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MINING WITH MICROBES: A SYSTEMATIC REVIEW OF BIOLEACHING OF RARE EARTH ELEMENTS FROM PHOSPHATE ROCKS

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Abstract

Rare earth elements (REEs) play a key role in advanced materials and clean energy technologies. However, traditional methods for extracting REEs are often complex, costly, and harmful to the environment. This systematic review explores the potential of using phosphate-solubilising microorganisms as a more sustainable alternative for recovering REEs, particularly from phosphate-rich minerals such as apatite found in phosphate rock. Following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, the review investigates existing research on microbial bioleaching of REEs using a range of microorganisms, including bacteria and fungi. It also compares important factors affecting the bioleaching process, including pH, temperature, media composition, pulp density, and particle size. The findings indicate that inconsistent data and varying parameters recorded in the studies make it difficult to establish clear correlations regarding the efficiency of bioleaching of REEs. The review highlights the need for further research to clarify the specific mechanisms behind microbial bioleaching and to understand better the roles of individual microorganisms involved in the process.

Keywords: Bioleaching, Microorganisms, Phosphate Rocks, Primary Mineral Sources, Rare Earth Elements

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Introduction

Rare earth elements (REEs) are a group of 17 naturally occurring elements, which include the 15 lanthanides with atomic numbers from 57 to 71, along with yttrium (Y) and scandium (Sc) (Dar et al., 2025). Based on their atomic numbers and chemical characteristics, REEs are commonly classified into three groups (Brouziotis et al., 2022; Balaram, 2023): Light rare earth elements (LREE): La, Ce, Pr, Nd, and Pm; Middle rare earth elements (MREE): Sm, Eu, Gd, Tb, Dy, and Ho; and Heavy rare earth elements (HREE): Er, Tm, Yb, and Lu.

REE recovery typically requires several sequential extraction steps and further processing and refining. Pyrometallurgy and hydrometallurgy are the common methods for the extraction of REEs. These processes require high temperatures, resulting in significant energy consumption, and require different chemicals in large quantities, necessitating proper disposal methods following extraction. The complex nature of these processes leads to high operational costs and protracted processing phases (Walawalkar, Nichol et al., 2016). Considering these issues, the development of alternative REE recovery technologies has become critical to protect the environment while fulfilling the growing demand for these valuable elements. Among the promising alternatives, biological processes have emerged as a sustainable, cost-effective, and environmentally friendly method of extracting REEs from various sources (Brisson, Zhuang et al., 2016; Fathollahzadeh, Hackett, et al., 2018). Phosphorus (P) plays an essential role in biological systems, supporting cell function, metabolism, and energy transfer (Vyas & Gulati, 2009). Phosphate-solubilising microorganisms (PSMs) help to convert insoluble forms of phosphorus into soluble forms through acid production, chelation, and ion exchange (Son, Park et al., 2006). In recent years, there have been many reports of leaching REEs from phosphate rock by pyrometallurgy and hydrometallurgy (Wu et al., 2018). Still, only a few studies have reported on bioleaching pathways. Previous studies have shown that PSMs can bioleach REEs from phosphate minerals (Brisson et al., 2016; Corbett et al., 2017; Corbett et al., 2018). These microorganisms dissolve phosphate ions from insoluble compounds, and some fungi preferentially release REEs over Thorium (Brisson et al., 2016).

The purpose of this comprehensive systematic review is to evaluate the present status of bioleaching of rare earth elements from the primary source of phosphate rocks. It aims to assess the impact of various process parameters on the efficacy of the bioleaching processes that demonstrate the potential of biological approaches as sustainable and efficient REE extraction methods.

Materials and Methods

This systematic review was conducted according to 'The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for Systematic Reviews checklist' (Tricco, Lillie et al., 2018). The PRISMA analysis is a systematic approach that comprises four consecutive steps: identification, screening, eligibility, and inclusion.

Identification: As the first step, relevant articles were searched using keywords like "Bioleaching," "Rare Earth Elements," "Microorganisms," "Primary mineral resources, and "Phosphate rocks", using the Boolean operators; single keyword search and also combining the keywords and making meaningful sentences across the databases including ELESVIER, Taylor and Francis, MDPI, PubMed, Google Scholar, Scopus and Web of science. The search was conducted from March 2023 to July 2025 without any date restrictions to collect studies related to the research topic.

Screening: Research conducted on the recovery of rare earth elements in phosphate minerals using bioleaching approaches was included in this review. Two independent reviewers performed the title/abstract screening and full-text screening. The conflicts were resolved by consensus. The eligible articles were retrieved for full-text review. Full texts were assessed in detail against the inclusion criteria, and the articles not meeting the inclusion criteria were excluded, with reasons for exclusion noted.

Eligibility: Two reviewers independently extracted data using structured tables and assessed full texts against defined criteria according to Perera et al., 2018. Only articles meeting these standards were included. Discrepancies were resolved by consensus, and ineligible studies were excluded after careful evaluation.

