

Upscaling the Recovery of Lithium from Waste Lithium-Ion Batteries by Microbial Bioleaching

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Abstract: The rapid use of lithium-ion batteries in electric cars and consumer gadgets has resulted in a significant increase in the amount of waste lithium-ion batteries. Large-scale waste Li-ion battery buildup is a major issue in the modern world. Disposing of these batteries is necessary because they can pose a significant threat to the environment. But these batteries contain valuable metals like lithium and cobalt, which are used to produce new batteries and electronic devices. Bioleaching is a cost-effective and environmentally sustainable approach for recovering valuable metals from spent lithium-ion batteries. This technique has demonstrated significant potential for economically recovering precious metals from diverse electronic wastes, and it has already proven successful in large-scale commercial mining. In addition to recovering valuable metals, bioleaching of lithium-ion batteries can also mitigate environmental pollution. Acidophilic bacteria, such as *Acidithiobacillus* and *Leptospirillum*, as well as fungal species such as *Aspergillus niger*, *Penicillium chrysogenum*, *Aspergillus tubingensis*, and *Penicillium simplicissimum*, have been used for metal extraction from waste lithium-ion batteries. Despite significant progress, a comprehensive understanding of the mechanisms and optimization strategies for microbial bioleaching of waste lithium-ion batteries remains lacking. Hence, this review provides an overview of the bioleaching process, the microbes involved, and the mechanisms underlying its advantages for lithium recovery from waste lithium-ion batteries. It also addresses the advantages and environmental concerns associated with bioleaching.

Keywords: lithium-ion battery; bioleaching; microorganisms; environmentally friendly.

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1. Introduction

By 2025, the global lithium (Li) market is anticipated to grow by 87% due to the increasing demand for lithium-ion batteries (LIBs) in electromobility technologies [1]. Ores, which make up half of brine sources, are the main sources of lithium supply. However, due to extended use, these primary resources are running out. This has led to the investigation of various methods for extracting lithium from both types of brine resources. Over the next 20 years, the lithium market is expected to demand up to six times as much as its mineral sources can provide. LIBs, or spent lithium-ion batteries, are becoming increasingly attractive due to their potential energy uses [2]. However, the use of important metals such as cobalt (Co) and lithium can be detrimental to the environment. The need to prevent contamination from these wastes has made it feasible to conduct research on recycling lithium-ion batteries (LIBs) using

various procedures. Historically, metal extraction from mines has had varying environmental consequences [3]. Current methods for recovering precious metals from WLIBs use high-temperature pyrometallurgical or hydrometallurgical processes, which are effective and feasible but not ideal due to their environmental impact [4]. Biotechnological approaches, such as microbiological metal dissolution (bioleaching), have gained popularity for extracting metals from ores, concentrates, and recycled materials. This environmentally friendly approach reduces energy needs and operational expenses. This technique reduces energy and operational expenses while being safe to use. Microorganisms are used in bioleaching, a sustainable and ecologically benign method of extracting metals [5].

Bioleaching is the process of extracting metals from solid matrices using microorganisms such as fungi and bacteria. Bioleaching offers several advantages over conventional methods like hydrometallurgy and pyrometallurgy [6]. It is an energy-efficient, low-cost, and environmentally safe process that lessens the need for strong chemicals and high temperatures. These microbes are responsible for the production of organic acids and other metabolites that facilitate the dissolution of metals [7]. Acidophilic microorganisms (APM) are employed in urban mines and natural ore as bioleaching agents. Critical microorganisms applied for bioleaching are *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Aspergillus niger* [8]. Such microbes produce metabolic products necessary for the dissolution of metals, including oxalic acid, citric acid, sulfuric acid, and gluconic acid [8,9]. This can be done on a large scale for the extraction of metals from ores or waste materials using microorganisms that develop biologically active leaching agents. Bioleaching is one of the ideal methods for mass applications, for example, in LIBs or LIB batteries. It produces less hazardous gas emissions and less acidic waste, thereby requiring minimal post-treatment, which helps save costs and energy expenditure in recycling [10]. It reduces the requirement of hazardous chemicals and thus increases the sustainability of bioleaching. Also, it is economical, especially when extracting metals from low-grade ores or electronic waste.

