Microwave Treatment of Minerals and Ores: Heating Behaviors, Applications, and Future Directions

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Abstract: The application of microwave technology in mineral metallurgy is a transformative approach to ore processing that offers new ideas about the current progressive depletion of resources and the environmental impact of mineral processing. This review delves into the principles, applications, and future directions of microwave treatment in mineral and ore processing. Microwave technology, characterized by its unique advantages such as rapid and uniform heating, selective heating, and energy efficiency, stands in contrast to traditional heating methods. It directly interacts with materials at the molecular level, enabling volumetric heating. The review encompasses a wide range of applications, including ore pre-treatment, drying, mineral processing, hydrometallurgy, smelting, and reduction. It highlights the role of microwave treatment in enhancing metal recovery, reducing energy consumption, and improving processing speeds. Future research directions are identified, focusing on enhanced equipment design, process optimization, integration with conventional methods, and technological innovations. The comprehensive overview assists researchers, engineers, and decision-makers in understanding the potential of microwave technology in mineral metallurgy, emphasizing its contribution to innovation and sustainability in the sector.

Keywords: microwave; mineral; applications; future directions

1. Introduction

Mineral metallurgy, a vital sector in global mineral resource development and metal production, involves extracting various ores from nature and transforming them into valuable metals and alloys [1–3]. With the increasing depletion of mineral resources and rising environmental concerns, the industry faces ongoing challenges that demand continuous innovation and improvement in processing methods [4,5]. These methods aim to enhance resource utilization efficiency, reduce energy consumption, and mitigate environmental impacts. Against this backdrop, microwave technology has emerged as a rapidly developing solution, gaining widespread attention and application in mineral metallurgy. This technology, operating in a frequency range of 300 MHz to 300 GHz, offers advantages over traditional heating methods, including rapid, uniform, selective heating and energy savings [6–8]. Such attributes grant microwave technology a broad spectrum of applications in mineral metallurgy [9,10]. Microwave heating differs fundamentally from conventional methods, quickly penetrating materials and interacting with their molecular and crystalline structures [11,12]. This interaction causes molecular vibration and frictional heating, making it more efficient than conduction heating [13,14]. Microwaves also ensure uniform heating, reducing thermal conduction delays and enhancing processing speed and quality [15,16]. This is particularly important for applications like ore drying, metal smelting, and ore pre-treatment. Another significant advantage of microwave technology is its selective heating feature [17]. The microwave wavelength’s correlation with the dielectric constant of heated materials allows for targeted heating effects, offering substantial...
benefits in ore processing [18]. Selective heating enhances the efficiency and recovery rates in metal extraction and pre-treatment processes [19,20]. The aim of this review is to provide a comprehensive guide that delves deeply into the application of microwave technology in mineral metallurgy, encompassing its heating mechanisms, processing methods, and future prospects. Initially, the fundamental principles of microwave heating will be explored, including the interactions between microwaves and materials, dielectricity, and conductivity aspects. This will aid readers in understanding how microwave technology impacts the field of mineral metallurgy. Following this, the specific applications of microwave technology in ore processing will be examined, including ore drying, metal extraction, ore pre-treatment, and environmentally friendly processing methods. The review will investigate how microwaves can enhance the efficiency of these processes, reduce energy consumption, and improve product quality. Subsequently, the future directions and trends of microwave technology in mineral metallurgy will be looked into, including the application of emerging technologies, digital control and automation, and potential contributions to sustainable development.

Through this review, researchers, engineers, and decision-makers in mineral metallurgy are provided with an in-depth guide to understanding the potential and prospects of microwave technology in this field. This will foster innovation and sustainable development in ore processing and metal production. The ongoing evolution of microwave technology will present new opportunities for the mineral metallurgy industry to enhance efficiency, reduce costs, and take greater strides on the path to sustainability.

