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REVIEW

Towards a Sustainable and Enhanced Iron Ore Recovery: Bio-beneficiation Review

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Abstract

Iron ore is essential in steel making; however, high-grade ores have diminished, making low-grade ores inevitable. These low-grade iron ores need further beneficiation to upgrade the iron content. Currently, traditional physical and chemical methods are utilized and are not environmentally friendly. Bio-beneficiation techniques have emerged as a sustainable alternative for mineral recovery. This review delves into recent bio-beneficiation advancements for enhanced low-grade iron ore recovery using microbes. Research has revealed that bio-beneficiation methods such as bio-leaching, bio-flotation, and bio-flocculation have proven successful in iron recovery from ores. The bio-beneficiation process occurs in mild conditions using bio-reagents derived from microbes and offers a reduction of chemicals used in processing. Bio-beneficiation of iron ore potentially offers a relatively energy-efficient, cost-effective, and environmentally friendly method of maximum iron ore recovery. However, this review has identified a scaling-up difficulty in which a future approach for industrial-use applications is offered following a thorough sustainability assessment. Bio-beneficiation, using microbial processes, provides a viable avenue for maximizing iron ore recovery while tackling the constraints of dwindling high-grade iron ore resources and environmental sustainability.

Keywords Iron ore · Sustainability · Bio-beneficiation · Bio-leaching · Bio-flocculation

1 Introduction

The demand for iron ore has increased substantially as modern societies continue to fulfill their development goals. Due to the extensive exploitation of high-grade reserves, viable iron ore deposits are diminishing rapidly. Traditional beneficiation of low-grade iron ores is also challenging because of the complexity of their mineralogy. Developing sustainable, efficient, and enhanced iron recovery processes for low-grade ores is urgently needed [1–4].

Iron ore is predominantly found in the form of magnetite (Fe_3O_4), goethite (FeO(OH)), hematite $\left(Fe_2O_3\right)$, siderite ($FeCO_3$) and limonite ($2Fe_2O_3{\cdot}3H_2O$) [5]. Iron ore, an essential raw material in the global market, plays a critical role in sustaining several industries, particularly the steel industry [6, 7]. Worldwide, deposits of iron ore are estimated to be approximately 900 billion tons of crude ore [8]. Globally, the largest iron ore producers are Brazil, China, India, and Australia, producing approximately 70% of the world's iron ore, whereas in Africa, South Africa leads in iron ore production at 4%, followed by Mauritania, Algeria, and Liberia with inferred deposits of crude ore of approximately 250 million tons [3, 4].

Iron ore extraction involves processes ranging from exploration to processing while utilizing traditional methods like gravity separation to innovative techniques like bio-leaching to enhance mineral recovery and minimize environmental impact [9]. Once extracted, raw iron ore undergoes beneficiation processes such as grinding and crushing, screening, washing, magnetic separation, and further concentration using froth flotation or leaching [10]. However, the choice of processing method depends on the ores' physical and chemical properties. Emerging and innovative technologies such as bio-leaching, bio-flotation,

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and bio-reduction are being adopted for efficient recovery, reduced energy consumption, and the need for more environmentally friendly techniques [9–14]. Traditional iron ore beneficiation techniques are generally physical, requiring high energy, grinding, and filtration capacity [15]. Rising costs and increasing regulations threaten the long-term viability of these traditional processes.

Additionally, these processing techniques produce voluminous waste, leading to environmental hazards. As iron ore mining focuses on low-grade reserves, beneficiating these ores via traditional methods is challenging. Various researchers have reported challenges such as silica contamination, iron losses to slimes, and handling of fines that make it challenging to maintain a quality concentrate [11, 16–20]. Therefore, there is an urgent call to adopt alternative iron beneficiation techniques that are both economically and environmentally sustainable.

In this context, bio-beneficiation methods represent new opportunities as viable and sustainable alternatives to conventional iron ore processing by utilizing microorganisms to extract desired minerals from ores using their metabolite products. This minimizes the need for energy, water, and chemicals while reducing waste generation.

