Discharge of lithium-ion batteries in salt solutions for safer storage, transport, and resource recovery

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Abstract

The use of lithium-ion batteries (LIBs) has grown in recent years, making them a promising source of secondary raw materials due to their rich composition of valuable materials, such as Cobalt and Nickel. Recycling LIBs can help reduce fossil energy consumption, CO₂ emissions, environmental pollution, and consumption of valuable materials with limited supplies. On the other hand, the hazards associated with spent LIBs recycling are mainly due to fires and explosions caused by unwanted short-circuiting. The high voltage and reactive components of end-of-life LIBs pose safety hazards during mechanical processing and crushing stages, as well as during storage and transportation. Electrochemical discharge using salt solutions is a simple, quick, and inexpensive way to eliminate such hazards. In this paper, three different salts (NaCl, Na₂S, and MgSO₄) from 12% to 20% concentration are investigated as possible candidates. The effectiveness of discharge was shown to be a function of molarity rather than ionic strength of the solution. Experiments also showed that the use of ultrasonic waves can dramatically improve the discharge process and reduce the required time more than 10-fold. This means that the drainage time was reduced from nearly 1 day to under 100 minutes. Finally, a practical setup in which the tips of the batteries are directly immersed inside the salt solution is proposed. This creative configuration can fully discharge the batteries in less than 5 minutes. Due to the fast discharge rates in this configuration, sedimentation and corrosion are also almost entirely avoided.

Keywords

Circular economy, battery discharge and drainage, waste electric and electronic equipment, e-waste, electrochemistry

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Introduction

As the use of intermittent energy sources such as solar and wind grows, the need for storage of electrical energy becomes more pronounced. One such storage method is the use of lithium-ion batteries (LIBs) (Jiang et al., 2018).

The use of LIBs is growing worldwide, and the global demand is projected to grow 7.8% annually reaching $120 billion in 2019. The increased use of personal electronic devices has resulted in a staggering rise in LIB waste. Meanwhile, electric vehicles are also on the rise, leading to large quantities of LIB waste coming from cars in the future. For example, currently about 50% of cars sold in Norway are electric (Karagiannopoulos and Solsvik, 2019). So, the topic of LIBs from electric vehicles has attracted considerable attention in recent years (Fujita et al., 2021; Qiao et al., 2021). Overall, electronic waste is one of the fastest growing solid waste streams worldwide causing significant challenges (Sattar et al., 2019).

LIBs can be a good alternative to other types of batteries due to their low weight, high energy density, and high capacity. Nowadays, electronic devices, such as cell phones, laptops, and cameras, have become basic requirements of daily life, all of which include LIBs (Nayaka et al., 2019). On the other hand, LIBs contain valuable and potentially dangerous metals. Therefore, recycling consumed LIB materials is a useful way to both prevent environmental damage and also recuperate valuable metals (Nayaka et al., 2019). Spent LIBs consist of metals, organic chemicals, and plastics. The constituents are approximately 5%–20% cobalt, 5%–10% nickel, 5%–7% lithium, 15% organics, and 7% plastics (Sun et al., 2018). Much research has been carried out on the extraction of valuable metals from electronic wastes (Marappa et al., 2020).

Several review papers on the technological options for recycling spent LIBs have been published (Makuza et al., 2021; Meng et al., 2021). Furthermore, the strategic importance and value of

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various materials in spent LIBs as well as the environmental impacts, sustainability, and quality of recycled materials resulting from various battery recycling processes have been assessed (Sambamurthy et al., 2021; Sommerville et al., 2021). It has been shown that the design of the battery pack, module, and cell can have a considerable impact on the end-of-life dismantling and recycling steps (Thompson et al., 2020; Yang et al., 2021).

The cathodes of LIBs are mainly composed of aluminum foil and cathodic materials, that is, LiCoO₂, LiMn₂O₄, LiFePO₄, and other lithium metal oxides, whereas the anodes contain copper foil and graphite (Zhang et al., 2018). Meanwhile, a diversification between high-performance and cost-efficient LIBs is expected in the future (Doose et al., 2021).

The discharge step is critically important for the safety of the recycling process, because if the batteries are not discharged, there is always a risk of the anode and cathode short-circuiting, which releases stored chemical energy (Yao et al., 2018). Such a sudden release of energy can be powerful and severe, causing sudden temperature rise, release of gas, fires, or even explosions. For example, according to one report, the source of 65% of the fires from waste plants in the US state of California are LIBs (Weise, 2018).