2. Principles of Microwave Heating

Before delving into the various applications and future prospects of microwave heating, it is crucial to grasp the fundamental principles of this technology. Microwaves are electromagnetic waves with specific energy levels, which depend on the microwave frequency and the strength of the electromagnetic field transmitted. In a high-frequency microwave field, polar molecules become polarized and oscillate at high frequencies along with the alternating electromagnetic field, resulting in the rapid oscillation of molecules and interactions between them. This converts the lost electromagnetic energy into thermal energy in the material [21].

2.1. Material Absorption of Microwave Power

The power absorbed by a unit volume of medium from microwaves is given by Equation (1) [22]:

\[ P = \sigma E^2 = 2\pi\varepsilon_0\varepsilon'' E^2 = 2\pi f\varepsilon_0\varepsilon'\tan\delta E^2 \]  

where \( P \) is the power absorbed per unit material in the microwave field, measured in W/cm\(^3\); \( E \) is the electric-field strength, in V/cm; \( \sigma \) is the electrical conductivity; \( f \) is the microwave frequency; \( \varepsilon_0 \) is the permittivity of the vacuum \( (8.854 \times 10^{-14} \text{ F/cm}) \); \( \varepsilon'' \) is the dielectric-loss factor; \( \varepsilon' \) is the dielectric constant; and \( \tan\delta \) is the tangent of the dielectric-loss angle.

Equation (1) indicates that the microwave power absorbed by the heated material is directly proportional to the square of the electric-field strength and the dielectric-loss coefficient of the material, where the electric-field strength relates to the microwave power, and the dielectric-loss coefficient is dependent on its compositional properties. This equation is critical for understanding the power absorption of materials subjected to microwave radiation. It quantifies how microwaves transfer energy to a material, which is fundamental in applications like microwave heating in mineral processing. In comparison with other studies, this equation has been instrumental in analyzing and optimizing microwave heating processes across different materials and industries. It provides a theoretical basis for tailoring microwave processing conditions to specific materials’ properties.

2.2. Dielectric Parameters

In microwave heating, the material’s ability to absorb microwaves is primarily described through its dielectric properties, represented by the composite dielectric constant.
(\varepsilon^*), dielectric constant (\varepsilon'), loss factor (\varepsilon''), and tangent of the dielectric-loss angle (\tan \delta), which are related as follows [23,24]:

\begin{align}
\varepsilon^* &= \varepsilon' - i\varepsilon'' \\
\tan \delta &= \frac{\varepsilon''}{\varepsilon'}
\end{align}

(2)

(3)

where \(\varepsilon^*\) is the composite dielectric constant, comprising a real part and an imaginary part as shown in Equation (2); \(\varepsilon'\) is the real part, indicating the material’s capacity to absorb and store electromagnetic energy; \(\varepsilon''\) is the imaginary part, representing the ability to convert microwave energy into thermal energy; and \(\tan \delta\) is the ratio of the loss factor to the dielectric constant, describing the efficiency of the material in converting absorbed microwave energy into thermal energy [25].

2.3. Material Heating Rate

The heating rate of a sample heated by microwaves, considering thermal losses and reaction heat, can be described by the following equation [25]:

\[
\frac{dT}{dt} = \frac{1}{\rho C_p} \left( 2\pi f \varepsilon_0 \varepsilon'' E^2 - \frac{eaA}{V} T^4 - \sum_{i=1}^{m} n_i \Delta H_{i}^{0} \frac{dF_i}{dt} \right)
\]

(4)

where \(T\) is the temperature (K); \(t\) is time (s); \(\rho\) is the material density (kg/m\(^3\)); \(V\) is the material volume (m\(^3\)); \(C_p\) is the specific heat capacity of the material (J/(kg·K)); \(A\) is the material surface area (m\(^2\)); \(e\) is the heat-dissipation coefficient; \(a\) is the Boltzmann constant (W/(m\(^2\)·K\(^4\))); \(n_i\) is the molar amount of the \(i\)-th component per unit volume; \(F_i\) is the conversion rate of the \(i\)-th component; and \(n_i \Delta H_{i}^{0}\) is the thermal effect of the \(i\)-th component’s chemical reaction (J/mol).