Bio-beneficiation technology utilizes microbiological interventions through processes such as bio-leaching, bio-flotation, and bioreduction to facilitate the recovery of minerals in an environmentally friendly and cost-effective manner [21]. Bio-leaching harnesses iron-oxidizing bacteria like *Leptospirillum ferrooxidans*, *Leptospirillum ferriphilum*, *Acidithiobacillus ferrooxidans*, or *Sulfolobus thermosulfidooxidans* cultured in bio-reactors to solubilize metals via metabolite [22]. Research indicates that bio-leaching efficiency is comparable or superior to conventional methods for low-grade iron ores while generating negligible wastes [23–25]. During bio-leaching, the iron ore is attacked by microorganisms directly or indirectly, as shown in Fig. 1, removing the gangue minerals and leaving the iron behind [26].

Additionally, selective iron sulfide bio-flotation from ores using *Bacillus methylotrophicus*, *Bacillus subtilis*, and *Pseudomonas aeruginosa* has shown promising results exceeding traditional flotation performance [10, 27, 28]. Further optimization of process and operating parameters like pulp density and particle size can improve bio-processes, allowing sustainable recovery [29, 30]. An overview of iron ore beneficiation techniques, including their limitations and environmental concerns, iron ore bio-beneficiation techniques, and future outlook toward mining sustainability, is presented and discussed in this manuscript.

2 Traditional Methods of Iron Ore Beneficiation and Their Limitations

Iron ore, the primary source of iron used in steel production for commercial use, often contains gangue mineral impurities such as alumina, quartz, and silica, which reduce iron content and affect the quality of the final products. Beneficiation, therefore, plays a critical role in iron ore grade improvement and enrichment by removal of those impurities [31–33]. Currently, the most used iron ore beneficiation techniques are gravity, magnetic separation, screening, crushing, and spiral concentration, as outlined in Fig. 2. These methods, however, are limited to high-grade iron ores and are less effective for ores with low iron concentrations (off-grade iron ore) [1, 34].

The crushing and screening separation technique reduces the runoff mine into small sizes by breaking and separating based on desired sizes. In this method, the fine waste particles are filtered during the initial concentration, and the focus is made on the coarse materials with a high iron

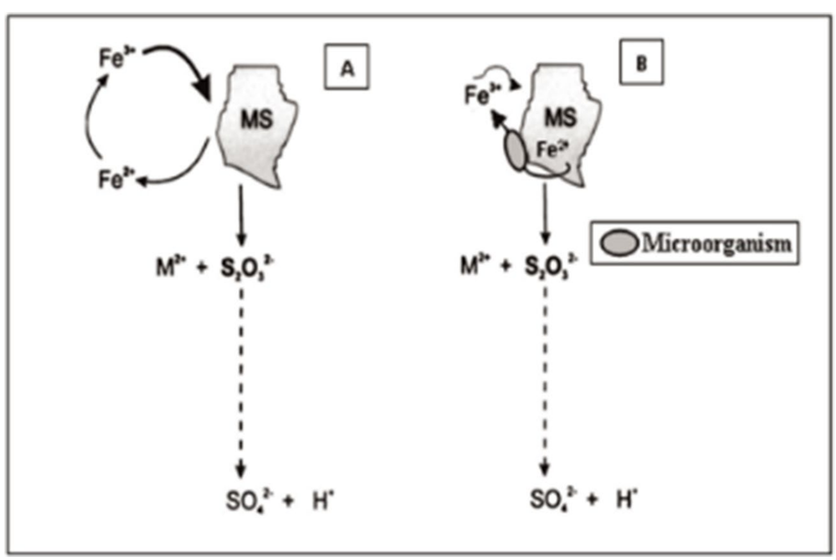

Fig. 1 Bio-leaching: **a** direct; **b** indirect [26]

