

Article

A Detailed Kinetic Analysis of the Environmentally Friendly Leaching of Spent Lithium-Ion Batteries Using Monocarboxylic Acid

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Abstract: It is essential to develop a leaching procedure that uses minimal acid consumption, is economical, recovers large amounts of metal, and has a minimal negative impact on the environment. In this paper, a viable hydrometallurgical method using acetic acid as a leachant is suggested for recovering critical metals from waste LCO-type batteries. Several leaching parameters were examined in order to optimize the leaching conditions. With 1.2 mol/L acetic acid, 7% H₂O₂, 90 °C, an S/L ratio of 10 g/L, and a 60 min leaching period, the maximum leaching efficiencies of Li (99.6%) and Co (95.6%) were attained. By investigating the different kinetic models, it was feasible to figure out the reaction's pace, as well as the mechanism involved in the leaching process. It was found, through the comprehensive kinetic studies of the leaching process, that the surface chemical reaction controls the leaching mechanism for waste LCO-type batteries. The economic viability of the current leaching procedure in comparison to those of earlier approaches is also discussed.

Keywords: leaching; kinetic studies; spent LIBs; acetic acid



Citation: Sahu, S.; Pati, S.; Devi, N. A Detailed Kinetic Analysis of the Environmentally Friendly Leaching of Spent Lithium-Ion Batteries Using Monocarboxylic Acid. *Metals* **2023**, *13*, 947. <https://doi.org/10.3390/met13050947>

Academic Editor: Jean François Blais

Received: 13 April 2023

Revised: 3 May 2023

Accepted: 12 May 2023

Published: 13 May 2023



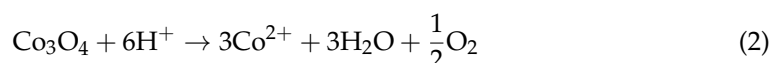
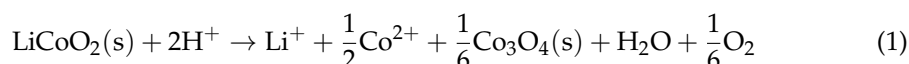
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1. Introduction

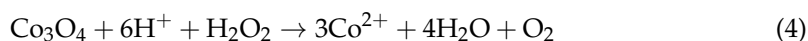
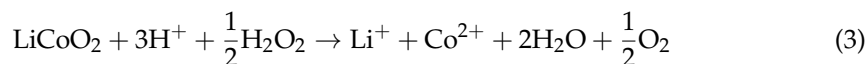
Rechargeable batteries are being used as a renewable and sustainable energy source in a wide range of modern electronic devices, including electric vehicles, laptops, mobile phones, and other everyday items, in response to the increasing amount of environmental pollution [1]. Due to their high energy density, wide operating voltage range, minimal self-discharge, and wide operating temperature range, lithium-ion batteries (LIBs) are outstanding electrochemical power sources that have been incorporated into daily life and used in different electric devices [2]. These benefits have led to significant growth in the production of LIBs, and the worldwide market for LIBs is projected to be worth USD 221 billion by 2045 [3]. Among all lithium-ion batteries NCA (lithium nickel cobalt aluminum oxides)-, LCO (lithium cobalt oxide)-, and NMC (lithium nickel manganese cobalt oxides)-type batteries require a higher amount of specific energy than other types of batteries do such as LMO (lithium manganese oxide), LFP (lithium iron phosphate), and LTO (lithium titanate). The capacity of different lithium-ion batteries in terms of specific energy is presented in Figure 1. LIBs are discarded after four to six years due to the increased usage of electronic equipment and electric vehicles, which will result in a rise in the number of waste batteries. The global number of spent LIBs reached 111,783 t in 2018, and the amount of scrap is estimated to reach roughly 641,595 t in 2025 [4]. According to Figure 1, there are higher percentages of NCA-, LCO-, and NMC-type battery scrap than those of others, such as LMO, LFP, and LTO. So, recycling these discarded batteries is crucial for both environmental preservation and producing metals needed to make new batteries [5]. Especially, LCO-type batteries contain precious metals such as cobalt, lithium, copper, and other elements; therefore, neglecting to recycle them may soon lead to a crisis in the metal market [6].

Spent LIBs, on the contrary hand, have some economic potential. Especially, Co and Li are important precious metals; they are often more abundant in waste LIBs than they are in natural sources, and recycling them using efficient technology has considerable economic repercussions.

Pyrometallurgy, bio metallurgy, and hydrometallurgy are currently the three basic technologies used to remove valuable metals from waste LIBs [7]. The main objective of hydrometallurgy is the transport of precious metals into leaching solutions in order to extract metal ions via precipitation and solvent extraction processes [8]. Because of their excellent efficiency and minimal energy usage, hydrometallurgical techniques are frequently employed as the most viable methods at both laboratory and industrial scales [9]. In comparison to other approaches, they have benefits such as high rates of essential metal recovery, minimal capital requirements, and the ease of industrialization during production. Acid leaching is crucial to the hydrometallurgy process due to its high recovery percentages and amazing capacity to adapt to complex systems [10]. The most frequently employed inorganic acids with good leaching effectiveness are hydrochloric acid, nitric acid, sulfuric acid, or phosphoric acid [11–14]. However, as inorganic acid is very corrosive and has strict equipment needs, it may have a severe impact on human health and the environment due to the production of hazardous gases, such as SO₃, Cl₂, NO_x, and P₂O₅. Thus, it is preferable to use organic acids instead of inorganic ones for the leaching process, such as ascorbic acid, tartaric acid, lactic acid, malic acid, citric acid, succinic acid, and aspartic acid [15–20]. It is possible to understand the mechanism behind the acid leaching of LiCoO₂ by examining the governing mechanisms on the basis of Reactions (1) and (2) based on the experimental findings [21].



