Vol. 04, Iss. 2 (2026) 142-154, DOI: 10.61552/JME.2026.02.002

JME

Journal of Materials and Engineering

www.jme.aspur.rs

Review article

Materials Processing Strategies for High-Purity Manganese Concentrates via Froth Flotation: Optimization, Control, and Industrial Relevance – A Review

Yemisi Elizabeth Gbadamosi[a,*], Oladunni Oyelola Alabi[a], Joseph Olatundeborode[a], Fatai Olufemi Aramide[a]

[a]*Metallurgical and Materials Engineering Department, School of Infrastructure, Minerals and Manufacturing Engineering, Federal University of Technology, Akure, P.M.B 704, Akure, Ondo State Nigeria.*

Keywords:

Froth flotation
Flotation properties
Manganese ore
Flotation optimization
Flotation efficiency

* Corresponding author:

Yemisi Elizabeth Gbadamosi
E-mail: gbadamosiyemisi.e@gmail.com

Received: 17 December 2025
Revised: 19 January 2026
Accepted: 13 February 2026

A B S T R A C T

Froth flotation is a key technique in mineral processing used to separate valuable minerals from gangue. Manganese ore poses specific challenges due to its complex mineralogy, which significantly affects its flotation behavior. The type of manganese minerals present influences how effectively they can be separated. A critical factor is the interaction between minerals and reagents, which determines recovery efficiency. Gangue minerals like iron and silica negatively impact flotation, requiring varied reagent strategies for effective separation. Particle size distribution and liberation influence flotation kinetics and recovery rates, making them essential to flotation performance. Additionally, pH levels play a vital role in modifying surface chemistry, thus affecting collector adsorption on manganese surfaces. Water chemistry, including dissolved ions such as calcium and magnesium, alters pulp conditions, necessitating water quality control. Pulp density also affects flotation by modifying hydrodynamic conditions, which influence bubble-particle interactions and froth stability. Parameters like agitation intensity and air dispersion further shape flotation outcomes. Mineralogical characteristics, reagent chemistry, particle features, pH levels, pulp density, and hydrodynamics can significantly enhance the beneficiation efficiency and economic value of manganese ore flotation processes.

1. INTRODUCTION

Manganese ore holds immense significance as a critical industrial mineral resource owing to its diverse applications across various sectors [1]. Manganese, a transition metal, exhibits unique properties that render it indispensable in the production of steel and alloys. The alloying properties of manganese, particularly its ability to enhance the strength, hardness, and wear resistance of steel, make it an essential component in the manufacturing of stainless steel, carbon steel, and high-strength low-alloy (HSLA) steels [2]. Beyond its role in metallurgy, manganese compounds find application in diverse industries such as battery manufacturing, ceramics, electronics, and agriculture. Manganese dioxide, derived from manganese ore, serves as a key component in dry-cell batteries, water treatment processes, and as a catalyst in chemical synthesis [3]. Additionally, manganese-based fertilizers contribute to soil enrichment and plant growth, highlighting the agricultural significance of this mineral. Given its multifaceted industrial importance, the efficient beneficiation of manganese ore assumes paramount importance. Froth flotation emerges as a prominent beneficiation technique for manganese ore, offering selective separation of manganese minerals from gangue constituents [4]. Understanding the factors influencing the froth flotation properties of manganese ore is thus imperative for optimizing its processing and maximizing its industrial utility.

Mineral processing encompasses a myriad of techniques aimed at extracting valuable minerals from their ores, playing a pivotal role in various industries ranging from mining to metallurgy [5]. Among these techniques, froth flotation stands out as one of the most widely employed methods due to its versatility and effectiveness in separating minerals based on their hydrophobicity [6 - 8]. The froth flotation process relies on the attachment of hydrophobic mineral particles to air bubbles, leading to their collection in a froth phase, while hydrophilic gangue minerals remain in the aqueous phase. This selective attachment is facilitated by the addition of various reagents, including collectors, frothers, and modifiers, which modify the surface properties of minerals and air bubbles, enhancing their interaction. The flotation process typically involves several stages: conditioning, where the ore slurry is treated with reagents to promote selective mineral adsorption; flotation, where air bubbles are introduced, carrying the hydrophobic mineral particles to the froth phase; and froth collection, where the froth containing the desired minerals is skimmed off for further processing [9,10]. Froth flotation finds wide application in the recovery of various metals such as copper, lead, zinc, and nickel, as well as industrial minerals like phosphate and potash.

The primary objective of this review is to comprehensively analyze the various parameters that influence the froth flotation properties of manganese ore. By synthesizing existing literature and research findings, we seek to elucidate the intricate interplay of factors such as mineralogy, particle characteristics, reagent chemistry, pH, pulp density, and hydrodynamic conditions in determining the efficiency and selectivity of manganese ore flotation [11]. Through a systematic examination of these parameters, we aim to provide valuable insights into the optimization of froth flotation processes for manganese ore beneficiation. By enhancing our understanding of the underlying mechanisms governing flotation behavior, this review endeavors to contribute to the development of efficient and sustainable mineral processing practices in the manganese mining industry. Ultimately, the insights gleaned from this analysis hold the potential to drive technological advancements and improve the economic viability of manganese ore beneficiation operations.

2. PROPERTIES OF MANGANESE ORE AFFECTING ITS FLOTATION

Manganese ore exhibits a diverse array of mineralogical compositions, each characterized by unique crystal structures and chemical properties [12]. Understanding the intricate interplay between these manganese minerals is essential for optimizing froth flotation processes aimed at their beneficiation. Manganese ore deposits typically contain a variety of manganese-bearing minerals, each contributing to the overall ore composition [13]. Some of the key manganese minerals encountered in ore deposits include: Pyrolusite is one of the most abundant and important manganese minerals. It crystallizes in the tetragonal system and exhibits a blackish to dark gray color. Pyrolusite often forms massive aggregates or fibrous crystals and is a primary ore mineral for manganese extraction [14]. Rhodochrosite is a manganese carbonate mineral with a pinkish-red to rose-red coloration, often exhibiting banded or botryoidal growth patterns. It is less common than pyrolusite but can occur as a significant ore mineral in certain deposits.

Hausmannite is a manganese oxide mineral that crystallizes in the tetragonal system, it typically appears as black to brownish-black crystals or massive aggregates. Braunite is a complex silicate mineral containing both divalent and trivalent manganese ions, it forms brown to black crystals and is often found in association with other manganese minerals in metamorphic and hydrothermal deposits [15]. Manganite is a hydrated manganese oxide mineral with a fibrous or botryoidal appearance. It exhibits a dark brown to black coloration and is commonly found in oxidized manganese ore deposits. Psilomelane is a group of complex manganese oxide minerals with varying composition, it typically occurs as botryoidal or stalactitic masses and is often associated with other manganese minerals in sedimentary and weathered deposits [16]. The mineral composition of manganese ore plays a crucial role in determining its flotation behavior. Different manganese minerals exhibit varying degrees of hydrophobicity and surface reactivity, thereby influencing their response to flotation reagents and the efficiency of separation processes [17]. Pyrolusite, for instance, tends to exhibit higher hydrophobicity compared to rhodochrosite or hausmannite, owing to differences in surface chemistry and crystal structure.

