and Metal Recovery
4. Quantification, Efficiency Analysis, and Cost Evaluation

4.1 Collection and Pre-treatment of Spent Batteries

- **Sample Collection:**
  Spent zinc–carbon (Zn–C) batteries were collected from household and institutional sources. To ensure safe handling, all batteries were discharged prior to dismantling. Controlled discharge was performed using motors with varying torque levels, simulating actual power draw, followed by verification with a multimeter.
- **Dismantling and Separation:**
  After discharge, the battery casings were carefully cut open using insulated cutters. Internal components such as the steel casing, graphite rod, and paper separators were removed. Only the **black mass** (active cathodic material containing MnO_2, Zn, and conductive carbon) was retained.
- **Grinding and Drying:**
  The recovered black mass was homogenized by mechanical grinding. To remove moisture and volatile impurities, it was oven-dried at **110 °C for 12 hours**.
- **Washing and Impurity Removal:**
  To reduce the concentration of soluble salts (e.g., ammonium chloride, zinc chloride) that interfere with leaching, the powder was washed with deionized (DI) water at a **10:1 liquid-to-solid ratio**. The suspension was filtered using Whatman 42 filter paper. The residue was re-dried at **110 °C for 12 hours**, yielding purified black mass ready for leaching.

- **Chemical Composition Verification:**
  The composition of the washed black mass was verified using X-ray fluorescence (XRF) analysis, showing the presence of approximately **55% Mn and 20% Zn**, consistent with prior literature reports.

4.2 Reductive Acid Leaching

- **Preparation of Leachant Solution:**
  Leaching solutions were prepared using **1 M H_2SO_4** as the primary leachant. To improve dissolution of Mn and Zn, environmentally benign reductants—**glucose** and **ascorbic acid**—were introduced. The choice of reductants was based on their reducing properties, renewability, and non-toxic nature, making them suitable substitutes for conventional reductants like hydrogen peroxide.
- **Experimental Conditions:**
  Leaching experiments were carried out under controlled conditions:
  - **Temperature:** 80 °C
  - **Stirring speed:** 800 rpm
  - **Duration:** 3 hours
  - **Reaction vessel:** 250 mL glass beaker on a magnetic hotplate stirrer
  - **Filtration:** Whatman 42 filter paper

- **Experimental Design:**

A factorial experimental design was adopted to study the effect of reagent dosage and black mass loading. Four variations were considered for each reductant:

Experiment No.	**H2SO4 (1M) (ml)**	**Reagent amount (g)**	**Black mass (g)**	**Reagent Used**
1	50	2.25 (Low)	5 (Low)	Glucose
2	50	13.5 (High)	5 (Low)	Glucose
3	50	2.25 (Low)	10 (High)	Glucose
4	50	13.5 (High)	10 (High)	Glucose
5	50	2.25 (Low)	5 (Low)	Ascorbic Acid
6	50	13.5 (High)	5 (Low)	Ascorbic Acid
7	50	2.25 (Low)	10 (High)	Ascorbic Acid
8	50	13.5 (High)	10 (High)	Ascorbic Acid

Filtration and Leachate Collection:

At the end of the reaction, the slurry was filtered to separate the metal-rich leachate (containing dissolved Zn^{2+} and Mn^{2+}) from solid residues. The filtrate was preserved for subsequent metal recovery, while residues were discarded.

4.3 Selective Precipitation and Metal Recovery

- **Sequential Precipitation Strategy:**
  The filtered leachate was subjected to pH-controlled precipitation using NaOH solution:
  - **Zinc Recovery:** Zn^{2+} was precipitated as $Zn(OH)_2$ at pH 8.
  - **Manganese Recovery:** Mn^{2+} was precipitated as $Mn(OH)_2$ at pH 12.
- **Rationale for Sequential Recovery:**
  Since Zn and Mn have different solubility products, adjusting the pH sequentially enabled selective recovery of each metal, minimizing cross-contamination and improving purity.
- **Collection and Drying of Precipitates:**
  The precipitated hydroxides were filtered, washed thoroughly with DI water to remove traces of acid or salts, and dried under ambient conditions. The dried materials represented the recovered Zn and Mn fractions.