This paper reviews the critical advancements in lithium extraction from spent lithium-ion batteries. It uniquely integrates bacterial and fungal bioleaching approaches, critical influencing factors, and perspectives on future scalability. It also provides an overview of the bioleaching process, the microbes involved, and the mechanisms underlying its advantages for lithium recovery from waste lithium-ion batteries. This evaluation centers on the effects of particle size on lithium recovery under bioleaching conditions (powder density, aeration, leaching medium pH, and concentrations of substrates/energy sources) and in LIB waste.

2. Lithium and Its Sources

Lithium is primarily used in batteries for electronic devices. Lithium is mainly sourced from minerals like spodumene and clays [11]. Spent lithium-ion batteries (LIBs) contain ten times more lithium than spodumene and thirty times more than brine. Lithium resources are divided into solid and liquid categories. Solid resources include spodumene, clays, and electronic waste. Liquid sources consist of geothermal brine, seawater, and salt lake brine [12]. These diverse sources highlight the potential for lithium recovery from both natural and recycled materials. In the global context, Chile holds one-third of the world's lithium reserves. Australia and Argentina also hold significant lithium reserves. Besides these, countries like China, Canada, and the United States also have substantial lithium reserves. Lithium deposits in India are rare. India lacks significant lithium reserves. As a result, all of the country's lithium requirements are met through imports. Some of the lithium resources are also found in India.

Lepidolite is found in Bihar's Bijaia area and Jharkhand's mica belt. It also occurs in Assam's Dibrugarh, Dhubri, and Goalpara districts, the Koraput district of Odisha, and the Bastar district of Chhattisgarh. A single spodumene deposit has been identified in Amareshwar, within Karnataka's Gurugunta schist belt [13]. 5.9 million metric tons of lithium reserves are also found in Salal-Haimana, Reasi district of Jammu and Kashmir.

Secondary lithium sources are not mined. These include WLIBs, lithium slags, e-waste, and industrial wastewater. Lithium slag is a by-product of the processing of lithium ores. Additionally, some industrial effluents contain trace amounts of lithium. Other electronic components, such as smartphones, headphones, laptops, and other portable devices, contain lithium. Over the past few years, among all secondary resources, WLIBs have emerged as the most prominent source for lithium recovery [12]. These batteries retain a significant amount of lithium that can be efficiently recovered and reused. Together, both primary and secondary sources offer promising solutions to support a particular economy.

2.1. Lithium-ion batteries (LIBs) and their key components.

LIBs typically use lithium metal, lithium alloys, or materials that absorb lithium ions as their anode material. A typical LIB consists of an aluminum cathode coated with active materials such as lithium cobalt oxide (LiCoO_2). The anode is primarily made of graphite, although some manufacturers use tetra-lithium penta-titanium dodeca-oxide ($\text{Li}_4\text{Ti}_5\text{O}_{12}$). Lithium-ion batteries generate energy by moving lithium ions between the cathode (+) and anode (-) through an electrolyte. LIBs have a separator, binder, and anode in addition to electrolytes. The lithium-oxygen bond in the battery is less strong than the cobalt-oxygen bond, making lithium leach more easily [14].

