

NRC Publications Archive Archives des publications du CNRC

Strategies for hydrocarbon removal and bioleaching-driven metal recovery from oil sand tailings

Joshi, Khyati; Magdouli, Sara; Kaur, Kamalpreet; Brar, Satinder Kaur

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.3390/min14111093>

Minerals, 14, 11, pp. 1-19, 2024-10-29

NRC Publications Archive Record / Notice des Archives des publications du CNRC :

<https://nrc-publications.canada.ca/eng/view/object/?id=d40266bd-033e-495c-a59f-20e1c33c0d8c>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=d40266bd-033e-495c-a59f-20e1c33c0d8c>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

Review

Strategies for Hydrocarbon Removal and Bioleaching-Driven Metal Recovery from Oil Sand Tailings

Khyati Joshi ¹, Sara Magdouli ², Kamalpreet Kaur ³  and Satinder Kaur Brar ^{1,*} 

¹ Department of Civil Engineering, Lassonde School of Engineering, York University, Toronto, ON M3J 1P3, Canada; khyati05@yorku.ca

² Department of Civil Engineering, Faculty of Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada; smagdoul@uottawa.ca

³ Clean Energy Innovation Research Centre (CEI), National Research Council of Canada, Montreal, QC H4P 2R2, Canada; kamalpreet.kaur@nrc-cnrc.gc.ca

* Correspondence: satinder.brar@lassonde.yorku.ca

Abstract: Oil sand tailings from bitumen extraction contain various contaminants, including polycyclic aromatic hydrocarbons, BTEX, and naphthenic acids, which can leak into surrounding environments, threatening aquatic ecosystems and human health. These tailings also contribute to environmental issues such as habitat disruption and greenhouse gas emissions. Despite these challenges, oil sand tailings hold significant potential for waste-to-resource recovery as they contain valuable minerals like rare earth elements (REEs), titanium, nickel, and vanadium. Traditional metal extraction methods are environmentally damaging, requiring high energy inputs and generating dust and harmful emissions. Furthermore, the coating of hydrocarbons on mineral surfaces presents an additional challenge, as it can inhibit the efficiency of metal extraction processes by blocking access to the minerals. This highlights the need for alternative, eco-friendly approaches. Bioleaching, which uses microorganisms to extract metals, emerges as a sustainable solution to unlock the valuable metals within oil sand tailings. This review discusses the minerals found in oil sand tailings, the challenges associated with their extraction, methods from hydrocarbon removal from minerals, and bioleaching as a potential metal recovery method.

Keywords: bioremediation; bioleaching; hydrocarbon degradation; minerals; metal recovery; rare earth elements; Athabasca oil sands; circular economy



Citation: Joshi, K.; Magdouli, S.; Kaur, K.; Brar, S.K. Strategies for Hydrocarbon Removal and Bioleaching-Driven Metal Recovery from Oil Sand Tailings. *Minerals* **2024**, *14*, 1093. <https://doi.org/10.3390/min14111093>

Academic Editor: Naoko Okibe

Received: 26 September 2024

Revised: 21 October 2024

Accepted: 22 October 2024

Published: 29 October 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Oil sands in Canada represent one of the largest petroleum reserves worldwide [1]. With an expansive area of more than 100,000 km², Alberta's oil sands yield approximately 3.3 million barrels of bitumen daily, underscoring its pivotal role in Canada's domestic energy production and economic landscape [2,3]. Bitumen extraction from oil sands has long been a cornerstone of the global energy industry [4] (Figure 1A). However, during the extraction process, various impurities such as fine clay particles, water, residual bitumen, and chemicals accumulate, leading to the formation of waste streams, known as oil sand tailings [5].

In a recent report, the Alberta Energy Regulator stated that the collective volume of oil sand tailings in the Athabasca oil sands region had expanded to 1392 million cubic meters (mm³) in 2022 from 1075 mm³ in 2021 [6] (Figure 1B). Based on current trends and the ongoing growth of oil sand extraction activities in Alberta, it is anticipated that the volume of oil sand tailings will continue to rise in the coming years.

The storage and management of oil sand tailings raise significant environmental concerns. Firstly, the storage and management of these tailings often result in the creation of large ponds, which can disrupt natural habitats and potentially lead to water and soil contamination [7]. Furthermore, the release of greenhouse gasses, primarily methane, from

these tailings is particularly worrisome due to its environmental impact [8]. Additionally, the presence of toxic compounds, such as mercury, arsenic, and polycyclic aromatic hydrocarbons (PAHs) in oil sand tailings and their potential to leach into nearby water bodies present a threat to aquatic ecosystems and human health [9,10].

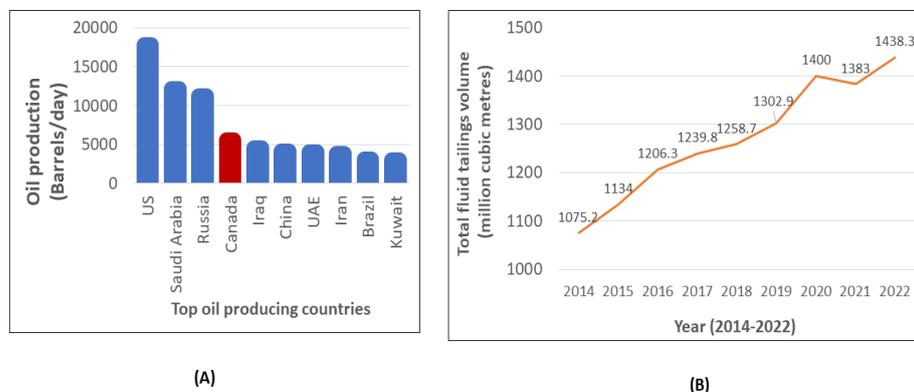


Figure 1. (A) World oil reserves by country, (B) fluid tailings volume over time (2014–2022).

Despite the challenges presented by oil sand tailings, a latent wealth of valuable metals lies concealed within [11]. The minerals and metals found in these tailings present an interesting opportunity for valorization. The concept of valorization goes beyond merely reducing the environmental impact of these tailings; it transforms what was once deemed as waste into valuable resources. The importance of this is highlighted by the presence of valuable metals within oil sand tailings, such as rare earth elements (REEs), vanadium, nickel, and copper, which are essential components in various industries [12].

Typically, pyrometallurgy and hydrometallurgy are employed for metal extraction from primary and secondary sources (ores and tailings respectively) [13,14]. Pyrometallurgy involves methods, such as smelting and refining at high temperatures, and demands vast energy and capital investments. It also contributes to hazardous gas emissions, such as SO_2 [15]. Hydrometallurgy, on the other hand, utilizes aqueous solutions for leaching, purification, and metal recovery. It operates at lower temperatures and capital costs compared to pyrometallurgy. However, it raises concerns about chemical disposal and the production of harmful off-gasses [16].

In the search for sustainable solutions, biomining emerges as a promising approach to unlock the hidden wealth within oil sand tailings [17,18]. Notably, bioleaching, a subset of biomining, has been successfully employed in the extraction of precious metals, including gold and copper, from printed circuit boards and electronic waste, providing a proven precedent for this innovative approach [19,20]. This review explores how biomining can be applied to oil sand tailings, challenging the conventional perception of these tailings as waste. It provides an in-depth analysis of the organic and inorganic composition of these tailings, discusses the microbial degradation of residual bitumen for mineral extraction, and evaluates biomining as a more sustainable alternative to traditional extraction methods.

2. Organic and Inorganic Composition of Oil Sand Tailings

During bitumen extraction from oil sands, three primary waste streams are typically produced: coarse sand tailings (CSTs), fluid fine tailings (FFT), and tailing solvent recovery unit (TSRU) [1]. CSTs primarily contain sand (particle size exceeding $44 \mu\text{m}$), while FFTs, with 15%–30% m/v solid content, consist mainly of fines (particle size less than $44 \mu\text{m}$) [1]. FFTs undergo settling for 1–2 years, resulting in the formation of mature fine tailings (MFTs), characterized by a highly dense, tar-like consistency, containing over 30% m/v solid content and particle sizes exceeding $30 \mu\text{m}$ [21]. A TSRU is a smaller stream resulting from the addition of solvent, like naphtha, to the extracted bitumen froth or concentrate [22,23].

The composition of these tailings is influenced by factors such as ore quality, age, source, and extraction processes [24]. The tailings typically consist of a diverse mixture of

aliphatic and aromatic hydrocarbons, including n-alkanes (such as heptane, octane, and nonane), BTEX compounds (benzene, toluene, ethylbenzene, and xylenes), naphthenic acids (NAs), and iso-paraffins. Another significant component is unrecovered bitumen, which includes complex, insoluble asphaltenes making up 2% to 5% by weight (wt%) [25,26].

Inorganic components include clay-sized minerals dominated by kaolinite, quartz, and illite-smectite, along with trace amounts of minerals such as pyrite, siderite, anatase, and rutile [27]. Oil sand tailings also contain heavy minerals like zircon, apatite, monazite, ilmenite, and tourmaline, primarily in sediment phases [27,28] (Table 1).

Table 1. Mineral composition of oil sand tailings.

Mineral	Element of Interest	TSRU (wt%)	FFT (wt%)	MFT (wt%)	Reference
Pyrite	Iron (Fe), Sulfur (S)	13.4	0.8	-	[29]
Kaolinite	Aluminum (Al), Silicon (Si)	15.4	27.6	36	[30–32]
Monazite	REEs	Trace	-	-	[12]
Illite	Aluminum (Al), Potassium (K)	5.3	10.1–15.3	30.7	[30–33]
Siderite	Iron (Fe)	6.6 ± 3.8	4	3.2	[30,32,34]
Quartz	Silicon	57 ± 13	25	27.4	[31,32,34]
Zircon	Zirconium (Zr), Hafnium (Hf)	2.2	-	-	[30]
Anatase	Titanium (Ti)	2.1	1	-	[30,32]

TSRU: Tailing solvent recovery unit; FFT: Fluid fine tailings; MFT: Mature fine tailings.

The concentrated presence of valuable metals, including vanadium (1380 mg/kg), nickel (540 mg/kg), copper (70 mg/kg), titanium (29,100 mg/kg), zirconium (9670 mg/kg), and REEs (1204 mg/kg), in different oil sand tailing types highlights the resource potential of these waste streams [12,33–35]. This composition presents significant opportunities for resource recovery, aligning with the principles of a circular economy. By utilizing these materials, environmental burdens can be transformed into economically valuable assets, promoting sustainable resource management.

Companies like Titanium Corporation and MGX Minerals Inc. are advancing recovery methods, focusing on technologies to reclaim valuable resources from oil sand operations [36,37]. Similarly, Halifax-based Ucore Rare Metals has made significant strides in extracting REEs from oil sand tailings with its proprietary processes. It has successfully leached select metals into various acidic pregnant leach solutions (PLSs) and is currently working to separate the ions and precipitate them as nearly pure carbonate salts using its proprietary Superlig[®]-One process [11].