A reducing agent must also be added to acids to help with the leaching process by converting metal ions with higher to lower oxidation states, which are leachable in the acidic medium [22]. Co exists as Co³⁺, an oxidative species that is hard to dissolve in any acidic medium, such as in LiNi_{0.33}Mn_{0.33}Co_{0.33}O₂ (NMC) and LiCoO₂ (LCO). Reductants are needed to convert Co(III) to Co(II) in order to improve the leaching efficiency. Hydrogen peroxide (H₂O₂) is, generally, the most widely employed reducing agent. Other reducing agents also utilized in acid-leaching systems are glucose, cellulose, sucrose, and NaHSO₃ [23,24]. Despite hydrogen peroxide's widespread use as an oxidizing agent, its employment as a reductant in this situation is justified by the strong reduction potential of Co(III) and the absence of any further ions being introduced to the system [25]. The expanded formulations of Reactions (1) and (2) suggest that the following reactions occur in the presence of H₂O₂.



Acetic acid, among all organic acids, is a weak monocarboxylic acid that has been advantageously used in this leaching study because it yields a high level of leaching efficiency without releasing any harmful gases. Furthermore, it is also less expensive and readily and naturally degrades. The impact of acetic acid on the leaching efficiency of critical metals in the presence and absence of a reductant was investigated in the present study. With acetic acid as the leaching agent, different leaching factors were investigated. To ascertain the mechanism involved in the leaching process, detailed leaching kinetics were analyzed, and the economic feasibility of the current leaching process in comparison to those of previous methods is also addressed in this present work.

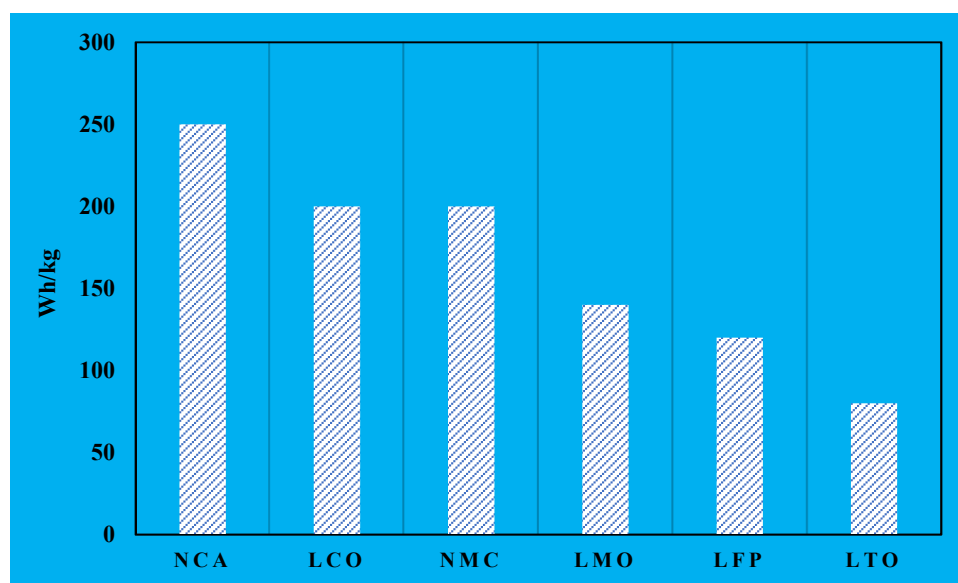


Figure 1. Capacity of different LIBs in terms of specific energy [26].

2. Materials and Methods

2.1. Reagents

The spent LIB sample was collected from the authorized seller. Acetic acid glacial with a purity of 99–100% and hydrogen peroxide with a purity of 30% were used. All other reagents were of analytical grade from Merck life science private limited Company.

2.2. Analytical Method

Cobalt and lithium concentrations in the leach liquor after leaching tests were quantified via inductivity-coupled plasma optical emission spectrometry (ICP-OES, iCAP PRO, Thermo Fisher Scientific, Waltham, MA 02451, USA). All metals in the LIB sample were digested using aqua regia (HCl: HNO₃ adjusted to a 3:1 ratio). The characterization of the LIB sample before and after leaching was examined via X-ray diffraction (XRD, Rigaku Ultima IV, Tokyo, Japan), SEM (scanning electron microscopy), and EDS (energy-dispersive X-ray spectroscopy, EVO-18, Carl Zeiss, Oberkochen, Germany).

2.3. Leaching Experiments

All tests were conducted in a 500 mL, three-necked, flat-bottomed flask, which was thermostatically controlled and fitted with a condenser and a magnetic stirrer. Additionally, the solution was heated and mixed using a magnetic stirrer. In all studies, the leaching period lasted 60 min. Whatman filter paper was used to filter the solution at the conclusion of each experiment.

3. Results and Discussions

3.1. Characterization of the Spent LIBs

The discarded LIB sample was subjected to elemental analysis using aqua regia digestion, followed by ICP-OES analysis (Table 1). In this sample, Co and Li are the main components, whereas Al and Cu are the minor ones. The primary elements employed in the active components of LIBs cathodes were Co, Li, and Ni. Figure 2a displays XRD patterns for the waste LIBs sample. Figure 2b,c shows an SEM image and results of the EDS analysis of the waste LIBs sample. The finding patterns revealed that this LIB sample is an LCO-type battery with mostly lithium cobalt oxide (LiCoO₂) and graphitic carbon and trace amounts of Al and Cu. The Laser Scattering Particle Size Distribution Analyzer LA-960, HORIBA, was used in order to analyze the particle size distribution of the discarded LIB

sample. It was found that before the leaching process was conducted, the average particle size was 16.3 μm , with $D_{10} = 11.4 \mu\text{m}$ and $D_{60} = 25.9 \mu\text{m}$.

Table 1. Total metal content in spent LIB sample.