The following inclusion criteria were employed for the review: studies focused on bioleaching of REEs; research on bio recovery of REEs; investigations related to biomining of REE; research concerning leaching from primary mineral sources, particularly phosphate minerals: phosphate rocks and apatite. Following exclusion criteria were employed: duplicate articles; papers with only abstracts available; review articles; books and chapters; articles containing methods not relevant to bioleaching processes, such as chemical leaching; studies related to recovering REEs from secondary sources and other primary mineral sources and other sources using bioleaching methods, such as waste, red mud, coal ash, monazite, etc.

Inclusion: Final analysis only included the studies meeting the key criteria. Relevant data on REE bioleaching from phosphate rocks were reviewed, organised into tables, and visually presented to ensure a clear, unbiased qualitative and quantitative in-depth review (Fig. 1).

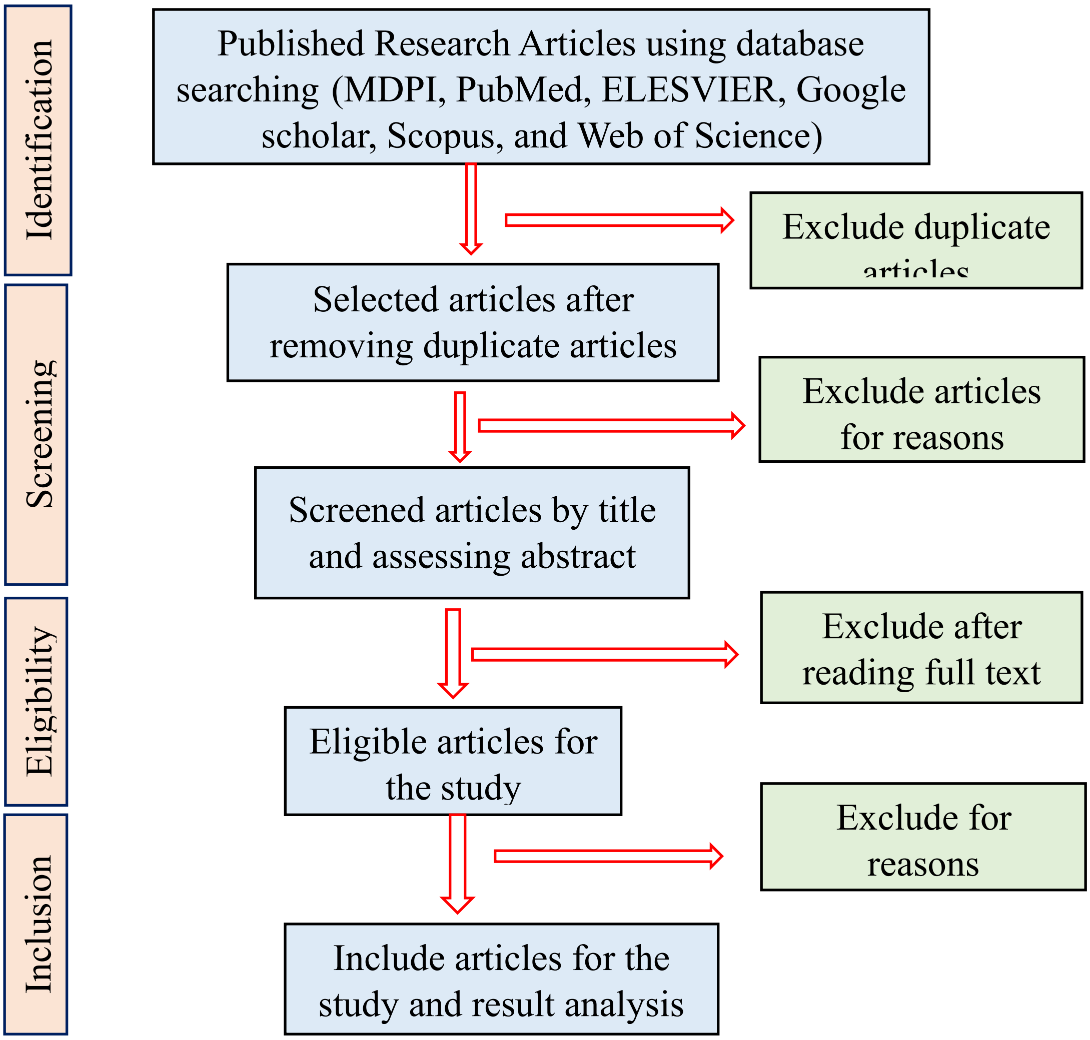

Figure 01: PRISMA Flow diagram indicating the recruitment process of scientific

Results

Through targeted keyword searches in databases, an initial 443 articles were identified. After the elimination of 61 duplicates, a total of 382 articles were screened. Screening against specific criteria excluded 50 articles. Of the remaining 332 articles, 292 were eliminated after reading the full study and removed the articles which were not included: the bioleaching process, REE leaching but include other metals and other sources, microorganisms bind leaching, phosphate minerals, phosphate rocks, apatite and bioleaching of REE but the environmental impact of REE productions as well as, papers that included: chemical leaching process, uranium leaching not the REE bioleaching and bioleaching of REE in other phosphate minerals except phosphate rocks. Further, 17 articles from books and book chapters, along with 18 review articles, were excluded. The remaining five articles directly contributed to the focus of the study on bioleaching of rare earth elements in phosphate rocks, apatite (Fig. 2).