4.4 Metal Quantification, Efficiency Analysis, and Cost Evaluation

- **Quantification Using Atomic Absorption Spectroscopy (AAS):**
  Dried precipitates were analyzed using AAS at INARS, BCSIR, Dhaka. Concentrations obtained in ppm were converted to g/kg and subsequently expressed as recovery efficiency (%) using the formula:
  Recovery Efficiency (%)=Mass of Metal RecoveredMass of Metal in Original Black Mass (XRF)×100Recovery Efficiency (%)=Mass of Metal in Original Black Mass (XRF)Mass of Metal Recovered×100
- **Comparative Performance Analysis:**
  The efficiency of glucose and ascorbic acid was benchmarked against conventional reductants (citric acid, H_2O_2) reported in literature. Results showed optimum recoveries of

74.83% Mn and 77.43% Zn with glucose, and 54.98% Mn and 52.32% Zn with ascorbic acid.

- **Economic Assessment:**
  Cost estimation was performed for each optimum trial based on reagent usage and local market prices. Results indicated that glucose-based leaching is more economical, with a total processing cost of ~118 Tk per batch, compared to ascorbic acid (~149 Tk per batch).

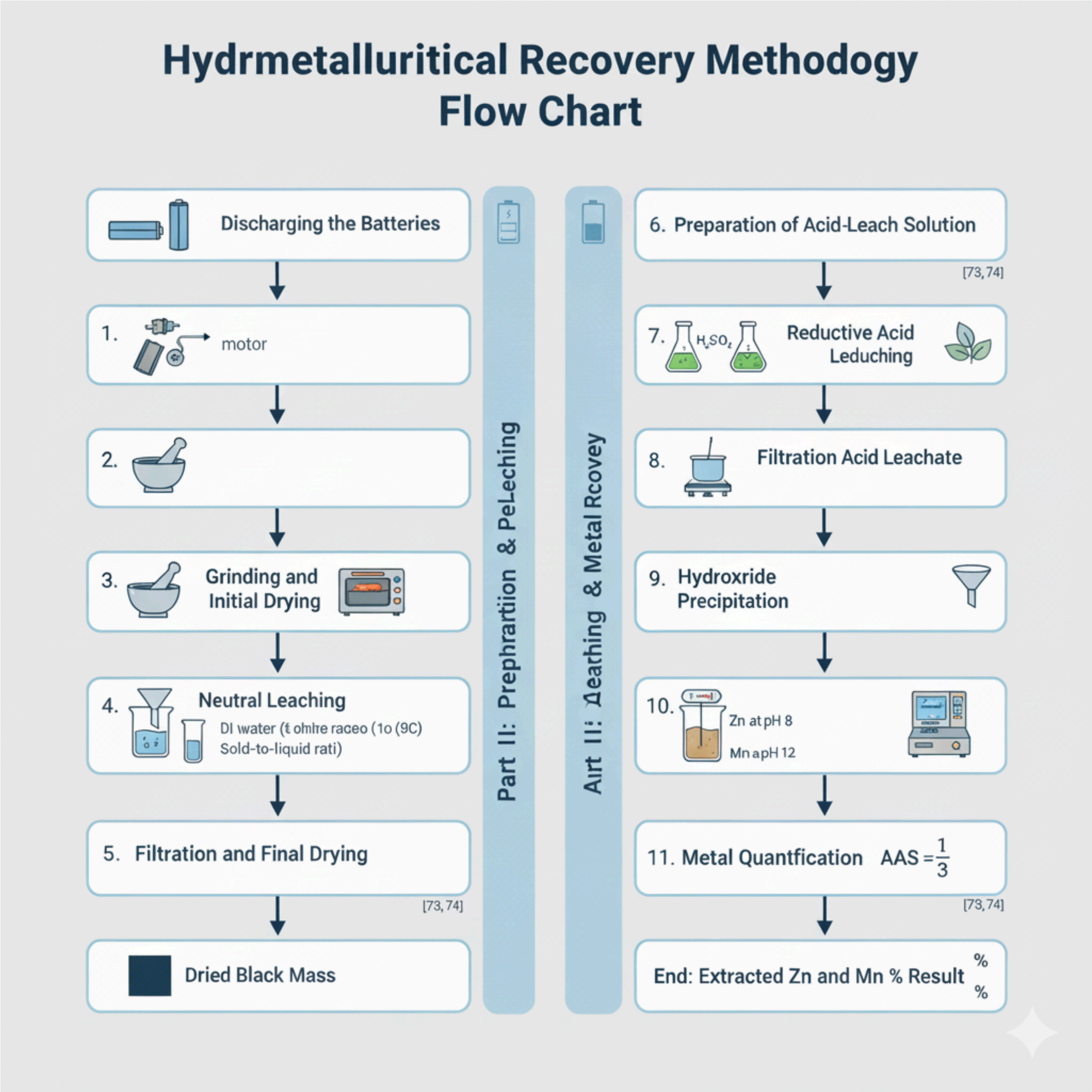


Image: Flow chart of the Methadology

Chapter 5: Results and Analysis

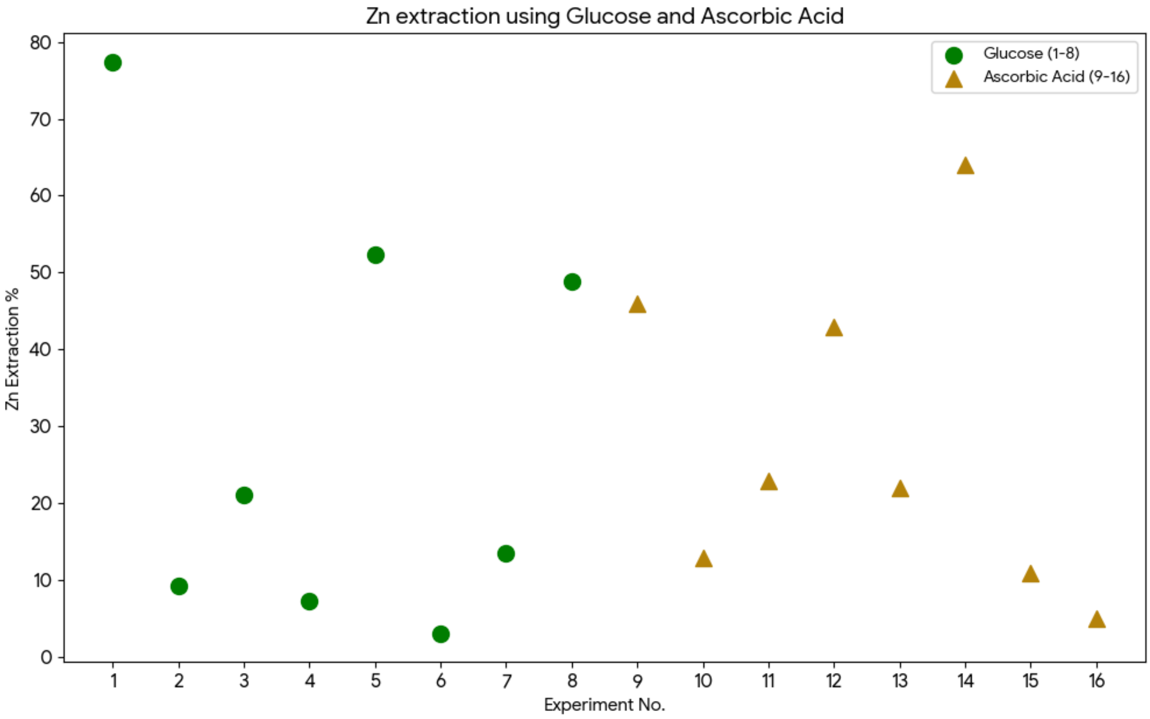
This chapter presents the outcomes of the experimental work, analyzing the efficiency of zinc (Zn) and manganese (Mn) recovery from spent Zn–C batteries using glucose and ascorbic acid as green reductants. The discussion integrates the experimental data, the effects of varying operating conditions, and the comparative economic and environmental implications of the results.