Current metal extraction methods from oil sand waste typically involve acid leaching and smelting, achieving significant recovery rates for some metals. However, these methods can also lead to environmental pollution and resource wastage due to bitumen combustion [33,38]. The diverse mineralogy and complex chemical composition of oil sand tailings further challenge the efficiency of these traditional techniques, highlighting the need for alternative approaches. Bioleaching emerges as a more sustainable and effective solution for metal recovery in this context. Bioleaching utilizes naturally occurring microorganisms to selectively solubilize metals from their mineral matrices, significantly improving recovery rates while minimizing the need for high-temperatures and harsh chemicals [39]. Bioleaching has been effectively utilized to recover metals found in different industrial wastes, indicating its potential for extracting similar metals present in oil sand tailings [40–43]. Moreover, bioleaching can effectively mobilize metals from solid phases, such as monazite and zircon, which are otherwise challenging to extract [44,45].

By applying bioleaching to oil sand tailings, valuable metals can be extracted while also utilizing hydrocarbons present in the tailings that would typically go to waste in traditional methods. This sustainable approach not only enhances metal recovery but

also reduces environmental impact, making it an effective alternative for addressing the challenges posed by oil sand tailings.

3. Removal of Residual Bitumen and Other Hydrocarbons from Mineral Surface

Metal recovery from minerals, such as zircon, monazite, pyrite, and anatase, from oil sand tailings poses a significant challenge due to bitumen coating on the mineral surface [46,47]. The humic content associated with organic-rich solids (clay minerals) tends to adsorb and securely bind bitumen to both internal and external aggregate surfaces [48,49]. Bitumen, being a heavy hydrocarbon with complex molecular structures, tends to form a cohesive and adhesive layer on the surface of mineral particles. This coating increases the surface tension of the minerals, influencing various aspects of their physical and chemical interactions, thereby impacting overall mineral behavior [50]. Therefore, it is necessary to remove the hydrocarbon coating from the mineral before extracting the metal (Figure 2). This section briefly discusses different methods utilized for the removal of residual bitumen and other hydrocarbons from the ore surface.

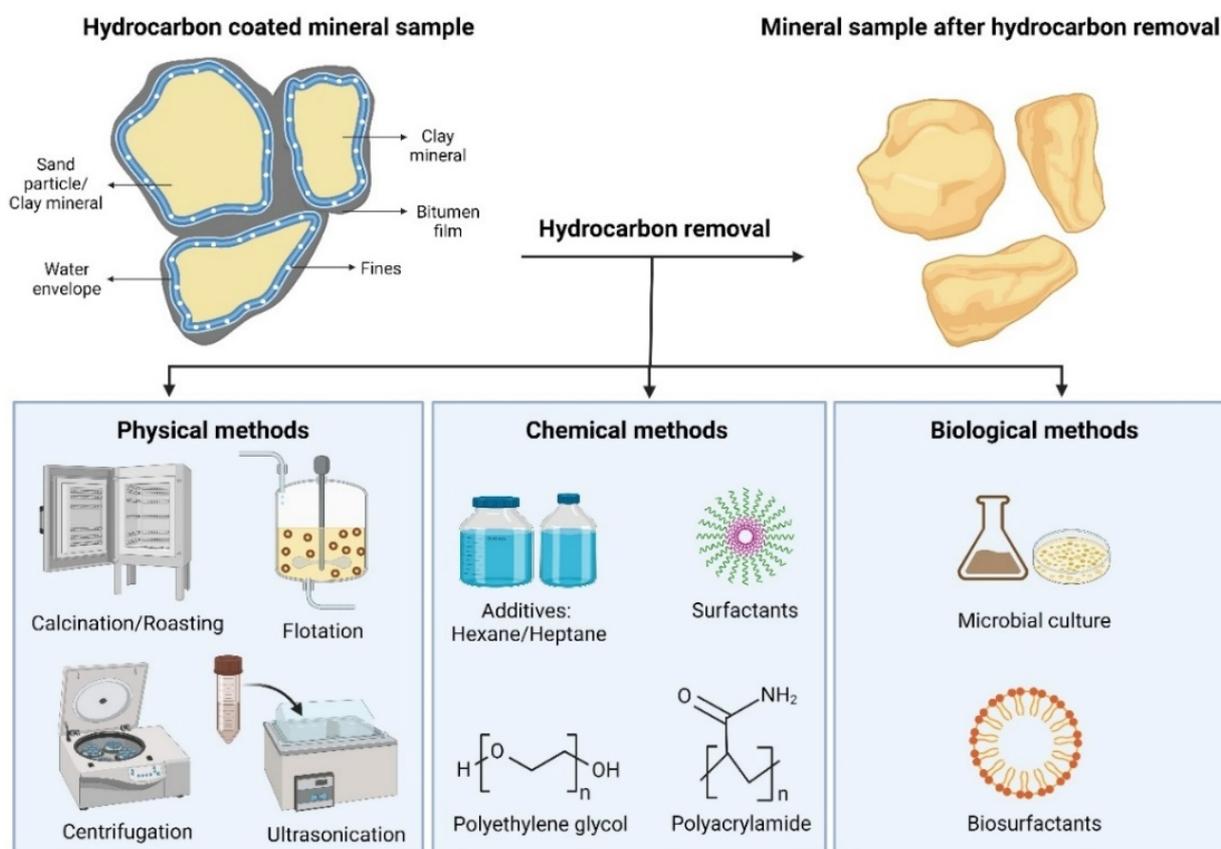


Figure 2. Methods of hydrocarbon removal from mineral samples.

3.1. Physical Methods

3.1.1. Calcination and Roasting

Calcination and roasting are thermochemical processes that involve heating materials to facilitate the removal of hydrocarbons and enhance the friability of the residue. Calcination typically occurs at high temperatures, ranging from several hundred to over a thousand degrees Celsius, in the absence of air or oxygen. The primary aim of calcination is to decompose carbonaceous materials, oxidize certain components, and render the solid matrix more porous and easier to process further [51]. For instance, calcination has been effectively employed for the removal of bitumen from ilmenite at approximately 700 °C, resulting in the elimination of bitumen and other carbonaceous materials, as well as secondary minerals like calcite, siderite, and pyrite. However, this process converts Fe(II)

in ilmenite to Fe(III), which diminishes its magnetic susceptibility and complicates the subsequent separation of altered ilmenite from ferro-silicates [52].

In contrast, roasting generally involves heating the ore in the presence of air or oxygen, but it can also be conducted in various atmospheres, including inert or reducing environments. This flexibility allows for the promotion of oxidation and chemical transformations to help remove residual hydrocarbons, such as bitumen, from the material [53–56]. Roasting has been a predominant method in metallurgical investigations, with studies demonstrating effective bitumen removal at temperatures ranging from 340 to 550 °C [56] and 600 to 700 °C [52]. For example, the patented methodology developed by Ityokumbul et al. incorporates flotation techniques prior to roasting, enhancing the overall efficiency of bitumen extraction. Despite its effectiveness, roasting has raised concerns about the contamination of rutile and zircon concentrates with varying levels of iron. This contamination may result from alterations in the magnetic properties of iron-bearing minerals during the roasting process, potentially leading to misplacement during subsequent processing [57].

For oil sand tailings, roasting may be more suitable due to its ability to operate in varying atmospheric conditions, allowing for effective bitumen removal while preserving the integrity of the minerals. This flexibility can enhance recovery efficiency and the adaptability to different operational setups. However, it is essential to manage the potential risk of contamination during the roasting process to ensure the purity of the final mineral products.

3.1.2. Flotation

Flotation is a separation technology based on surface wettability. It employs air bubbles as carriers to capture specific hydrophobic entities in aqueous suspensions, lifting them to the surface of the slurry as a froth product [58]. In 1987, Ityokumbul et al. patented a bulk flotation process aimed at collectively floating heavy minerals and residual bitumen into a bulk concentrate from the froth treatment tailings. However, flotation has been reported to encounter limitations due to the presence of the polar components and surfactants introduced to the oil sands during the bitumen recovery process. The presence of polar components, primarily concentrated in the asphaltene fraction of bitumen, influences the surface hydrophobicity of bitumen negatively. The polar components and surfactants attach themselves to solid particles within the slurry, causing an increase in hydrophobicity and thereby competing with bitumen for flotation [59]. To overcome the challenges posed by polar components and surfactants, using specialized collectors that enhance the hydrophobicity of bitumen can improve flotation efficiency. Additionally, implementing pre-treatment steps to reduce polar compound concentration may further optimize the flotation process.

3.1.3. Centrifugation

Centrifugation is based on the principle of sedimentation, where particles in a heterogeneous mixture are separated under the influence of a centrifugal force. The application of high-speed rotation to generate a strong gravitational force causes denser particles to move outward and settle more rapidly [60]. Centrifugation is usually the first step for the removal of bulk bitumen surrounding the mineral particles. Roth et al. utilized centrifugation at 3000 rpm for 15 min, with a reported relative centrifugal force of 1590 for the separation of minerals from the liquid sample. The liquid supernatants were decanted and filtered using a 0.45-micron filter for the measurement of metals [12]. In another study, Liu et al. utilized centrifugal forces to separate bitumen from the tailing solids, successfully removing 70% of the contained bitumen [55]. However, this processing method has demonstrated inadequacy in eliminating bitumen to levels below the critical concentration necessary for efficient mineral production. It has been reported that even after the heavy minerals are separated from the bitumen concentrate through centrifugation, they are still coated with bitumen [55]. Optimizing centrifugation parameters, such as rotational speed and duration, along with the addition of chemical surfactants could enhance the separation efficiency

and reduce the residual bitumen coating on the minerals, ultimately improving mineral recovery rates.

3.1.4. Ultrasonication

Ultrasonication involves the use of high-frequency sound waves to produce mechanical vibrations in a liquid medium. The phenomenon is based on the creation and collapse of microscopic bubbles, a process known as cavitation [61]. The effectiveness of ultrasonication in removing contaminants from solid particles relies on the characteristic size of cavitation microjets, generated during the collapse of bubbles [62]. For effective removal, these microjets must be smaller than the size of the particles being cleaned. When bubbles collapse at a frequency of 20 kHz, as commonly used in ultrasonication, the resulting microjets have an average characteristic size in the range of tens of microns. Therefore, for effective removal, the solid particles should ideally have a critical larger than the size of these microjets. During the cleaning of mineral particles from CuO via ultrasonication, it was determined that the critical size, below which ultrasonication had negligible effects, was estimated to be 45 μm [62]. Given that mineral particles in oil sand tailings can be much smaller than this critical size, the effectiveness of ultrasonication for their removal from minerals may be limited. Another drawback of this method is the cost required for the setup and the substantial energy demand, which is only applicable on a laboratory scale [63].

Additionally, the operational costs associated with ultrasonication are significant as it requires specialized equipment and consumes substantial energy, making it less feasible for large-scale applications. Other drawbacks include potential thermal effects on the particles being treated, which may alter their properties [64,65]. These factors may hinder the practicality of ultrasonication as a standalone method for effective bitumen and contaminant removal in oil sand tailings. A possible solution could involve integrating ultrasonication with other separation techniques, such as flotation or centrifugation, to enhance the overall efficiency while mitigating operational costs and maximizing contaminant removal.