2.4. Microwave Penetration Depth

As microwaves penetrate a material medium, their energy diminishes due to the absorption by the material. The distance from the surface of the material at which the energy of the microwaves decreases to \(E_m^{-1}\) times that at the surface is defined as the penetration depth \((d_p)\) in the medium. The relationship between the dielectric constant and the penetration depth is shown in Equation (5) [26]:

\[
d_p = \frac{1}{4\pi f \sqrt{\mu_0 \varepsilon_0 \varepsilon'/2} \sqrt{1 + (\varepsilon''/\varepsilon')^2 - 1}}
\]

(5)

where \(d_p\) is the penetration depth of microwaves in the material medium, measured in meters; \(\mu_0\) is the magnetic permeability of the vacuum \((\mu_0 = 1.2566 \times 10^{-6} \text{ H/m})\); \(\varepsilon_0\) is the permittivity of the vacuum, \(\varepsilon_0 = 1/(\mu_0 c^2)\), with \(c\) being the speed of electromagnetic waves in air; \(c = 3 \times 10^8 \text{ m/s}\); Thus \(\varepsilon_0 = 8.854 \times 10^{-12} \text{F/m}\); \(f\) is the microwave frequency, which is commonly 915 MHz and 2450 MHz in industrial applications. Substituting Equation (3) and the above constants into Equation (5), the penetration depth \(d_p\) of microwaves in the material medium can be simplified to Equation (6):

\[
d_p = \frac{0.013770706}{\sqrt{1 + (\tan \delta)^2 - 1}}
\]

(6)

When the size of the heated material is smaller than the penetration depth \(d_p\) of microwaves in the material, the material size has little influence on microwave heating, and uniform heating can be achieved throughout the material. Conversely, when the size of the heated material is larger than the penetration depth \(d_p\), uniform heating throughout the material cannot be achieved [27].
Based on the above, the interaction of microwaves with materials can be categorized as three types [28]:

1. The first type is microwave-transparent, where the material does not absorb microwave energy, and no energy dissipation occurs within the object. The heated object does not increase in temperature, as shown in Figure 1a. Such materials are often used as containers for the materials to be heated (glass, ceramics, and plastics).

2. The second is microwave-reflective, where the material acts like a mirror, reflecting all microwaves (as shown in Figure 1b) without absorbing microwave energy and, therefore, does not heat up. Most metallic materials belong to this category, and thus they are commonly used as waveguides or cavities in microwave heating equipment.

3. The third is microwave-absorbing, where the material absorbs microwave energy, resulting in a temperature increase. Such materials are referred to as microwave absorbers (as shown in Figure 1c).

![Figure 1. The interaction of microwaves with materials: (a) Microwave-transparent; (b) Microwave-reflective; (c) Microwave-absorbing.](image)

### 3. Heating Behaviors in Microwave Treatment

Microwave treatment harnesses the interactions between electromagnetic waves and minerals, resulting in a range of unique heating behaviors. Understanding these behaviors is the key to unlocking the technology's potential in mineral metallurgy.

One of the primary characteristics of microwave heating is its rapid and volumetric nature (Figure 2a). Unlike conventional heating methods that primarily transfer heat from the surface inward, microwaves penetrate materials deeply, heating them uniformly [21,29]. This volumetric heating results in a quicker and more efficient energy transfer, thereby reducing processing times and energy consumption. In a study conducted by Guo S.H. et al., it was demonstrated that under the condition of a pulse microwave with an average power of 1 kW, 50 g of ilmenite could be heated to 300 °C after 30 s of microwave irradiation. Within a span of 2 min, the material reached a temperature of 440 °C [30]. This high level of microwave heating efficiency was also reflected in the treatment of various minerals such as bauxite [31], ultramafic nickel ores [32], pyrolusite [33], and gold concentrate [34]. The consistency of these results across a diverse range of mineral types highlights the potential of microwave heating as a versatile and effective tool in mineral processing, offering rapid temperature elevation and significant energy efficiencies.