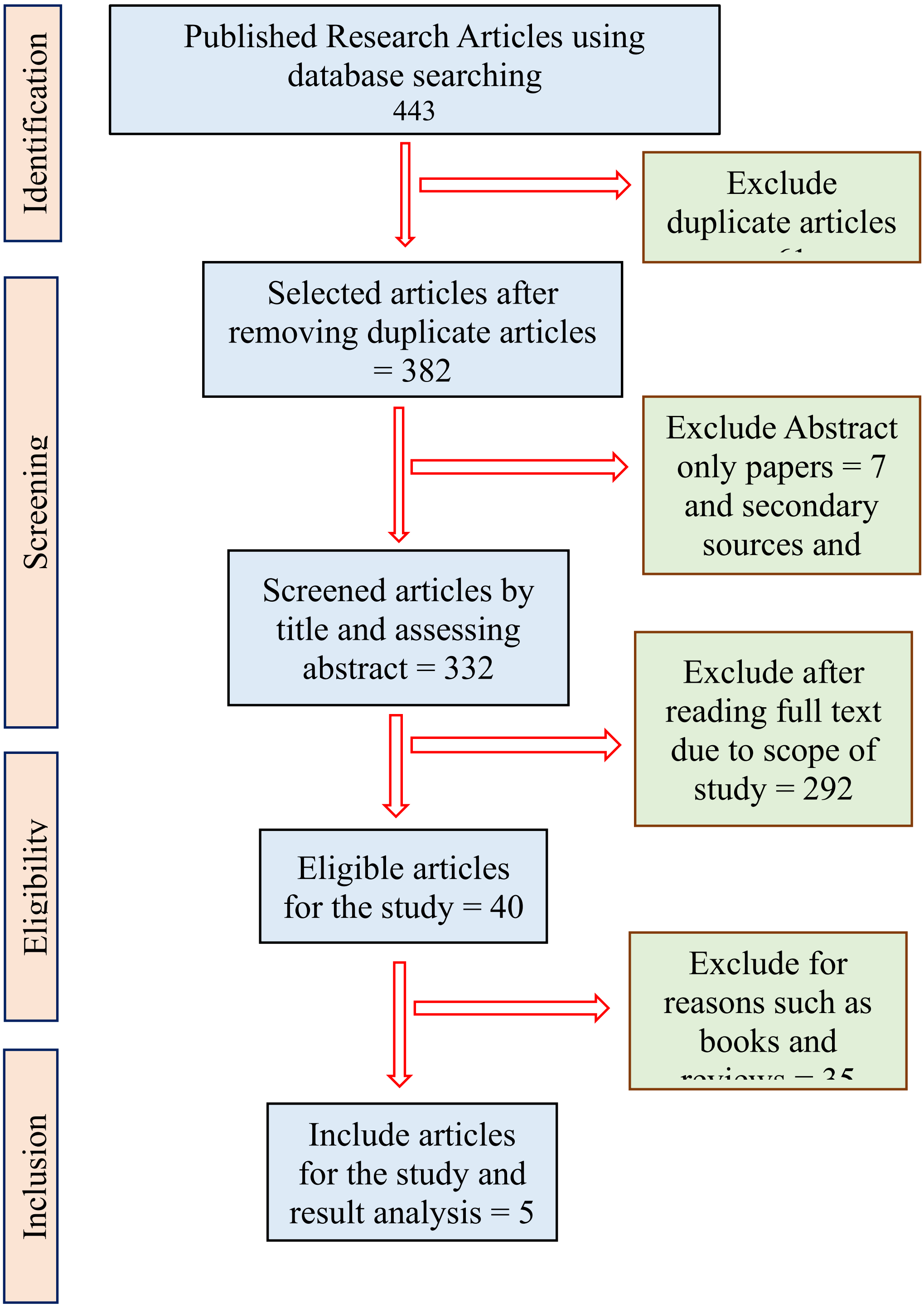

Figure 02: Flow diagram explaining the search strategy, inclusion, and exclusion criteria used for the systematic review of scientific literature for systematic review.

Discussion

Phosphate rocks and apatite

Phosphate deposits are mainly classified as igneous or sedimentary. Igneous types are often associated with carbonatites, while sedimentary deposits, which are known as phosphorites, form through the chemical precipitation of elements like phosphorus, iron, and silicon. Phosphorite is the most common and widely studied phosphate rock, though it also occurs in forms such as phosphatized limestone, sandstone, and shale. Phosphorites are significant sources of REEs, with concentrations reaching up to 2000 µg/g. These deposits are widely distributed globally, with primary igneous sources in Brazil, Finland, Canada, South Africa, and Russia. Igneous phosphate deposits are most commonly found in Phanerozoic carbonatites, although some silica-deficient alkalic intrusions can also contain high concentrations of apatite. (Dar et al., 2025).