Metals	Co	Li	Cu	Al
Wt. %	3.9	34.12	0.31	0.27

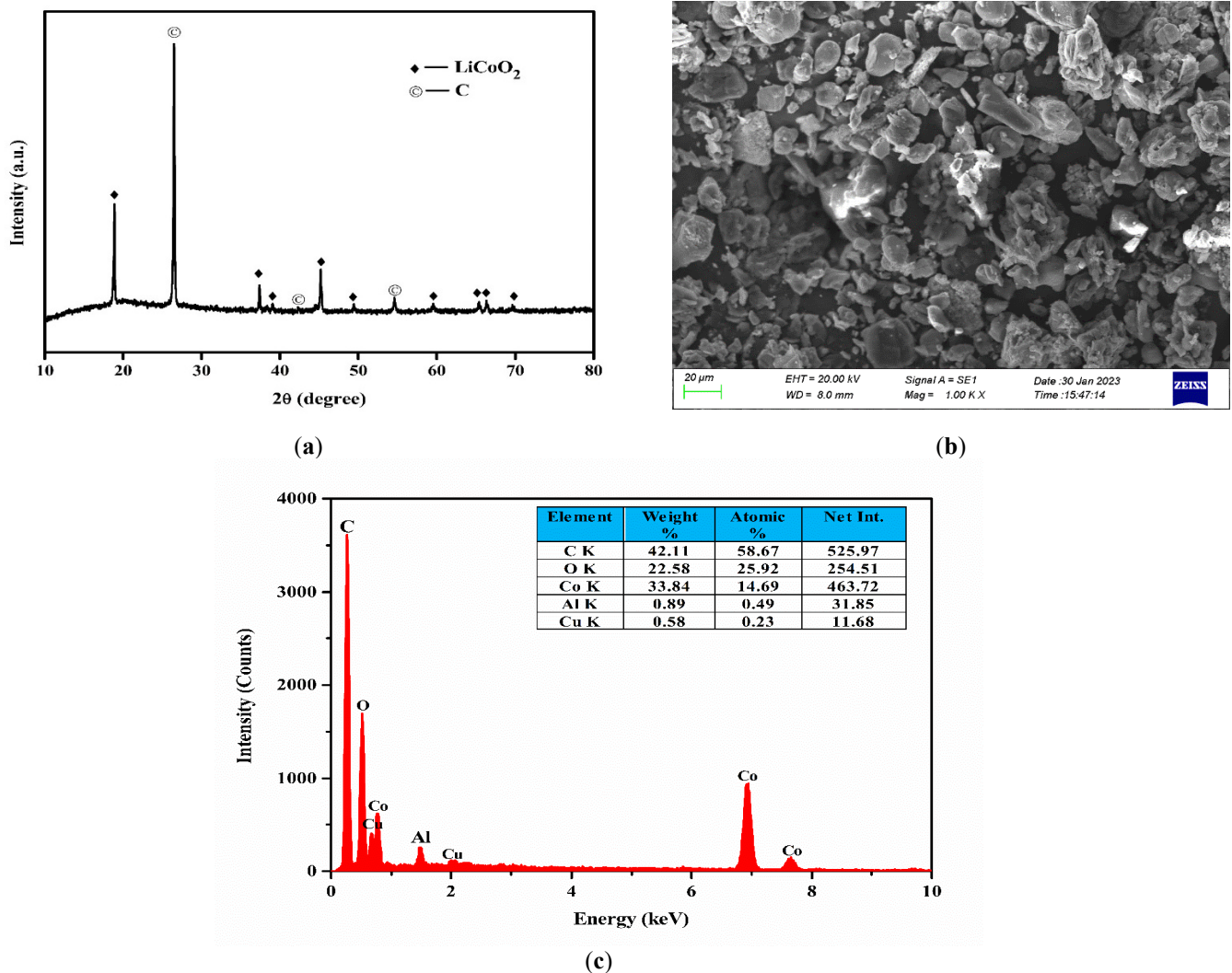


Figure 2. (a) XRD plot (b), SEM image, and (c) EDS analysis of the waste LIB sample.

3.2. Leaching of the Metal Ions from the Spent LIBs

3.2.1. Impact of Leaching Time

The impact of leaching time on the efficiency of Li and Co leaching was investigated over a period from 10 to 120 min, and samples were taken for examination at various time intervals. Figure 3 displays the results and shows that the leaching period clearly affects the extraction of lithium. For a 60 min leaching period, the lithium extraction efficiency improved. The leaching efficiency continued to increase after this point, but only with insignificant contents. It reached 20.2% (Li) and 3.8% (Co) in 60 min, as well as 20.7% (Li) and 3.9% (Co) in 90 min. Consequently, the best leaching time was 60 min.

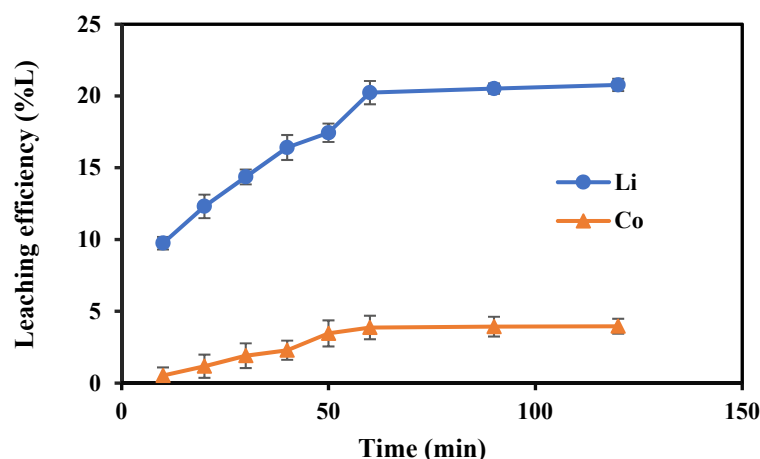


Figure 3. Impact of leaching time on leaching yield of Co and Li. ((acetic acid) = 0.5 mol/L, temperature = 30 °C, and S/L = 10 g/L).

3.2.2. Impact of Acetic Acid Concentration

The leaching efficiency of metals is significantly assisted by the rise in acid content. The relationship between acid concentration and leaching efficiency was investigated (Figure 4). There was an increase in leaching efficiency when the acetic acid concentration was increased from 0.1 mol/L to 1.2 mol/L. At 0.1 mol/L, 1.5% Co and 6.92% of Li leaching were attained. A total of 11.7% of cobalt and 42.8% of lithium were leached out with the 1.2 mol/L acetic acid concentration. Because a higher concentration gradient enables the dissolved acid reactant to diffuse more quickly to the surface during the reaction, the leaching efficiency increases as the acid concentration increases [6]. A further increase in acetic acid content from 1.2 mol/L did not significantly alter the yield during leaching.