Pretreatment processes are essential in LIB recycling (Kim et al., 2021), and different approaches have been suggested to minimize the risks when crushing batteries (Sonoc et al., 2015). Some suggestions include freezing LIBs with liquid nitrogen before crushing or processing batteries under vacuum or in the presence of inert gases, such as argon or CO₂. However, these approaches are expensive and require additional equipment and resources (Ojanen et al., 2018; Sonoc et al., 2015).

One of the proposed methods for discharging batteries is their immersion in a salt solution which results in controlled short-circuiting (Li et al., 2016). This method can be performed without major challenges and relatively quickly. The electrolysis of the salt solution will eliminate the battery charge (Lu et al., 2013). Another benefit of discharge in salt solutions is that this process requires resources that are readily available (Ojanen et al., 2018). However, the published literature pertaining to this subject is limited and inadequate, which should be elaborated upon and more closely examined.

To this end, the current manuscript has examined the issue of discharging spent LIBs in more detail. Various salts are examined with the aim of finding a quick, safe, and inexpensive solution. After the examination of different operating parameters, an innovative solution is proposed, which can drain the batteries quickly with minimal effort.

**Materials and methods**

To ensure repeatability, all batteries used in the study were Japanese-made Apple 3.82 V batteries used and discarded from iPhone 6 mobile phones (Apple Inc., Cupertino, CA, USA). The net weight of the batteries measuring 80 samples is 27.02 ± 3.05 g (95% CI).

As shown in Figure 1, in discharge tests, a pair of wires with crocodile clips (tips) were used. One end of first wire was connected to the anode, and the other end was placed in the salt solution. In addition, the second wire was connected to the cathode, and the other end was placed in the salt solution. A voltmeter was also used to record the battery discharge throughout the study.

The electrodes experienced extreme corrosion and deposition problems during testing, and hence new electrodes (wires with crocodile clips) were used for each test to reduce the error. The battery was not directly submerged in the salt solution so its physical condition was not endangered. With this methodology, the evolution of the battery discharge can be properly monitored and controlled, and it is possible to evaluate the discharge potential of the electrolyte solution. All salts were supplied by Merck (Merck KGaA, Darmstadt, Germany), in general reagent grade.

The following investigations were carried out:

1) Studying battery discharge in 12%–20% NaCl solutions.
2) Studying battery discharge in 12%–20% Na₂S solutions.
3) Studying battery discharge in 12%–20% MgSO₄ solutions.
4) Studying battery discharge in 16% NaCl solution in the temperature range of 30°–60°C. The concentration of 16% was used as the midpoint between 12% and 20%.
5) Studying battery discharge in 16% NaCl solution with stirring.
6) Studying battery discharge in 16% NaCl solution alongside ultrasonication (50 W, Yaxun XY2000A).
7) Finally, in a separate set of experiments, rather than using electrodes/wires, the battery tips were placed vertically in the salt solution directly. This innovative setup was used to simulate possible industrial application.
During the test, the residual voltage percent ($E_r$) in the battery was calculated by comparing voltage remaining after the discharge to the initial voltage of the battery. The residual voltage percent was calculated as follows:

$$E_r = \left( \frac{V_t}{V_0} \right) \times 100\%$$  \hspace{1cm} (1)

where $V_t$ is the voltage at time $t$, and $V_0$ is the initial voltage of the LIB. In addition, we can calculate the percentage of voltage drop ($E_t$) with the following equation (Shakhashiri, 1985):

$$E_t = 1 - E_r = \left( 1 - \frac{V_t}{V_0} \right) \times 100\%$$  \hspace{1cm} (2)

The ionic strength of the salt solutions was calculated with the following equation (Karim and Zahari, 2019; Majlesi et al., 2019):

$$I = \frac{1}{2} \sum_{i=1}^{n} z_i^2 c_i$$  \hspace{1cm} (3)

**Results and discussion**

When the anode and cathode of batteries come into contact with water containing salts, the potential difference between the poles leads to electrolysis of the water as the LIB is discharged. During experimentation, this is clearly visible in the form of small bubbles emerging in the solution when conducting the test. As the discharge process progresses and the battery voltage decreases, the amount of bubbles produced also decreases. This can be justified with the following explanation. Water electrolysis is the breakdown of water molecules into hydrogen gas and oxygen gas using electric force. Electrochemical reactions occur at the anode and cathode:

**Anode:**

$$H_2O(l) \leftrightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- E_{anode}^{25°C} = 1.23\text{V}$$  \hspace{1cm} (4)