Apatite, which is a crucial REE resource, is widely used in the manufacturing of phosphoric acid. It usually comprises about 0.1-1 wt% REO (Ogata, Narita et al., 2016). A notable geological occurrence is the formation of carbonatites, which are igneous rocks rich in carbonate that result from the intrusion of carbonate magma into the Earth's crust. In comparison to ordinary igneous rocks, carbonatites often contain a higher concentration of REEs, ranging from 250 to 8000 ppm (Batapola, Dushyantha et al., 2020). In contrast to their HREEs counterparts, Carbonatites are notable for being richer in LREEs (Smith, Moore et al., 2016). This review emphasises phosphate mineral resources with REE-rich apatite and phosphate rocks.

Bioleaching microorganisms

In bioleaching of rare earth elements, phosphate-solubilising microorganisms (PSMs) play a vital role. Since inorganic phosphates are often insoluble, PSMs produce enzymes and organic acids that dissolve insoluble forms, making phosphorus more available. (Alori et al., 2017). Several studies have investigated the bioleaching potential of different bacterial and fungal species from phosphate rocks (Kamal et al., 2012; P et al., 2018; Tian et al., 2022; Feng et al., 2011; Osman et al., 2019). Bacteria such as *Acidithiobacillus ferrooxidans*, *Pseudomonas fluorescens*, *Bacillus megaterium*, and *Pantoea agglomerans* have been studied. Fungal species like *Aspergillus niger* and *Penicillium* spp. have also shown bioleaching ability. These findings emphasise the wide range of microorganisms capable of extracting REEs from phosphate rocks.

Table 01. Bioleaching microorganisms in all the phosphate rock studies

Microorganisms type	Species	Reference
Fungus	*Aspergillus niger*	(Kamal et al., 2012), (P et al., 2018), (Osman et al., 2019)
	Penicillium sp.	(Kamal et al., 2012)
Bacteria	*Acidithiobacillus ferrooxidans*	(Tian et al. 2022), P et al., 2018),
	Pseudomonas fluorescence	(Kamal et al., 2012)
	Pantoea agglomerans	(Feng et al., 2011)
	Bacillus megaterium	(Feng et al., 2011)

Bioleaching microorganisms: Fungi

Studies have shown that some fungi, like *Aspergillus niger*, can effectively leach REEs from phosphate minerals. This mainly occurs through the release of organic acids such as citric, oxalic, and gluconic acids, which dissolve the minerals. Phosphatase activity and microbial attachment also support the leaching process.

P et al., (2018 explored a bioleaching mechanism involving *Aspergillus niger*, based on different organic compounds released during its growth. These include low-molecular-weight organic acids (LMWOAs), such as simple aliphatic acids with one to three carboxyl groups, and aromatic acids like substituted benzoic and cinnamic acids. LMWOAs are important for mineral dissolution due to their ability to form stable metal complexes. The study highlights three key roles: contribution of H^+ ions in procedures involving proton-induced dissolution, formation of inner-sphere complexes that separate structural metals, and creation of soluble metal-organic complexes. Citric acid, with three carboxyl and one hydroxyl group, plays a central role by donating protons, enhancing mineral solubilization in this process (Fig.3).

$$C_6H_8O_7 \rightarrow (C_6H_3O_7)^{3-} + 3H^+$$

$$(C_6H_3O_7)^{3-} + Ca_7(RE)_3(PO)_4 6F_2 \rightarrow 3[(RE)(C_6H_5O_7)] + Ca_7(PO_4)_6F_2$$

Oxalic acid has two carboxylic groups. As a result of the interaction of rare earths with the oxalate anion, a variety of possible complexes can form. The following are some complexation possibilities the researchers have proposed (Somasundaran et al., 2018):

$$C_2H_2O_4 \rightarrow (C_2HO_4)^- + H^+$$

$$9(C_2H_2O_4)^- + Ca_7(RE)_3(PO)_4 6F_2 \rightarrow 3[(RE)(C_2HO_4)_3] + Ca_7(PO_4)_6F_2$$

Osman et al. (2019 investigated *Aspergillus niger* siderophores in bioleaching REEs from phosphorites. Under low iron conditions, fungi produced trihydroxamate siderophores that successfully extracted uranium, samarium, thorium, lanthanum, and caesium, performing their role in rare earth element bioleaching through strong chelation.