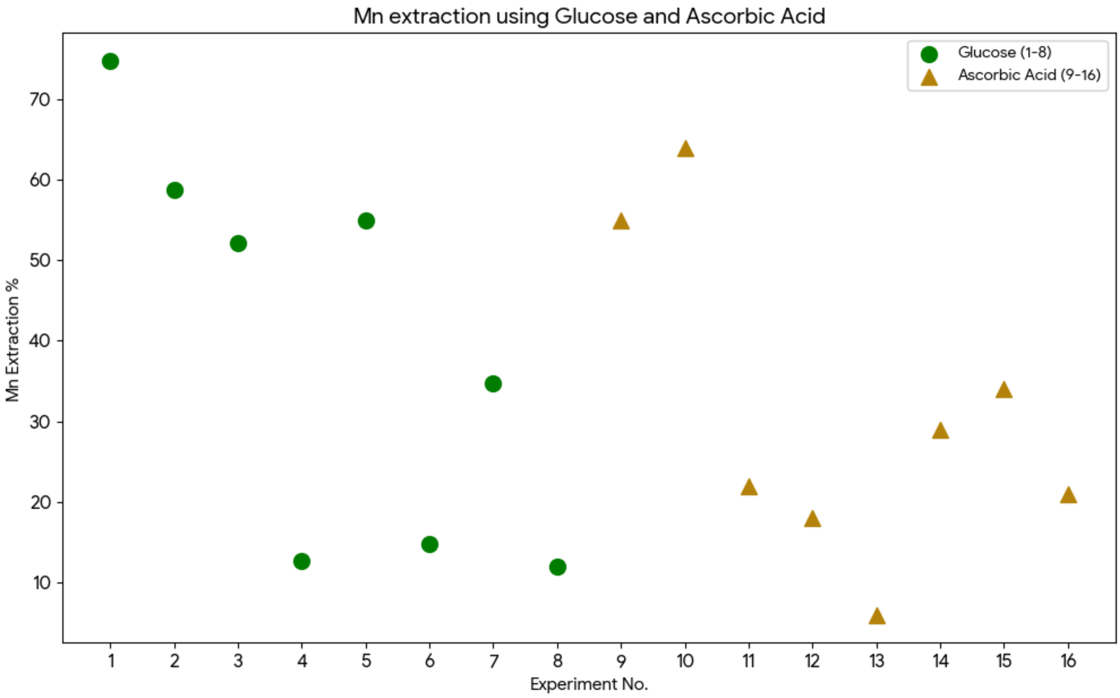
5.1 Extraction Performance under Different Conditions

The experimental trials revealed that the recovery efficiency of Zn and Mn was strongly dependent on reductant type, reductant dosage, and black mass loading. Among all trials, the optimum condition was obtained when **2.25 g glucose**was used with **5 g black mass**, achieving **74.83% Mn extraction** and **77.43% Zn extraction**. In contrast, the best result with ascorbic acid under similar conditions yielded **54.98% Mn** and **52.32% Zn**, clearly indicating the superior performance of glucose.

High reductant dosages (13.5 g) consistently lowered efficiency for both metals, suggesting that excess organic matter reduces the effective acid-to-solid ratio, increases slurry viscosity, and may lead to unwanted side reactions that hinder dissolution. Similarly, increasing the black mass loading to 10 g reduced recovery due to acid limitation and mass transfer resistance. Thus, the results confirm that an optimal balance between reductant amount and solid loading is essential for maximizing recovery efficiency.

Experiment No.	**Mn Extraction %**	**Zn Extraction %**
1 (optimum)	74.83	77.43
2	58.77	9.28
3	52.21	21.04
4	12.65	7.32
5 (optimum)	54.98	52.32
6	14.8	3.15
7	34.67	13.46
8	22.86	48.86


Zn extraction using Glucose and Ascorbic Acid
Glucose (1-8)
Ascorbic Acid (9-16)
Zn Extraction %
0
10
20
30
40
50
60
70
80
Experiment No.
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16