**Cathode:**

$$2H^+ + 2e^- \leftrightarrow H_2 E_{cathode}^{25°C} = 0\text{V}$$  \hspace{1cm} (5)

Thus, the complete reaction in the electrolytic cell will be:

$$H_2O(l) \leftrightarrow H_2 + \frac{1}{2}O_2 E_{cell}^{25°C} = 1.23\text{V}$$  \hspace{1cm} (6)

The Nernst equation expresses the potential of water electrolysis with thermodynamic parameters shown in equation (7).

$$E_{cell}^{0} = 1.23 - 0.9 \times 10^{-3}(T - 298) + \frac{RT}{4F} \ln \left( \frac{p_{H_2} \cdot p_{O_2}}{p_{H_2O}} \right)$$  \hspace{1cm} (7)

where $p_{H_2}$, $p_{O_2}$, and $p_{H_2O}$ are the hydrogen, oxygen, and water vapor pressures, respectively. Although the potential of water electrolysis in standard conditions at 25°C is 1.23 V, the water degradation potential in the experiments in this paper is affected by the activity of the electrodes and the presence of salt solutions. For example, under particular conditions, decomposition potentials of 1.68 V have also been measured (Shen et al., 2011).

During electrochemical discharge in aqueous solutions, reactions in equations (4) and (5) are responsible for the production and consumption of electrons present in the cell. And, as mentioned, the battery potential must be higher than the decomposition potential to produce a water splitting reaction. In the case of LIBs, this is easily met, as a fully charged battery usually has an initial potential of about 4 V. The more the discharge proceeds, the less potential remains to induce water splitting reactions (Chagnes and Swiatowska, 2015; Lu et al., 2013; Ojanen et al., 2018). It is noteworthy that the voltage in other types of batteries, such as Ni–MH and alkaline batteries are lower at 1.35 V and 1.5 V, respectively.

When sufficient voltage is present across the electrodes in a cell containing NaCl solution in water, it results in the release of $H_2$ gas in one electrode and oxygen or chlorine gas in the other. In other words, at the anode, chloride ions may be oxidized to $Cl_2$. But the $Na^+$ ions in the cathode are not reduced to Na metal. Instead, $H_2$ and $OH^-$ ions are produced by reducing the $H_2O$ molecules because water is reduced more readily than $Na^+$ ions. This is primarily because the reduction of $Na^+$ results in the production of highly active sodium metal, whereas the decrease in $H_2O$ results in the production of more stable $H_2$ (g) and $OH^-$ (aq) products.

As salt concentrations increase, the possibility of the participation of various ions rather than just water at the anode and cathode becomes more likely. For example, when chloride ions are present in water, the following reaction may occur:

$$\text{Anode (Oxidation): } 2Cl^- \rightarrow Cl_2 + 2e^- E^0 = 1.36\text{V}$$  \hspace{1cm} (8)

Due to the higher potential of reaction in equation (8) compared to reaction in equation (6), water decomposition at the anode seems more likely, but due to the limitations in ion transport and diffusion, the possibility of chlorine gas formation cannot be completely ruled out (Shen et al., 2011; Zumdahl et al., 2018). Chlorine gas is toxic when inhaled, but the amount of chlorine produced in this process is negligibly low. Although in the electrolysis process both hydrogen and chlorine gas are produced, but since chlorine gas is more soluble in water than hydrogen, more hydrogen gas is observed in the form of bubbles in this process (Shakhashiri, 1985).

**Effect of salt type and concentration on discharge**

The discharge tests for LIBs were conducted with electrolyte solutions of NaCl, Na$_2$S, and MgSO$_4$ at different concentrations. These salts were chosen in order to observe the effects of a wide range of molarities and ionic strengths on discharge. Table 1 shows the ionic strength of each solution at a given weight percent.
As will be seen in subsequent sections, ionic strength of the solution was not a good indicator for predicting the discharge rate of the batteries. To some extent, molarity can be used to predict discharge performance of the solution; but merely relying on molarity does not take into account important phenomena, such as deposition of sediments, which have a considerable influence on the process.