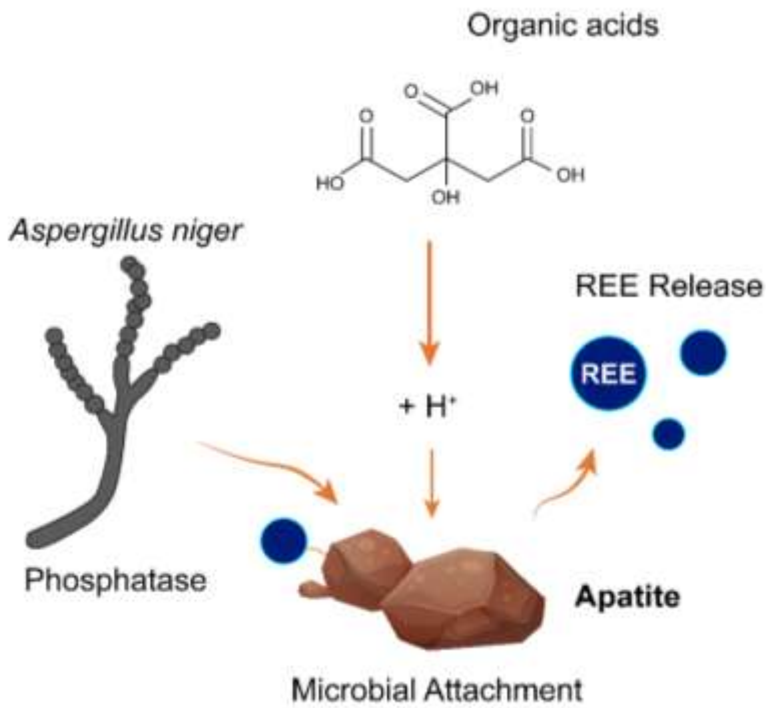

Figure 03: Conceptual model of REE release from apatite by fungi

Fig.3 explains that *Aspergillus niger* releases low molecular weight organic acids such as citric, oxalic, and gluconic acids, which lower the pH and chelate metal ions, facilitating apatite dissolution. Phosphatase enzymes further release phosphate groups, while microbial attachment to apatite enhances the acidification. Together, these processes disrupt the apatite lattice, leading to the release of REEs into the solution.

Bioleaching microorganisms: Bacteria

Researchers have studied utilising bacteria for REE bioleaching from phosphate rocks (Tian et al., 2022; P et al., 2018; Feng et al., 2011). *Acidithiobacillus ferrooxidans* is a widely used chemolithotrophic bacterium for REE bioleaching from phosphate rocks (Tian et al., 2022). This acidophilic bacterium oxidises iron and sulfur, producing ferric iron and sulfuric acid, which promote mineral breakdown. It survives in metal-rich environments and releases redox enzymes to disrupt mineral lattices (Pathak et al., 2017; Vera et al., 2013). Additionally, it secretes extracellular polymeric substances (EPS) that enhance mineral attachment and concentrate Fe^{3+} and H^{+} ions at the surface (Costa et al., 2018).

In Feng et al., they used *Pantoea agglomerans* and *Bacillus megaterium* for Bacterial dissolution of fluorapatite. This study found that negatively charged areas on bacterial cell walls promote REE adsorption. However, over time, organic matter from cell lysis can bind metals in solution, lowering overall adsorption, except for light rare earth elements (Feng et al., 2011) (Fig.4).

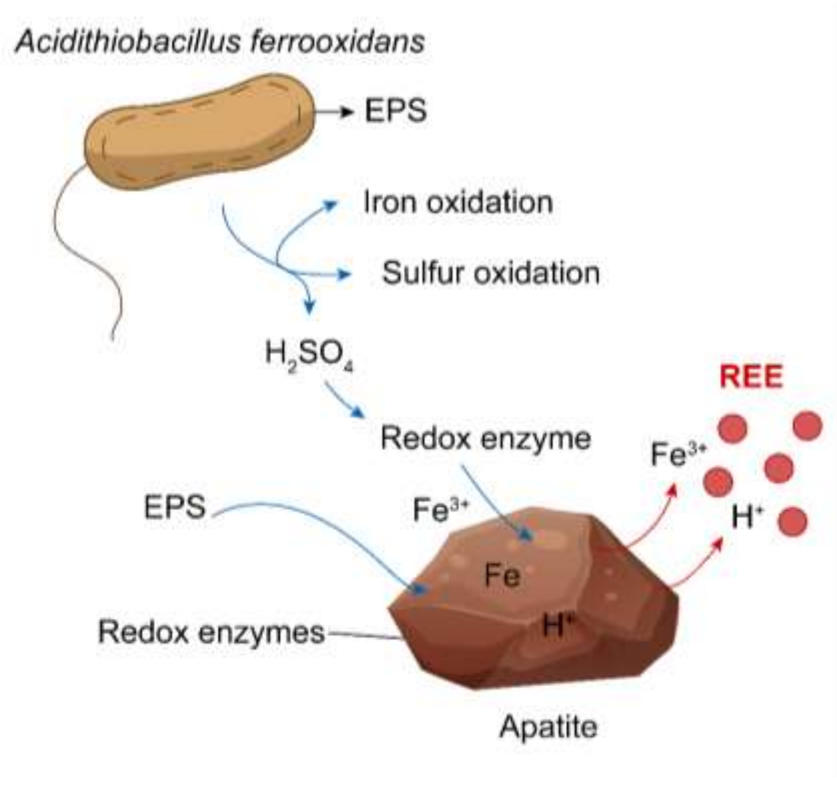

Figure 04: Conceptual model of REE release from apatite by bacteria

Fig.4 explains that the bacterium secretes EPS, which enhances the attachment to the apatite surface, where Fe^{3+} and H^{+} ions promote mineral dissolution. Iron and sulfur oxidation by bacteria creates an acidic environment and releases redox enzymes that disrupt the mineral lattice, eventually leading to the release of REEs.