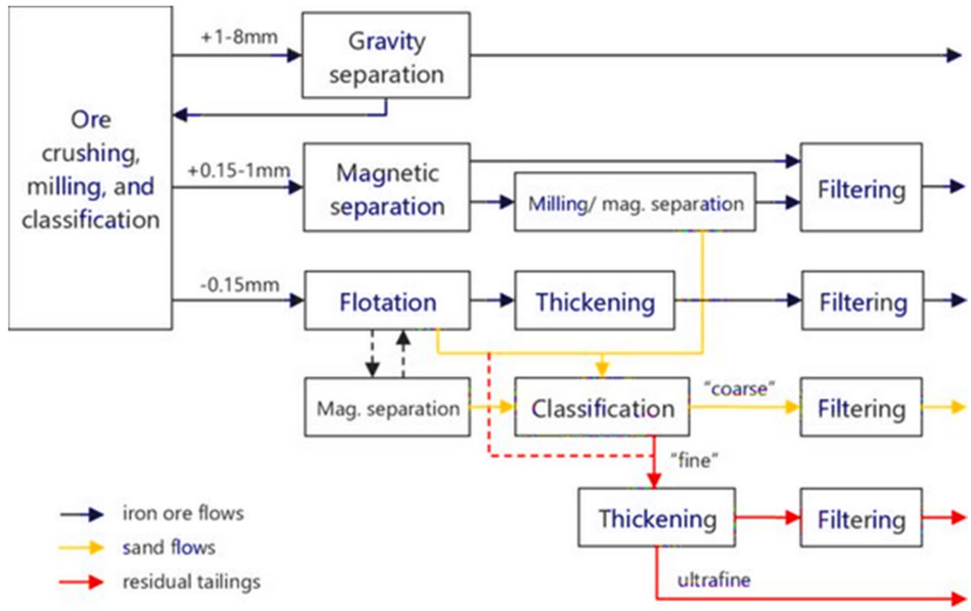

Fig. 2 Iron ore beneficiation process [35]

ore content. This process may be either dry or wet, utilizing water as the main wetting agent. This conventional method, however, tends to generate large amounts of fine tailings and particulate matter as waste products [36, 37].

Gravity-based iron ore separation relies on density for effective recovery. The density differences between the iron ore and gangue minerals in the ore assist during separation. The crushed ore is washed over in the feed, jiggling and shaking tables, and spirals where the heavy iron ore particles settle faster, and the light gangue minerals are washed off as tailings. However, this technique is inefficient for lower grade concentration as it would require other methods for further beneficiation [19, 38].

Magnetic separation of iron ore happens by passing crushed iron ore over electromagnets. Highly magnetic iron ore is attracted to the magnets while the non-magnetic materials and gangue minerals drop away as tailings. This process produces high-content iron ore concentrates but is limited to low magnetic iron ores and, therefore, not suitable for processing low-grade iron containing fine iron [1, 12, 39].

In addition to physical iron ore beneficiation techniques, traditional chemical methods of iron ore beneficiation, such as leaching, froth flotation, and magnetic agglomeration, exist [31]. During leaching, iron is dissolved from the ores using acidic or alkali solutions, allowing the gangue minerals (impurities) to be washed away. Research done by Silva et al. [40] revealed that acid leaching using both nitric and hydrochloric acid reduced the phosphorous content in iron ore. However, more significant iron losses were reported due to the high reactivity of both acids, as shown in Eqs. (1)–(3). This method requires high reagent consumption and produces large volumes of chemical-laden tailings that are not friendly to the environment [41, 42].

$$Ca_5F(PO_4)_{3solids} + 10H^+ \rightarrow 3H_3PO_4 + HF + 5Ca^{2+} \quad (1)$$

$$Fe_3O_{3Solids} + 10H^+ + NO_3 \rightarrow 5H_2O + 3Fe^{3+} + NO_{2gas} \quad (2)$$

$$8Fe_3O_{4Solids} + 74H^+ + NO_3 \rightarrow 35H_2O + 24Fe^{3+} + NH_4 \quad (3)$$

In froth flotation, collectors are used to selectively bind the iron ore and float them from gangue minerals using air bubbles. Conventional chemicals used in froth flotation, such as cyanide, amines, and acids, tend to be exorbitant and toxic to the environment.

The magnetic agglomeration technique is used to finely concentrate ground iron and palletize it using magnetite or ferro silicone powders. This beneficiation process is inadequate for the selectivity of low-grade iron ores, utilizes toxic chemicals, and releases gasses that are not environmentally friendly [43, 44].