Moreover, microwave treatment offers selective heating capabilities (Figure 2b). Different minerals and mineral phases within a sample possess distinct dielectric properties, which dictate their capacity to absorb microwave energy. Minerals with higher dielectric constants absorb more microwave energy and consequently experience more significant heating [35,36]. This selective heating can be harnessed for targeted mineral separation and liberation, presenting advantages in cases where the objective is to free valuable minerals from their gangue components. In an analytical study conducted by Zhao Q.H. on fourteen types of igneous-rock-forming minerals subjected to microwave heating, it was revealed...
that the type of mineral exerts the most significant influence on the selective heating effect of microwaves, followed by the crystal structure and iron content of the minerals [37]. Furthermore, the study highlighted that the different types of water contained within the minerals profoundly impact their heating characteristics. This finding underscores the nuanced relationship between mineral composition, structure, and microwave heating efficiency, suggesting that the specific characteristics of minerals can greatly affect their responsiveness to microwave treatment. The research provides valuable insights into optimizing microwave heating applications in mineral processing, emphasizing the importance of tailoring approaches to the unique properties of each mineral type.

Another advantageous aspect of microwave heating is its non-contact nature (Figure 2c). Unlike traditional methods that rely on conduction or convection for heat transfer, microwaves directly interact with the material. This eliminates the need for physical contact with heating elements, reducing the risk of contamination and allowing for precise temperature control [38].

![Figure 2. The heating behaviors in microwave treatment [34,37,38].](image)

These heating behaviors collectively contribute to the efficacy of microwave treatment in various mineral-processing stages. Volumetric and rapid heating are advantageous in ore pre-treatment, where enhancing the brittleness of ores facilitates the subsequent comminution processes. In mineral processing, selective heating aids in the separation of valuable minerals from gangue materials, resulting in increased recovery rates and improved product quality. In hydrometallurgy, microwave-assisted leaching accelerates the
dissolution of target metals, reducing reagent consumption and enhancing resource recovery. These behaviors collectively foster sustainability and efficiency in mineral-processing operations, making microwave treatment an appealing choice for the industry.

4. Applications of Microwave Treatment in Mineral Metallurgy

The versatility of microwave treatment is exemplified by its diverse applications throughout the mineral metallurgy domain. From ore pre-treatment to smelting and beyond, this technology has demonstrated its potential to enhance process efficiency, reduce energy consumption, and minimize the environmental impact [9,39].

4.1. Ore Pre-Treatment

Microwave-assisted ore pre-treatment represents a pivotal step in unlocking the value contained within mineral deposits. Ores typically require size reduction through comminution processes like grinding to expose valuable minerals for subsequent processing. Microwave treatment can expedite this pre-treatment stage by inducing thermal stress within the ore, as shown in Figure 3. The rapid volumetric heating results in differential expansion and contraction of mineral phases, creating internal stresses that weaken the ore’s structure. Consequently, ores become more brittle and easier to grind, reducing the energy requirements for comminution. For instance, studies by Kingman et al. found that microwave pre-treatment of sulfide ores resulted in a reduction of up to 30% in grinding energy requirements [9,40]. Moreover, the preferential heating of specific mineral phases can improve the liberation of valuable minerals from gangue components, increasing the overall recovery rate.