3. Recovery Methods of LIBs

3.1. Traditional recovery methods.

Physical and chemical processes are combined in the traditional method of recovering valuable metals from secondary resources. Direct recycling methods such as pyrometallurgy, hydrometallurgy, or a combination of both are the most widely used metal recovery techniques in industry [15]. Pyrometallurgy creates alloys by heating organic substances such as polymers, graphite, and electrolytes under oxidative conditions to produce volatile organics. Alloys are formed from melted metals that can be reduced by carbon, while slag is produced from metals like Al, Li, and Mn. The hydro-metallurgical recovery procedure involves separating metals from aqueous solutions based on their chemical properties. This approach typically involves leaching using acids or alkalis. It is followed by purification and recovery steps such as regeneration, extraction, and precipitation [16]. Hydrometallurgical processes offer advantages over pyrometallurgical methods, including reduced energy consumption and lower emissions of toxic gases. However, there are also challenges, such as insufficient metal recovery, high energy and water consumption, and intricate operation steps [17]. In the industrial sector, companies in China, the United States of America, Japan, Germany, and Canada have developed the necessary infrastructure to support pyrometallurgical and hydrometallurgical methods for battery recycling. However, there is still little research on eco-friendly methods for recycling spent LIBs. To better align with sustainable goals, noble, eco-friendly approaches to recycling LIBs are needed. These methods must optimize recycling efficiency while accounting for both economic and environmental factors to reduce energy consumption and

carbon emissions. Researchers and the mineral processing industry are continually working to refine the recycling process to lower costs and increase metal recovery yield.

The pyrometallurgy method uses large amounts of energy to extract metals directly. Thus, there is a risk of metal loss, especially lithium, during the recycling process. It releases harmful gases, which contribute to air pollution [15]. Hydrometallurgy is an energy-efficient method for metal extraction. However, it produces a vast amount of acid waste. The complex process also releases hazardous greenhouse gases. Managing these effluents and gases increases the environmental risk and high operational costs [17]. In comparison, bioleaching uses naturally occurring microbes to extract metals from ores or waste materials. Even if the metal concentration is very low, it will be much more effective than other extraction methods. It is a more efficient and sustainable method over time due to its low operational cost, less toxicity, and minimal environmental impact [6].

3.2. Microbial leaching: the potential recovery methods.

Bioleaching offers the potential for higher metal recovery with lower energy use, but the slow cultivation process makes it time-consuming. A small number of bacteria, such as *Acidithiobacillus ferrooxidans*, have been found to react differently when feed and media are present [18]. Bacteria are vital for the bioleaching of LCO(Lithium cobalt oxide) from spent LIBs. These techniques are critical because they prevent LIBs from exploding during recycling, reduce the volume of by-product waste, and enrich the LIB constituents for additional treatment [19]. Today, a complex combination of hydro- and pyrometallurgical processes is used to process LIBs in industries. Key commercial proprietary extractive metallurgical technologies for metal recovery from WLIBs include those developed by Toxco Process (Canada), AEA Technology, Sony/Sumitomo Process (Japan), Batrec Industrie AG (Switzerland), Recupyl Process (France), Accurec GmbH (Germany), Umicore Process (Belgium and Sweden), and Onto Technology (USA) [20]. Bioleaching is a method that uses sulfur- and iron-oxidizing bacteria to oxidize metals, making them soluble. Researchers have focused on these bacteria's ability to oxidize elemental sulfur or ferrous iron, enabling them to produce acids that facilitate the dissolution and extraction of valuable metals from materials such as LiCoO_2 and lithium manganese oxide used in lithium-ion batteries [21]. Bioleaching's minimal environmental impact is its main benefit over conventional recycling techniques (Table 1). It produces fewer hazardous gas emissions and less acidic waste, reducing the need for extensive post-treatment.

Table 1. Different microbial bioleaching methods and their advantages and disadvantages.