The presence of gangue minerals and impurities further complicates the flotation behavior of manganese ore. Gangue minerals such as quartz, calcite, and clay minerals may interfere with the flotation of manganese minerals, leading to lower recovery rates and reduced concentrate quality [18]. Iron-bearing minerals, in particular, can pose significant challenges due to their similar flotation behavior to manganese minerals and their tendency to form complex intergrowths. Selective flotation of manganese minerals from gangue constituents requires tailored reagent regimes and optimization strategies [19]. Collectors, frothers, and depressants play pivotal roles in enhancing the selectivity of flotation processes by promoting the adsorption of reagents onto desired mineral surfaces while suppressing the flotation of undesirable minerals. Understanding the surface chemistry and flotation kinetics of different manganese minerals is essential for designing effective flotation circuits and maximizing the recovery of valuable manganese ores [20,21]. A complex interplay of electrochemical, surface, and solution-phase phenomena governs the interaction of manganese minerals with flotation reagents. Collectors, typically cationic or anionic surfactants, selectively adsorb onto mineral surfaces, forming hydrophobic monolayers that facilitate particle-bubble attachment during flotation. Common collectors for manganese ore flotation include fatty acids, amines, and sulfonates, each exhibiting varying degrees of selectivity and affinity for different manganese minerals [22]. Frothers, on the other hand, are surface-active agents that stabilize air bubbles and promote the formation of a stable froth phase. By reducing the surface tension of the aqueous phase, frothers enhance the mobility and stability of air bubbles, thereby facilitating the transport of hydrophobic mineral particles to the froth phase [23]. The selection of an appropriate frother is crucial for achieving optimal froth properties and maximizing the recovery of valuable manganese minerals. Depressants are reagents used to selectively inhibit the flotation of certain minerals, thereby improving the selectivity of the flotation process [24]. In the case of manganese ore flotation, depressants may be employed to suppress the flotation of gangue minerals or undesirable manganese-bearing phases, enhancing the purity and grade of the final concentrate. The chemical composition of manganese ore, encompassing a diverse array of manganese minerals and associated gangue constituents, significantly influences its flotation behavior [25]. Understanding the surface chemistry, crystallography, and reactivity of manganese minerals is essential for optimizing flotation processes and maximizing the recovery of valuable manganese ores. Through tailored reagent regimes and optimization strategies, it becomes possible to achieve selective separation of manganese minerals from gangue constituents, thereby enhancing the economic viability of manganese ore beneficiation operations [26,27].

2.1 Impurities and Their Impact on Manganese Ore Flotation

Impurities are ubiquitous in manganese ore deposits, presenting challenges to the beneficiation process due to their adverse effects on flotation efficiency and concentrate quality [28]. Manganese ore deposits often contain a variety of impurities, which can vary depending on the geological origin of the ore. Common impurities encountered in manganese ore include: Iron is one of the most prevalent impurities in manganese ore deposits. It can occur in various forms, including iron oxides, hydroxides, and silicates. Iron-bearing minerals such as hematite, goethite, and magnetite are often associated with manganese minerals and gangue constituents [29]. Silica is another common impurity in manganese ore deposits, typically occurring as quartz or silicate minerals. Silica can adversely affect flotation efficiency by coating mineral surfaces, reducing particle-bubble attachment, and interfering with reagent adsorption [30]. Calcium may be present in manganese ore deposits in the form of carbonate minerals such as calcite or dolomite. Calcium ions can influence pulp chemistry and reagent performance, affecting the selectivity and efficiency of the flotation process [31]. Trace elements such as aluminum and magnesium may also occur as impurities in manganese ore. While their concentrations are often low, they can still impact flotation behavior and concentrate quality. The presence of impurities in manganese ore can have profound effects on the efficiency and selectivity of the flotation process. Impurities may interfere with the adsorption of flotation reagents onto mineral surfaces, inhibit bubble-particle attachment, and alter pulp chemistry, thereby affecting the separation of manganese minerals from gangue constituents [32,33]. Impurities such as iron and silica can hinder the kinetics of flotation by competing for reagent adsorption sites and obstructing the interaction between collector molecules and mineral surfaces. This results in slower flotation rates and reduced mineral recovery. Impurities may influence froth properties, including stability, bubble size distribution, and froth density. High concentrations of certain impurities, such as calcium ions, can destabilize the froth phase, leading to froth collapse and reduced concentrate grades [34]. The presence of impurities necessitates careful selection of flotation reagents to achieve selective separation of manganese minerals from gangue constituents [35,36]. Reagents must be chosen based on their affinity for target minerals and their ability to suppress the flotation of impurity-bearing phases.

To mitigate the adverse effects of impurities on manganese ore flotation, various strategies can be employed: Pre-concentration techniques such as ore sorting, gravity separation, and magnetic separation can be utilized to remove coarse impurities and upgrade the ore feed before flotation [37]. This reduces the load of deleterious elements entering the flotation circuit, thereby improving overall process efficiency. Selective flocculation techniques can be employed to selectively agglomerate and remove impurity-bearing minerals from the ore slurry before flotation. This helps reduce the concentration of impurities in the feed, leading to improved flotation performance and concentrate quality. Tailored reagent regimes, comprising collectors, frothers, and depressants, can be optimized to selectively target manganese minerals while minimizing the flotation of impurities [38]. Reagents with high selectivity and affinity for manganese minerals should be chosen to enhance process efficiency. pH control is essential for optimizing flotation performance and mitigating the effects of impurities [39]. Adjusting the pH of the flotation pulp to the optimal range can help minimize the activation of gangue minerals and promote the selective flotation of target minerals. The quality of process water, including its mineral content and chemical composition, can impact flotation performance [40,41]. Utilizing high-quality process water with low concentrations of impurities can help reduce the deleterious effects of impurities on flotation efficiency. Impurities pose significant challenges to the flotation of manganese ore, affecting process efficiency, concentrate quality, and reagent selection [42]. By understanding the nature of impurities and implementing appropriate control and mitigation strategies, it becomes possible to optimize flotation performance and maximize the recovery of valuable manganese minerals [43,44]. Continued research and innovation in impurity control techniques are essential for advancing the sustainability and economic viability of manganese ore beneficiation operations.