**NaCl solution.** Discharge experiments were performed with NaCl solution at 12%, 16%, and 20%. Initially, crocodile clip wires were used at the rated 10 A, which resulted in a low battery discharge rate and efficiency due to the high corrosion and decomposition on the clip submerged in the solution. It is known that the corrosion mechanism of copper is strongly dependent on the presence of chloride ions. For example, Arjmand et al. (2012) reported that the effects of chloride concentration on the electrochemical corrosion of copper in aqueous NaCl could include the following equations:

\[
Cu + 2Cl^- \leftrightarrow CuCl_2 + e^- \quad (9)
\]

\[
Cu \leftrightarrow Cu^{+} + e^- \quad (10)
\]

\[
Cu^{+} + 2Cl^- \leftrightarrow CuCl_2 \quad (11)
\]

\[
Cu + Cl^- \leftrightarrow CuCl + e^- \quad (12)
\]

\[
CuCl + Cl^- \leftrightarrow CuCl_2 \quad (13)
\]

It should also be noted that the size and configuration of the electrode cell affects the mass transfer process (Sanchez et al., 2010). Thus, in subsequent tests, the clip in the salt solution was augmented with a stranded copper wire, which yielded much more favorable results. However, if the electrodes are in contact with the NaCl solution for a long time (about 12 hours, shown in Figure 2), even the stranded wires experience corrosion and deposition problems and could not be reused in subsequent experiments. As the concentration of the solution increases, the effect of corrosion and deposition increases. Although expensive, platinum and silver electrodes were less prone to such problems.

The effects of different concentrations of NaCl salt solution are shown in Figure 3. The higher the concentration, the faster the discharge rate will be at the beginning of the test; however, due to corrosion and sedimentation on the electrodes, the advantage of higher concentrations is offset in the long run, reducing conductivity, leading to comparable discharge rates regardless of salt concentration. Discharge data for 16% NaCl concentration falls between the two curves as shown in Figure 3.

The reduction in the rate of discharge due to deposition on the electrodes has been reported in the literature as well (Ojanen et al., 2018). In the current manuscript, it was attempted to reduce the amount of sedimentation by adding other compounds such as metals to the solution. It was hypothesized that the compounds would react with the species producing the sediments and reduce the amount of deposition. However, this attempt yielded mixed results and hence will not be discussed further.

In the literature, reported values for discharge time are widely different among research groups. For example, Lu et al. (2013) reported that complete discharge in 24 hours was obtained using 5% NaCl solution (Lu et al., 2013). Ojanen et al. (2018) reported that using zinc powder in 20% NaCl solution resulted in significantly faster discharge than in the absence of metal powder and reduced the total discharge time from 4.4 hours to 0.32 hours (Ojanen et al., 2018). However, the differences in battery composition and type, as well as discharge methodology may hinder the comparison of these results.

| Mass concentration (%) | NaCl | Na2S | MgSO4 |
|------------------------|------|------|-------|
|                        | Molarity (mol/L) | Ionic strength (mol/L) | Molarity (mol/L) | Ionic strength (mol/L) | Molarity (mol/L) | Ionic strength (mol/L) |
| 12                     | 2    | 0.2  | 1.5   | 0.37 | 1    | 0.4 |
| 16                     | 2.7  | 0.27 | 2     | 0.5  | 1.3  | 0.52 |
| 20                     | 3.4  | 0.34 | 2.5   | 0.62 | 1.6  | 0.64 |

Table 1. The ionic strength and molar concentration of the various salt solutions used to discharge the LIB.
As evident from Figures 4 and 5, the Na$_2$S and MgSO$_4$ solutions, similar to the NaCl solution, the discharge rate in more concentrated solutions is higher at the start of the experiments. Furthermore, with time, the effect of concentration becomes less significant. In the MgSO$_4$ solution, corrosion and sedimentation are significantly reduced compared to the NaCl solution, but even over long periods of time and at high concentrations, the battery will not fully discharge. This phenomenon can be attributed to the fact that despite the same mass concentration, due to the higher molecular mass, the number of ions present in the MgSO$_4$ solution are far lower than the number of ions in the NaCl solution (lower molarity). The lower number of ions results in a more difficult transfer of electrons resulting in slower and weaker discharge of batteries.

The performance of Na$_2$S solution was better than that of MgSO$_4$, and it was possible to fully discharge the battery with higher concentrations of this solution. This observation also points to the fact that evidently the molarity of the salt solution plays a role in the discharge behavior, with molarities that are too low being incapable of fully depleting the batteries. Ionic strength is proven not to be a good predictor, since although the ionic strength of the Na$_2$S and MgSO$_4$ solutions are comparable, their discharge profiles are significantly different. Chervyakov et al. (2004) have previously investigated the corrosion behavior of copper alloys in chloride solutions with and without Na$_2$S additives by radiometric and electrochemical methods. It was reported that in blank solutions, a film of corrosion products forms on the surface of the alloy. The thickness and copper content of the film increase with decreasing chloride concentration. In addition, the rate of corrosion in sulfide-containing solutions is higher than in sulfide-free solutions. Corrosion is accelerated by increasing the concentration of sodium sulfide (Chervyakov et al., 2004).