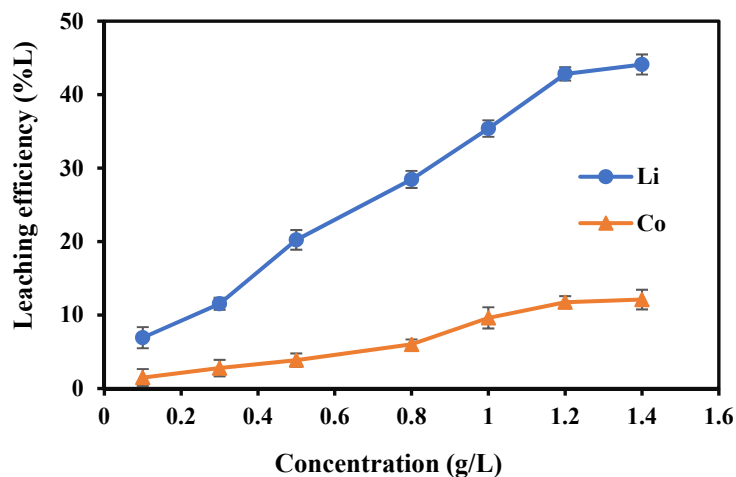


Figure 4. Impact of acetic acid concentration on leaching yield of Co and Li. (Temperature = 30 °C, S/L = 10 g/L, and leaching time = 60 min.)

3.2.3. Impact of H₂O₂ Concentration

Numerous tests were conducted employing H₂O₂ volume fractions ranging from 2 to 9 vol%. Without the presence of H₂O₂, the yields after Li and Co leaching were 42.8% and 11.7%, respectively. When 2% H₂O₂ was added to the leaching agent as a reductant, Li and Co were leached out, with yields of 45.4% and 17.5%, respectively. When the H₂O₂ content was raised from 2% to 7%, the leaching efficiency of Li and Co increased from 45.4% to 67.2% and 17.5% to 58.1%, respectively (Figure 5). H₂O₂ was used to convert Co (III) into Co (II) and transfer it into the leach liquor, improving the yield of Co leaching. As a result of the LiCoO₂ structure being destroyed, the leaching of lithium ions at the same time makes it easier to form complexes with acetic acid. With a rise in H₂O₂ initial dosage, metals often

leach more quickly. However, the leaching efficiency of Co and Li considerably changed up to an H_2O_2 dosage of 7%. This could be explained by the presence of alkaline groups ($-\text{CH}_3$), in addition to acidic groups in acetic acid ($-\text{COOH}$). The Co and Li leaching yield can be reduced by adding too much H_2O_2 to the leaching solution because this reaction with $-\text{CH}_3$ lowers the coordination of acid with Co (II). Consequently, it has been decided that an H_2O_2 dosage of 7% is the best scenario.

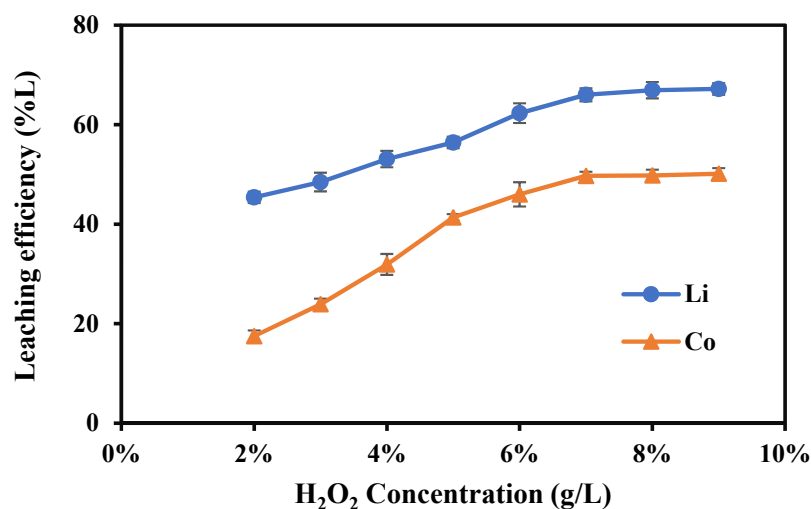


Figure 5. Impact of H_2O_2 concentration on leaching yield of Co and Li. ((Acetic acid) = 1.2 mol/L, temperature = 30 °C, S/L = 10 g/L, and leaching time = 60 min.)

3.2.4. Impact of Temperature

When the reaction temperature was maintained at 30 °C, the Co and Li leaching efficiencies remained low, 58.1% and 66.2%, respectively. When the leaching temperature was raised to 90 °C, the leaching efficiencies of Co and Li increased to 95.6% and 99.6%, respectively (Figure 6). In a chemical reaction, temperature always has a considerable impact on the rate of the reaction. Actually, raising the reaction temperature would considerably improve the collision rates, resulting in the faster dissolution of metal ions. A lengthier extraction time is caused by acetic acid's reduced acidity compared to those of these organic acids, but it is less expensive and more environmentally friendly. In order to leach Co and Li from spent LIBs, acetic acid is a suitable leachant.