Figure 3. Applications of microwave treatment in mineral metallurgy (schematic diagram of microwave-pretreated laterite ores [41]).
Studies have demonstrated its efficacy in transmitting energy rapidly to heat-absorbing materials, inducing thermal stress, and creating micro-fractures along mineral boundaries. This not only facilitates the grindability of ores such as iron and ultramafic nickel but also improves the overall throughput and energy efficiency of processing plants. Specifically, the transformation of minerals like serpentine into more amenable forms underscores the potential of microwave treatment to refine the processability of challenging ores [42,43]. These advancements point toward significant energy savings and heightened recovery rates, making microwave pre-treatment a promising avenue in mineral-processing operations [39,44].

4.2. Mineral Processing

Mineral processing encompasses various techniques to separate valuable minerals from waste materials. The efficacy of these techniques often depends on achieving high liberation of valuable minerals, which is facilitated by microwave treatment.

Microwave treatment in mineral processing enhances the efficiency of comminution by inducing thermal stress within the ore, leading to fracturing along the mineral boundaries, as shown in Figure 4. This selective heating aids in the better liberation and separation of valuable minerals, improving recovery rates and product quality. Key studies in this field have demonstrated that microwaves provide rapid, selective, and volumetric heating, which is energy-efficient and advantageous for processing materials with varied thermal properties [45]. In particular, the differential dielectric and thermal properties of mineral particulates are exploited for selective heating, which promotes enhanced boiling and fracturing at the grain boundaries. This is increasingly interesting for primary metallurgy and the processing of ores with low-thermal-conductivity minerals [46]. Experimental investigations have further shown that varying the microwave power and processing times can significantly affect the grinding and liberation of minerals such as oolitic hematite [47]. Thus, the application of microwave energy in mineral processing, which has been explored at institutions like the Institute of Geotechnics and the Slovak Academy of Sciences, underscores the transformative potential of this technology in the field [39].

![Figure 4. Applications of microwave treatment in mineral metallurgy (microwave-heating-assisted grinding [44]).](image)

4.3. Hydrometallurgy

In the realm of hydrometallurgy, the application of microwaves has shown promise in enhancing the extraction of valuable metals from ores. Microwave-assisted leaching is increasingly recognized as an innovative approach in mineral processing, offering significant advantages over traditional methods. Research has shown that microwave heating can rapidly and uniformly raise temperatures, thus accelerating the reaction rates in leaching processes. For instance, studies focusing on vanadium leaching report enhanced efficiency through microwave heating, as evidenced by microscopic analysis and numerical simulations. These methods have proven not only to expedite the leaching process but also to
increase leaching rates significantly, as demonstrated in research comparing microwave-assisted and conventional heating techniques, as shown in Figure 5 [48,49].

Figure 5. Applications of microwave treatment in mineral metallurgy (enhanced leaching of a pyrolusite–pyrite mixture in sulfuric acid systems by microwave heating [50]).

A notable aspect of microwave-assisted leaching is its selectivity and efficiency in energy consumption. Microwave heating acts directly at the molecular or atomic level, allowing for rapid, uniform, and selective heating. This characteristic leads to a notable reduction in energy usage, making it a more sustainable and cost-effective approach [51]. Furthermore, microwave-assisted leaching significantly shortens the leaching time while slightly improving leaching efficiency, underscoring its potential to enhance overall production efficiency in mineral processing [52]. The adoption of microwave technology in leaching processes, therefore, marks a significant step toward more efficient, environmentally friendly, and economically viable mineral extraction methods.

4.4. Smelting and Reduction

In the downstream stages of mineral processing, where metal extraction and refining take place, microwaves have found their place in smelting and reduction processes. Microwave-assisted smelting and reduction in mineral processing are gaining recognition for their efficiency and environmental benefits. A review of the microwave treatment of minerals indicates that while some minerals are transparent to microwave radiation, others, particularly sulfides and arsenides, respond strongly to it, suggesting their suitability for microwave-assisted processes [41]. Research on carbothermic microwave reduction demonstrates that microwave heating can initiate chemical reactions at lower temperatures, thus impacting the reduction mechanism significantly, as shown in Figure 6 [53]. Furthermore, the application of microwaves in the recycling of iron from oolitic hematite through fluidization roasting and magnetic separation underscores the technology’s usability in recovery [54]. These studies collectively emphasize the transformative potential of microwave technology in mineral processing, particularly in smelting and reduction operations.
Figure 6. Applications of microwave treatment in mineral metallurgy (microwave-enhanced carbothermal reduction of low-grade pyrolusite [55]).