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**Figure 3.** Battery discharge rate with 12% and 20% NaCl solutions. In the beginning, there are differences in the discharge rates (left), which over time, due to corrosion and the formation of sediments on the electrodes, become less pronounced. Ultimately, the discharge rate curves converge regardless of solution concentration (right).

**Figure 4.** Battery discharge rate with 12% and 20% Na$_2$S solutions. Contrary to the curves for NaCl solutions, here, the initial rapid discharge difference (left) still persists over time (right) because the lower concentration does not fulfill the required minimum molarity, whereas the higher concentration is adequate. In the Na$_2$S solution, far less corrosion and sedimentation is observed compared to the NaCl solution.

**Figure 5.** Battery discharge rate with 12% and 20% MgSO$_4$ solutions shows that neither concentration is adequate for full discharge, when compared to NaCl solutions.
In a solution containing sulfide ions, copper electrodes result in the production of cuprous sulfide as the main corrosion product. This process happens through the ionization of Cu metal, combination of cuprous ions and sulfide, followed by the precipitation of cuprous sulfide on the surface in the form of a dark porous scale. The Cu₂S first forms a thin film, followed by the adsorption of sulfide ions and the formation of islands. The non-stoichiometric Cu₂S will induce the outward diffusion of Cu²⁺ ions to the film solution interface and allows cuprous sulfide scale growth on the top of the oxide film. Hydroxide ions may also interact at the boundary of sulfide films and induce the formation or growth of oxides.

Here, as the molar concentration of sodium sulfide increases, it is possible to achieve a complete discharge of the batteries; however, it is time-consuming due to the increased corrosion.

Battery discharge under mixing or ultrasonication

As shown in Figure 6(a), the discharge process using a 275-rpm mixer did not offer better performance compared to when no mixer was used. Observations showed no difference between the deposition of solids on the electrodes when the mixer was on or off, and since deposition and corrosion were identified as the most important hindrances to battery discharge, no noticeable change in the discharge curve was observed.

On the other hand, Figure 6(b) shows the strong effect of using ultrasonication (50 W) during discharge. The positive effect of ultrasonic waves can be explained as follows: first, ultrasonication can accelerate the motion of the solvent (water) thereby increasing the dissolution rate and efficiency. When ultrasonication is underway, at the expansion step, the pressure in the solvent becomes negative and ultrasonication can cause a number of small vacuum holes in the solvent. The dissolved gas in the solvent then enters these holes, creating millions of holes and then expanding into bubbles as more gas enters these holes (Bolne et al., 2021). During compression, the bubbles burst and cause a large amount of shock force around the bubbles which is called cavitation (He et al., 2015). Upon occurrence, cavitation bubbles begin to oscillate in two modes of radial oscillation. The first type of oscillation known as stable cavitation is nonlinear and occurs during acoustic oscillations. In the second type known as transient cavitation, the bubble expands rapidly and bursts suddenly (i.e. implodes). When the bubbles burst, the surrounding liquids fill the empty space with a severe shock wave caused by rapid flow. The wave causes shear forces and cleans surfaces (Verhaagen and Fernandez Rivas, 2016). In particular, imploding of bubbles that form near the surface of the electrodes produces shock waves that dislodge the deposited salts and disturbs the sedimentation of deposits on the electrodes. This preserves the conductivity of the electrodes, thus increasing the discharge rate of the battery. With ultrasonication, the batteries are fully discharged in less than 2 hours, which is equivalent to a reduction of more than 90% in the required duration. As stated, the main reason for the time-consuming discharge of the LIBs was the deposition and corrosion caused by the reactions between the salt solution and the electrodes. Ultrasonication almost completely eliminates the problem (Figure 6(c)). Since the lack of sediments allows for shorter discharge durations, corrosion also becomes less of a problem (because corrosion is a problem that requires extended durations of time).