3.2. Chemical Methods

Unlike other waste treatment methods, where chemical oxidation is utilized for the removal of hydrocarbons from contaminated samples, chemical oxidation is not a primary method for the removal of bitumen from minerals. This is because oxidized bitumen (brown asphalt) is harder and more viscous compared to unoxidized bitumen [66]. Instead, chemical methods utilize antisolvents, additives, and polymers to separate the mineral particles from bitumen.

Antisolvents, such as hexane, heptane, or their combinations, are employed for segregating asphaltenes from bitumen solutions. The resulting precipitated asphaltenes create network-structured clusters, effectively removing fine mineral solids [67]. Another effective method involves utilizing water droplets in conjunction with chemical additives to separate fine minerals from bitumen. Upon the introduction of water along with additives to the solvent, the fines typically adhere to the water surface and are subsequently collected. Numerous studies have investigated mineral removal using additives including cationic surfactants and water-soluble organics, like formic acid, resorcinol, and chloral hydrate, for the removal of mineral solids [67]. This approach can be combined with antisolvents, resulting in a significant improvement in the efficiency of fine solids separation.

Polymers, such as polyethylene glycol (PEG) and polyacrylamide (PAM), have shown promise in enhancing fine solid removal. They work by bridging the flocculation of fine mineral particles, enlarging their size, and aiding in their separation [68,69]. The literature findings indicate that PAM flocculants exhibit high efficiency in enhancing the settling rate of medium and large solids in tailings [69]. However, they prove ineffective in removing very small particles, particularly those smaller than 44 μm , which are especially evident in high-fine ore tailings [70].

Given these considerations, adopting a combined approach that integrates antisolvents with water-based additives presents a compelling solution for effectively managing oil sand tailings. This synergistic method not only enhances the separation of fine minerals but also reduces the environmental impacts commonly associated with traditional chemical solvents. Ultimately, selecting the most effective cleaning or purification method requires a thorough assessment of the specific context, including factors such as the particle size distribution of the tailings, economic implications, and compliance with environmental regulations. By conducting this comprehensive evaluation, practitioners can identify the approach that best aligns with their operational goals and sustainability standards, leading to more effective hydrocarbon removal from oil sand tailings.

3.3. Biological Methods

Microbial degradation for bitumen removal has been emerging as a promising method for overcoming the challenges associated with conventional physical and chemical methods. Genera such as *Pseudomonas*, *Rhodoferrax*, *Acidovorax*, *Zavarzinia*, and *Methyloversalis* are commonly associated with hydrocarbon degradation in oil sand tailings [71,72] (Table 2).

Table 2. List of bitumen-degrading bacteria.

Microbial Species	Matrix	Target	Growth Conditions	Asphaltenes/NA Degradation Conditions	Degradation Efficiency	Degradation Time	Reference
<i>Bacillus</i> sp.	Oil sand ore	Asphaltenes	Medium: mineral medium + glucose; Working volume: 300 mL; Temperature: 30 °C; Agitation: 150 rpm; Time: 48 h	Medium: 300 g oil sand ore + 200 mL mineral medium + 1 g glucose; Seed volume: 0.5 mL; Temperature: 30 °C; Agitation: 150 rpm	94%	21 days	[73]
<i>Pseudomonas putida</i>	Oil sand pond water (OSPW)	Naphthenic acids	Medium: LB medium; Temperature: 22 °C; Agitation: 200 rpm; Overnight incubation	Medium: OSPW; Temperature: 22 °C; Agitation: 200 rpm	11%	30 days	[74]
<i>Pseudomonas protegens</i>	Oil sand pond water	Naphthenic acids	Medium: LB medium; Temperature: 22 °C; Agitation: 200 rpm; Overnight incubation	Medium: OSPW; Temperature: 22 °C; Agitation: 200 rpm	12%	30 days	[74]
<i>Pseudomonas putida</i> + <i>Pseudomonas protegens</i> (Co-culture)	Oil sand pond water	Naphthenic acids	Medium: LB medium; Temperature: 22 °C; Agitation: 200 rpm; Overnight incubation	Medium: OSPW; Temperature: 22 °C; Agitation: 200 rpm	31%	30 days	[74]
<i>Bacillus</i> sp. + <i>Serratia liquifaciens</i> (Co-culture)	Petroleum hydrocarbon polluted soil	Asphaltenes	Medium: Mineral salt media + 600 mg/L asphaltenic fraction + 50 mg/L yeast extract; Working volume: 25 mL; Temperature: 28 °C; Agitation: 180 rpm; pH: 6.8, grown until culture reached log phase	Medium: Mineral salt media + 600 mg/L asphaltenic fraction + 50 mg/L yeast extract; Seed volume: 0.1 mL; Working volume: 25 mL; Temperature: 28 °C; Agitation: 180 rpm; pH: 6.8	50%	7 days	[75]
<i>Pseudomonas aeruginosa</i> strains (Gx and Fx)	Pure asphalt	Asphaltenes	Medium: beef extract–peptone broth; Working volume: 100 mL; Temperature: 37 °C; Agitation: 150 rpm; 3 days	Medium: beef extract–peptone broth + asphalt covered slide; Seed volume: 10 mL; Temperature: 37 °C; Agitation: Slight agitation 4 times a day	~10% of pure asphalt	Pure asphalt—35 days	[76]
<i>Pseudomonas aeruginosa</i> strains (Gx and Fx)	Crude oil	Asphaltenes	Medium: beef extract–peptone broth; Working volume: 100 mL; Temperature: 37 °C; Agitation: 150 rpm; 3 days	Medium: 200 mL beef extract–peptone broth + 18 g crude oil; Seed volume: 100 mL; Temperature: 37 °C; Agitation: Slight agitation every 3 h during day and every 6 h during night	59%–72% of crude oil asphaltenes	Crude oil—5 days	[76]

Yu et al. evaluated the inherent capability of indigenous microorganisms within tailings to degrade bitumen aerobically, and species like *Rhodoferrax*, *Acidovorax*, and *Pseudomonas* sp. demonstrated potential for the same [71].

In another study, Ding et al. conducted microbial treatment on a low-quality ore by incubating it with *Bacillus subtilis* for 51 days. Subsequent flotation tests revealed a notable enhancement in bitumen recovery, reaching 94% after the microbial treatment on day 21 [73]. The impact of the co-culture on bitumen degradation has also been investigated. Chegounian et al. isolated *Pseudomonas protegens* and *Pseudomonas putida* from tailing samples. *P. protegens*, and *P. putida* could individually decrease the concentration of naphthenic acids (NAs) in the culture media by 11% and 12%, respectively. A co-culture in a 1:1 ratio of these microorganisms exhibited a more significant reduction, achieving a 31% decrease in NAs concentration [74].

Recently, the addition of rhamnolipid biosurfactants has also been reported to accelerate sedimentation in fine tailings, showcasing the potential of biosurfactants in the removal of hydrocarbons from mineral solids [10,77].

While microbial degradation presents a promising alternative, it is essential to conduct a comparative analysis with conventional methods such as flotation, centrifugation, and chemical treatments. Factors such as the effectiveness of bitumen removal, treatment time, cost implications, and environmental impact should be critically assessed. For example, microbial methods may require longer processing times but could offer environmental benefits and lower operational costs in certain contexts. In contrast, chemical methods may achieve rapid results but could pose significant environmental risks. In conclusion, the selection of the most suitable method for bitumen removal from oil sand tailings should consider the identification of the most effective approach for hydrocarbon removal, ensuring a balance between efficiency and sustainability.

4. Bioleaching for Metal Recovery After Bitumen Removal

Once bitumen coating and other hydrocarbons are removed from the minerals in oil sand tailings, the metals within these minerals become accessible for extraction. Traditional methods of metal recovery include pyrometallurgical and hydrometallurgical processes. Pyrometallurgy involves methods such as smelting and vacuum carbon-thermal reduction to recover metals [78,79]. Although effective, these methods are energy-intensive, require expensive equipment, and have significant environmental impacts, limiting their use, particularly in smaller operations. On the other hand, hydrometallurgy uses leaching agents to dissolve metals, followed by processes like precipitation, ion exchange, and electrochemical reduction. It offers advantages such as lower equipment costs and operational ease but also poses environmental challenges, such as the generation of acidic or basic waste and the emission of toxic gasses [80–83].

Bioleaching, a subset of biomining, represents a more environmentally friendly approach, developed to address the negative impacts of pyro- and hydrometallurgical methods. It employs microorganisms for metal recovery, even from very low-grade urban minerals [84]. Interestingly, bioleaching has become a prominent method for metal extraction from diverse sources, such as electronic waste, fly ash, sewage sludge, and contaminated soil, despite their varying complexities [19,20,85–88] (Table 3). However, bioleaching has not yet been utilized for metal recovery from oil sand tailings, highlighting a potential area for future research and application.

In this section, we will discuss the mechanism of bioleaching, followed by the microorganisms present in oil sand tailings with bioleaching potential, followed by the factors that might affect bioleaching in oil sand tailing environments.

Table 3. Application of bioleaching in industrial waste treatment.

Industrial Waste	Metal	Microorganism	Maximum Bioleaching Efficiency (%)	References
Fly ash	Zn, Al, Fe	<i>Aspergillus niger</i>	Zn—98%, Al—97%, Fe—56%	[89]
Sediment	Cr, Cu, Zn	<i>Acidithiobacillus thiooxidans</i>	Cr—25.3%, Cu—71.8%, Zn—58.2%	[90]
Electronic scrap	Zn, Cu, Al, Ni	<i>Thermoplasma acidophilum</i> and <i>Sulfobacillus thermosulfidooxidans</i>	Zn—80%, Cu—86%, Al—64%, Ni—74%	[91]
Spent refinery catalyst	Ni, V	<i>Acidithiobacillus</i> sp.	Ni—83%, V—90%	[92]
Spent fluid cracking catalyst	Al, Ni	<i>Aspergillus niger</i>	Al—54.5%, Ni—58.2%	[93]
Waste electric device	Au	<i>Chromobacterium violaceum</i>	Au—14.9%	[93]
Sewage sludge	Cu, Ni, Zn, Cr	<i>Acidithiobacillus thiooxidans</i>	Cu—64%, Ni—58%, Zn—76%, Cr—52%	[94]
Tannery sludge	Cr	<i>Acidithiobacillus thiooxidans</i>	Cr—99%	[95]
Spent petroleum catalyst	Ni, Mo, V	<i>Acidithiobacillus</i> sp.	Ni—88.3%, Mo—46.3%, V—94.8%	[93]

4.1. Mechanism of Bioleaching

The primary mechanism of bioleaching is attributed to the metabolic activities of certain bacteria, fungi, and microalgae, which possess the ability to catalyze specific chemical reactions that result in the solubilization and mobilization of target metals from their mineral host. The predominant bacteria involved in bioleaching belong to *Acidithiobacillus* and *Leptospirillum* species [15]. These microorganisms exhibit the capability to oxidize ferrous iron (Fe²⁺), sulfur compounds, and/or organic compounds resulting in the production of ferric iron, sulfuric acid, and organic acids. These oxidants (Fe³⁺, H₂SO₄, and organic acids) perform a crucial role in the solubilization of metals. Specifically, *A. thiooxidans* exclusively oxidizes elemental sulfur, *A. ferrooxidans* oxidizes ferrous ions and sulfur compounds, *Leptospirillum ferriphilum* and *Leptospirillum ferrooxidans* oxidize ferrous ions, and *Gluconobacter oxydans* utilize carbon substrates their energy source [96].