Bioleaching methods	Description	Advantages
One-step	Microorganisms and solid waste are inoculated together in the microbial medium for culturing and metal leaching.	Simple process; Lower operational costs due to combined fermentation and bioleaching;
Two-step	Microorganisms are first grown without solid waste, and then solid waste is added to initiate leaching after the logarithmic phase.	Higher bioleaching efficiency as microorganisms generate acids before adding solid waste. Decreased toxicity from heavy metals;
Spent-medium	Microorganisms are cultured in a growth medium, followed by separation and filtration,	Less processing time; easier operation; High efficiency for metal recovery;

Bioleaching methods	Description	Advantages
	and then solid waste is added to the cell-free medium for leaching.	Allows independent optimization of chemical and biological processes;

4. Microorganisms in the Bioleaching of LIBs

Bioleaching microorganisms are divided into two types based on their nutrient requirements: heterotrophs and chemoautotrophs [22]. Heterotrophic microorganisms rely on organic compounds for energy, and chemoautotrophic microorganisms derive energy from inorganic compounds [9]. Both groups can produce different acids to extract valuable metals from metal-rich waste materials. Several species of fungi and bacteria are used in the leaching of spent Li-ion batteries. Among the microorganisms used in biological processes, *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans*, *Aspergillus niger*, and *Acidithiobacillus ferrooxidans* are included. These represent a more sustainable and economical route for metal recovery from spent Li-ion batteries [23]. The described microorganisms can extract or adsorb one or more metals from LIBs; therefore, they make very good metal recovery agents.

4.1. Bacteria in recovering lithium.

Examine the use of acidophilic bacteria *Sulfobacillus thermosulfidooxidans*, *Leptospirillum ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Acidithiobacillus ferrooxidans* in bioleaching procedures to enhance metal extraction [24]. Bioleaching is a microbiological process in which bacteria dissolve metals utilizing inorganic chemicals, primarily Fe_2O_3 , FeS_3 , and sulfur, as their major energy sources. This procedure is commonly used for the sustainable extraction of metals from waste and other resources. Some researchers have focused on bacteria that oxidize iron and sulfur during bioleaching, a process that uses metals as a source of energy. *Acidithiobacillus* and *Leptospirillum* species are the most well-known bioleaching bacteria, having been identified from acidic environments such as acid mine drainage and acid rock drainage [25] (Table 2). Acidophilic microorganisms, such as *Acidithiobacillus ferrooxidans*, exhibit remarkable metabolic versatility. They can survive in highly acidic environments [26]. This unique adaptation makes them essential for bioleaching applications in mining and metal recovery processes. Valuable metals, especially Co and Li, can be recovered from spent LIBs using bacterial bioleaching. According to research, *A. thiooxidans* 80191 and PTCC 1717 outperform Mn (20%) in two-step bioleaching experiments, recovering more Co (60%) and Li (99%) [9]. To recover metals from spent LIBs, several researchers have isolated acidophilic bacteria from acid mine wastewater. Biswal and Balasubramanian reported that, after 14 days of incubation, *A. ferrooxidans* cells isolated from coal mine pond water samples were used to bioleach spent LIBs, yielding a 57.81% recovery of Co in a pH 2.5 medium [9]. Other studies demonstrated substantial lithium dissolution from spent lithium-ion batteries under ideal experimental conditions (Table 2).

However, bioleaching consortia are less successful at large-scale metal recovery from solid wastes such as spent lithium-ion batteries (LIBs), which contain higher levels of organic compounds than low-grade ores [8]. This is due to the long leaching cycles of these organisms and their sensitivity to low-molecular-weight water-soluble organic compounds. To improve bioleaching efficiency for solid waste with higher organic content, more research is needed to develop microbial strains or consortia that can withstand higher solid-to-liquid ratios and have

shorter leaching cycles. Recent research indicates that some strains of bioleaching bacteria can survive in neutral or alkaline environments, such as sewage sludge, municipal activated sludge, and tannery sludge [27]. However, the majority of these bacteria's genomes are still unknown, and it is unclear how they adapt to environments with high organic content.

4.2. Fungus in recovering lithium.

Metals are extracted from electronic waste using fungi such as *Aspergillus niger*, *Penicillium chrysogenum*, *Aspergillus tubingensis*, and *Penicillium simplicissimum* [9,28]. *A. niger* is highly preferred due to its simpler growth and harvesting technique and greater yields [29]. Fungal bioleaching of metals from solid waste streams relies on heterotrophic fungi that produce organic acids, and understanding the effects of toxic metals on organic acid synthesis is necessary to optimize fungal bioleaching processes [30].