The main limitations shared by these conventional beneficiation methods are inadequate selectivity that leads to loss of iron in the tailings and the exorbitant and toxic chemical utilized in the recovery process. With the current strict environmental regulations and policies in the mining industry and the need for sustainability, these techniques pose massive inefficiencies.

2.1 Environmental Concerns of Traditional Iron Ore Beneficiation

The iron ore processing and the waste produced during beneficiation employing traditional methods pose significant environmental concerns. These issues include the following.

2.1.1 Land Use and Land Cover Change Impacts

Land use and land cover are radically altered during mineral extraction and waste storage. Open pits change the landscape and habitat during iron ore extraction, while tailing dumps cover vast lands. The tailings dumped may be laded with potentially toxic elements that affect the ecosystem [45].

2.1.2 Dust and Particulate Matter Emissions

Grinding, crushing, and screening produce voluminous fine particulates that end up polluting the air [43].

2.1.3 Acid Mine Drainage

Chemical leachate tailings may seep from the tailing dam, leaking potentially toxic metals and chemicals into the waterways and causing acid mine drainage [44].

Low recovery rates when utilizing traditional methods represent an inefficient use of these natural resources, as much of the iron in the ore is disregarded as waste rather than being utilized effectively.

In order to fully address the selectivity and environmental issues associated with conventional beneficiation techniques, research is focused on developing alternative beneficiation processes, such as utilizing bio-beneficiation techniques. Research using the bio-flotation method revealed that waste production is significantly reduced [46, 47].

The innovative techniques of using microbes and bacteria for beneficiation in leaching and flotation methods are promising for transformative iron ore beneficiation and target a cleaner and sustainable process. Developing bio-beneficiation techniques can provide a sustainable pathway to recovering more complex and low-grade ores currently mined due to high-grade depletion.

3 Bio-beneficiation of Iron Ore

Bio-beneficiation of iron ore is a mineral processing technique that utilizes microbes or microorganisms to selectively separate the needed minerals from gangue. Bio-beneficiation offers an alternative method to conventional and chemical methods of iron ore recovery. Some existing bio-beneficiation methods for iron ore recovery are bio-leaching, bio-flotation, and bio-flocculation. Bio-leaching methods utilize acidophile microbes such as *Acidithiobacillus ferrooxidans* to dissolve iron from ores via the oxidation of iron ore and the production of sulfuric acid.

The use of microbes or microorganisms and their derived microbial products for mineral bio-flotation has resulted in significant advancements in the mineral beneficiation industry [4]. These microbes and their metabolite derivates have been extensively studied and used to selectively remove gangue minerals from ores to form concentrates [48, 49]. Various research has revealed that these microbes or their derivates are used during mineral processing to modify the surface of the minerals, depress gangue or required minerals, and, to some ores, act as collectors in froth flotation [30, 50, 51]. Bio-flocculation, on the other hand, utilizes microbes to aggregate fine gangue mineral particles for removal from ore slurries, thereby increasing the iron content of the concentrate [52, 53].

3.1 Bio-flotation of Iron Ore

Iron ore beneficiation is highly enhanced by utilizing different types of microbes that alter the surface of the particles, thereby aiding in the successful upgrading of iron. The effect of the activity of different microbes on the iron ores is summarized in Table 1.

3.2 Bio-leaching of Iron Ore

Bio-leaching is often used to recover minerals and metal elements in low concentrations for which other beneficiation methods would not recover efficiently. The most active microbes in bio-leaching are from the genus *Thiobacillus*, which are gram-negative and grow under aerobic conditions. Bio-leaching is most successful in acidic environments at low pH of 1.5 to 3 for effective dissolution of metal ions in the solution. On the other hand, *Leptospillirum* species, though acidophilic, cannot oxidize sulfur in sulfidic iron ores on their own unless combined with *T. ferrooxidans* or *T. thiooxidans* [58]. Members of the *Acidithiobacillus*, *Pseudomonas*, and *Leptospirillum* species are mesophilic acidophiles with high efficiency in bio-leaching iron ore [59, 60]