Bioleaching is categorized into contact (an electrostatic attachment) and noncontact (planktonic) mechanisms. The contact mechanism involves the adhering of bacteria to the ore surface using extracellular polymeric substances (EPSs), while the noncontact mechanism involves the free-living bacterial stage known as planktonic cells (Figure 3). Overall, bioleaching offers an environmentally friendly alternative to traditional methods by utilizing microbial processes to recover valuable metals efficiently.

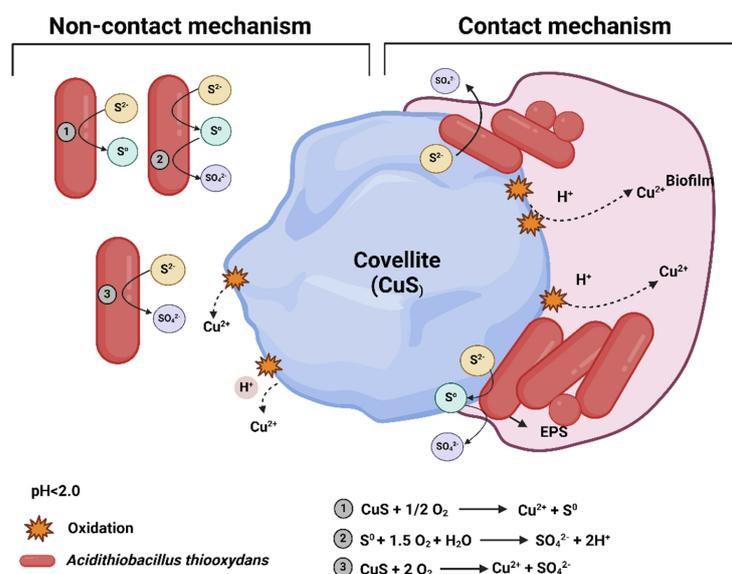


Figure 3. Noncontact and contact bioleaching.

4.2. Microbes with Bioleaching Potential in Oil Sand Tailings

Due to the presence of a low pH and nutrient-poor environment in primary and secondary ores, bioleaching is typically carried out by acidophilic chemolithoautotrophs (Figure 4). In minerals or matrices where sulfur is not present, heterotrophs play an indirect role in mineral dissolution by metabolizing organic compounds and producing organic acids [39]. In the surface layers of oil sand tailings, aerobic microbial sulfide oxidation may take place; however, the tailings are inherently characterized by highly anoxic environments in the deeper layers. This suggests the possible occurrence of anaerobic sulfur oxidation in these conditions [97]. In this section, we will discuss the action of chemolithoautotrophs and heterotrophs in oil sand tailings.

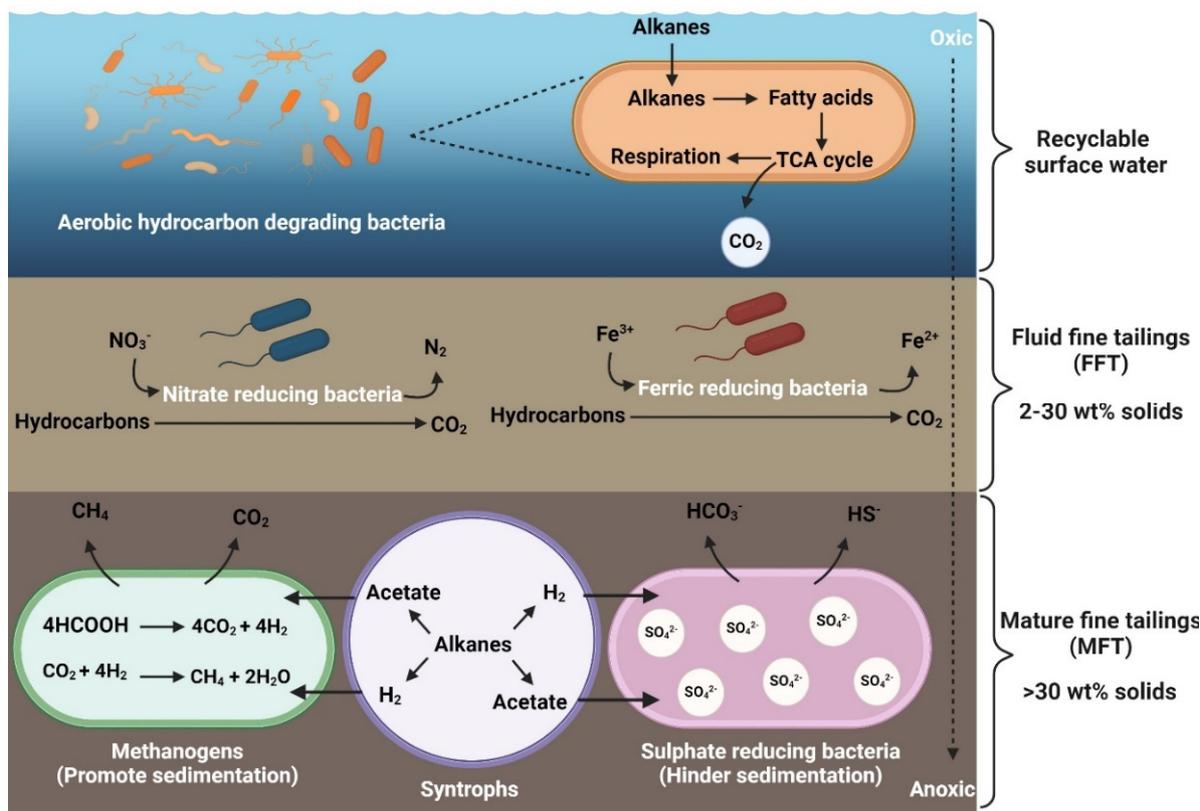


Figure 4. Stratification of oil sand tailing ponds (OSTPs) and their microbiome profiles.

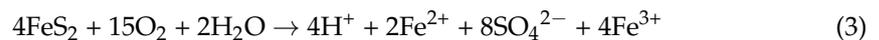
4.2.1. Chemolithoautotrophs in Oil Sand Tailings

Oil sand tailings possess a significant capacity for anaerobic microbial oxidation, exhibiting rates comparable to or even surpassing those observed in other aquatic environments. Sulfur-, iron-, and thiosulfate-oxidizing microbes are the major chemolithotrophs found in oil sand tailings [98]. Dean et al. reported that sulfur-oxidizing microorganisms identified in oil sand tailings are most closely linked to *Achromobacter* spp., *Halothiobacillus neapolitanus*, and *Curtobacterium* spp. [99].

Sulfur-oxidizing bacteria enhance the oxidation of sulfide ores present in the oil sand tailings. This oxidation not only promotes the breakdown of sulfides but also releases additional compounds, influencing the overall redox conditions. For example, pyrite (FeS₂) oxidation within oil sand tailings has the potential to generate acid and release metals [32,100]. The acidification can be described with the help of the following Equations (1) and (2):



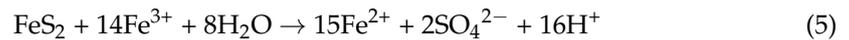
Combining Equations (1) and (2) gives Equation (3):



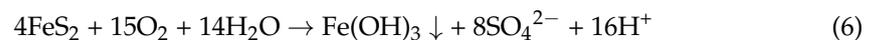
The released Fe^{3+} in Equations (2) and (3) may hydrolyze the ore to generate ferric hydroxide, leading to the precipitation of iron, as shown in Equation (4):



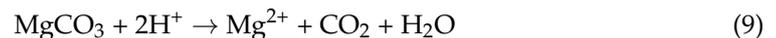
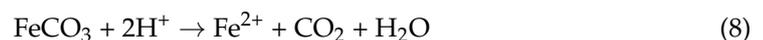
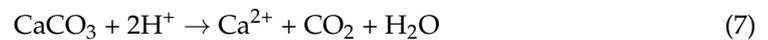
or may lead to the oxidation of additional pyrite, as shown in Equation (5):



Combining Equations (3) and (4) gives Equation (6):



Since the oil sand tailings not only contain pyrite but also other minerals, such as CaCO_3 , FeCO_3 , and MgCO_3 , the acid may react with them, as shown in Equations (7)–(9):



4.2.2. Heterotrophs in Oil Sand Tailings

Oil sand tailings host a variety of heterotrophic microbes with diverse metabolic capabilities, playing crucial roles in the degradation and transformation of organic compounds by producing organic acids.

Mehrabad et al. reported the presence of aerobic methanotroph Gammaproteobacteria (OTU 12 103) in the Alberta oil sand tailings pond. Other methanotrophs like *Methylomonas*, *Crenothrix/Methylosoma*, and *Methylobacter* were also detected, although at lower relative abundances. These microbes are involved in the oxidation of methane and naphthenic acids, showcasing their potential to assist chemolithotrophs in biomining [101].

Apart from aerobic microbes, tailing ponds host several anaerobic microbial communities capable of the methanogenic degradation of solvent hydrocarbons. Anaerobic methanogenic hydrocarbon degradation involves the β -oxidation of naphtha to acetate and H_2 , followed by methane production through acetoclastic or hydrogenotrophic methanogenesis.

In a study by An et al., various taxa, including Actinobacteria and Euryarchaeota, were reported to be engaged in methanogenesis as well as anaerobic hydrocarbon degradation [102]. Furthermore, 16S rRNA gene analysis by Siddique et al. found an increased presence of acetoclastic and hydrogenotrophic methanogens (*Methanosaeta* and *Methanoregula*, respectively) within MFT [103].

Heterotrophic sulfate-reducing bacteria (SRB) are also found in oil sand tailings. These bacteria derive energy through the oxidation of organic compounds while concurrently reducing sulfate to hydrogen sulfide. Sulfate is added to the ponds as gypsum, promoting microbial sulfate reduction, which is crucial for the anaerobic transformation of organic matter and plays a significant role in tailings detoxification and reclamation [104]. In the study by Warren et al., an investigation across all depths of oil sand tailings revealed the identification of ten genera known for sulfate reduction. These included *Clostridium* spp., *Desulfocapsa* spp., and *Desulfuromonas* spp. [105].

Iron-reducing bacteria, such as *Rhodoferrax*, and denitrifying bacteria, such as *Acidovorax*, are associated with anoxic hydrocarbon-contaminated environments, suggesting their involvement in iron reduction and nitrogen cycling in the tailings [106].