2.2 Particle-Mineral Interaction in Manganese Ore Processing

Particle characteristics are fundamental to mineral processing, affecting various stages from comminution to separation [45]. Manganese ore, a crucial resource for the metallurgical industry, undergoes complex processing to extract valuable metals. Understanding the particle characteristics of manganese ore is essential for optimizing processing methods, particularly in flotation, which is widely used for manganese ore beneficiation [46]. Particle size distribution (PSD) refers to the range of particle sizes present in a sample. In manganese ore, PSD significantly influences processing efficiency as it affects grinding requirements, liberation, and separation efficiency [47]. Various techniques such as sieve analysis, laser diffraction, and image analysis are employed to determine PSD in manganese ore samples [48]. Each method offers unique insights into particle size distribution, aiding in process optimization. Several factors, including ore type, mineralogy, and processing conditions, influence PSD in manganese ore [49]. For instance, different ore types exhibit distinct PSD profiles due to variations in mineral composition and grain size distribution. Examination of PSD in different manganese ore deposits provides valuable insights into the variability and characteristics of particle size distribution. Case studies elucidate the relationship between PSD and processing efficiency, guiding optimization efforts [50]. Liberation refers to the extent to which valuable minerals are separated from the gangue matrix. In manganese ore, liberation is critical for maximizing recovery rates during flotation. Particle size, mineral associations, and comminution methods profoundly impact liberation efficiency in manganese ore [51]. Proper liberation enhances the selectivity of flotation processes, improving concentrate quality. Comminution techniques such as crushing, grinding, and milling are employed to achieve optimal liberation [52]. Selecting appropriate comminution strategies is crucial for achieving desired liberation outcomes. The liberation characteristics of manganese ore directly influence flotation efficiency by affecting the exposure of valuable minerals to the flotation reagents [53]. Enhanced liberation promotes effective particle-bubble attachment, leading to improved recovery rates.

Flotation kinetics encompass the rate and extent of flotation processes influenced by factors such as particle size, reagent dosage, and agitation intensity [54]. Understanding the kinetics of manganese ore flotation is essential for optimizing recovery rates. Particle size significantly influences flotation kinetics, with finer particles exhibiting faster flotation rates due to increased surface area and reagent accessibility [55]. However, excessively fine particles may pose challenges in froth stability and concentrate quality. Particle size distribution directly impacts recovery rates in manganese ore flotation. Optimal particle size distribution ensures efficient liberation and flotation kinetics, maximizing the recovery of valuable minerals while minimizing losses to tailings [56]. Controlled comminution, selective grinding, and particle size classification are strategies employed to optimize particle size for enhanced flotation kinetics and recovery rates in manganese ore processing. Particle characteristics, including size distribution and liberation, profoundly influence the efficiency of manganese ore flotation processes. By understanding these characteristics and their implications for flotation efficiency, mineral processors can implement targeted strategies to optimize processing methods and improve overall performance [57].

2.3 Influence of Operation Parameters on Manganese Ore Flotation Performance

The pH and pulp chemistry exert significant control over the surface interactions between minerals and reagents in flotation processes [58]. In the context of manganese ore beneficiation, understanding the role of pH is paramount for achieving optimal flotation performance. The surface chemistry of manganese minerals dictates their response to flotation reagents and determines flotation selectivity, as illustrated in Figure 1 [59,60].

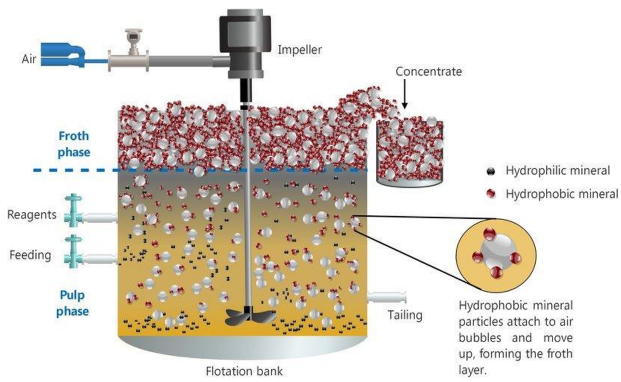

Fig. 1. Flotation cell [59 - 60].

pH influences surface charge, hydrophobicity, and adsorption behavior of both minerals and reagents. pH affects the protonation/deprotonation of mineral surfaces, altering their electrochemical properties and reactivity towards collectors, depressants, and activators [61]. Understanding pH-dependent surface reactions is crucial for optimizing reagent adsorption and mineral separation. Different manganese minerals exhibit varied pH-dependent behaviors due to differences in surface chemistry and crystal structure. Tailoring pH conditions to suit specific mineral species enhances flotation selectivity and recovery. pH influences the adsorption kinetics and equilibrium of flotation reagents onto mineral surfaces [62,63]. Optimal pH conditions promote the selective adsorption of collectors while minimizing unwanted interactions with gangue minerals. Dissolved ions in the pulp solution can significantly alter the electrochemical environment, affecting mineral solubility, surface charge, and reagent interactions [64]. Common ions present in manganese ore processing include calcium, magnesium, and sulfate. Different ions exert varying effects on pulp chemistry and flotation performance. For example, calcium ions may form precipitates with collector ions, reducing their availability for mineral flotation, while sulfate ions can influence pH buffering capacity. The presence of dissolved ions can modify reagent behavior, froth stability, and mineral recovery in flotation circuits; understanding ion-specific effects is crucial for mitigating deleterious impacts on flotation performance [65]. Various pH control strategies, including lime addition, acid/base dosing, and pH modifiers, are employed to maintain optimal pH conditions in flotation circuits [66]. Continuous pH monitoring and feedback control systems enhance process stability and efficiency. Tailoring reagent formulations to pH conditions enhances their performance and selectivity in manganese ore flotation. pH-responsive collectors and depressants offer versatility in optimizing flotation processes across a range of pH regimes [67]. Integrating pH control strategies with other process parameters such as pulp density, particle size, and agitation intensity enables comprehensive optimization of manganese ore flotation circuits. Holistic approaches maximize recovery while minimizing reagent consumption and environmental impact. pH and pulp chemistry play pivotal roles in determining the efficiency and selectivity of manganese ore flotation processes. By understanding the intricate relationships between pH, surface chemistry, reagent adsorption, and dissolved ions, mineral processors can implement targeted pH control strategies to optimize flotation performance and enhance overall process efficiency [68,69].

2.4 Impact of Pulp Density on Flotation Efficiency in Manganese Ore Processing

Pulp density, defined as the mass of solids per unit volume of pulp, is a fundamental parameter in flotation processes [70]. In the context of manganese ore beneficiation, optimizing pulp density is essential for achieving efficient mineral separation and maximizing concentrate quality. Pulp density refers to the concentration of solids in the flotation pulp, typically expressed as the mass of solids per unit volume of pulp (g/L or % solids). It is a critical parameter that influences the efficiency and selectivity of flotation processes. Optimal pulp density ensures proper dispersion of reagents, facilitates particle-particle and particle-bubble interactions, and regulates froth stability [71]. Pulp density directly impacts flotation kinetics, froth properties, and, ultimately, separation efficiency in manganese ore processing.