Parameters affecting the bioleaching process

An effective REE bioleaching process requires evaluation of various physical, chemical, and biological factors such as REE composition, treatment methods, microbial strains, and their byproducts, leaching medium, pH, temperature, particle size, agitation, and leaching duration. The following sections summarise findings from 05 related studies about those parameters.

Medium composition

Different microbes need specific growth conditions. Thus, comparison of results from different bioleaching studies is difficult. Choosing the most effective strains and the media is critical to developing an efficient REE recovery. While carbon sources significantly affect leaching, nitrogen has less impact (Thompson et al., 2018). Some medium components can even block the production of compounds like siderophores, which only form under limited iron conditions (Bau et al., 2013).

In Feng et al., (2011, the bioleaching experiment with Pantoea agglomerans and Bacillus megaterium was conducted in a minimal medium containing 0.012 g/L KBr, 0.2 g/L glucose, and 0.38 g/L NH_4Cl with and without fluorapatite. The study of Osman et al. (2019 used the Chromeazurol S (CAS) assays for siderophore production. Studies have used 9K medium to grow *Acidithiobacillus ferrooxidans* (P et al., 2018; Tian et al., 2022), which extracts metals via two main pathways: oxidation of Fe^{2+} to Fe^{3+} in solution, and direct contact with minerals through redox enzymes that break the mineral structure, thus releasing metal ions (Vera et al., 2013). The culture media used in the study by Hesham et al. and Somasundaran et al. were Czapek-Dox Broth, with sucrose serving as the carbon source in the study of Hesham et al. (Kamal et al., 2012; P et al., 2018). The researchers studied the leaching efficiency of REEs while altering the sucrose concentrations. Their findings revealed the impact of diverse nitrogen sources on *Aspergillus niger* leaching efficiency. Ammonium chloride was recognised as a more favourable nitrogen source for the bioleaching of phosphate rocks than sodium nitrate (Fig.5).

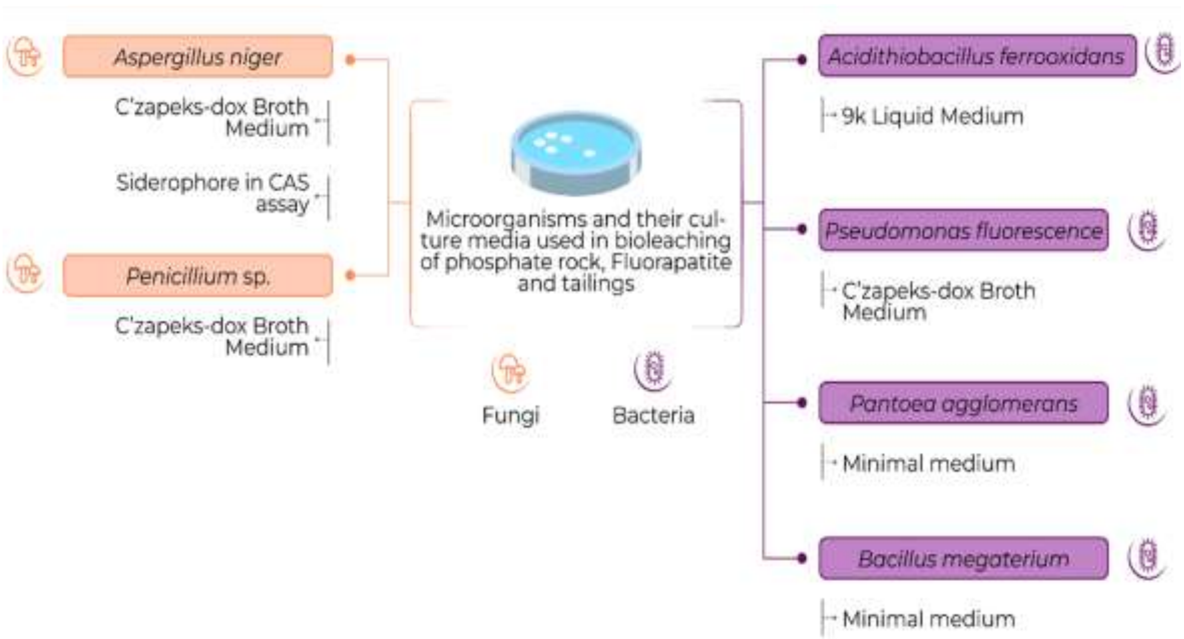

Figure 05: Different microorganisms and their culture media used in past studies for source Phosphate rocks, Fluorapatite and tailings