4.3. Parameters Affecting Bioleaching

The bioleaching of oil sand tailings is influenced by various parameters that can significantly affect the process's efficiency. Although specific studies on oil sand tailings are limited, insights from research on other mineral ores offer valuable guidance. Two common bioleaching methods, heap leaching and vat/agitation leaching, could be considered for oil sand tailings.

Heap leaching, often used for coarser materials, offers certain advantages, especially in large-scale, low-cost operations. In Alberta's environment, with vast open spaces, heap leaching could be appealing due to the availability of land and the ability to handle large volumes of material. However, the fine-grained nature of oil sand tailings presents some challenges, such as reduced oxygen diffusion and microbial access [1,107]. These factors, combined with Alberta's colder climate, could slow microbial activity and limit the overall bioleaching efficiency in heap systems.

In contrast, vat/agitation leaching may offer more precise control over the bioleaching process, making it better suited for oil sand tailings. This method involves mixing tailings in vats or tanks with continuous agitation, ensuring more effective contact between microorganisms and minerals. The controlled environment allows for the regulation of pH, temperature, and oxygen levels, which is particularly important given the nutrient-poor and low-pH conditions of oil sand tailings [108]. Furthermore, vat/agitation leaching can mitigate the impacts of Alberta's variable weather, providing a more consistent and efficient bioleaching process.

This section outlines key parameters for optimizing bioleaching, drawing from related studies to inform considerations for oil sand tailings

4.3.1. pH

pH plays a pivotal role in bioleaching, significantly impacting its efficiency and outcomes. Acidophilic microorganisms, such as *Acidithiobacillus* spp., are particularly sensitive to pH levels, thriving in acidic environments [109]. The growth of these bacteria is contingent on strain-specific optimal and minimum pH values. For instance, *A. ferrooxidans* exhibits an optimum pH of 2.5 and a minimum pH of 1.3, while *L. ferrooxidans* typically thrive at pH levels around 1.7 and maintain viability at a minimum of 1.0 [110].

In the context of oil sand tailings, where major ores may include metal sulfides like pyrite, maintaining a lower pH range of around 1.5–2.5 might be effective for bioleaching. This aligns with the optimal pH range for iron- and sulfur-oxidizing microorganisms found in oil sand tailings, ensuring enhanced microbial activity and efficient mineral dissolution in the presence of these specific ores. On the other hand, the presence of other clay minerals, such as kaolinite, might require a different pH range for effective bioleaching.

4.3.2. Temperature

The metabolic functions of bioleaching microorganisms, such as bacteria and archaea, are directly impacted by temperature, with most species exhibiting optimal growth within specific temperature ranges. In the study conducted by Lin et al., the optimum temperature for the growth of bioleaching bacteria was determined to be between 20 °C and 30 °C. Maximum bioleaching activity was observed at 28.9 °C, resulting in a sulfate yield of 461.66 (mg/L)/d [111].

In cold regions like Canada, maintaining optimal temperatures for bioleaching can be challenging, especially during winter. While heap leaching, typically used in warmer climates, may face limitations in colder environments, it can be enhanced by incorporating psychrotolerant microorganisms. These microbes can tolerate low temperatures and could facilitate bioleaching processes, making them viable even when maintaining warmth is challenging [112]. Vat/agitation leaching, on the other hand, offers a more controlled environment where temperature can be regulated with heating or insulation systems [108]. This method ensures consistent bioleaching efficiency in such climates. Additionally,

combining vat/agitation leaching with psychrotolerant microbes could further optimize the process for Canada's cold conditions.

In conclusion, targeted research tailored to the mineral composition of oil sand tailings is imperative to precisely determine the optimal temperature conditions for the bioleaching of these materials.

4.3.3. Dissolved Oxygen

Bioleaching typically requires oxygen to support the metabolic activities of acidophilic microorganisms. Oxygen facilitates the oxidation of metal sulfides, leading to the release of metal ions and sulfate. This ion conversion is a fundamental step in the bioleaching mechanism, allowing for the recovery of valuable metals from ores. Several studies report the significance of dissolved oxygen in bioleaching [113,114].

Traditionally, atmospheric air is introduced into the system at low to moderate temperatures to supply the dissolved oxygen needed for microbial activities. However, high concentrations of suspended solids and sulfides demand a greater supply of dissolved oxygen to support optimal bacterial growth. In such cases, using oxygen-enriched air proves beneficial. This approach becomes particularly advantageous when the solid load reaches 20% (*w/w*) as it maintains a consistent dissolved oxygen level in the culture, ranging from 4 to 13 ppm [109].

For oil sand tailings, it is important to understand the unique oxygen conditions present in oil sand tailing ponds (OSTPs). The top layer of OSTPs tends to be oxygenated (oxic), whereas deeper layers gradually become oxygen-deprived (anoxic) as the depth increases [10]. Additionally, the variation in particle size throughout the depth of the oil sand tailings must also be taken into account. Therefore, it is essential to optimize oxygen levels according to the tailing depth for effective bioleaching in OSTPs.

4.3.4. Nutrient Availability

Bioleaching depends on the availability of essential nutrients such as nitrogen, phosphorus, and trace elements. In a study conducted by Zheng et al., it was noted that the addition of over 1.6 g/L of KH_2PO_4 into the tannery sludge successfully promoted *Acidithiobacillus* sp. growth. This supplementation resulted in an increased removal rate of the chromium (Cr) present in the sludge. The results imply that the addition of inorganic phosphate, particularly at the optimal dosage of 1.6 g/L KH_2PO_4 , can expedite the bioleaching process of tannery sludge, especially when dealing with sludge containing 5.1% total solids [115].

In a distinct investigation conducted by Shen et al., the study explored the influence of elemental sulfur concentrations (5 to 40 g/L) while maintaining a constant sludge concentration (40 g/L). The results revealed that higher sulfur concentrations caused a more rapid decrease in sludge pH. It took approximately 15 days to reach the lowest pH, regardless of sulfur concentration. The leaching efficiencies of Cr(III), Fe, and Al increased with higher initial sulfur concentrations. The study identified 20 g/L as the preferred sulfur concentration for chromium leaching, considering economic factors [116].

Considering the influence of nutrients on the bioleaching of oil sand tailings based on the minerals found, it can be inferred that specific nutrients, such as phosphorus and sulfur, may play crucial roles in stimulating microbial activity and enhancing metal solubilization. Further research exploring the optimal nutrient supplementation tailored to the mineral composition of oil sand tailings could offer valuable insights into optimizing bioleaching processes in this context.

4.3.5. Co-Culturing

Co-cultures often exhibit synergistic effects that lead to increased bioleaching efficiency. The collaborative metabolic activities of different microorganisms can enhance the solubilization of metals from ores. In a study by Corbett et al., it was reported that non-sterile conditions, where a phosphate-solubilizing microorganism (PSM) was intro-

duced, a greater mobilization of REEs into the solution was observed compared to sterile conditions. Combining native microbial consortia with an introduced PSM resulted in a synergistic effect, significantly enhancing REE leaching compared to using a single PSM or the indigenous population alone. Experiments with *Penicillium* sp. CF1 on sterile monazite released 12.32 mg L^{-1} of total REEs after 8 days, while on non-sterile ores, double the concentration (23.7 mg L^{-1}) was achieved [117]. In a different study by Fathollahzadeh et al., it was found that the bioleaching capacity of *Enterobacter aerogenes* and *Acidithiobacillus ferrooxidans* to recover REEs from monazite was increased in the co-culture (40 mg/L) compared to their pure cultures (3.97 mg/L and 23.6 mg/L , respectively) [118].

These findings highlight the potential of co-cultures to significantly enhance the bioleaching process, making it a promising approach for the efficient recovery of valuable elements from challenging substrates such as oil sand tailings.

5. Conclusions

Bitumen extraction from the Canadian oil sands has long been a crucial aspect of the global energy industry. However, this extraction process gives rise to oil sand tailings which cause serious environmental concerns, such as GHG emissions, habitat destruction, and water pollution. Despite the challenges, the concept of valorization offers a promising avenue to mitigate environmental impacts and generate economic value by harnessing the valuable minerals present in these tailings.

One notable challenge in this process is the presence of a bitumen coating over the minerals, requiring removal for successful metal extraction. Various methods, including physical, chemical, and biological approaches, can be employed for this purpose. The choice of the most appropriate method depends on various factors, including operational efficiency, cost-effectiveness, and environmental considerations. For example, physical methods tend to be quicker and easier to implement, while chemical methods may achieve thorough bitumen removal but can incur higher costs and pose environmental risks. In contrast, biological approaches offer a more sustainable solution, typically resulting in reduced environmental impacts despite potentially longer processing durations.

Once the bitumen coating has been removed and the mineral is exposed, the metals can be extracted. While traditional methods like pyrometallurgy and hydrometallurgy raise environmental concerns due to high energy consumption and toxic compound release, biomining, particularly bioleaching, emerges as an eco-friendly alternative. Bioleaching, utilizing microbes to release metals from the ore, has been extensively explored in the context of metal extraction from electronic waste and industrial byproducts. However, its application to oil sand tailings remains relatively unexplored. Given the increasing requirements of metals and the untapped potential of oil sand tailings as a resource, bioleaching presents a viable solution.

The utilization of bioleaching for metal extraction from oil sand tailings not only addresses environmental concerns associated with traditional methods, but also presents an economically viable and sustainable pathway. As technological advancements continue, bioleaching holds the promise of transforming oil sand tailings from environmental challenges into valuable resources for a greener and more economically sound future.