Pulp density variations alter the collision frequency and probability between particles and bubbles, thereby affecting flotation kinetics [72]. Higher pulp densities may enhance particle-bubble attachment rates, leading to faster flotation kinetics. Pulp density influences froth stability, bubble size distribution, and froth mobility; higher pulp densities tend to produce more stable froths with higher bubble concentrations, affecting froth recovery and concentrate grade [73,74]. The effect of pulp density on flotation kinetics and froth properties may vary depending on particle size distribution. Fine particles may require lower pulp densities for optimal flotation, whereas coarser particles may exhibit improved flotation performance at higher pulp densities.

Various experimental techniques, including batch flotation tests, kinetic studies, and froth characterization, are employed to determine the optimum pulp density for manganese ore flotation. Systematic experimentation allows for the evaluation of pulp density effects on flotation performance under controlled conditions. Mathematical models, such as population balance models and computational fluid dynamics simulations, aid in predicting the optimal pulp density for desired flotation outcomes [75]. Modeling approaches integrate process parameters to optimize pulp density for maximum recovery and grade. In plant-scale operations, continuous monitoring of pulp density and real-time process control enables dynamic adjustment to achieve optimal flotation performance. Utilizing advanced instrumentation and automation technologies enhances process efficiency and productivity. Pulp density is a critical parameter in manganese ore flotation, exerting profound effects on flotation kinetics, froth properties, and overall process efficiency [76]. By understanding the importance of pulp density and its impact on flotation performance, mineral processors can implement strategies to optimize pulp density and enhance manganese ore beneficiation.

2.5 Role of Hydrodynamic Parameters in Flotation Efficiency

Hydrodynamic parameters play a pivotal role in determining the effectiveness of flotation processes, affecting particle-bubble interactions, air dispersion, and froth stability, as illustrated in Figure 2 [77,78].

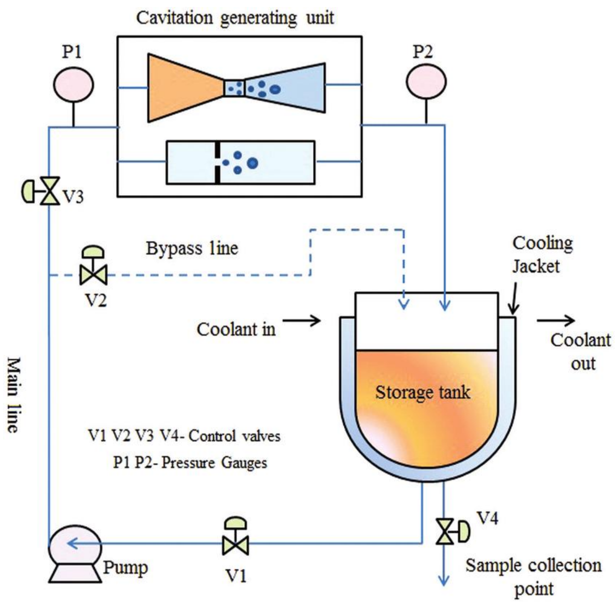

Fig. 2. Schematic representation of Hydrodynamic Parameters in Flotation Efficiency [77,78].

In the context of mineral processing, optimizing hydrodynamic parameters is essential for achieving efficient separation and maximizing concentrate quality. Agitation intensity refers to the energy input into the flotation cell, typically characterized by impeller speed or power consumption [79]. Higher agitation intensities enhance the turbulence within the pulp, increasing the collision probability between bubbles and particles. Its intensity directly influences the hydrodynamics of the flotation cell, affecting the distribution and residence time of bubbles and particles. Intense agitation promotes turbulent flow patterns, facilitating effective bubble-particle collision and attachment. Optimizing agitation intensity involves balancing energy input with the desired level of turbulence for efficient particle-bubble interactions. Adjusting impeller design, rotational speed, and cell geometry enables fine-tuning of agitation intensity to maximize collision probability and flotation efficiency [80]. Effective air dispersion is essential for generating fine bubbles and promoting bubble-particle attachment in flotation cells. Proper dispersion enhances bubble surface area, facilitating efficient particle collection and froth recovery. Froth stability, governed by factors such as bubble size distribution, frother concentration, and froth drainage kinetics, influences concentrate grade and recovery [81]. Stable froths promote selective mineral flotation while minimizing the entrainment of gangue minerals. Optimal air dispersion and froth stability are critical for maximizing flotation efficiency and selectivity. Well-dispersed fine bubbles enhance mineral recovery by increasing the probability of particle-bubble collision and reducing froth collapse.

Optimizing flotation cell design and configuration, including impeller type, cell geometry, and froth crowding, influences hydrodynamic parameters such as agitation intensity and air dispersion [82]. Tailoring equipment specifications to specific ore characteristics enhances flotation performance. Implementing advanced process control systems allows for real-time monitoring and adjustment of hydrodynamic parameters in flotation circuits. Automated control strategies optimize agitation intensity, air dispersion, and froth stability to achieve desired flotation outcomes. Adopting an integrated approach that considers multiple hydrodynamic parameters simultaneously enables comprehensive optimization of flotation processes. By optimizing agitation intensity, air dispersion, and froth stability in tandem, mineral processors can maximize flotation efficiency and concentrate quality. Hydrodynamic parameters exert significant control over the efficiency and selectivity of flotation processes, influencing bubble-particle interactions, air dispersion, and froth stability. By understanding the influence of agitation intensity, air dispersion, and froth stability on flotation efficiency and implementing targeted control strategies, mineral processors can optimize hydrodynamic parameters to enhance flotation performance and maximize mineral recovery [83,84].

2.6 Future Recommendations

Utilize advanced analytical techniques, such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR), to characterize the mineralogical and chemical properties of manganese ore samples more comprehensively. Investigate the use of eco-friendly and renewable reagents, such as bio-based collectors and frothers, to reduce the environmental impact of flotation processes. Additionally, explore innovative reagent formulations that improve selectivity and reduce reagent consumption. Continue to optimize process parameters, including particle size distribution, liberation characteristics, pH control, and hydrodynamic parameters, through systematic experimentation and advanced modeling techniques. Integration of these approaches will enable more efficient and sustainable manganese ore beneficiation processes. Implement digitalization and automation technologies to enhance process monitoring, control, and optimization in manganese ore flotation plants. Real-time data analytics and predictive modeling can help identify process inefficiencies and optimize flotation performance promptly. The froth flotation properties of manganese ore are influenced by a complex interplay of parameters, including particle size distribution, liberation characteristics, pH, pulp chemistry, and hydrodynamics. Future research efforts should focus on integrating advanced analytical techniques, developing sustainable reagent formulations, optimizing process parameters, and embracing digitalization and automation technologies to enhance the efficiency and sustainability of manganese ore beneficiation processes. By addressing these challenges and implementing innovative solutions, the mining industry can achieve more efficient and environmentally friendly extraction of manganese resources.