Effect of temperature increase on battery discharge

After numerous repeated experiments in different temperatures ranging from 25°C to 60°C, it was concluded that the effect of
temperature on the discharge profile is negligible. However, it is possible to hypothesize a series of opposing effects which leads to this observation. On the one hand, conductive metals have a large number of valence electrons, which conduct electricity via free movement in the lattice. As temperatures increase, atomic vibrations in the lattice also increase, leading to more collisions and hindrances in the movement of the electrons, which in turn leads to a decrease in electrical conductivity. A decrease in conductivity should logically lead to a worse discharge profile. In addition, as temperatures increase, the corrosion of metals in salt solutions also increases (Li et al., 2011), which could additionally lead to less favorable discharge profiles. On the other hand, an increase in temperature also leads to higher solubility of salts and lower sedimentation rates. Since sedimentation is observed to be one of the main problems in the process, it is rational to assume that the less the sedimentation on the conducting surfaces, the better the discharge should be. Hence, in fact, the opposing effects of decreased conductivity and increased corrosion on the one hand and the decreased sedimentation rate on the other are more or less cancelling each other out. Furthermore, it has been previously shown that the corrosion of metals is dependent on the temperature, with copper showing a dramatic increase beyond 70°C under particular testing conditions (Perissi et al., 2006). The reason attributed to the increase of corrosion at higher temperatures is due to the fact that the diffusion of oxygen increases. This also influences the parameters in the Arrhenius equation, which ultimately determine (and increase) the corrosion rate (Ahmad, 2006; Davis, 2000; McCafferty, 2010; Popov, 2015).

**Proposed setup for discharge by immersion**

Previously, the idea of immersing the batteries into salt solutions in order to speed up the discharge process has been investigated. However, Ojanen et al. (2018) claim that the reports presented in the electrochemical battery discharge articles are inaccurate, and that the capacity loss is due to battery degradation rather than discharge. They also mention that the immersion method causes corrosion, damages the battery cover, and leaks its electrolytes and internal materials into the solution. However, Lu et al. (2013) reported that using a less concentrated solution such as 1% NaCl results in no corrosion, requiring more than 1 hour to fully discharge the batteries (Lu et al., 2013).

In order to overcome the problems previously reported, while achieving shorter discharge durations, the setup in Figure 7 has been proposed. The proposed setup, which is simple and can be scaled up to meet industrial needs, takes advantage of the fact that only the immersion of the tips of the battery into the salt solution is required for discharge (rather than the entire battery body). With this creatively simple configuration, the salt solution has minimal intrusion into the battery and therefore concerns regarding leakage of the battery materials into the solution are minimized. In addition, adequately high salt concentrations can be used which considerably reduce the discharge time.

For instance, in this study, it was observed that complete discharge of the battery is possible in less than 5 minutes in 5% NaCl solution. In this way, direct contact damage was minimized, and since the test time was short, there was no significant corrosion or deposition witnessed on the battery tips.

This effective configuration was used consistently and satisfactorily in a separate study conducted by our group (Jafari et al., 2020) in which after discharge, the LIBs were thermally and ultrasonically treated to separate and purify the cathodic powder without the need for chemical solvents.

**Conclusion**

Prior to downstream recycling processes, it is imperative to conduct pretreatment steps on spent LIBs. The discharge step is critically important for the safety of the recycling process, because if the batteries are not discharged, there is always a risk of the anode and cathode short-circuiting, potentially causing fires and explosions. There are several ways to discharge batteries, but electrochemical discharge using salt solutions has proven to be simple, fast, and inexpensive.

So far, there is no consensus in the literature on the time and concentration for the appropriate electrochemical solution for discharge. For further elucidation, in this study, the discharge of 3.82V Apple iPhone 6 batteries with NaCl, Na2S, and MgSO4 solutions was investigated.

In discharge tests, NaCl showed the most favorable discharge profile followed by Na2S. Solutions containing MgSO4 were not capable of fully discharging the batteries.

The main problem in the battery discharge process was the deposition of sediments and the corrosion of the electrodes. Variation of temperature did not yield significant differences. However, when ultrasonication was used, very positive effects were observed, and the discharge time was reduced to less than 2 hours. This is because the problem of sedimentation was overcome via the action of ultrasonic waves.

Finally, a simple yet effective configuration was proposed, by which the batteries are vertically immersed inside the salt solution. Such a configuration reduces the time required for full discharge to

![Figure 7. The proposed configuration results in minimum contact between the batteries and the salt solution while providing quick and safe discharge.](Image 314x646 to 532x781)
less than 5 minutes. Due to short durations, adequate concentrations of salt can be used, and since the process is fast, no significant sedimentation or corrosion is witnessed on the batteries.

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