Author Contributions: Conceptualization, K.J., S.M., K.K. and S.K.B.; writing—original draft preparation, K.J.; writing—review and editing, K.J., S.M., K.K. and S.K.B.; supervision, S.M. and S.K.B.; funding acquisition, S.M. and S.K.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery Grants (RGPIN-2021-03633; Grant #: DGEER-2021-00458); (RGPIN-2020-06067; RGPIN-2020-06140) and Alliance Mission (ALLRP 570473-2021), as well as James and Joanne Love Chair in Environmental Engineering.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kasperski, K.L.; Mikula, R.J. Waste Streams of Mined Oil Sands: Characteristics and Remediation. *Elements* **2011**, *7*, 387–392. [CrossRef]
2. ST39 | Alberta Energy Regulator. Available online: <https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st39> (accessed on 30 January 2024).
3. ST53 | Alberta Energy Regulator. Available online: <https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st53> (accessed on 30 January 2024).
4. Resources and Data Downloads | Statistical Review of World Energy. Available online: <https://www.energyinst.org/statistical-review/resources-and-data-downloads> (accessed on 30 January 2024).
5. Mamer, M.; Eng, P. *Oil Sands Tailings Technology: Understanding the Impact to Reclamation*; British Columbia Technical and Research Committee on Reclamation: Vancouver, BC, Canada, 2010. [CrossRef]
6. Alberta Energy Regulator. *State of Fluid Tailings Management for Mineable Oil Sands*; Alberta Energy Regulator: Calgary, AB, Canada, 2022.
7. Adamo, N.; Al-Ansari, N.; Sissakian, V.; Laue, J.; Knutsson, S. Dam Safety: The Question of Tailings Dams. *J. Earth Sci. Geotech. Eng.* **2021**, *11*, 1–26. [CrossRef]
8. You, Y.; Staebler, R.M.; Moussa, S.G.; Beck, J.; Mittermeier, R.L. Methane Emissions from an Oil Sands Tailings Pond: A Quantitative Comparison of Fluxes Derived by Different Methods. *Atmos. Meas. Tech.* **2021**, *14*, 1879–1892. [CrossRef]
9. Tenenbaum, D.J. Oil Sands Development: A Health Risk Worth Taking? *Environ. Health Perspect.* **2009**, *117*, A150. [CrossRef]
10. Rezaeitamijani, M.; Mulligan, C.N. *Evaluation of Hydrocarbon Degradation by Indigenous Bacteria Degrade Residual Hydrocarbons of Mature Fine Tailings Under Anaerobic Conditions*; Concordia University: Montreal, QC, Canada, 2022.
11. Generating Cash from Tailings: A “Green Chemistry” Approach to Extracting More Value from the Oil Sands | Oil Sands Magazine. Available online: <https://www.oilsandsmagazine.com/news/2017/6/27/generating-cash-from-tailings-a-green-tech-approach-to-extracting-more-value-from-the-oil-sands> (accessed on 30 January 2024).
12. Roth, E.; Bank, T.; Howard, B.; Granite, E. Rare Earth Elements in Alberta Oil Sand Process Streams. *Energy Fuels* **2017**, *31*, 4714–4720. [CrossRef]
13. Potysz, A.; van Hullebusch, E.D.; Kierczak, J. Perspectives Regarding the Use of Metallurgical Slags as Secondary Metal Resources—A Review of Bioleaching Approaches. *J. Environ. Manag.* **2018**, *219*, 138–152. [CrossRef]
14. Keshavarz, S.; Faraji, F.; Rashchi, F.; Mokmeli, M. Bioleaching of Manganese from a Low-Grade Pyrolusite Ore Using *Aspergillus Niger*: Process Optimization and Kinetic Studies. *J. Environ. Manag.* **2021**, *285*, 112153. [CrossRef]
15. Tezyapar Kara, I.; Kremser, K.; Wagland, S.T.; Coulon, F. Bioleaching Metal-Bearing Wastes and by-Products for Resource Recovery: A Review. *Environ. Chem. Lett.* **2023**, *21*, 3329–3350. [CrossRef]
16. Owusu-Fordjour, E.Y.; Yang, X. Bioleaching of Rare Earth Elements Challenges and Opportunities: A Critical Review. *J. Environ. Chem. Eng.* **2023**, *11*, 110413. [CrossRef]
17. Das, A.P.; Ghosh, S. Role of Microorganisms in Extenuation of Mining and Industrial Wastes. *Geomicrobiol. J.* **2022**, *39*, 173–175. [CrossRef]
18. Schippers, A.; Hedrich, S.; Vasters, J.; Drobe, M.; Sand, W.; Willscher, S. Biomining: Metal Recovery from Ores with Microorganisms. In *Advances in Biochemical Engineering/Biotechnology*; Springer: Berlin/Heidelberg, Germany, 2014; Volume 141, pp. 1–47. [CrossRef]
19. Hanumanthakari, S.; Gift, M.D.M.; Kanimozhi, K.V.; Bhavani, M.D.; Bamane, K.D.; Boopathi, S. Biomining Method to Extract Metal Components Using Computer-Printed Circuit Board E-Waste. In *Handbook of Research on Safe Disposal Methods of Municipal Solid Wastes for a Sustainable Environment*; 1AD; IGI Global: Harrisburg, PA, USA, 2023; pp. 123–141. [CrossRef]
20. Baniyadi, M.; Graves, J.E.; Ray, D.A.; Lindamulage, A.; Silva, D.; Renshaw, D.; Farnaud, S. Closed-Loop Recycling of Copper from Waste Printed Circuit Boards Using Bioleaching and Electrowinning Processes Statement of Novelty. *Waste Biomass-Valorization* **2021**, *12*, 3125–3136. [CrossRef]
21. Willis, C.E.; St Louis, V.L.; Kirk, J.L.; St Pierre, K.A.; Dodge, C. Tailings Ponds of the Athabasca Oil Sands Region, Alberta, Canada, Are Likely Not Significant Sources of Total Mercury and Methylmercury to Nearby Ground and Surface Waters. *Sci. Total. Environ.* **2018**, *647*, 1604–1610. [CrossRef]
22. Van Dongen, A.; Samad, A.; Heshka, N.E.; Rathie, K.; Martineau, C.; Bruant, G.; Degenhardt, D. A Deep Look into the Microbiology and Chemistry of Froth Treatment Tailings: A Review. *Microorganisms* **2021**, *9*, 1091. [CrossRef]
23. Burkus, Z.; Wheler, J.; Pletcher, S. *GHG Emissions from Oil Sands Tailings Ponds: Overview and Modelling Based on Fermentable Substrates. Part I: Review of the Tailings Ponds Facts and Practices*; Alberta Environment and Sustainable Resource Development: Calgary, AB, Canada; University of Alberta: Edmonton, AB, Canada, 2014.
24. Allen, E.W. Process Water Treatment in Canada’s Oil Sands Industry: I. Target Pollutants and Treatment Objectives. *J. Environ. Eng. Sci.* **2008**, *7*, 123–138. [CrossRef]
25. Ding, L.; Azimi, G. Separation of Heavy (Dysprosium) and Light (Praseodymium, Neodymium) Rare Earth Elements Using Electrodialysis. *Hydrometallurgy* **2023**, *222*, 106167. [CrossRef]
26. Siddique, T.; Fedorak, P.M.; Mackinnon, M.D.; Foght, J.M. Metabolism of BTEX and Naphtha Compounds to Methane in Oil Sands Tailings. *Environ. Sci. Technol.* **2007**, *41*, 2350–2356. [CrossRef]

27. Cossey, H.L.; Batycky, A.E.; Kaminsky, H.; Ulrich, A.C. Geochemical Stability of Oil Sands Tailings in Mine Closure Landforms. *Minerals* **2021**, *11*, 830. [CrossRef]
28. Zaman, M.; Nassichuk, B.; Twemlow, C.; Spray, G.; Harder, E.; Hu, P.; Tu, Q. Laboratory Investigation for Critical Minerals, Including REE and Lithium in an Unconventional Source-Oil Sands Tailing. In Proceedings of the GeoConvention, Calgary, AB, Canada, 15–17 May 2023. Available online: <https://geoconvention.com/wp-content/uploads/abstracts/2023/91426-laboratory-investigation-for-criti.pdf> (accessed on 30 January 2024).
29. Dean, C.; Siddiqua, S.; Roberts, D.J. Geotechnical Properties of Polymer-Amended Tailings Solvent Recovery Unit (TSRU) Oil Sands Tailings. *Can. Geotech. J.* **2017**, *54*, 1331–1339. [CrossRef]
30. Nusri, S.; Tan, X.; Choi, P.; Liu, Q. Using Surface Geopolymerization Reactions to Strengthen Athabasca Oil Sands Mature Fine Tailings. *Can. J. Chem. Eng.* **2016**, *94*, 1640–1647. [CrossRef]
31. Demoz, A. Accelerating the Consolidation of Thickened Tailings Using Sand Co-Disposal. *Minerals* **2023**, *13*, 1277. [CrossRef]
32. Lindsay, M.B.J.; Vessey, C.J.; Robertson, J.M. Mineralogy and Geochemistry of Oil Sands Froth Treatment Tailings: Implications for Acid Generation and Metal(Loid) Release. *Appl. Geochem.* **2019**, *102*, 186–196. [CrossRef]
33. Jack, T.R.; Sullivan, E.A.; Zajic, J.E. Leaching of Vanadium and Other Metals from Athabasca Oil Sands Coke and Coke Ash. *Fuel* **1979**, *58*, 589–594. [CrossRef]
34. Geochemical Studies—3; Geochemistry of Some Alberta Shales and Associated Kerogen | Alberta Geological Survey. Available online: <https://ags.aer.ca/publication/ofr-1993-21> (accessed on 17 October 2024).
35. Abdolhazehzad, M. Metal Leaching from Oil Sands Fluid Petroleum Coke Under Different Geochemical Conditions. Ph.D. Thesis, University of Saskatchewan, Saskatoon, SK, Canada, 2020. Available online: <https://harvest.usask.ca/items/84a508b3-428f-42ac-a45b-a347049c8f2c> (accessed on 17 October 2024).
36. Titanium Recovers Valuable Minerals from Oil Sands Waste—Emissions Reduction Alberta. Available online: <https://www.eralberta.ca/story/titanium-recovers-valuable-minerals-from-oil-sands-waste/> (accessed on 17 October 2024).
37. MGX Set to Produce Lithium from Oil Sands Waste—Resource World Magazine. Available online: <https://resourceworld.com/mgx-set-to-produce-lithium-from-oil-sands-waste/> (accessed on 17 October 2024).
38. Stemerowicz, A.; Bruce, R.W.; Sirianni, G.V.; Viens, G.E. Recovery of Vanadium and Nickel from Athabasca Tar Sands Fly Ash. *CIM (Can. Min. Metall.) Bull.* **1976**, *69*, 768.
39. Jones, S.; Santini, J.M. Mechanisms of Bioleaching: Iron and Sulfur Oxidation by Acidophilic Microorganisms. *Essays Biochem.* **2023**, *67*, 685. [CrossRef]
40. Ma, J.; Li, S.; Wang, J.; Jiang, S.; Panchal, B.; Sun, Y. Bioleaching Rare Earth Elements from Coal Fly Ash by *Aspergillus Niger*. *Fuel* **2023**, *354*, 129387. [CrossRef]
41. Qu, Y.; Li, H.; Shi, B.; Gu, H.; Yan, G.; Liu, Z.; Luo, R. Bioleaching Performance of Titanium from Bauxite Residue Under a Continuous Mode Using *Penicillium Tricolor*. *Bull. Environ. Contam. Toxicol.* **2022**, *109*, 61–67. [CrossRef]
42. Bansal, V.; Syed, A.; Bhargava, S.K.; Ahmad, A.; Sastry, M. Zirconia Enrichment in Zircon Sand by Selective Fungus-Mediated Bioleaching of Silica. *Langmuir* **2007**, *23*, 4993–4998. [CrossRef]
43. Wang, X.; Ma, L.; Wu, J.; Xiao, Y.; Tao, J.; Liu, X. Effective Bioleaching of Low-Grade Copper Ores: Insights from Microbial Cross Experiments. *Bioresour. Technol.* **2020**, *308*, 123273. [CrossRef]
44. Brisson, V.L.; Zhuang, W.Q.; Alvarez-Cohen, L. Bioleaching of Rare Earth Elements from Monazite Sand. *Biotechnol. Bioeng.* **2016**, *113*, 339–348. [CrossRef]
45. Hedrich, S.; Breuker, A.; Martin, M.; Schippers, A. Rare Earth Elements (Bio)Leaching from Zircon and Eudialyte Concentrates. *Hydrometallurgy* **2023**, *219*, 106068. [CrossRef]
46. Moran, K.; Doiron, J.; Hill, A.; Sishla, C. Production of Heavy Minerals Concentrate and Bitumen from Oil Sands Froth Treatment Tailings. *Can. J. Chem. Eng.* **2013**, *91*, 1383–1394. [CrossRef]
47. Majid, A.; Toll, F.; Sparks, B.D.; Turak, A. *Centrifuge Tailings from Oil Sands Plants—A Resource Material for Titanium and Zirconium*; National Research Council: Ottawa, ON, Canada, 1998.
48. Foght, J.M.; Gieg, L.M.; Siddique, T.; Foght, J. The Microbiology of Oil Sands Tailings: Past, Present, Future. *FEMS Microbiol. Ecol.* **2017**, *93*, 34. [CrossRef] [PubMed]
49. Mbadozie, O.; Ben-Awuah, E. *Incorporation of Geo-Metallurgical and Geochemical Properties in Oil Sands Mine Planning and Waste Management*; Mining Optimization Laboratory: Edmonton, AB, Canada, 2018.
50. Chen, Q.; Liu, Q. Bitumen Coating on Oil Sands Clay Minerals: A Review. *Energy Fuels* **2019**, *33*, 5933–5943. [CrossRef]
51. Rand, B. Calcination. In *Concise Encyclopedia of Advanced Ceramic Materials*; Springer: Berlin/Heidelberg, Germany, 1991; pp. 49–51. [CrossRef]
52. Oxenford, J. *Heavy Minerals from Alberta's Oil Sands*; Canadian Institute of Mining: Montreal, QC, Canada, 2001.
53. Trevoy, L.W.; Schutte, R. A New Source of Heavy Minerals from Canadian Oil Sands Mining Operations. Preprint, Annual Meeting of SME/AIME. 1981. Available online: <https://g.co/kgs/quEPNey> (accessed on 30 January 2024).
54. Holloway, P.C.; Etsell, T.H. Transformational Roasting in the Treatment of Metallurgical Wastes. *Miner. Process. Extr. Metall.* **2008**, *117*, 23–31. [CrossRef]
55. Liu, Q.; Cui, Z.; Etsell, T.H. Pre-Concentration and Residual Bitumen Removal from Athabasca Oilsands Froth Treatment Tailings by a Falcon Centrifugal Concentrator. *Int. J. Miner. Process* **2006**, *78*, 220–230. [CrossRef]