3. CONCLUSION

Froth flotation stands as a cornerstone in the beneficiation of manganese ore, offering a versatile and effective method for separating valuable minerals from gangue. Throughout this discourse, we have explored key parameters influencing the froth flotation properties of manganese ore, emphasized the importance of understanding and optimizing these parameters for efficient beneficiation, and outlined future research directions for sustainable mineral processing practices.

The size distribution of particles significantly affects flotation efficiency, with finer particles often requiring lower pulp densities for optimal recovery. Proper liberation of valuable minerals from gangue is essential for maximizing flotation efficiency and concentrate grade. pH regulates the surface chemistry of minerals and influences reagent adsorption, while pulp chemistry, including dissolved ions, affects flotation kinetics and froth stability. Agitation intensity, air dispersion, and froth stability play pivotal roles in bubble-particle interactions and, ultimately, flotation efficiency. Various parameters, including particle size distribution, liberation characteristics, pH, pulp chemistry, and hydrodynamics intricately influence the froth flotation properties of manganese ore. Understanding and optimizing these parameters are essential for efficient beneficiation, leading to enhanced recovery, grade, and process stability. Future research efforts should focus on advancing characterization techniques, modeling approaches, sustainable reagent development, and integrated process optimization to ensure sustainable mineral processing practices for the benefit of both industry and the environment.

REFERENCES

[1] F. Nurjaman, S. Amarela, A. Noegroho, D. Ferdian, and B. Suharno, "Beneficiation of two different low-grade Indonesian manganese ores to improve the Mn/Fe ratio," *AIP Conference Proceedings*, vol. 1823, no. 1, pp. 020021-1–020021-7, Mar. 2017, doi: 10.1063/1.4978094.

[2] E. I. Khlusova, O. V. Sych, and V. V. Orlov, "Cold-resistant steels: Structure, properties, and technologies," *Phys. Met. Metallogr.*, vol. 122, pp. 579–613, 2021, doi: 10.1134/S0031918X21060041.

[3] S. Dey and V. P. Kumar, "The performance of highly active manganese oxide catalysts for ambient conditions carbon monoxide oxidation," *Curr. Res. Green Sustain. Chem.*, vol. 3, p. 100012, 2020, doi: 10.1016/j.crgsc.2020.100012.

[4] K. Ochromowicz, K. Aasly, and P. B. Kowalczuk, "Recent advancements in metallurgical processing of marine minerals," *Minerals*, vol. 11, no. 12, p. 1437, 2021, doi: 10.3390/min11121437.

[5] G. T. Nwaila, H. E. Frimmel, S. E. Zhang, J. E Bourdeau, L. C. Tolmay, R. J. Durrheim, and Y. Ghorbani, "The minerals industry in the era of digital transition: An energy-efficient and environmentally conscious approach," *Resour. Policy*, vol. 78, p. 102851, 2022, doi: 10.1016/j.resourpol.2022.102851.

[6] W. Chimonyo, B. Fletcher, and Y. Peng, "Starch chemical modification for selective flotation of copper sulphide minerals from carbonaceous material: A critical review," *Miner. Eng.*, vol. 156, p. 106522, 2020, doi: 10.1016/j.mineng.2020.106522.

[7] C. Wang, C. Sun, and Q. Liu, "Entrainment of gangue minerals in froth flotation: Mechanisms, models, controlling factors, and abatement techniques—A review," *Mining, Metall. Explor.*, vol. 38, no. 2, pp. 673–692, 2021, doi: 10.1007/s42461-020-00379-x.

[8] C. I. Castellón, N. Toro, E. Gálvez, P. Robles, W. H. Leiva, and R. I. Jeldres, "Froth flotation of chalcopyrite/pyrite ore: A critical review," *Materials*, vol. 15, no. 19, p. 6536, 2022, doi: 10.3390/ma15196536.

[9] F. Nakhaei and M. Irannajad, "Reagents types in flotation of iron oxide minerals: A review," *Miner. Process. Extract. Metall. Rev.*, vol. 39, no. 2, pp. 89–124, 2018, doi: 10.1080/08827508.2017.1391245.

[10] X. Zhang, X. Gu, Y. Han, N. Parra-Álvarez, V. Claremboux, and S. K. Kawatra, "Flotation of iron ores: A review," *Miner. Process. Extract. Metall. Rev.*, vol. 42, no. 3, pp. 184–212, 2021, doi: 10.1080/08827508.2019.1689494.

[11] K. Asgari, H. Khoshdast, F. Nakhaei, M. R. Garmsiri, Q. Huang, and A. Hassanzadeh, "A review on floc-flotation of fine particles: Technological aspects, mechanisms, and future perspectives," *Miner. Process. Extract. Metall. Rev.*, vol. 45, no. 7, pp. 669 - 696, Taylor and Francis Group; Taylor and Francis, Jan 2024, doi.org/10.1080/08827508.2023.2236770

[12] S. K. Ghosh, "Diversity in the family of manganese oxides at the nanoscale: From fundamentals to applications," *ACS Omega*, vol. 5, no. 40, pp. 25493–25504, 2020, doi: 10.1021/acsomega.0c03316.

[13] V. Singh, T. Chakraborty, and S. K. Tripathy, "A Review of Low Grade Manganese Ore Upgradation Processes", *Mineral Processing and Extractive Metallurgy Review*, pp. 1-23, 2019, doi.org/10.1080/08827508.2019.1634567

[14] S. Niu, L. Zhao, X. Lin, T. Chen, Y. Wang, L. Mo, X. Niu, H. Wu, M. Zhang, and J.M. Huizenga, "Mineralogical characterization of manganese oxide minerals of the Devonian Xialei manganese deposit," *Minerals*, vol. 11, p. 1243, 2021, doi: 10.3390/min11111243.

[15] M. J. Peterson, J. R. Manuel, and S. Hapugoda, "Geometallurgical characterisation of Mn ores," *Appl. Earth Sci.*, vol. 130, no. 1, pp. 2–22, 2021, doi: 10.1080/25726838.2020.1863013.

[16] A. Lu, Y. Li, C. Wang, and H. Ding, Environmental Property of Minerals, in Introduction to Environmental Mineralogy, *Singapore: Springer*, pp. 1–25, 2023, doi: 10.1007/978-981-19-7792-3.