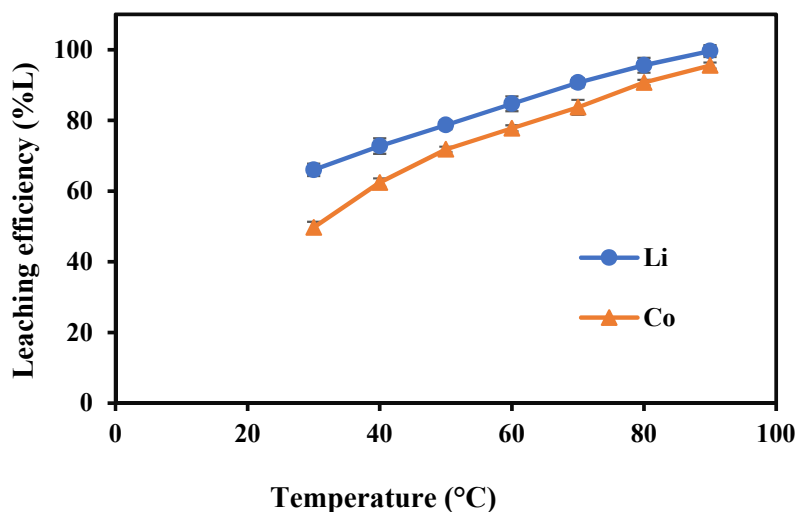


Figure 6. Impact of temperature on leaching yield of Co and Li. ((Acetic acid) = 1.2 mol/L, H_2O_2 = 7 vol%, S/L = 10 g/L, and leaching time = 60 min.)

3.2.5. Impact of Solid to Liquid (S/L) Ratio

Indeed, the leaching efficiencies of Co and Li were as high as 95.5% and 99.6%, respectively, when the S/L ratio was 10 g/L, but they tended to decline as the S/L ratio increased. However, when the S/L ratio was raised to 20 g/L, the leaching efficiencies drastically dropped to 75.07% for Co and 84.48% for Li, demonstrating that high S/L ratios do not promote optimal leaching (Figure 7). The S/L ratio obviously has a considerable impact on the leaching yield, and the results indicated that the leaching efficiencies of Co and Li declined as the S/L ratio increased. Additionally, Figure 7 reveals that the amount of both metals' dissolution increased when the S/L ratio increased up to 20 g/L, and the concentration of Li and Co remained constant above S/L ratios of 20 g/L. As a result, it could be caused by a deficiency of acetic acid or the achievement of a solubility limit, which affects efficiency as the S/L ratio increases. Based on the experimental results and the fact that a sizable amount of both metals remained in the residue, we, therefore, came to the conclusion that an S/L ratio of 10 g/L is the optimal condition.

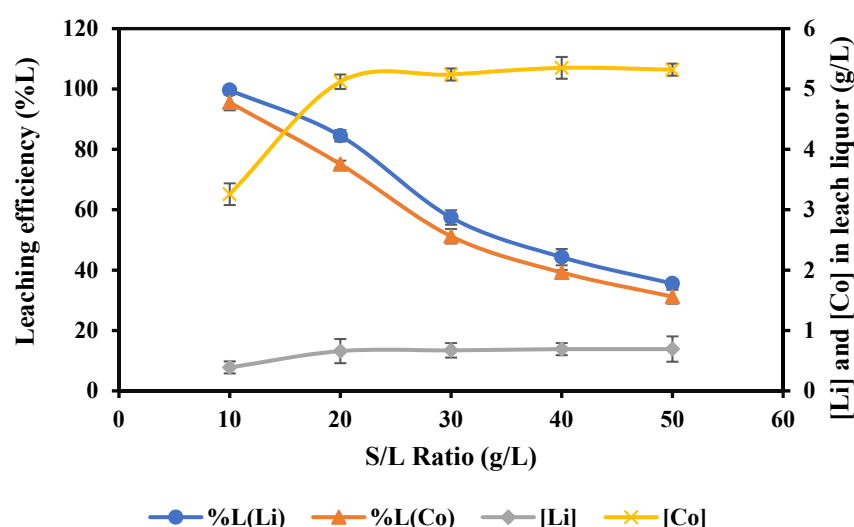


Figure 7. Impact of S/L ratio on leaching yield of Co and Li ((acetic acid) = 1.2 mol/L, H₂O₂ = 7 vol%, temperature = 90 °C, and leaching time = 60 min).

3.3. Kinetics Study

Leaching kinetics studies on hydrometallurgical processes are typically needed in order to pinpoint the process's regulatory steps. Leaching kinetics was traditionally built on the shrinking core model, with surface chemical reaction control (SCRC) and a diffusion control model controlling various steps [27–29]. The Avrami equation model, a mixed kinetic model that incorporates surface chemical reaction control and diffusion control, is considered as another kinetic model used to understand the leaching of multi-metals for several solid–liquid heterogeneous systems. The associated mathematical equations are addressed in Table 2.

Table 2. Mathematical equations for various kinetics models.

Kinetic Model	Integrated Form of the Equation	Parameters
Surface chemical reaction control	$1 - (1 - X)^{\frac{1}{3}} = k_c t$	X is the leaching rate of a metal; k_c is the chemical reaction rate constant
Diffusion control	$1 - \frac{2}{3}X - (1 - X)^{\frac{2}{3}} = k_d t$	k_d is the diffusion rate constant
Avrami kinetic model	$\ln(-\ln(1 - X)) = \ln k_r + \ln t$	k_r is the reaction rate constant

The applicability of these models for the information received from the leaching tests at various temperatures was, therefore, examined. Due to the diffusion control model's

lower R^2 values (<0.9), which clearly rule it out for the further justification of the kinetic study, it was determined from Table 3 that either the Avrami equation model or the SCRC model are better fits for this leaching process. R^2 values are tabulated in Table 3, and the values indicate that the SCRC model is a better fit than the Avrami equation model is to depict the leaching process of Li and Co with correlation coefficients (R^2) greater than 0.98.

Table 3. Correlation coefficient and rate constant values for the fitting of the kinetic model at various temperatures.