Table 02: Summary of the culture media used for bioleaching

Source	Microorganism used for leaching	Culture medium	Reference
Florida phosphate tailing	Acidithiobacillus ferrooxidans	9K medium	(P et al., 2018)
	Aspergillus niger	Modified Czapek's- Dox liquid media	
Phosphate rock	Acidithiobacillus ferrooxidans	9k liquid medium	(Tian et al., 2022)
	Aspergillus niger	C'zapeks-dox Broth medium	(Kamal et al., 2012)
	Penicillium sp.		
	Pseudomonas fluorescence		
Fluorapatite	Pantoea agglomerans	Minimal medium containing 0.012 g/L KBr, 0.2 g/L glucose, and 0.38 g/L NH4Cl and fluorapatite	(Feng et al., 2011)
	Bacillus megaterium		
Phosphorites	Aspergillus niger	Siderophore in CAS assay	(Osman et al., 2019)

Effect of pH

The pH plays a key role in bioleaching by affecting both microbial activity and metal recovery. Optimising pH enhances the production of microbial leaching agents. Since different microbes survive at various pH levels, selecting a suitable microorganism depends on its pH preference and the nature of the REE-containing material.

The initial pH of the bioleaching experiment measured in the leachate for Acidithiobacillus ferrooxidans was observed as 1.7 pH, and for the *Aspergillus niger* as 7.5 pH, per the observations by Somasundaran et al. (P et al., 2018). In *Acidithiobacillus ferrooxidans* leaching experiments, the pH initially increased due to the consumption of H^+ by bacteria. Subsequently, the pH decreased owing to the abiotic hydrolysis of ferric sulfate. The substantial increase in the redox potential of Fe^{3+}/Fe^{2+} is attributed to the oxidation of ferrous ions by *Acidithiobacillus ferrooxidans*. With *Aspergillus niger,* the leaching reactions are believed to be influenced directly by the breakdown of organic acids in the leaching solution by *Aspergillus niger*.

According to Tian et al. 2022 the initial pH of both the bioleaching and abiotic control setups' leachates was adjusted to 2 pH. In both cases, the pH increased rapidly within the first two days, which may be due to mineral acid consumption and microbial oxidation of Fe^{2+}. Then, the pH values began to decrease in the leachate gradually and fell to 1 pH on the 14th day in the bioleaching experiment, which may be due to continuous H^+ production from microbial synthesis of organic acids. The amount of acid produced exceeded what was consumed. In contrast, the abiotic control showed only a slight pH drop in later stages, probably due to Fe^{3+} hydrolysis and precipitate formation (Li et al., 2021).

Feng et al., (2011 recorded that the high rare earth content in Durango apatite may lead to REE phosphate precipitation, which contributes to a pH drop in the leachate of both biotic and abiotic systems. Given that the flasks were partially opened to the atmosphere using a vented cap, atmospheric

CO_2 likely dissolved in the medium, forming carbonic acid that reacts with REEs, further lowering the pH through complexation.

Effect of temperature

The influence of temperature on the bioleaching process is a critical factor to consider, impacting various aspects of the process, such as metal solubility, the kinetics of chemical reactions, and the growth and metabolic activities of microorganisms. Among the five studies, none has explained the temperature-dependent impacts on efficiency in detail. Therefore, it is recommended to study how temperature affects the bioleaching process of REE.

Pulp density and particle size

Usually, bioleaching studies have limited analysis of particle sizes and pulp densities. The section below provides limited optimisation data.

P et al., studied REE bioleaching from Florida phosphate rocks using *Acidithiobacillus ferrooxidans* and *Aspergillus niger* at different particle sizes, ranging from 32 µm to 105 µm, and pulp densities of 0.1 g/50 mL to 1.5 g/50 mL. Maximum REE recovery was achieved at a particle size of 75 µm and a pulp density of 1.0 g/50 mL. Leaching efficiency improved when the particle size decreased to 75 µm, but decreased with finer sizes, possibly due to reduced oxygen availability affecting microbial activity. Higher pulp densities enhanced the initial leaching, likely due to increased surface area. However, particles that are too large or too fine may slow down microbial attachment or damage cells, thereby affecting overall bioleaching performance (P et al., 2018).

Kamal et al., (2012 investigated the impact of particle size and pulp density on REE bioleaching using *Aspergillus niger*, *Penicillium* sp., and *Pseudomonas fluorescens*. For *Aspergillus niger*, smaller particle sizes enhanced leaching efficiency due to greater surface area exposure. Maximum recovery of 34.2% was achieved at a 0.5% solid-to-liquid ratio. *Penicillium* sp. showed minimal variation with particle size but a slight increase in efficiency with reduced pulp density, reaching 42.5%. *P. fluorescens* exhibited irregular trends, and the authors did not provide a clear explanation for the observed variations in leaching activity.

Why do parameters vary so much within the study?