[17] M. Derhy, Y. Taha, R. Hakkou, and M. Benzaazoua, "Review of the main factors affecting the flotation of phosphate ores," *Minerals*, vol. 10, no. 12, p. 1109, 2020, doi: 10.3390/min10121109.

[18] J. Zhai, P. Chen, W. Sun, W. Chen, and S. Wan, "A review of mineral processing of ilmenite by flotation," *Miner. Eng.*, vol. 157, p. 106558, 2020, doi: 10.1016/j.mineng.2020.106558.

[19] A .J. Whitworth, E. Forbes, I. Verster, V. Jokovic, B. Awatey, and A. Parbhakar-Fox, "Review on advances in mineral processing technologies suitable for critical metal recovery from mining and processing wastes," *Cleaner Eng. Technol.*, vol. 7, p. 100451, 2022, doi: 10.1016/j.clet.2022.100451.

[20] F. Mennik, N. İ. Dinç, and F. Burat, "Selective recovery of metals from spent mobile phone lithium-ion batteries through froth flotation followed by magnetic separation procedure," *Results Eng.*, vol. 17, p. 100868, 2023, doi: 10.1016/j.rineng.2022.100868.

[21] S. Nazari, A. B. Vakylabad, K. Asgari, J. Li, H. Khoshdast, Y. He, and A. Hassanzadeh, "Bubbles to batteries: A review of froth flotation for sustainably recycling spent lithium-ion batteries," *J. Energy Storage*, vol. 84, p. 110702, 2024, doi: 10.1016/j.est.2024.110702.

[22] J. F. Scamehorn, Surfactant - Based Separation Processes (1st ed.), CRC Press, 1989, doi:10.1201/9781003066002

[23] M. R. Kadagala, S. Nikkam, and S. K. Tripathy, "A review on flotation of coal using mixed reagent systems," *Miner. Eng.*, vol. 173, p. 107217, 2021, doi: 10.1016/j.mineng.2021.107217.

[24] A. El-Bahi, Y. Taha, Y. Ait-Khouia, R. Hakkou, and M. Benzaazoua, "Advancing phosphate ore minerals separation with sustainable flotation reagents: An investigation into highly selective biobased depressants," *Adv. Colloid Interface Sci.*, p. 102921, 2023, doi: 10.1016/j.cis.2023.102921.

[25] S. K. Das, C. H. R. V. S. Nagesh, T. Sreenivas, T. Kundu, and S. I. Angadi, "A treatise on occurrence, beneficiation and plant practices of tungsten-bearing ores," *Powder Technol.*, p. 118938, 2023, doi: 10.1016/j.powtec.2023.118938.

[26] R. Nkuna, G. N. Ijoma, T. S. Matambo, and N. Chimwani, "Accessing metals from low-grade ores and the environmental impact considerations: A review of the perspectives of conventional versus bioleaching strategies," *Minerals*, vol. 12, no. 5, p. 506, 2022, doi: 10.3390/min12050506.

[27] N. R. Kiprono, T. Smoliński, M. Rogowski, I. Herdzik-Koniecko, M. Sudlitz, and A. G. Chmielewski, "Kenya's mineral landscape: A review of the mining status and potential recovery of strategic and critical metals through hydrometallurgical and flotation techniques," *Minerals*, vol. 14, no. 1, p. 21, 2023, doi: 10.3390/min14010021.

[28] A. Eskanlou and Q. Huang, "Phosphatic waste clay: Origin, composition, physicochemical properties, challenges, values and possible remedies—A review," *Miner. Eng.*, vol. 162, p. 106745, 2021, doi: 10.1016/j.mineng.2020.106745.

[29] J. M. F. Clout and J. R. Manuel, "Mineralogical, chemical, and physical metallurgical characteristics of iron ore," in *Iron Ore*, Woodhead Publishing, 2022, pp. 59–108, doi: 10.1016/B978-1-78242-156-6.00002-2

[30] S. O. Adewuyi, H. A. M. Ahmed, and H. M. A. Ahmed, "Review: Methods of Ore Pretreatment for Comminution Energy Reduction," *Minerals*, vol. 10, no. 5, p. 423, May 2020, doi: 10.3390/min10050423.

[31] I. Aarab, M. Derqaoui, K. El Amari, A. Yaacoubi, A. Abidi, A. Etahiri, and A. Baçaoui, "Influence of surface dissolution on reagents' adsorption on low-grade phosphate ore and its flotation selectivity," *Colloids Surf. A: Physicochem. Eng. Asp.*, vol. 631, p. 127700, 2021, doi: 10.1016/j.colsurfa.2021.127700.

[32] M. Pawlik, "Fundamentals of froth flotation," *ChemTexts*, vol. 8, no. 4, p. 19, 2022, doi: 10.1007/s40828-022-00170-5.

[33] S. J. Anzoom, G. Bournival, S. Ata Coarse particle flotation: A review, Minerals Engineering, 206, 2024,108499, doi: 10.1016/j.mineng.2023.108499.

[34] X. Hu and Z. Meng, "An overview of edible foams in food and modern cuisine: Destabilization and stabilization mechanisms and applications," *Compr. Rev. Food Sci. Food Saf.*, vol. 23, no. 1, pp. 1–30, 2024, doi:10.1111/1541-4337.13284.

[35] N. S. Nzeh, S. Adeosun, A. P. Popoola, A. Adeleke, and D. Okanigbe, "Process applications and challenges in mineral beneficiation and recovery of niobium from ore deposits—A review," *Miner. Process. Extract. Metall. Rev.*, vol. 43, no. 7, pp. 833–864, 2022, doi: 10.1080/08827508.2021.1964965.

[36] S. Luukkanen, A. Tanhua, Z. Zhang, R. M. Canales, and I. Auranen, "Towards waterless operations from mine to mill," *Miner. Eng.*, vol. 187, p. 107793, 2022, doi: 10.1016/j.mineng.2022.107793.

[37] G. Jain, H. Havskjold, P. Dhar, H. Ertesvåg, I. Chernyshova, and H.R. Kota, "Green foam-based methods of mineral and ion separation," in *Multidisciplinary Advances in Efficient Separation Processes*, *American Chemical Society*, pp. 265–301, 2020, doi: 10.1021/bk-2020-1348.ch009.

[38] N. S. Inchaurrondo and J. Font, "Clay, zeolite and oxide minerals: Natural catalytic materials for the ozonation of organic pollutants," *Molecules*, vol. 27, no. 7, p. 2151, 2022, doi: 10.3390/molecules27072151.

[39] P. Kinnunen, H. Miettinen, and M. Bomberg, "Review of potential microbial effects on flotation," *Minerals*, vol. 10, no. 6, p. 533, 2020, doi: 10.3390/min10060533.

[40] K. Witecki, I. Polowczyk, and P. B. Kowalczuk, "Chemistry of wastewater circuits in mineral processing industry—A review," *J. Water Process Eng.*, vol. 45, p. 102509, 2022, doi: 10.1016/j.jwpe.2021.102509.