Mn extraction using Glucose and Ascorbic Acid
Glucose (1-8)
Ascorbic Acid (9-16)
Mn Extraction %
10
20
30
40
50
60
70
Experiment No.
1
2
3
4
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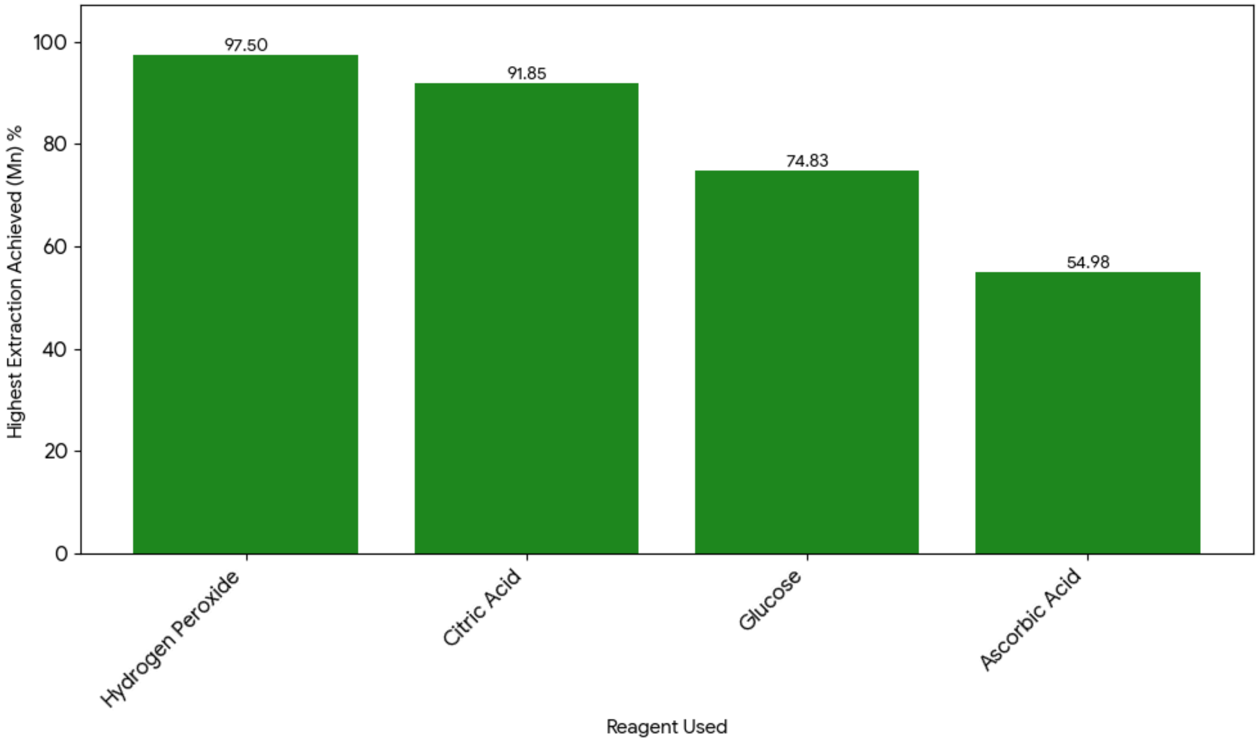
16

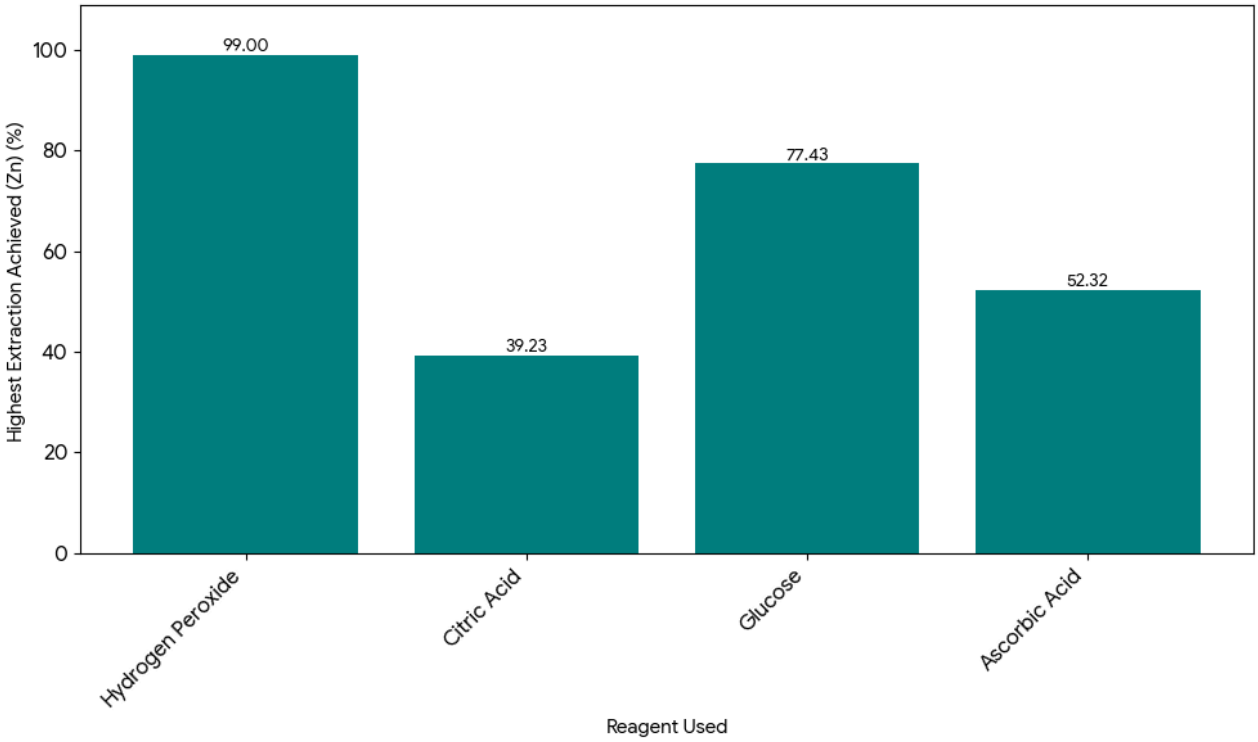
5.2 Influence of Reductant Type: Glucose vs. Ascorbic Acid