Compared to bacterial leaching, the fungal lithium leaching technique is more efficient in scalability. Their hyphal growth allows fungi to increase the surface area for leaching. Species like *Aspergillus niger* and *Penicillium chrysogenum* generate strong organic acids such as citric, oxalic, and gluconic acids [18]. Organic acid produced by fungi solubilizes lithium from minerals like spodumene and lepidolites, forming stable metal-organic complexes (Table 2). They also have greater tolerance to high concentrations of metals than bacteria do. Furthermore, their rapid growth and operation under a wide range of environmental factors contribute to high metal recovery efficiency. Due to these advantages, fungal lithium leaching offers an effective alternative to conventional techniques, paving the pathway for eco-friendly extraction [9].

Table 2. Diverse microorganisms are utilized as energy sources in the recovery of lithium.

Microorganism type	Energy source	Microbes species	pH range	Reference
Chemolithotrophs	Inorganic compounds	<i>Acidithiobacillus ferrooxidans</i> , <i>Leptospirillum ferrooxidans</i>	≤2.0	[31-33]
Chemoorganotrophs	Organic compounds	<i>Aspergillus sp.</i> , <i>Penicillium sp.</i> , <i>Pseudomonas sp.</i>	3.0–7.0; 7.0–11.0 (cyanogenic)	[34,35]
Microbial Consortium	Combined energy sources based on the species involved	<i>Acidithiobacillus ferrooxidans</i> + <i>A. thiooxidans</i>	Varies with the consortium	[36,37]

5. Bioleaching Mechanisms for Improved Lithium Recovery

Bioleaching can be classified as contact or non-contact, depending on how microorganisms interact with the ore. Contact leaching involves the formation of biofilms and the adsorption of bacteria to the surface of sulfide ore via electrostatic attraction [38]. Sessile cells and bacteria living in biofilms continuously oxidize sulfide ores, converting electrons into oxygen molecules. Non-contact leaching prevents the direct binding of bacterial cells to the surface of the sulfide ore. Planktonic cells, microorganisms floating in a liquid medium, provide APM planktonic cells with energy through ferrous ions [22,39]. Acidophilic bacteria like *Sulfobacillus thermosulfidooxidans*, *Leptospirillum ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Acidithiobacillus ferrooxidans* are used in bioleaching processes for metal extraction and bioremediation [40]. This method has the potential to recover important metals from spent lithium-ion batteries.

By chelating with metal ions, fungi like *Aspergillus niger* can produce soluble metal-organic complexes by converting organic carbon sources like glucose into organic acids [41]. This bioleaching technique uses metal mobilization and the formation of soluble metal complexes with an organic ligand to remove metals in their solubilized state [42]. Lithium-ion batteries (LIBs) can have both Co and Li extracted using fungus-based bioleaching based on complexolysis. While many studies on the bioleaching of different metals have been published, few have concentrated on using fungi to recover lithium from used LIBs (Figure 1).

The microbial consortia typically include combinations of different microorganisms, such as bacteria and fungi species, that work together to enhance metal solubilization [36]. They are more effective than a single species due to metabolic cooperation. In consortia, bacteria may create an acidic microenvironment that supports fungal activity. Combining autotrophic bacteria and heterotrophic fungi plays a synergetic role in metal recovery. Autotrophic bacteria, such as *Acidithiobacillus ferrooxidans*, oxidize iron or sulfur compounds, which help break them down and release lithium ions into solution [37]. On the other hand, heterotrophic fungi, like *Aspergillus niger*, release organic acids that dissolve lithium minerals by chelating metal ions [41]. These cross-feeding and redox cycling enhance the consortium's overall metabolic activity and stability.