Research by Rouchalova et al. [61] revealed a high potential for recovery of iron by bio-leaching, utilizing the acidophilic microbial stain of *Acidithiobacillus ferroxidans*. The research further revealed that using an acid such as sulfuric acid to recover iron and other metals achieved lower yields than using microbes at an optimal pH of 1.8 and particle size of 71–100 μm. Research by Jones and Santini [62] on mechanisms of bio-leaching pointed out that bio-leaching is a complex process that requires a series of enzymes released by acidophiles to oxidize iron for effective recovery. The study also revealed that members of the *Acidithiobacilus* genes, such as *ferivorans* and *ferriphilus*, have succeeded in iron oxidation as they contain high potential iron protein (HIPIP). Further, it was discovered that *Leptospirilllum ssp.*, *Ferroplasma spp.*, *Feroplasma acidarmanus*, and *Leptospirillllum ferrodiazotrophum* species contain complex structures capable of oxidizing iron in bio-leaching [59].

Bio-leaching was successfully used in the dissolution of gangue minerals (zinc, phosphorus, potassium, and calcium

Table 1 Microbial activity on iron ore beneficiation

Microbes	Activity	Key results	References
Rhodococcus opacus	Enhancement of hematite hydrophobicity	There was a recovery of 95% of hematite at a pH of 5 using the microbe at 100ppm concentration of the cells	[49]
Paenibacillus polymyxa	Galena and pyrite selective separation	The biosurfactant using the microbe had a double efficiency of 95% in acidic conditions	[50]
Mycobacterium phlei	Hematite hydrophobicity modification	The microbe acted as a modifier in enhancing hematite recovery by 80% at low pH of 1–3	[24]
Mycobacterium phlei	Quartz-hematite bio-flotation	Optimal recovery of hematite occurred at a pH of 5 in the presence of the microbe	[51]
Bacillus subtilis	Hematite hydrophobicity modification	There was a high floatability of hematite to a high of 90% recovery at a pH of 5 after the microbe interaction with the sample	[10, 54]
Rhodococcus opacus	Hematite-quartz bio-flotation	Microbial interactions resulted in 90% hematite flotation at a pH of 5 after contact time of 5 min with the microbes	[53]
Paenibacillus polymyxa	Pyrolusite depression	The microbial interactions led to a flotation reduction of pyrite by 10%	[55]
Rhodococcus erythropolis	Quartz-hematite bio-flotation	Biosurfactant was used to effectively recover hematite from quartz gangue at varying concentrations and pH	[56]
Rhodococcus erythropolis	Hematite bio-flotation	Biosurfactant was used to enhance the maximum recovery of hematite, varying the pH and the concentration	[57]
Bacillus pumilus	Iron ore bio-flotation	The microbes produce biosurfactants capable of oxidizing the iron in the pyrite sample	[54]

oxide) in iron ore containing hematite (Fe_2O_3) and magnetite (Fe_3O_4), utilizing acidophile microbes in enhancing iron recovery. The bio-leaching process dissolved the impurities by 50% and increased iron recovery at the end of the microbial growth phase [63].

A study done to analyze the effectiveness of bio-leaching to remove phosphorous gangue in iron ore using *Acidithiobacillus ferroxidans* microbes revealed a successful removal of phosphorous by 6.2% and increased iron content [64–66].

Mixed cultures consisting of *Ferroplasma acidiphilum*, *Sulfobacillus thermotolerans*, and *Leptospirillum ferriphilum* were used to leach sulfur content in iron ore under varied pH, temperature, and pulp density conditions. Results revealed that at a pH of 1.8, pulp density of 15%, and operating temperature of 33 °C, bio-leaching yielded 80.05% of iron and decreased sulfur content by 95% [67].