T (°C)	Li						Co					
	Surface Chemical Reaction		Diffusion Control		Avrami Equation		Surface Chemical Reaction		Diffusion Control		Avrami Equation	
	$k_c \times 10^3$ (min^{-1})	R^2	$k_d \times 10^3$ (min^{-1})	R^2	$\ln k_r$	R^2	$k_c \times 10^3$ (min^{-1})	R^2	$k_d \times 10^3$ (min^{-1})	R^2	$\ln k_r$	R^2
30	4.8	0.990	1.0	0.857	−4.240	0.977	3.3	0.975	0.5	0.831	−5.607	0.983
40	5.5	0.987	1.2	0.845	−3.895	0.965	4.4	0.983	0.8	0.818	−4.629	0.978
50	6.4	0.987	1.6	0.875	−3.498	0.967	5.3	0.986	1.2	0.827	−4.464	0.979
60	7.4	0.986	2.0	0.889	−3.389	0.969	6.2	0.990	1.5	0.850	−4.099	0.978
70	8.8	0.988	2.6	0.896	−3.394	0.960	7.2	0.987	1.9	0.861	−3.711	0.965
80	10.4	0.989	3.3	0.928	−3.301	0.964	8.7	0.990	2.6	0.884	−3.658	0.967
90	13.9	0.988	4.9	0.983	−3.189	0.953	10.3	0.994	3.3	0.918	−3.600	0.974

From Table 3, the k values (specific rate constants) for Li and Co based on the SCRC model were considered. Using the Arrhenius equation, k and T (leaching temperature) can be related as (Equation (5)).

$$k = A e^{\frac{-E_a}{RT}} \quad (5)$$

where E_a (kJ/mol) is the activation energy, and A is the pre-exponential factor. The simplified form of Arrhenius equation (Equation (6)) can be used to determine the apparent activation energies for different metals.

$$\ln k = \ln A - \frac{E_a}{RT} \quad (6)$$

An Arrhenius plot of $\ln k$ versus $1000/T$ is presented in Figure 8, and the activation energies for the leaching of Li and Co are 15.5 and 16.6 kJ/mol, respectively, suggesting that the rate-controlling step of this leaching process is the surface chemical reaction.

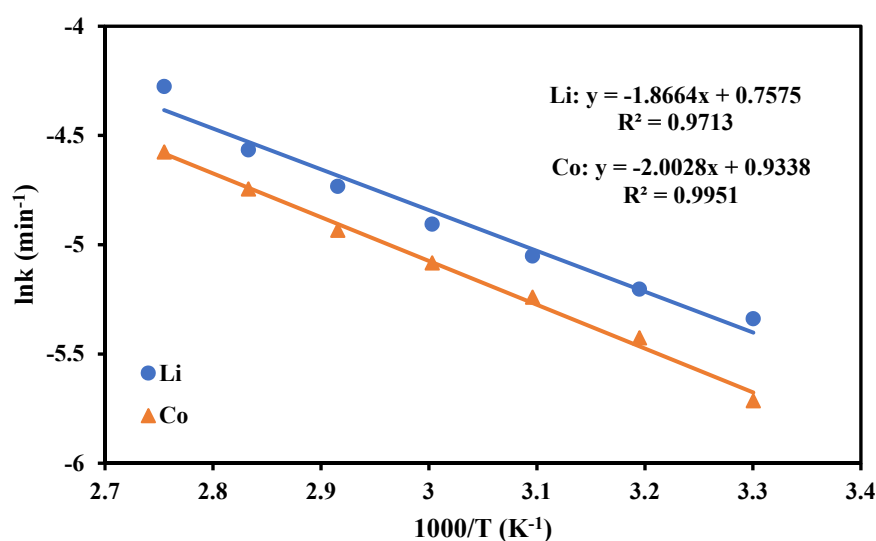


Figure 8. Plot of $\ln k$ vs. $1000/T$ for fitting of the SCRC model.

The equation for the SCRC model was used to investigate the effects of acetic acid concentration without the addition of H_2O_2 in order to determine whether or not the leaching method is controlled by the model. Following the acquisition of the specific

rate constants for Li and Co (Table 4), a plot between $\ln k$ and $\ln$ (acetic acid) was created (Figure 9). The SCRC model was fitted to the leaching of both metals based on higher R^2 values (>0.98). Because the Co^{3+} ion needs three moles of acetate ion to produce cobalt acetate, (data from Figure 4) this shows that the synthesis of cobalt acetate is difficult without the use of a reductant.

Table 4. Correlation coefficient and rate constant values for the fitting of the kinetic model with different acetic acid concentrations.

Acetic Acid Concentration	Surface Chemical Reaction			
	Li		Co	
	$k_c \times 10^3 \text{ (min}^{-1}\text{)}$	R^2	$k_c \times 10^3 \text{ (min}^{-1}\text{)}$	R^2
0.1	0.4	0.995	0.05	0.996
0.3	0.7	0.980	0.18	0.978
0.5	1.2	0.982	0.21	0.980
0.8	1.8	0.981	0.31	0.985
1.0	2.3	0.984	0.5	0.987
1.2	2.9	0.983	0.7	0.983

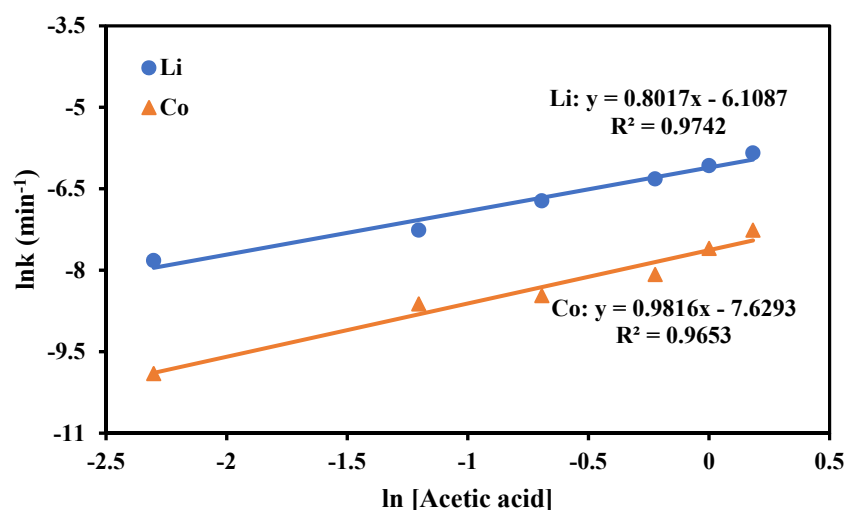


Figure 9. Plot of $\ln k$ vs. $\ln$ (acetic acid) for fitting of the SCRC model.