[41] B. Marmiroli, L. Rigamonti, and P. R. Brito-Parada, "Life cycle assessment in mineral processing—A review of the role of flotation," *Int. J. Life Cycle Assess.*, vol. 27, no. 1, pp. 62–81, 2022, doi: 10.1007/s11367-021-02005-w.

[42] C. G. Anderson and H. Cui, "Advances in mineral processing and hydrometallurgy," *Metals*, vol. 11, no. 9, p. 1393, 2021, doi: 10.3390/met11091393.

[43] S. K. Sarker, N. Haque, M. Bhuiyan, W. Bruckard, and B. K. Pramanik, "Recovery of strategically important critical minerals from mine tailings," *J. Environ. Chem. Eng.*, vol. 10, no. 3, p. 107622, 2022, doi: 10.1016/j.jece.2022.107622.

[44] P. S. Parapari, M. Parian, and J. Rosenkranz, "Breakage process of mineral processing comminution machines—An approach to liberation," *Adv. Powder Technol.*, vol. 31, no. 9, pp. 3669–3685, 2020, doi:10.1016/j.apt.2020.08.005.

[45] R. Elliott and M. Barati, "A review of the beneficiation of low-grade manganese ores by magnetic separation," *Can. Metall. Q.*, vol. 59, no. 1, pp. 1–16, 2020, doi: 10.1080/00084433.2020.1711654.

[46] N. Matsanga, W. Nheta, and N. Chimwani, "A review of the grinding media in ball mills for mineral processing," *Minerals*, vol. 13, no. 11, p. 1373, 2023, doi: 10.3390/min13111373.

[47] E. J. Koh, E. Amini, C. A. Spier, G. J. McLachlan, W. Xie, and N. Beaton, "A mineralogy characterisation technique for copper ore in flotation pulp using deep learning machine vision with optical microscopy," *Miner. Eng.*, vol. 205, p. 108481, 2024, doi: 10.1016/j.mineng.2023.108481.

[48] S. K. Bhoja, S. K. Tripathy, Y. R. Murthy, T. K. Ghosh, C. R. Kumar, and D. P. Chakraborty, "Influence of mineralogy on the dry magnetic separation of ferruginous manganese ore—A comparative study," *Minerals*, vol. 11, no. 2, p. 150, 2021, doi: 10.3390/min11020150.

[49] M. Elahi, S. O. Afolaranmi, J. L. Martinez Lastra, and J. A. Perez Garcia, "A comprehensive literature review of the applications of AI techniques through the lifecycle of industrial equipment," *Discover Artif. Intell.*, vol. 3, no. 1, p. 43, 2023, doi: 10.1007/s44163-023-00098-x.

[50] H. Gholami, B. Rezai, A. Hassanzadeh, A. Mehdilo, and M. B. Jabbari, "The effect of microwave's location in a comminution circuit on improving grindability of a porphyry copper deposit," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1–20, 2020, doi:10.1080/15567036.2020.1753859.

[51] C. Mafra, H. Bouzahzah, L. Stamenov, and S. Gaydardzhiev, "Insights on the effect of pyrite liberation degree upon the acid mine drainage potential of sulfide flotation tailings," *Appl. Geochem.*, vol. 123, p. 104774, 2020, doi: 10.1016/j.apgeochem.2020.104774.

[52] J. Rincon, S. Gaydardzhiev, and L. Stamenov, "Coupling comminution indices and mineralogical features as an approach to a geometallurgical characterization of a copper ore," *Minerals Engineering*, vol. 130, pp. 57–66, 2019, doi: 10.1016/j.mineng.2018.10.007.

[53] B. Demeusy, D. Madanski, H. Bouzahzah, and S. Gaydardzhiev, "Mineralogical study of electrum grain size, shape and mineral chemistry in process streams from the Krumovgrad mine, Bulgaria," *Minerals Engineering*, vol. 198, p. 108080, 2023, doi: 10.1016/j.mineng.2023.108080.

[54] Z. Xue, Y. Feng, H. Li, Z. Zhu, C. Xu, J. Ju, and Y. Yang, "A comprehensive review on progresses of coal and minerals bioflotation in presence of microorganisms," *J. Environ. Chem. Eng.*, p. 111182, 2023, doi: 10.1016/j.jece.2023.111182.

[55] O. Guven, B. Kaymakoğlu, A. Ehsani, A. Hassanzadeh, and O. Sivrikaya, "Effects of grinding time on morphology and collectorless flotation of coal particles," *Powder Technol.*, vol. 399, p. 117010, 2022, doi: 10.1016/j.powtec.2021.11.054.

[56] Y. Ait-Khouia, M. Benzaazoua, and I. Demers, "Environmental desulfurization of mine wastes using various mineral processing techniques: Recent advances and opportunities," *Miner. Eng.*, vol. 174, p. 107225, 2021, doi: 10.1016/j.mineng.2021.107225.

[57] P. Vallejos and J. Yianatos, "Analysis of industrial flotation circuits using top-of-froth and concentrate mineralogy," *Miner. Process. Extract. Metall. Rev.*, vol. 42, no. 7, pp. 511–520, 2021, doi: 10.1080/08827508.2019.1687468.

[58] P. Forson, M. Zanin, W. Skinner, and R. Asamoah, "Differential flotation of pyrite and arsenopyrite: Effect of pulp aeration and the critical importance of collector concentration," *Miner. Eng.*, vol. 178, pp. 1-14, 107421, 2022, doi: 10.1016/j.mineng.2022.107421.

[59] Z. Li, M. Huang, W. Gui, and Z. P. Jiang, "Data-driven adaptive optimal control for flotation processes with delayed feedback and disturbance," *IEEE Access*, vol. 7, pp. 163138–163149, 2019, doi: 10.1109/ACCESS.2019.2952396.

[60] C. Marion, R. Li, and K. E. Waters, "A review of reagents applied to rare-earth mineral flotation," *Adv. Colloid Interface Sci.*, vol. 279, p. 102142, 2020, doi: 10.1016/j.cis.2020.102142.

[61] A. Alizadeh Sahraei, D. Azizi, A. H. Mokarizadeh, D. C. Boffito, and F. Larachi, "Emerging trends of computational chemistry and molecular modeling in froth flotation: A review," *ACS Eng. Au*, vol. 3, no. 3, pp. 128–164, 2023, doi: 10.1021/acsengineeringau.2c00053.

[62] G. Fan, L. Wang, Y. Cao, and C. Li, "Collecting agent–mineral interactions in the reverse flotation of iron ore: A brief review," *Minerals*, vol. 10, no. 8, p. 681, 2020, doi: 10.3390/min10080681.