The comparison between the two reductants demonstrated that glucose was consistently more effective and economical than ascorbic acid. On average, glucose yielded higher Mn recoveries and produced the single best trial result for Zn. The stronger reducing capability of glucose under acidic conditions enhances the conversion of MnO_2 to soluble Mn^{2+}, improving dissolution and facilitating simultaneous Zn release. Ascorbic acid showed moderate performance but was less stable under the experimental conditions and required higher cost per unit of extraction. This indicates that glucose not only ensures higher technical recovery but also aligns better with the goal of sustainable and low-cost green chemistry.

5.3 Selective Recovery and Efficiency Analysis

6 Following leaching, sequential precipitation with NaOH enabled selective recovery of Zn at pH 8 and Mn at pH 12. The effectiveness of this approach was confirmed through Atomic Absorption Spectroscopy (AAS), which provided precise quantification of recovered metals. Correlation between Mn and Zn extraction efficiencies showed that conditions favorable for one metal generally benefited the other, although some selective shifts were observed. For example, certain high-dose experiments favored Mn while suppressing Zn recovery, whereas other cases showed relatively higher Zn selectivity. Overall, the optimum glucose condition achieved balanced co-recovery, yielding gram-scale recoveries of approximately **2.06 g Mn** and **0.76 g Zn** per 5 g of processed black mass. These results highlight the viability of pH-controlled precipitation as a simple, scalable method for separating and purifying target metals from complex leachates.


Highest Extraction Achieved (Mn) %
100
80
60
40
20
0
97.50
91.85
74.83
54.98
Hydrogen Peroxide
Citric Acid
Glucose
Ascorbic Acid
Reagent Used


Highest Extraction Achieved (Zn) (%)
100
80
60
40
20
0
99.00
39.23
77.43
52.32
Hydrogen Peroxide
Citric Acid
Glucose
Ascorbic Acid
Reagent Used

Analysis of Reagent Performance

The table compares the extraction efficiency of different reductants for manganese (Mn) and zinc (Zn) recovery from spent dry-cell batteries. Both literature data and experimental results are included.

Hydrogen Peroxide (Not Green)

- **Mn Recovery:** >97.5%
- **Zn Recovery:** >99%
- **Source:** Literature (Al Mahbub et al., 2015)
- **Analysis:** Hydrogen peroxide demonstrated the highest recovery rates for both Mn and Zn. However, it is **not considered green** due to safety hazards, instability, and potential environmental impact. While efficient, its large-scale application may lead to handling and sustainability concerns.

Citric Acid (Green)

- **Mn Recovery:** 91.85%
- **Zn Recovery:** 39.23%
- **Source:** Literature (Al Mahbub et al., 2015)
- **Analysis:** Citric acid provided excellent Mn recovery but significantly lower Zn extraction. As a biodegradable and non-toxic organic acid, it qualifies as a green reagent, but its limited Zn recovery makes it less favorable compared to other options.

Glucose (Green, Our Experiment)

- **Mn Recovery:** 74.83%
- **Zn Recovery:** 77.43%
- **Analysis:** Glucose achieved a balanced recovery of both Mn and Zn, though Mn recovery was lower than citric acid and hydrogen peroxide. However, glucose is cheap, biodegradable, and widely available in Bangladesh, making it highly promising for sustainable industrial-scale adoption. Its **cost-effectiveness** offsets the moderate recovery efficiency.

Ascorbic Acid (Green, Our Experiment)

- **Mn Recovery:** 54.98%
- **Zn Recovery:** 52.32%
- **Analysis:** Ascorbic acid showed moderate recovery for both metals, lower than glucose and citric acid. Despite its strong reducing power, the efficiency was less favorable under the conditions tested in this experiment. The reagent cost is also higher compared to glucose, which limits industrial feasibility.