A combination of *Acidithiobacillus ferrooxidans* and *Sphingomonas sp.* on bio-leaching of phosphorous gangue from hematite ore increased leaching by 1.5 times [68]. *Exiguobacterium oxidotolerans* microbial genes were found to be effective in dissolving iron from hematite under alkaline conditions [69]. The *Exiguobacterium oxidotolerans* microbes' cell walls had direct contact with the iron ore and, therefore, exchanged electrons directly with iron (III) oxide via surface contact, aiding its reduction to soluble Fe(II), as shown in Fig. 3.

Though researchers have reported the successful use of microbes for bio-beneficiation using bio-leaching techniques, there remain both technical and biological challenges

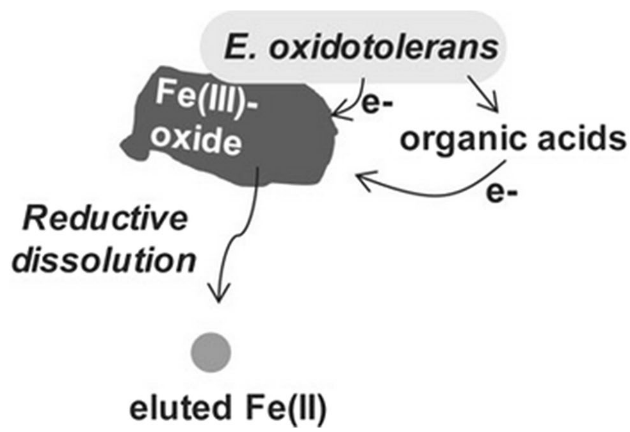

Fig. 3 Direct bio-leaching of iron ore [69]

to their industrial application. The much time required for culturing and action on the ores of interest, including the tolerance of the microbes to heavy metals present in ores, needs genetic improvement to bring quicker results and save time. Such notable advancements have been made to *T. ferrooxidans* species [58].

3.3 Bio-flocculation of Iron Ore

Bio-flocculation is an iron ore beneficiation method utilizing microbes, bacteria, algae, or fungi to aggregate and flocculate fine iron ore particles for separation in slurries enriched with cultures. These bio-flocculants are extracellular polymeric substances like proteins and polysaccharides secreted by these microbes, hence inducing mineral flocculation [14, 70]. The mechanism of action of these bio-flocculants involves the binding and bridging of fine ore particles by biopolymers with high molecular weight and, therefore, the formation of flocs that settle out fast. Microbes used in flocculation include stains from *Bacillus*, *Aspergillus*, and *Chlorella* species.

Research on the evaluation of flocculation of ultrafine particles of hematite in iron ore tailing was done using a biosurfactant extracted from *Candida stellata* yeast. Analysis revealed that the biosurfactant efficiently modified the surface properties of the iron ore at a pH of 3.3 to recover iron by 90% successfully [71]. Metabolites and cell walls of *Bacillus licheniformis* microbe were used for bio-flocculation of goethite and hematite at varying concentrations of the biosurfactant, pulp density, and pH. The highest recovery of hematite and geothite was achieved between pH of 5 and 7 [72].

Gram-positive *Bacillus cereus* bacterium was isolated and cultured from Egyptian iron ore surface and solely used as a flocculation agent to recover hematite from silica gangue selectively. There was a successful removal of silica and a high recovery of hematite at 89.2% [73]. *Paenibacillus polymyxa* bacteria was used for hematite pretreatment to assist in flocculation at a pH of 6.5 and attained a 67.9% recovery of hematite. It was revealed that the bacterial walls were adsorbed onto the hematite, causing aggregation for the mineral and changing the size distribution of particles [74]. Farghaly et al. [75] investigated the use of *Paenibacillus polymyxa* as a surface modifier for the removal of manganese in iron ore, where a high efficiency of iron ore recovery was observed.

Candida parapsilosis was successfully used in the flocculation of − 38 microns of hematite. The microbe's relative cell size and the hematite's particle size assisted in the effective flocculation [76].

Different microbes, including heterotrophic and autotrophic yeast, fungi, and archaea, may act as beneficiation agents for iron ore recovery, as summarized in Table 2. These microbes solubilize gangue minerals such as silica and alumina, and their metabolites dissolve metal ions from the ore using hydrogen ions, forming soluble metals and chelates [77].