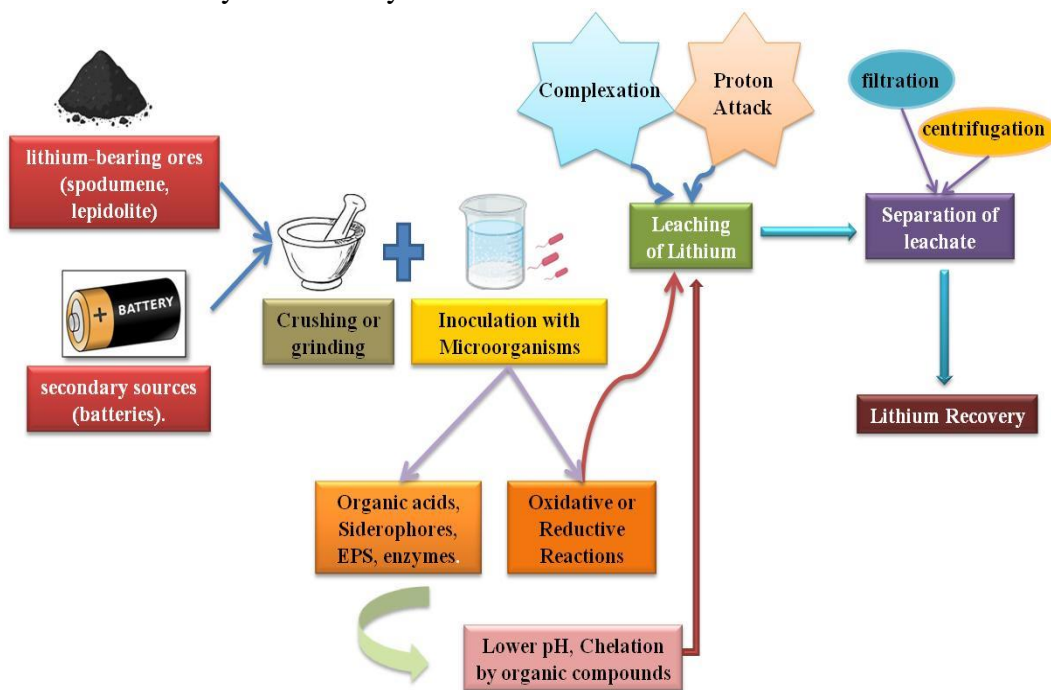


Figure 1. Process of leaching of lithium from ores and waste lithium-ion batteries.

6. Critical Factors Influencing Bioleaching of Spent LIBs

The catalyst, solid/liquid ratio, reagent concentration, oxidant concentration, temperature, and pH are all important factors in determining leaching efficiency.

6.1. Biotic and abiotic factors.

Various biotic and abiotic factors influence the bioleaching process. Biotic factors include microorganisms like microbes, culture contamination, and growth inhibition. Abiotic factors encompass the concentration of energy, carbon sources, nutrients, and pH of the leaching solution. Other significant abiotic factors include LIB particle size, density, aeration,

catalyst presence, and temperature [28]. Both these factors can collectively influence the leaching efficiency.

6.2. Substrate concentration and energy sources.

The type and concentration of carbon, energy, and nutrient sources in the leaching medium significantly impact microbial growth, metabolite production, and the overall bioleaching process. Autotrophic bacteria, such as *Acidithiobacillus ferrooxidans*, use substrates like pyrite (FeS_2) and $\text{FeSO}_4 \times 7\text{H}_2\text{O}$ as energy sources or electron donors. Nutrient-rich medium removed more metal (Co: 67% and Li: 80%) than nutrient-limited medium (Co: 1.5% and Li: 35%). Variations in substrate concentration can influence bioleaching kinetics, necessitating precise optimization. Insufficient substrate levels may limit microbial growth, while excessive levels could inhibit activity [1].

6.3. pH and toxicity of the leaching medium.