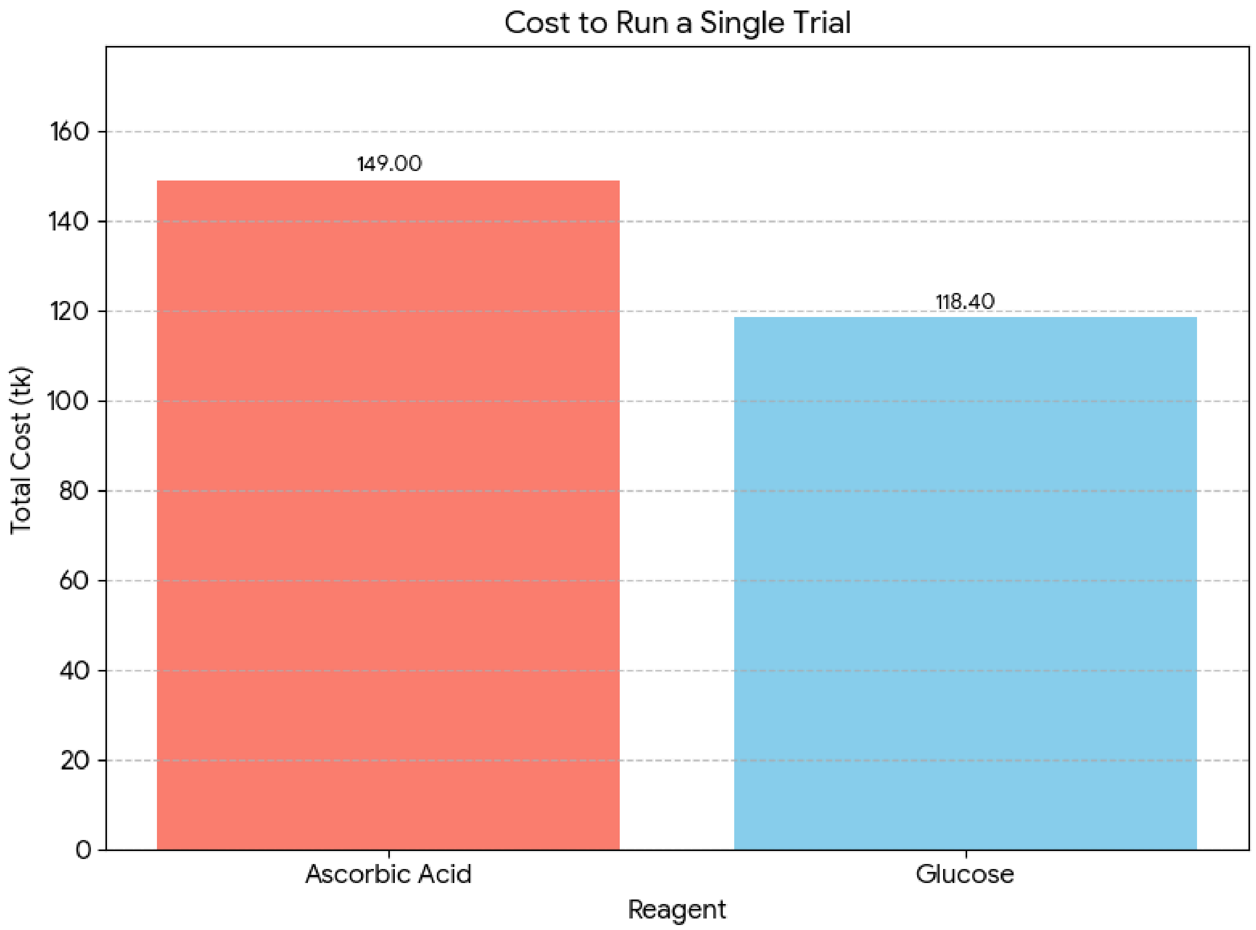
Key Findings from Comparison

1. **Hydrogen peroxide** is the most effective chemically, but not environmentally sustainable.
2. **Citric acid** achieves high Mn recovery but fails in Zn recovery, limiting its overall use.
3. **Glucose** balances Mn and Zn recovery with good overall performance, while being cost-effective and green, making it the **most practical solution** for Bangladesh.

4. **Ascorbic acid** is environmentally safe but less efficient than glucose under the tested conditions.