56. Ityokumbul, M.T.; Bulani, W.; Kosaric, N. Economic and Environmental Benefits from Froth Flotation Recovery of Titanium, Zirconium, Iron and Rare Earth Minerals from Oilsand Tailings. *Water Sci. Technol.* **1987**, *19*, 323–331. [[CrossRef](#)]
57. Cui, Z.; Liu, Q.; Etsell, T.H. Magnetic Properties of Ilmenite, Hematite and Oilsand Minerals after Roasting. *Miner. Eng.* **2002**, *15*, 1121–1129. [[CrossRef](#)]
58. Flotation Technology. *Flotation Technology*; Springer: Berlin/Heidelberg, Germany, 2010. [[CrossRef](#)]
59. Zhou, J.; Li, H.; Zhao, L.; Chow, R. Role of Mineral Flotation Technology in Improving Bitumen Extraction from Mined Athabasca Oil Sands: I. Flotation Chemistry of Water-Based Oil Sand Extraction. *Can. J. Chem. Eng.* **2018**, *96*, 1986–1999. [[CrossRef](#)]
60. Chapter 3: Centrifugation. *Lab. Tech. Biochem. Mol. Biol.* **1988**, *18*, 18–69. [[CrossRef](#)]
61. Ghamartale, A.; Afzali, S.; Rezaei, N.; Zendejboudi, S. *Asphaltene Deposition Control by Chemical Inhibitors: Theoretical and Practical Prospects*; Elsevier: Amsterdam, The Netherlands, 2021; ISBN 9780323905107.
62. Abramov, O.; Abramov, V.; Myasnikov, S.; Mullakae, M. Extraction of Bitumen, Crude Oil and Its Products from Tar Sand and Contaminated Sandy Soil under Effect of Ultrasound. *Ultrason. Sonochem.* **2008**, *16*, 408–416. [[CrossRef](#)]
63. Ahmed, S.; Kumari, K.; Singh, D. Different Strategies and Bio-Removal Mechanisms of Petroleum Hydrocarbons from Contaminated Sites. *Arab. Gulf J. Sci. Res.* **2023**; ahead-of-print. [[CrossRef](#)]
64. Büks, F.; Kayser, G.; Zieger, A.; Lang, F.; Kaupenjohann, M. Particles under Stress: Ultrasonication Causes Size and Recovery Rate Artifacts with Soil-Derived POM but Not with Microplastics. *Biogeosciences* **2021**, *18*, 159–167. [[CrossRef](#)]
65. Dnyaneshwar Patil, N.; Bains, A.; Kaur, S.; Yadav, R.; Ali, N.; Patil, S.; Goksen, G.; Chawla, P. Influence of Dual Succinylation and Ultrasonication Modification on the Amino Acid Content, Structural and Functional Properties of Chickpea (*Cicer arietinum* L.) Protein Concentrate. *Food Chem.* **2024**, *445*, 138671. [[CrossRef](#)] [[PubMed](#)]
66. Soenen, H.; Lu, X.; Laukkanen, O.-V. Oxidation of Bitumen: Molecular Characterization and Influence on Rheological Properties. *Rheol. Acta* **2016**, *55*, 315–326. [[CrossRef](#)]
67. Zhang, Z.; Allen, L.; Podder, P.; Free, M.L.; Sarswat, P.K. Recovery and Enhanced Upgrading of Rare Earth Elements from Coal-Based Resources: Bioleaching and Precipitation. *Minerals* **2021**, *11*, 484. [[CrossRef](#)]
68. Zhang, H.; Tan, X.; Liu, Q. Fine Solids Removal from Non-Aqueous Extraction Bitumen: A Literature Review. *Fuel* **2021**, *288*, 119727. [[CrossRef](#)]
69. Abdulnabi, A.; Amoako, K.; Moran, D.; Vanadara, K.; Aldaeef, A.A.; Esmailzadeh, A.; Beier, N.; Soares, J.; Simms, P. Evaluation of Candidate Polymers to Maximize Geotechnical Performance of Oil Sands Tailings. *Can. Geotech. J.* **2022**, *59*, 359–371. [[CrossRef](#)]
70. Vedoy, D.R.L.; Soares, J.B.P. Water-Soluble Polymers for Oil Sands Tailing Treatment: A Review. *Can. J. Chem. Eng.* **2015**, *93*, 888–904. [[CrossRef](#)]
71. Yu, X.; Lee, K.; Ma, B.; Asiedu, E.; Ulrich, A.C. Indigenous Microorganisms Residing in Oil Sands Tailings Biodegrade Residual Bitumen. *Chemosphere* **2018**, *209*, 551–559. [[CrossRef](#)]
72. Rochman, F.F.; Sheremet, A.; Tamas, I.; Saidi-Mehrabad, A.; Kim, J.J.; Dong, X.; Sensen, C.W.; Gieg, L.M.; Dunfield, P.F. Benzene and Naphthalene Degrading Bacterial Communities in an Oil Sands Tailings Pond. *Front. Microbiol.* **2017**, *8*, 1845. [[CrossRef](#)]
73. Ding, M.-S.; Jia, W.-H.; Lv, Z.-F.; Ren, S.-L. Improving Bitumen Recovery from Poor Processing Oil Sands Using Microbial Pretreatment. *Energy Fuels* **2014**, *28*, 7712–7720. [[CrossRef](#)]
74. Chegounian, P.; Flibotte, S.; Peru, K.; Headley, J.; McMartin, D.; Gramlich, B.; Yadav, V.G. Transcriptome Analysis of Environmental Pseudomonas Isolates Reveals Mechanisms of Biodegradation of Naphthenic Acid Fraction Compounds (NAFCs) in Oil Sands Tailings. *Microorganisms* **2021**, *9*, 2124. [[CrossRef](#)] [[PubMed](#)]
75. Rojas-Avelizapa, N.G.; Cervantes-Gonzalez, E.; Cruz-Camarillo, R.; Rojas-Avelizapa, L.I. Degradation of Aromatic and Asphaltenic Fractions by *Serratia liquefaciens* and *Bacillus* sp. *Bull. Environ. Contam. Toxicol.* **2002**, *69*, 835–842. [[CrossRef](#)] [[PubMed](#)]
76. Gao, H.; Zhang, J.; Lai, H.; Xue, Q. Degradation of Asphaltenes by Two Pseudomonas Aeruginosa Strains and Their Effects on Physicochemical Properties of Crude Oil. *Int. Biodeterior. Biodegrad.* **2017**, *122*, 12–22. [[CrossRef](#)]
77. Mulligan, C.N. Sustainable Remediation of Contaminated Soil Using Biosurfactants. *Front. Bioeng. Biotechnol.* **2021**, *9*, 635196. [[CrossRef](#)]
78. Gomez-Bueno, C.O.; Spink, D.R.; Rempel, G.L. Extraction of Vanadium from Athabasca Tar Sands Fly Ash. *Metall. Trans. B* **1981**, *12*, 341–352. [[CrossRef](#)]
79. Feng, J. *Feasibility of Utilizing Oil-Sands Fluid Coke as a Secondary Source of Vanadium*; University of Toronto: Toronto, ON, Canada, 2017.
80. Willner, J.; Fornalczyk, A.; Cebulski, J.; Janiszewski, K. Preliminary Studies on Simultaneous Recovery of Precious Metals from Different Waste Materials by Pyrometallurgical Method. *Arch. Metall. Mater.* **2014**, *59*, 801–804. [[CrossRef](#)]
81. Wędrychowicz, M.; Piotrowicz, A.; Skrzekut, T.; Noga, P.; Bydalek, A. Recovery of Non-Ferrous Metals from PCBs Scrap by Liqutation from Lead. *Materials* **2022**, *15*, 2089. [[CrossRef](#)]
82. Ghassa, S.; Noaparast, M.; Shafaei, S.Z.; Abdollahi, H.; Gharib, F.; Magdouli, S. Optimization of Pyrite Bio-Oxidation to Produce Ferric Reagent for Sphalerite Leaching. *J. Hazard. Toxic. Radioact. Waste* **2022**, *26*, 04021035. [[CrossRef](#)]
83. Wang, L.; Liu, S.; Vishnyakov, A. Vanadium and Nickel Recovery from the Products of Heavy Petroleum Feedstock Processing: A Review. *Metals* **2023**, *13*, 1031. [[CrossRef](#)]
84. Ehrlich, H.L. Past, Present and Future of Biohydrometallurgy. *Hydrometallurgy* **2001**, *59*, 127–134. [[CrossRef](#)]