A key factor influencing microbial activity is the leaching medium's pH (acidity). For *Acidithiobacillus ferrooxidans*, the optimum pH range is 1.0–4.0, with most iron-oxidizing bacteria (IOB) preferring pH 2.0–2.5. The highest cobalt (Co) recovery of 47.6% was achieved at pH 1.5 during the bioleaching of spent Li-ion batteries with *A. ferrooxidans* [1]. Toxic metals and harmful compounds in spent LIBs can reduce microbial efficiency, particularly at higher pulp densities. Increased pulp density may elevate medium viscosity, reducing oxygen mass transfer and slowing metal extraction kinetics [20].

6.4. Temperature effects on bioleaching.

Temperature significantly affects microbial growth and leaching efficiency. Most IOB and fungi, such as *Aspergillus niger*, exhibit optimal growth at temperatures between 28°C and 30°C. Experimental bioleaching typically occurs within a broader range of 22°C to 35°C [1]. Temperature variations impact reaction kinetics through thermodynamic changes, as described by the Arrhenius law. Beyond optimal temperatures, microbial growth may decline, reducing bioleaching efficiency. *Acidithiobacillus* and *Leptospirillum* genera demonstrate better growth and bioleaching functionality at temperatures between 25°C and 35°C [1].

6.5. Oxygen availability.

Most acidophilic microorganisms, including bacteria like *A. ferrooxidans* and fungi like *A. niger*, require aerobic conditions for optimal activity. *A. ferrooxidans* from acid mine drainage enhanced Co extraction from spent LIBs by 74% with aeration, while Co leaching dropped by 52% without aeration. Microbial activity and metal leaching efficiency increase when an adequate oxygen supply is ensured through aeration, stirring, or shaking [43].

6.6. Metallic ions and mass transfer.

The presence of toxic metals often slows bioleaching, as it is considered a slow-kinetic process. Adding metallic ions like Ag^+ , Cu^{2+} , Bi^{3+} , Hg^{2+} , and Co^{2+} can accelerate electron transfer and enhance metal dissolution kinetics. Effective mass transfer, influenced by the contact surface of LIB particles, is another critical factor. Smaller particle sizes with higher

surface areas generally improve the mass transfer rate, boosting bioleaching performance. Thus, in the majority of studies, the size of LIB in bioleaching is between 75 and 300mm [9].

7. Environmental Concerns Associated with Lithium Extraction

Lithium extraction, particularly through brine mining, has significant environmental consequences. Lithium mining often leads to habitat disturbance and contamination of soil and water bodies. These include the destruction of biodiversity near mining zones. Lithium extraction is also highly resource-intensive. It requires vast amounts of water and energy for its processes [44]. It poses risks to water quality, which indirectly affects both humans and wildlife. Communities near mining sites often face water shortages. The contamination of water sources in these regions is a growing concern [45]. Air pollution near mining sites is another serious issue. Inhalation of fine dust particles emitted from mines poses serious health risks like respiratory diseases, chronic obstructive pulmonary disease, and lung cancers in humans. Energy-intensive extractions contribute significantly to greenhouse gas emissions. Biodiversity in these areas is under threat due to mining activities. The extraction process produces large amounts of tailings, including hazardous heavy metals. The environmental cost of lithium extraction extends beyond local ecosystems. It raises global concerns about sustainable practices for this critical resource. Addressing these challenges requires innovative solutions and stricter environmental regulations. Waste lithium batteries are often discarded improperly [46]. Landfills are thought to receive 98.3% of lithium-ion batteries. This improper disposal contributes to underground fires. These fires release toxic chemicals into the environment. The resulting air pollution poses threats to human health and biodiversity. Local ecosystems are often severely impacted by such pollution.