5.4 Economic and Environmental Implications

The cost analysis revealed that the glucose-based process was significantly more economical than the ascorbic acid route. For the optimum trial, glucose required approximately **118 Tk per batch**, compared to **149 Tk for ascorbic acid**, translating into a lower cost per percentage of recovery efficiency. From an environmental standpoint, both reductants are green alternatives to conventional agents such as hydrogen peroxide or strong mineral acids, but glucose has the added advantage of being renewable, inexpensive, and less hazardous. In comparison with literature benchmarks, while peroxide-assisted systems can achieve very high recoveries (>95%), they involve higher chemical hazards and costs. The glucose system, therefore, represents a balanced compromise between efficiency, safety, and sustainability. The findings suggest that this process can be scaled up for industrial application in Bangladesh, providing a circular-economy solution to the growing problem of battery waste.


Cost to Run a Single Trial
Total Cost (tk)
0
20
40
60
80
100
120
140
160
149.00
118.40
Ascorbic Acid
Glucose
Reagent

Chapter 6: Conclusion and Recommendations

6.1 Conclusion

This study investigated the recovery of manganese (Mn) and zinc (Zn) from spent dry-cell batteries using a hydrometallurgical approach based on sulfuric acid leaching with glucose and ascorbic acid as green reductants. The black mass, primarily composed of manganese dioxide and zinc oxide, was first washed, dried, and characterized using XRF and AAS. The results confirmed Mn and Zn as the major constituents, consistent with literature values.

Experimental leaching trials demonstrated that:

- **Sulfuric acid alone** provided significant dissolution of zinc, but manganese extraction remained limited due to the stability of MnO_2.
- **Ascorbic acid** acted as a strong reductant, successfully converting insoluble Mn^{4+} species into soluble Mn^{2+}, thereby enhancing manganese recovery rates.
- **Glucose**, while less effective than ascorbic acid, offered a cost-effective and environmentally safer alternative, making it attractive for large-scale applications in Bangladesh.
- **Process parameters** such as acid concentration, reductant dosage, temperature (80 °C), and reaction time had notable influence on extraction efficiency, with optimized conditions yielding higher overall recoveries.

The study also highlighted the **environmental benefits** of adopting green reductants. Unlike conventional methods that rely on hazardous chemicals, glucose and ascorbic acid are biodegradable, non-toxic, and reduce the environmental footprint of recycling processes. Additionally, this work establishes a potential framework for introducing sustainable battery recycling in Bangladesh, where no formal recycling infrastructure currently exists.

Overall, the findings confirm that green reductant-assisted hydrometallurgy is a promising route for zinc and manganese recovery, offering both economic and ecological advantages.

6.2 Recommendations for Future Works

Although the present study achieved promising results, further work is required to advance the process toward industrial adoption. Future research should focus on:

1. **Optimization Studies:** Conducting systematic parametric optimization using techniques such as Design of Experiments (DOE) or metaheuristic algorithms (e.g., Genetic Algorithm) to fine-tune reagent ratios, temperatures, and reaction times.

2. **Scale-Up Investigations:** Extending laboratory experiments to pilot- and industrial-scale reactors, examining reactor design, mixing efficiency, and heat management.

3. **Alternative Green Reductants:** Exploring other low-cost, biodegradable reducing agents (e.g., organic acids from agricultural waste, molasses-derived sugars) to further reduce reagent costs.

4. **Kinetic and Thermodynamic Modeling:** Developing detailed kinetic models to describe Mn and Zn leaching mechanisms and predict recovery performance under different conditions.

5. **Life Cycle and Economic Analysis:** Assessing the feasibility of industrial adoption through cost–benefit analysis, environmental life-cycle assessment (LCA), and comparison with conventional recycling and mining practices.

6. **Integration with Circular Economy:** Investigating how the recovered metals can be reused in local industries (e.g., fertilizers, alloys, or battery re-manufacturing) to close the material loop in Bangladesh.

7. **Policy and Infrastructure Development:** Collaborating with policymakers to design regulations and collection systems that ensure safe disposal and systematic recycling of spent batteries

6.3 Final Remark

The rapid growth of battery consumption in Bangladesh and worldwide calls for urgent development of sustainable recycling solutions. This study demonstrates that green reductant-assisted hydrometallurgy can serve as an effective pathway for recovering valuable metals while minimizing environmental damage. By bridging scientific innovation with eco-friendly practices, the work not only contributes to advancing waste management strategies but also supports broader goals of resource conservation and circular economy. With continued research, scale-up, and policy support, such approaches can transform hazardous waste into valuable resources and play a vital role in building a cleaner, greener future.

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THANK YOU