[63] R. Li, H. Zhao, L. Wang, Q. Zhou, X. Yang, L. Jiang, X. Luo, J. Yu, J. Wei, and S. Mu, "Strengthened d–p orbital hybridization and hydrogen diffusion in a hollow N-doped porous carbon/Ru cluster catalyst system for hydrogen evolution reactions," *Chemical Science*, vol. 16, 2025, doi: 10.1039/D4SC08498E.

[64] Y. Miao, S. Wen, Z. Shen, Q. Zhang, and Q. Feng, "Enhancement of xanthate adsorption on cerussite surfaces by Pb(II) activation and its effect on floatability," *Molecules*, vol. 28, no. 6, p. 2455, 2023, doi: 10.3390/molecules28062455.

[65] I. V. Chernyshova, S. Ponnurangam, and Q. Liu, Multidisciplinary Advances in Efficient Separation Processes. Washington, DC: American Chemical Society, 2020.

[66] N. Shekhar Samanta, P. P. Das, S. Dhara, and M. K. Purkait, "An overview of precious metal recovery from steel industry slag: Recovery strategy and utilization," *Ind. Eng. Chem. Res.*, vol. 62, no. 23, pp. 9006–9031, 2023, doi: 10.1021/acs.iecr.3c00604.

[67] L. Xie, J. Wang, Q. Lu, W. Hu, D. Yang, C. Qiao, X. Peng, Q. Peng, T. Wang, W. Sun, and Q. Liu, "Surface interaction mechanisms in mineral flotation: Fundamentals, measurements, and perspectives," *Adv. Colloid Interface Sci.*, vol. 295, p. 102491, 2021, doi: 10.1016/j.cis.2021.102491.

[68] C. E. Gibson, S. Kelebek, and M. Aghamirian, "Pyrochlore flotation from silicate gangue minerals: Amine adsorption mechanisms and the effect of modifying reagents," *Miner. Eng.*, vol. 171, p. 107100, 2021, doi: 10.1016/j.mineng.2021.107100.

[69] K. Sun, C. V. Nguyen, N. N. Nguyen, and A. V. Nguyen, "Flotation surface chemistry of water-soluble salt minerals: From experimental results to new perspectives," *Adv. Colloid Interface Sci.*, vol. 309, p. 102775, 2022, doi: 10.1016/j.cis.2022.102775.

[70] G. Bhutani and P. R. Brito-Parada, "A framework for polydisperse pulp phase modelling in flotation," *Sep. Purif. Technol.*, vol. 236, p. 116252, 2020, doi: 10.1016/j.seppur.2019.116252.

[71] S. J. Anzoom, G. Bournival, and S. Ata, "Coarse particle flotation: A review," *Miner. Eng.*, vol. 206, p. 108499, 2024, doi: 10.1016/j.mineng.2023.108499.

[72] M. Sajjad and A. Otsuki, "Correlation between flotation and rheology of fine particle suspensions," *Metals*, vol. 12, no. 2, p. 270, 2022, doi: 10.3390/met12020270.

[73] S.Y. Park, S. Goo, H. Shin, J. Kim and H.J. Youn. Properties of cellulose nanofibril foam depending on wet foaming conditions. In Advances in Pulp and Paper Research, Cambridge 2022, Trans. of the XVIIth Fund. Res. Symp. Cambridge, 2022 (D. Coffin and W. Batchelor, eds), pp 45–64. FRC, Manchester, 2022. doi: 10.15376/frc.2022.1.45.

[74] G. C. DSouza, H. Ng, P. Charpentier, and C. C. Xu, "Recent developments in biobased foams and foam composites for construction applications," *ChemBioEng Rev.*, vol. 11, no. 1, pp. 7–38, 2024, doi: 10.1002/cben.202300014.

[75] M. Azhin, K. Popli, and V. Prasad, "Modelling and boundary optimal control design of hybrid column flotation," *Can. J. Chem. Eng.*, vol. 99, pp. S369–S388, 2021, doi: doi:10.1002/cjce.24010.

[76] A. Tanhua, M. Peltoniemi, R. Kallio, S. Peräniemi, and S. Luukkanen, "The effects of dry grinding and chemical conditioning during grinding on the flotation response of a Cu–Zn sulphide ore and a spodumene pegmatite silicate ore," *Miner. Eng.*, vol. 189, p. 107865, 2022, doi: 10.1016/j.mineng.2022.107865.

[77] J. Carpenter, M. Badve, S. Rajoriya, S. George, V. K. Saharan, and A. B. Pandit, "Hydrodynamic cavitation: An emerging technology for the intensification of various chemical and physical processes in a chemical process industry," *Rev. Chem. Eng.*, vol. 33, no. 5, pp. 433–468, 2017, doi: 10.1515/revce-2016-0032.

[78] N. Rajapakse, M. Zargar, T. Sen, and M. Khiadani, "Effects of influent physicochemical characteristics on air dissolution, bubble size and rise velocity in dissolved air flotation: A review," *Sep. Purif. Technol.*, vol. 289, p. 120772, 2022, doi: 10.1016/j.seppur.2022.120772.

[79] D. Mesa, K. Cole, M. R. van Heerden, and P. R. Brito-Parada, "Hydrodynamic characterisation of flotation impeller designs using positron emission particle tracking (PEPT)," *Sep. Purif. Technol.*, vol. 276, p. 119316, 2021, doi: 10.1016/j.seppur.2021.119316.

[80] C. Castillo, P. Fawell, and A. Costine, "Optimising the activity of acrylamide-based polymer solutions used to flocculate mineral processing tailings suspensions—A review," *Chem. Eng. Res. Des.*, Vol. 199, pp, 214-237, 2023, doi: 10.1016/j.cherd.2023.10.001.

[81] F. Nakhaei, M. Irannajad, and S. Mohammadnejad, "A comprehensive review of froth surface monitoring as an aid for grade and recovery prediction of flotation process. Part A: Structural features," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 45, no. 3, pp. 1-19, 2023, doi: 10.1080/15567036.2019.1663313.

[82] T. M. Jera and C. Bhondayi, "A review of flotation physical froth flow modifiers," *Minerals*, vol. 11, no. 8, p. 864, 2021, doi: 10.3390/min11080864.

[83] A. Hassanzadeh, M. Safari, D. H. Hoang, H. Khoshdast, B. Albijanic, and P. B. Kowalczuk, "Technological assessments on recent developments in fine and coarse particle flotation systems," *Miner. Eng.*, vol. 180, p. 107509, 2022, doi: 10.1016/j.mineng.2022.107509.

[84] A. Szmigiel, D. B. Apel, K. Skrzypkowski, L. Wojtecki, and Y. Pu, "Advancements in machine learning for optimal performance in flotation processes: A review," *Minerals*, vol. 14, no. 4, p. 331, 2024, doi: 10.3390/min14040331.