4.5. Drying

Beyond these core mineral-processing stages, microwave treatment also plays a significant role in drying and preheating operations. In mineral processing, drying is a critical step before further processing, as it reduces the moisture content of materials, making them easier to handle and transport. Microwaves excel in this application due to their ability to rapidly remove moisture from mineral concentrates, ores, and intermediate products, as shown in Figure 7. The selective heating capabilities of microwaves can be employed to target water molecules, effectively drying the material while minimizing thermal damage to valuable minerals. In a study conducted by Idris A. et al., multimode microwaves were used to dry silicon mud of varying masses. The research revealed that the drying rate of silicon mud was fastest when the microwave power was set at 800 W. They also developed a theoretical approach to generate drying curves, which showed good agreement between the theoretical predictions and experimental results [56]. Regarding the drying mechanism, Pickles et al. investigated the microwave drying kinetics of coal. They concluded that the microwave drying rate was higher than that of conventional room-temperature drying, conforming to the Midilli–Kucuk exponential-decay model. Additionally, they studied the diffusion activation energy of water during microwave drying, providing insights into the mechanisms of microwave drying [57]. In the realm of process research, Guo L. et al. explored a new microwave drying technique for white tungsten concentrate, examining the effects of microwave power, duration, and material mass on the relative dehydration rate of the concentrate. Compared with conventional electric-heating drying, the microwave drying time was reduced by 97.5% [58]. Further research conducted by Zhang Y.T. et al. demonstrated that laterite nickel ore, under silicon carbide-assisted microwave drying, could rapidly remove most of the water adsorbed on the mineral surface and some of the crystalline water. Additionally, by controlling the proportion of silicon carbide, overheating was avoided. The study also emphasized that microwave drying altered the microstructure of the lateritic ore, facilitating the decomposition of minerals. Further hydrogen-reduction experiments indicated that microwave drying was conducive to the reduction of nickel and iron oxides in laterite ore, with a higher reduction rate than that achieved with conventional drying [59].
Preheating is another essential aspect of mineral metallurgy, particularly in high-temperature processes such as smelting, roasting, and reduction. Microwaves can be utilized to preheat feed materials before they enter energy-intensive processes. This preheating step not only conserves energy but also ensures a uniform and controlled temperature distribution, reducing the risk of thermal shock and improving process efficiency.

Figure 7. Applications of microwave treatment in mineral metallurgy (microwave-heating drying of low-grade manganese ore [60]).

5. Future Directions and Research Opportunities

As the mineral-processing industry continues to evolve, embracing innovative technologies, microwave treatment is emerging as one of the pivotal forces driving transformative change. Researchers, engineers, and mineralogists are collectively rushing into new realms of discovery, aiming to push the boundaries of current knowledge in microwave treatment and its multifaceted applications. The ensuing section delves into promising research avenues and future trajectories within this dynamic and evolving field.

5.1. Enhanced Equipment Design

The ongoing pursuit in the realm of microwave equipment design focuses on creating systems that are not only efficient and scalable but also specifically tailored to the nuanced requirements of mineral processing. Contemporary research is channeling efforts toward pioneering designs, incorporating cutting-edge materials and advanced control systems to refine microwave processing systems across diverse operational scales [61,62]. These innovations are poised to bolster the reliability and efficacy of microwave technology significantly. Moreover, such advancements hold promise for amplifying the commercial appeal of microwave treatment by enhancing operational efficiency, reducing maintenance demands, and catering to a broader range of mineral-processing applications, ultimately setting new benchmarks in the industry.