85. Tay, S.B.; Natarajan, G.; Rahim, M.N.B.A.; Tan, H.T.; Chung, M.C.M.; Ting, Y.P.; Yew, W.S. Enhancing Gold Recovery from Electronic Waste via Lixiviant Metabolic Engineering in *Chromobacterium Violaceum*. *Sci. Rep.* **2013**, *3*, 2236. [[CrossRef](#)] [[PubMed](#)]
86. Mata, Y.N.; Torres, E.; Blázquez, M.L.; Ballester, A.; González, F.; Muñoz, J.A. Gold(III) Biosorption and Bioreduction with the Brown Alga *Fucus Vesiculosus*. *J. Hazard. Mater.* **2009**, *166*, 612–618. [[CrossRef](#)] [[PubMed](#)]
87. Mishra, D.; Rhee, Y.-H. Current Research Trends of Microbiological Leaching for Metal Recovery from Industrial Wastes. *Curr. Res. Technol. Educ. Top. Appl. Microbiol. Microb. Biotechnol.* **2010**, *2*, 1289–1296.
88. Kamizela, T.; Worwag, M. Processing of Water Treatment Sludge by Bioleaching. *Energies* **2020**, *13*, 6539. [[CrossRef](#)]
89. Xu, T.-J.; Ting, Y.-P. Fungal Bioleaching of Incineration Fly Ash: Metal Extraction and Modeling Growth Kinetics. *Enzym. Microb. Technol.* **2009**, *44*, 323–328. [[CrossRef](#)]
90. Fang, D.; Zhao, L.; Yang, Z.; Shan, H.; Gao, Y.; Yang, Q. Environmental Technology Effect of Sulphur Concentration on Bioleaching of Heavy Metals from Contaminated Dredged Sediments Effect of Sulphur Concentration on Bioleaching of Heavy Metals from Contaminated Dredged Sediments. *Environ. Technol.* **2009**, *30*, 1241–1248. [[CrossRef](#)]
91. Ilyas, S.; Ruan, C.; Bhatti, H.N.; Ghauri, M.A.; Anwar, M.A. Column Bioleaching of Metals from Electronic Scrap. *Hydrometallurgy* **2009**, *101*, 135–140. [[CrossRef](#)]
92. Beolchini, F.; Fonti, V.; Ferella, F.; Vegliò, F. Metal Recovery from Spent Refinery Catalysts by Means of Biotechnological Strategies. *J. Hazard. Mater.* **2010**, *178*, 529–534. [[CrossRef](#)]
93. Faramarzi, M.A.; Stagars, M.; Pensini, E.; Krebs, W.; Brandl, H. Metal Solubilization from Metal-Containing Solid Materials by Cyanogenic *Chromobacterium Violaceum*. *J. Biotechnol.* **2004**, *113*, 321–326. [[CrossRef](#)]
94. Pathak, A.; Dastidar, M.G.; Sreekrishnan, T.R. Bioleaching of Heavy Metals from Sewage Sludge by Indigenous Iron-Oxidizing Microorganisms Using Ammonium Ferrous Sulfate and Ferrous Sulfate as Energy Sources: A Comparative Study. *J. Hazard. Mater.* **2009**, *171*, 273–278. [[CrossRef](#)] [[PubMed](#)]
95. Wang, Y.-S.; Pan, Z.-Y.; Lang, J.-M.; Xu, J.-M.; Zheng, Y.-G. Bioleaching of Chromium from Tannery Sludge by Indigenous *Acidithiobacillus Thiooxidans*. *J. Hazard. Mater.* **2007**, *147*, 319–324. [[CrossRef](#)] [[PubMed](#)]
96. Aston, J.E.; Thompson, V.S.; Fujita, Y.; Reed, D.W. Metabolic Flux Modeling of *Gluconobacter Oxydans* Enables Improved Production of Bioleaching Organic Acids. *Process Biochem.* **2022**, *122*, 350–356. [[CrossRef](#)]
97. Arriaga, D.; Nelson, T.C.; Risacher, F.F.; Morris, P.K.; Goad, C.; Slater, G.F.; Warren, L.A. The Co-Importance of Physical Mixing and Biogeochemical Consumption in Controlling Water Cap Oxygen Levels in Base Mine Lake. *Appl. Geochem.* **2019**, *111*, 104442. [[CrossRef](#)]
98. Stasik, S.; Schmidt, J.; Wendt-Potthoff, K. High Potential for Anaerobic Microbial Sulfur Oxidation in Oil Sands Tailings Ponds. *Microorganisms* **2021**, *9*, 2529. [[CrossRef](#)]
99. Dean, C.; Xiao, Y.; Roberts, D.J. Enriching Acid Rock Drainage Related Microbial Communities from Surface-Deposited Oil Sands Tailings. *Can. J. Microbiol.* **2016**, *62*, 870–879. [[CrossRef](#)]
100. Xu, Y. A Study of Pyrite Acidification in Oil Sand Froth Treatment Tailings Deposits. *Int. J. Environ. Sci. Nat. Resour.* **2021**, *27*, 556218. [[CrossRef](#)]
101. Saidi-Mehrabad, A.; He, Z.; Tamas, I.; Sharp, C.E.; Brady, A.L.; Rochman, F.F.; Bodrossy, L.; Abell, G.C.J.; Penner, T.; Dong, X.; et al. Methanotrophic Bacteria in Oilsands Tailings Ponds of Northern Alberta. *ISME J.* **2012**, *7*, 908–921. [[CrossRef](#)]
102. An, D.; Brown, D.; Chatterjee, I.; Dong, X.; Ramos-Padron, E.; Wilson, S.; Bordenave, S.; Caffrey, S.M.; Gieg, L.M.; Sensen, C.W.; et al. Microbial Community and Potential Functional Gene Diversity Involved in Anaerobic Hydrocarbon Degradation and Methanogenesis in an Oil Sands Tailings Pond. *Genome* **2013**, *56*, 612–618. [[CrossRef](#)]
103. Siddique, T.; Mohamad Shahimin, M.F.; Zamir, S.; Semple, K.; Li, C.; Foght, J.M. Long-Term Incubation Reveals Methanogenic Biodegradation of C5 and C6 Iso-Alkanes in Oil Sands Tailings. *Environ. Sci. Technol.* **2015**, *49*, 14732–14739. [[CrossRef](#)]
104. Stasik, S.; Wendt-Potthoff, K. Sulfur Cycling in an Oil Sands Tailings Pond. In Proceedings of the IMWA 2016—Mining Meets Water—Conflicts and Solutions, Leipzig, Germany, 11–15 July 2016.
105. Warren, L.A.; Kendra, K.E.; Brady, A.L.; Slater, G.F. Sulfur Biogeochemistry of an Oil Sands Composite Tailings Deposit. *Front. Microbiol.* **2016**, *6*, 170243. [[CrossRef](#)]
106. Golby, S.; Ceri, H.; Gieg, L.M.; Chatterjee, I.; Marques, L.L.R.; Turner, R.J. Evaluation of Microbial Biofilm Communities from an Alberta Oil Sands Tailings Pond. *FEMS Microbiol. Ecol.* **2012**, *79*, 240–250. [[CrossRef](#)]
107. Thenepalli, T.; Chilakala, R.; Habte, L.; Tuan, L.Q.; Kim, C.S. A Brief Note on the Heap Leaching Technologies for the Recovery of Valuable Metals. *Sustainability* **2019**, *11*, 3347. [[CrossRef](#)]
108. Kaksonen, A.H.; Boxall, N.J.; Bohu, T.; Usher, K.; Morris, C.; Wong, P.Y.; Cheng, K.Y. Recent Advances in Biomining and Microbial Characterisation. *Solid State Phenom.* **2017**, *262*, 33–37. [[CrossRef](#)]
109. Vo, P.H.N.; Danaee, S.; Hai, H.T.N.; Huy, L.N.; Nguyen, T.A.H.; Nguyen, H.T.M.; Kuzhiumparambil, U.; Kim, M.; Nghiem, L.D.; Ralph, P.J. Biomining for Sustainable Recovery of Rare Earth Elements from Mining Waste: A Comprehensive Review. *Sci. Total Environ.* **2024**, *908*, 168210. [[CrossRef](#)] [[PubMed](#)]
110. Yahya, A.; Johnson, D.B. Bioleaching of Pyrite at Low PH and Low Redox Potentials by Novel Mesophilic Gram-Positive Bacteria. *Hydrometallurgy* **2002**, *63*, 181–188. [[CrossRef](#)]

111. Lin, H.; Huang, M.; Huang, H. Effect of Temperature on Bioleaching Heavy Metals from Sewage Sludge. In Proceedings of the 2010 4th International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2010, Chengdu, China, 18–20 June 2010. [[CrossRef](#)]
112. Seitkamal, K.N.; Zhappar, N.K.; Shaikhutdinov, V.M.; Shibayeva, A.K.; Ilyas, S.; Korolkov, I.V.; Kim, H. Bioleaching for the Removal of Arsenic from Mine Tailings by Psychrotolerant and Mesophilic Microbes at Markedly Continental Climate Temperatures. *Minerals* **2020**, *10*, 972. [[CrossRef](#)]
113. Li, Y.B.; Song, J.L.; Yao, Q.J.; Chen, Z.X.; Wei, Y.; Li, H.L.; Wang, M.X.; Wang, B.J.; Zhou, J.M. Effects of Dissolved Oxygen on the Sludge Dewaterability and Extracellular Polymeric Substances Distribution by Bioleaching. *Chemosphere* **2021**, *281*, 130906. [[CrossRef](#)]
114. Sun, L.X.; Zhang, X.; Tan, W.S.; Zhu, M.L. Effects of Dissolved Oxygen on the Biooxidation Process of Refractory Gold Ores. *J. Biosci. Bioeng.* **2012**, *114*, 531–536. [[CrossRef](#)]
115. Zheng, G.; Zhou, L. Supplementation of Inorganic Phosphate Enhancing the Removal Efficiency of Tannery Sludge-Borne Cr through Bioleaching. *Water Res.* **2011**, *45*, 5295–5301. [[CrossRef](#)]
116. Shen, S.B.; Vidyarthi, A.S.; Tyagi, R.D.; Blais, J.F.; Surampalli, R.Y. Effect of Sulphur Concentration on Bioleaching of Cr(III) and Other Metals from Tannery Sludge by Indigenous Sulphur-Oxidizing Bacteria. *Pract. Period. Hazard. Toxic Radioact. Waste Manag.* **2002**, *6*, 244–249. [[CrossRef](#)]
117. Corbett, M.K.; Eksteen, J.J.; Niu, X.-Z.; Watkin, E.L.J. Syntrophic Effect of Indigenous and Inoculated Microorganisms in the Leaching of Rare Earth Elements from Western Australian Monazite. *Res. Microbiol.* **2018**, *169*, 558–568. [[CrossRef](#)] [[PubMed](#)]
118. Fathollahzadeh, H.; Hackett, M.J.; Khaleque, H.N.; Eksteen, J.J.; Kaksonen, A.H.; Watkin, E.L.J. Better Together: Potential of Co-Culture Microorganisms to Enhance Bioleaching of Rare Earth Elements from Monazite. *Technol. Rep.* **2018**, *3*, 109–118. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.