4 Environmental Impact and Sustainability of Iron Ore Beneficiation

Conventional and traditional beneficiation methods utilizing exorbitant and toxic chemicals in ore processing significantly impact the environment. Bio-beneficiation methods offer a more sustainable method of mineral processing, relying on microbes that usually operate at near-ambient conditions with minimal external energy requirements or chemical reagents for processing.

Bio-leaching and bio-flotation use sustainable sources of organic matter as nutrient sources for the microbes. Bio-flocculation, on the other hand, uses organic waste from other processes to effectively recover minerals. Furthermore, bio-beneficiation also assists with environmental restoration during mine closure by solubilizing nutrients like potassium and phosphorus during ore decomposition in the tailing dam. Responsible implementation of the iron ore recovery beneficiation method can enhance sustainability across the value chain. Further research should be done to assess the life cycle analysis (LCA) of bio-beneficiation processes to quantify and assert sustainability benefits against conventional and traditional approaches.

5 Constraints and Limitations of Bio-beneficiation

Bio-beneficiation, however, is posed with various challenges and limitations. These include scale-up challenges from bench laboratory studies to industrial-scale usage. The transition entails complexities such as ensuring consistent microbial activities, maintaining optimal conditions of the microbes, and handling large volumes of ores. The composition of the complex iron ores of low grade can

Table 2 Archaea, fungi, and yeast capable of beneficiation of iron ore

Name	Microbe	Iron ore mineral	Microbial activity	Reference
Archaea	*Thermoplasma acidophilum*	Pyrite	Iron ore bio-leaching at low pH (< 3)	[78]
	Ferroplasma acidarmanus	Pyrite	Iron ore bio-leaching at a pH of 0.3–2	[79]
	Sulfolobus acidocaldarius	Pyrite	Iron ore bio-leaching at a pH of 0.9–5.8	[80]
Fungi	*Aspergillus niger*	Magnetite and geothite	Phosphorous removal from iron ore	[81]
	Penicillium sp.	Hematite	Potassium and phosphorous removal from iron ore	[82]
	Aspergillus terreus	Magnetite and goethite	Phosphorous removal from iron ore	[83]
Yeast	*Saccharomyces cerevisiae*	Hematite	Hematite separation from calcite and quartz	[84]

also vary significantly, therefore affecting the bio-beneficiation technique. Adapting these intricate processes to accommodate variations in ore composition increases complexity during recovery and requires tailored solutions for different ores to increase efficiency, as the bio-beneficiation process operates at relatively slow rates compared to conventional methods using chemicals.

Assessing the technical and economic feasibility of the adoption of bio-beneficiation techniques necessitates thorough examinations of capital and operating expenses (CAPEX and OPEX), possible returns on investment (ROI), and competitiveness with methods. Environmental factors are also important, as bio-beneficiation may provide environmental benefits over traditional approaches; however, aspects such as bio-waste disposal and potential consequences on local ecosystems must be carefully evaluated and managed.

Regulatory and ethical requirements of industrial-scale bio-beneficiation technology may pose challenges, particularly regarding waste management and the safety of using microbial processes. Despite significant advancements, there are still gaps regarding the utilization of bio-beneficiation techniques in mineral processing. Addressing these challenges requires a collaborative approach between researchers, policymakers, and industry stakeholders to overcome the technical hurdles and ensure the successful implementation of mineral bio-beneficiation for a sustainable recovery.

6 Conclusions

Bio-beneficiation presents a long-term, environmentally friendly, and sustainable alternative to traditional iron ore processing methods. Bio-leaching, bio-flotation, and bio-flocculation have proved effective in increasing iron ore content in off-grade iron ores through the activity of microbes. Further research needs to be done to optimize these intricate processes and scale up laboratory studies to pilot studies and then to industrial applications. Bio-beneficiation has a high potential in iron ore processing in an environmentally friendly way, minimizing water, energy, and toxic chemicals. With continued research, development, and integration into mineral processing operations, bio-beneficiation is promising for sustainable iron ore recovery.

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Data Availability Data included in this review is referenced in the article.

Declarations

Competing Interests The authors declare no competing interests.

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