The impact of the H_2O_2 concentration was tested to further justify the kinetic model (data from Figure 5). The k values for each metal were calculated (Table 5), and a plot of $\ln k$ and $\ln (\text{H}_2\text{O}_2)$ was formed (Figure 10). The kinetics model was justified by having higher values for the correlation coefficient ($R^2 > 0.98$). The slope value for Co was two times higher than that of Li, showing that the presence of H_2O_2 was efficient to enhance the leaching yield of Co.

Table 5. Correlation coefficient and rate constant values for the fitting of the kinetic model with LH_2O_2 concentration.

H_2O_2 Concentration	Surface Chemical Reaction			
	Li		Co	
	$k_c \times 10^3 \text{ (min}^{-1}\text{)}$	R^2	$k_c \times 10^3 \text{ (min}^{-1}\text{)}$	R^2
2%	0.31	0.997	0.1	0.996
3%	0.34	0.992	0.15	0.984
4%	0.39	0.984	0.2	0.982
5%	0.43	0.980	0.29	0.988
6%	0.48	0.981	0.32	0.981
7%	0.53	0.981	0.36	0.980

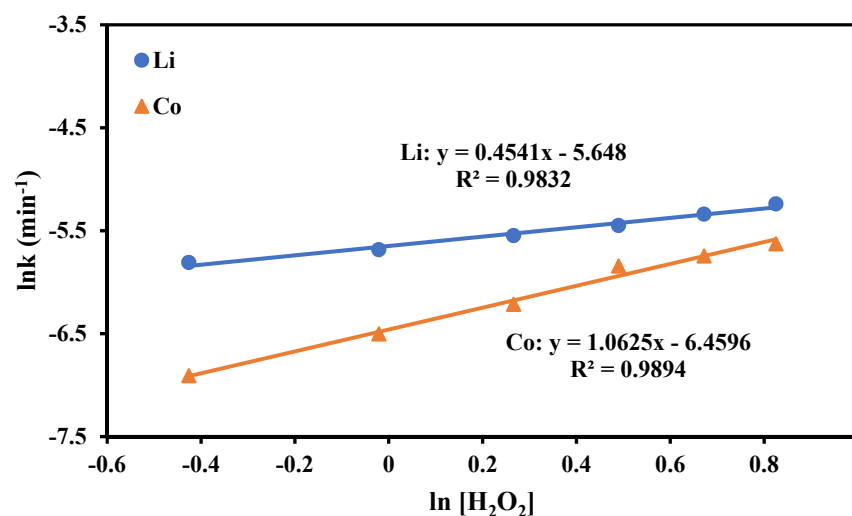


Figure 10. Plot of $\ln k$ vs. $\ln (H_2O_2)$ for fitting of the SCRC model.

After formic acid, the second-simplest carboxylic acid is acetic acid ($C_2H_4O_2$). It is a weak acid, with one H^+ replaceable ion ($pK_a = 4.76$). The dissociation of acetic acid can be expressed as follows:



It was found through the comprehensive kinetic studies of the leaching process that the surface chemical reaction controls the leaching mechanism for waste LCO-type LIB batteries. Because of the trivalent cobalt ions used in the leaching studies, it was found that cobalt acetate formation is challenging. In order to improve the leaching efficiency of Co, Co(III) ions must be converted into Co(II) ions using H_2O_2 , and the complete reaction during the leaching process is expressed by Equation (8). $LiC_2H_3O_2$ and $Co(C_2H_3O_2)_2$ are the two most probable and stable products (Figure 11) [30].

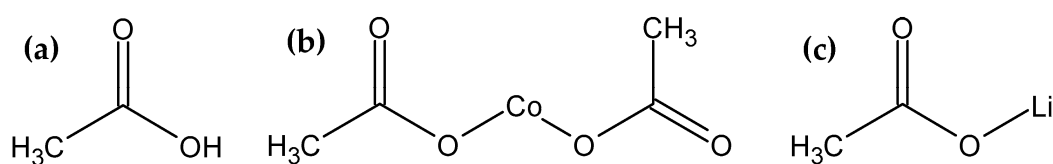
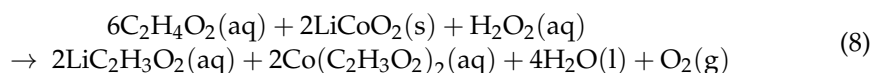


Figure 11. Structures of (a) acetic acid, (b) cobalt acetate, and (c) lithium acetate.

Figure 12b shows SEM images of the leached residue at various magnifications. It was noticed that after leaching with acetic acid and H_2O_2 , spherical particles with an aggregated geometry vanished, which were compared to those in Figure 2b. The XRD patterns of leached residue were examined after leaching. Additionally, EDS analysis of the leached residue was studied to check the residual metal content in the residue (Figure 12c). The analysis of the grain size distribution of the leached residue showed that the average particle size was $12.5 \mu m$, with $D_{10} = 6.4 \mu m$ and $D_{60} = 16.3 \mu m$. According to the results, it was concluded that the combination of acetic acid and H_2O_2 was favorable for the selective leaching of Co and Li from the spent LCO-type batteries.