5.2. Process Optimization and Modeling

In the pursuit of enhancing microwave-assisted mineral processing, there is a pivotal need for concerted research efforts aimed at the development of holistic modeling frameworks. These comprehensive models are anticipated to deliver precise predictions of mineral responses within microwave fields, thereby facilitating the implementation of highly refined processing optimizations that are meticulously tailored to the distinct characteristics of specific ores [63,64]. Such an initiative necessitates the integration of
the latest advancements in modeling and simulation technologies, setting the stage for the creation of microwave-treatment processes that are not only more effective but also markedly more energy-efficient. A significant emphasis of this research endeavor is devoted to a thorough understanding of the complex thermal and electromagnetic interactions involved, which holds the potential to catalyze revolutionary enhancements in processing efficiency and yield, ultimately transforming the paradigm of microwave treatment in the mineral-processing industry. This comprehensive approach underscores the importance of leveraging cutting-edge scientific and technological advancements to foster innovations that promise to redefine existing processing methodologies, ensuring that they are both sustainable and economically viable.

5.3. Integration with Conventional Methods

The amalgamation of microwave treatment with traditional mineral-processing methods presents fertile ground for exploration. Research in this domain is actively investigating hybrid methodologies that synergize the unique advantages of microwave technology with time-tested conventional techniques. This integrative approach aims to harness the rapid and selective heating capabilities of microwaves alongside the robustness of conventional methods, striving to achieve a harmonious balance that optimizes overall processing efficiency. Such collaborative strategies could lead to more sustainable, cost-effective, and environmentally friendly mineral-processing solutions, effectively bridging the gap between traditional practices and modern technological advancements.

5.4. Technological Innovation

The horizon of microwave treatment in mineral processing is witnessing an upsurge in technological innovation, fueled by the synergistic collaboration among diverse disciplines, including materials science, engineering, and mineralogy. The exploration of groundbreaking materials, notably microwave-absorbing nanoparticles, is at the forefront of this innovation wave [65,66]. These novel materials are expected to substantially enhance efficiency and broaden the scope of microwave-processing applications. Additionally, ongoing research is delving into the development of new microwave generation and application methodologies, potentially unlocking new dimensions in mineral processing. This surge in technological innovation is set to redefine the operational paradigms of microwave treatment, driving it toward a future replete with limitless possibilities and unprecedented advancements.

As the mineral-processing industry embarks on an era of transformation, microwave treatment is emerging as a beacon for mineral metallurgical progress and sustainability. It is a testament to the industry’s commitment to embracing innovation while reducing its environmental footprint. The continued exploration of heating behaviors, diverse applications, and future directions in microwave treatment is not only a pursuit of efficiency and cost-effectiveness but also a commitment to environmental stewardship and responsible resource utilization. By embarking on this journey, researchers are honoring the legacy of progress in mineral processing and anticipating a future in which microwave treatment is one of the cornerstones of sustainable mineral metallurgy.

6. Conclusions

Microwave technology in mineral metallurgy presents a progressive and efficient approach to ore processing, aligning with the industry’s need for innovation and sustainability. The exploration of microwave-heating principles has revealed its capacity for rapid, uniform, and selective heating, translating into enhanced processing efficiencies across various stages of mineral metallurgy. The practical applications of microwave treatment, from ore pre-treatment to drying and preheating, have demonstrated significant improvements in process efficiency, energy consumption, and environmental impact. Future advancements in equipment design, process modeling, and integration with conventional methods are poised to further elevate the effectiveness of microwave technology. Additionally, ongoing technological innovations, particularly in materials science, promise to expand the
applicability and efficiency of microwave treatment. Overall, the integration of microwave technology into mineral processing signifies a substantial shift toward more efficient, cost-effective, and environmentally friendly practices, offering a promising avenue for the future of mineral metallurgy.

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