8. Advantages of Bioleaching in Lithium Recovery

Given the aforementioned environmental concerns, bioleaching is considered one of the most successful methods for extraction, thanks to its affordability and ecological benefits. Advancements in biotechnology have made bioleaching feasible, and numerous studies are currently being conducted to explore its diversity. Lithium battery recycling offers a significant opportunity to reduce the need for additional extraction, prolonging the life of these vital materials and providing numerous environmental benefits [47]. Reducing greenhouse gas emissions is one of the main environmental benefits of recycling lithium. We can reduce greenhouse gas emissions and the energy needed for extraction by recycling LIBs and other lithium-based components [48]. Lithium recycling also helps avoid contaminating soil and water. After extraction, lithium is essential for sustaining renewable energy sources such as solar, wind, and hydropower, but it also contributes to the overall carbon footprint [49]. These renewable energy sources greatly reduce carbon emissions and help develop a more sustainable energy future by enabling cities, businesses, and homes to be powered by naturally replenishable fuels.

While bioleaching offers a sustainable, eco-friendly approach to lithium recovery, scaling it up to industrial levels poses several challenges [50]. One of the primary issues is maintaining optimal conditions, such as temperature, nutrient supply, and other environmental factors. Scaling from bioreactors to large heaps is non-linear. Maintaining environmentally favorable conditions on large heaps is often energy-intensive. Nutrient diffusion in large heaps reduces microbial efficiency and the metal recovery process [51]. Additionally, the variability

in ore composition poses a significant challenge due to strict microbial growth conditions. Due to slow microbial kinetics and the lack of a standardized protocol, operational complexity and scalability are high.

9. Circular Economy Strategies for Lithium Recovery

Lithium recovery from spent lithium-ion batteries, low-grade ores, and slags presents a transformative opportunity for sustainable resource management [52]. Bioleaching of lithium is an alternative to traditional mining. This process recovers lithium seamlessly from used batteries and e-waste. Instead of discarding batteries, they are treated as resources to leach lithium and other critical metals. These strategies aim to minimize waste and extend the use. It consumes less energy and doesn't generate toxic pollutants [53]. This improves sustainability and economic efficiency. The recovered lithium can be reused to produce new batteries and other lithium-based products. Hence, lithium recovery by bioleaching offers potential solutions to support the circular economy [47]. This reduces dependency on high-grade minerals and also supports a closed-loop system. It also secures critical raw materials like lithium for future use and supports global sustainable goals.

10. Conclusion

Recovering valuable metals from spent Li-ion batteries through bioleaching is a viable and efficient method. The operational difficulties and knowledge gaps in this area must be addressed by ongoing research and development if bioleaching technologies are to be implemented widely. The potential of using microorganism-based bioleaching to promote the circular economy and sustainable management of WLIBs. Acidophilic bacteria, such as *Leptospirillum* and *Acidithiobacillus*, are commonly used in bioleaching for metal extraction. Fungal species, including *Penicillium chrysogenum*, *Aspergillus niger*, *Penicillium simplicissimum*, and *Aspergillus tubingensis*, are used to extract metals from WLIBs. *A. niger* is widely valued because of its ease of growth and recuperation, as well as its better yields. Temperature, pH, dissolved oxygen levels, and other biotic and abiotic factors also influence how the process unfolds. The recent advancements in bioleaching have centered on scaling up the process to make it more efficient. Advancing omics-driven bioleaching in the future can contribute to sustainable, eco-friendly metal recovery solutions. These advancements might help researchers better understand gene expression, regulatory networks, and metabolic flexibility in complex microbial environments. Understanding how microorganisms respond to metal ion stress will allow researchers to create strains that are more efficient and tolerant. Additionally, scientists are conducting research on genetically altered microbes designed to be resistant to heavy metal ions while also enhancing their bioleaching capacity.

Author Contributions

Conceptualization, D.P.K.S. and L.B.S.; methodology, D.P.K.S. and L.B.S.; investigation, D.P.K.S.; resources, D.P.K.S.; data curation, D.P.K.S.; writing—original draft preparation, D.P.K.S.; writing—review and editing, L.B.S.; supervision, L.B.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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