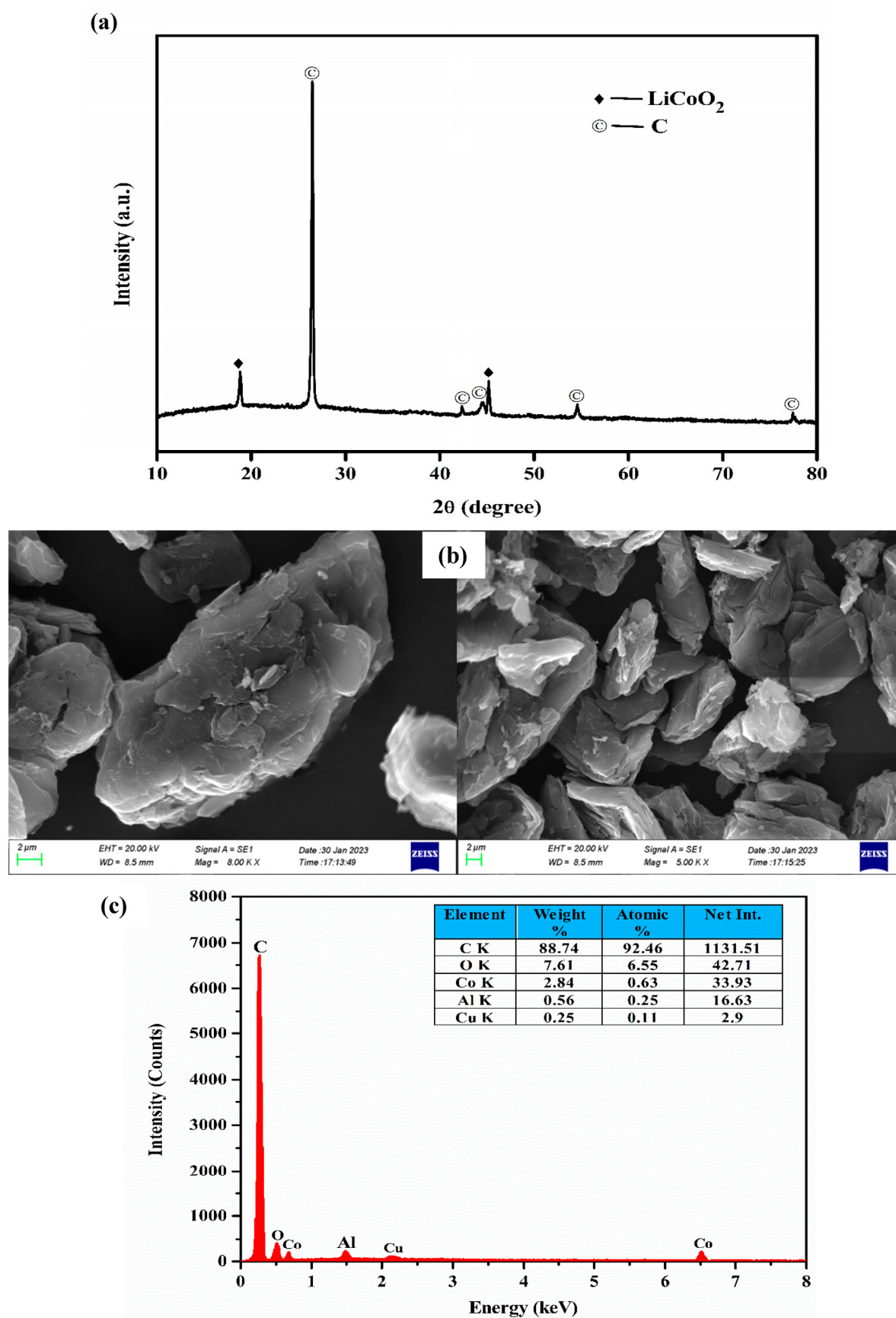


Figure 12. (a) XRD plot, (b) SEM image, and (c) EDS analysis of the leached residue.

3.4. Economic Viability of the Current Leaching Process

Based on the price of leaching agents, Table 6 describes how various leaching techniques are economically valued. To examine the economic feasibility of various leaching processes, the prices for various acids were considered to be estimates. Leaching agents, such as acids and reductants, are the process' major costs. The prices for succinic acid, L-aspartic acid, L-tartaric acid, and citric acid are 4.15, 3.18, 29.33, and 8.56 USD/kg, respectively, according to the Indian market. H₂O₂ and acetic acid were provided by Merck Life Science Private Limited, India, for 0.73 and 1.27 USD/kg, respectively. The economic profitability value for the current work, which is the most cost-effective method among all other procedures and is commercially feasible, is shown in Table 6 to be at a minimum of USD 0.279 at an S/L ratio of 10 g/L.

Table 6. Economic valuation of various leaching procedures based on the cost of leaching agents.

SL No.	Leaching Agent	Acid Strength (mol/L)	Reductant (H ₂ O ₂) (vol%)	Cost of Acid/USD	Cost of Reductant/USD	Total Cost/USD	References
1.	Acetic Acid	1.2	7%	0.09	0.189	0.279	Present Work
2.	Succinic acid	1.5	4%	0.73	0.108	0.838	[15]
3.	L-Aspartic acid	1.5	4%	0.63	0.108	0.738	[31]
4.	L-Tartaric acid	2.0	4%	8.80	0.108	8.908	[32]
5.	Citric acid	1.0	8%	1.80	0.216	2.016	[33]

4. Conclusions

In the current study, the impact of acetic acid on the efficacy of the leaching of critical metals in the presence and absence of a reductant was studied. Several leaching variables with acetic acid as the leaching agent were investigated. The optimum leaching efficiencies of Li (99.6%) and Co (95.6%) were observed at 1.2 mol/L acetic acid, 7% H₂O₂, 90 °C, an S/L ratio of 10 g/L, and a 60 min leaching duration. The comprehensive leaching kinetics were examined to determine the mechanisms involved in the leaching process, and it was observed that with apparent activation energies of Li (15.5 kJ/mol) and Co (16.6 kJ/mol), the surface chemical reaction model fit the data better, based on them having higher correlation coefficient values. This work also addresses the economic viability of the current leaching procedure in contrast to those of earlier approaches, and this process will be commercially feasible, with a minimum cost of USD 0.279 at an S/L ratio of 10 g/L. The employment of some leaching techniques, such as microwave reduction leaching [34], ultrasound-assisted leaching [35], and closed-vessel microwave leaching [36] on an industrial scale, should be emphasized in the future to accomplish the complete leaching of all metals.

Author Contributions: S.S.: Writing—original draft, visualization, data curation, formal analysis, investigation, and software. S.P.: Formal analysis, investigation, and writing—original draft. N.D.: Conceptualization, methodology, supervision, writing—review and editing, and validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable.

Acknowledgments: The authors express their gratitude to S'O'A (Deemed to be University) for providing the research facilities.

Conflicts of Interest: The authors declare that there is no conflict of interest.

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