The wide variation in reported outcomes from REE bioleaching studies can be attributed to the lack of standardised experimental protocols and the mineralogical diversity of phosphate rocks. Different studies use different growth media, ranging from minimal salts (Feng et al., 2011) to 9K medium (P et al., 2018; Tian et al., 2022) and Czapek-Dox broth (Kamal et al., 2012), which affect microbial metabolism in unique ways. Additionally, strain-specific traits, such as differences in pH tolerance and acid production, contribute to the varying findings (Thompson et al., 2018). Mineralogical differences also play a critical role; for example, the high REE content of Durango apatite affects both dissolution behaviour and secondary precipitation processes (Feng et al., 2011). Apart from the biological factors, abiotic influences, including atmospheric CO_2 dissolution and Fe^{3+} hydrolysis, can further modify leachate pH and redox potential, complicating the overall system (Li et al., 2021).

Critical parameters for standardisation

Key parameters need standardisation to improve reproducibility. Initial pH is essential, as small changes affect microbial activity and precipitation (P et al., 2018; Tian et al., 2022). Medium composition also matters: carbon source strongly drives leaching, while nitrogen has weaker but notable effects (Thompson et al., 2018; Kamal et al., 2012). Particle size and pulp density control surface area, attachment, and diffusion (P et al., 2018; Kamal et al., 2012). Even though Temperature is less studied, it strongly influences microbial growth and enzyme activity (Osman et al., 2019).

Summary of the results of the review

Although a clear correlation between the parameters, microorganisms, and bioleaching patterns cannot be established, the following points summarise the key findings of the five papers included in this systematic review. It should also be noted that these studies are not interrelated.

- Best parameters: Low pH (1–2 for bacteria; gradual acidification for fungi), particle size ~75 µm, moderate pulp density.
- Best microorganisms: *Aspergillus niger* (fungus) and *Acidithiobacillus ferrooxidans* (bacterium).
- Highest REE recovery reported: 70% with *A. ferrooxidans* under optimal acidic conditions.

Table 03: Summary of bioleaching studies from primary REE resources: phosphate rocks

Microorganism used for leaching	Source	Extracted REE	Leaching agents	Pulp density (% w/v)	Temp (°C)	Time (d)	Total REE leaching efficiency (%)	Total REE leaching efficiency	Reference
Aspergillus niger	Florida phosphate tailing	not mentioned	citric, oxalic	1	30	24Hr	42.5%	not mentioned	(P et al., 2018)
	Phosphate rock	not mentioned	not mentioned	not mentioned	not mentioned	10 - 15	11.4% 30.2%	not mentioned	(Kamal et al., 2012)
	Phosphorites	Sm, La, Ce	Siderophores	1	30	2	Sm 66.7%, La 51%, Ce 50.1%	not mentioned	(Osman et al., 2019)
Penicillium sp	Phosphate rock	not mentioned	not mentioned	not mentioned	not mentioned	10	15.9% 17.8%	not mentioned	(Kamal et al., 2012)
Acidithiobacillus ferrooxidans	Florida phosphate tailing	not mentioned	sulfuric acid	1	30	2-3	70%	not mentioned	(P et al., 2018)
	Phosphate rock	Ce, La, Nd, Y,	not mentioned	1	30	14	28.46%	0.2025 mg/g	(Tian et al., 2022)
Pseudomonas fluorescence	Phosphate rock	not mentioned	not mentioned	not mentioned	not mentioned	10	37.6 %	not mentioned	(Kamal et al., 2012)
Pantoea agglomerans	Fluorapatite	La,Ce,Pr,Nd,Sm,Eu,Gd, Tb,Dy,Ho,Er,Tm,Yb,Lu	not mentioned	0.006	25	26	not mentioned	not mentioned	(Feng et al., 2011)
Bacillus megaterium	Fluorapatite	La,Ce,Pr,Nd,Sm,Eu,Gd, Tb,Dy,Ho,Er,Tm,Yb,Lu	not mentioned	0.006	25	26	not mentioned	not mentioned	(Feng et al., 2011)

Table 04: Comparative summary data table for bioleaching: fungi vs. bacteria

	Fungus	Bacteria
Species	*Aspergillus niger* *Penicillium sp.*	*Acidithiobacillus ferrooxidans* *Pseudomonas fluorescence* *Bacillus megaterium*
pH variation	7.5 and decreased	1-1.7
General mechanisms	Organic acid secretion, siderophore production	H^+ consumption, Fe/S oxidation, acid regeneration
Experimental duration	1-15 days	2-26 days
REE recovery (%)	11.4-66.7	28.5-70

Conclusion

This systematic review investigated laboratory-scale studies on the bioleaching of REEs from phosphate rocks using bacteria, fungi, or both. Media composition, mainly carbon sources, varied depending on the microbes used. These variations, along with altered microbial behaviour, made it challenging to combine pH and optimal conditions. pH changes occurred mainly due to organic acid production and microbial respiration. Temperature is an essential factor for microbial activity and leaching efficiency, but none of the reviewed studies thoroughly evaluated temperature's influence on bioleaching outcomes. Further research is needed better to understand the role of temperature in REE bioleaching. However, due to irregular parameters and a lack of sufficient data, clear correlations in REE bioleaching from phosphate minerals could not be established. Further studies are necessary to clarify the mechanisms involved and to understand better the distinct roles of each microorganism in the leaching process.

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Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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