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COMPARATIVE CHEMICAL PROPERTIES ANALYSIS OF NANOBUBBLE-TREATED GOLD MINE TAILINGS FROM AMALGAMATION AND CYANIDATION

ANALISIS KOMPARATIF SIFAT KIMIA TAILING TAMBANG EMAS HASIL PERLAKUAN *NANOBUBBLE* DARI PROSES AMALGAMASI DAN SIANIDASI

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ABSTRACT

Tailings, the waste residue from gold mining processes, typically contain hazardous heavy metals that have the potential to contaminate the environment, particularly soil. This study aims to evaluate the changes in the chemical properties of gold mine tailings following nanobubble flotation treatment as an initial step toward sustainable remediation. Tailings samples were collected in a composite from two mining sites using different processing methods: cyanidation (GMBU Antam Pongkor, Bogor) and amalgamation (ASGM Kertajaya, Sukabumi). Nanobubble flotation was applied using combinations of reagents consisting of collectors (EDTA or NaOH), a frother (MIBC), and depressants (Na_2SiO_3 or Na_2CO_3). Parameters analyzed included pH (H_2O, KCl, H_2O_2), Cation Exchange Capacity (CEC), and exchangeable base cations (Ca, Mg, K, Na), measured using standard soil chemical methods. Comparative analysis was performed to assess changes in tailings chemistry before and after treatment. Results showed that nanobubble flotation slightly increased the pH of both tailings, indicating the neutralization of residual acidity. Varied CEC values depending on reagent composition, reflecting differences in the interaction between reagents and clay mineral surfaces. Base saturation in both sites remained low, suggesting that additional amelioration, such as gypsum or organic matter, is still required to improve cation balance. Nanobubble technology affected the tolerated tailings' chemical properties for soil and plants and demonstrated potential as a preliminary step toward the reclamation and reutilization of gold mine tailings for future land use.

Keywords: CEC, Cimapag formation, flotation, Jampang formation, pH

ABSTRAK

Tailing, limbah residu dari proses penambangan emas, umumnya mengandung logam berat berbahaya yang berpotensi mencemari lingkungan, terutama tanah. Studi ini bertujuan untuk mengevaluasi perubahan sifat kimia tailing tambang emas setelah perlakuan flotasi *nanobubble* sebagai langkah awal menuju remediasi berkelanjutan. Sampel tailing diambil secara komposit dari dua lokasi penambangan yang menerapkan metode pengolahan berbeda, yakni sianidasi (UBPE Antam Pongkor, Bogor) dan amalgamasi (PESK Kertajaya, Sukabumi). Flotasi *nanobubble* diterapkan menggunakan kombinasi reagen yang terdiri dari *collector* (EDTA atau

NaOH), *frother* (MIBC), dan *depressant* (Na_2SiO_3 atau Na_2CO_3). Parameter yang dianalisis meliputi pH (H_2O, KCl, H_2O_2), Kapasitas Pertukaran Kation (KPK), dan kation basa yang dapat ditukar (Ca, Mg, K, Na). Analisis komparatif dilakukan untuk mengevaluasi perubahan sifat kimia tailing sebelum dan setelah pengolahan. Hasil menunjukkan bahwa flotasi *nanobubble* meningkatkan pH kedua tailing, menunjukkan netralisasi keasaman residual. Nilai KPK bervariasi tergantung pada komposisi reagen, mencerminkan perbedaan interaksi antara reagen dan permukaan mineral lempung. Kejenuhan basa di kedua lokasi tetap rendah, sehingga diperlukan perbaikan tambahan seperti gipsum atau bahan organik untuk meningkatkan keseimbangan kation. Secara keseluruhan, flotasi nanobubble berdampak pada beberapa sifat kimia tailing yang dapat ditoleransi tanah dan tanaman dan menunjukkan potensi sebagai langkah awal rehabilitasi dan pemanfaatan kembali tailing tambang emas untuk penggunaan lahan di masa mendatang.

Kata Kunci : Formasi Cimapag, Formasi Jampang, Flotasi, KPK, pH

INTRODUCTION

Gold mining and processing activities have the potential to cause tailings that contaminate the environment, including soil (Nurcholis *et al*., 2017). According to Boul (1981), tailings from gold mining are the powdered rock residues derived from mineral rocks that have been crushed in the processing plant. Nevertheless, tailings have the potential to be a resource that can be utilized because their main composition includes quartz, silicate clays, and some metals (Prasetyo, 2008). However, one of the major challenges in tailings management is reducing contaminants in tailings, such as heavy metals and gangue minerals within them.

Nanobubbles, known as ultrafine bubbles, are defined by the International Standards Organization (ISO) as gas-filled cavities with a volume equivalent diameter of less than 1 µm (Jia *et al*., 2023). Nanobubble technology, with its unique ability to separate contaminants from liquid and solid media, offers an innovative solution to this problem. The immensely small bubble size in the use of nanobubbles can increase the effectiveness of contaminants separation from tailings through improved physical and chemical properties. Tailings management as a countermeasure by handling or treating waste after the production process is referred to as “end of pipe”, the implementation which involves reducing the volume, concentration, toxicity, and level of hazard that can spread in the environment through reutilization, waste recycling, and increased recovery (Prasetyo, 2008). The mechanism of heavy metal flotation method by nanobubble is illustrated in Figure 1 and Figure 2.

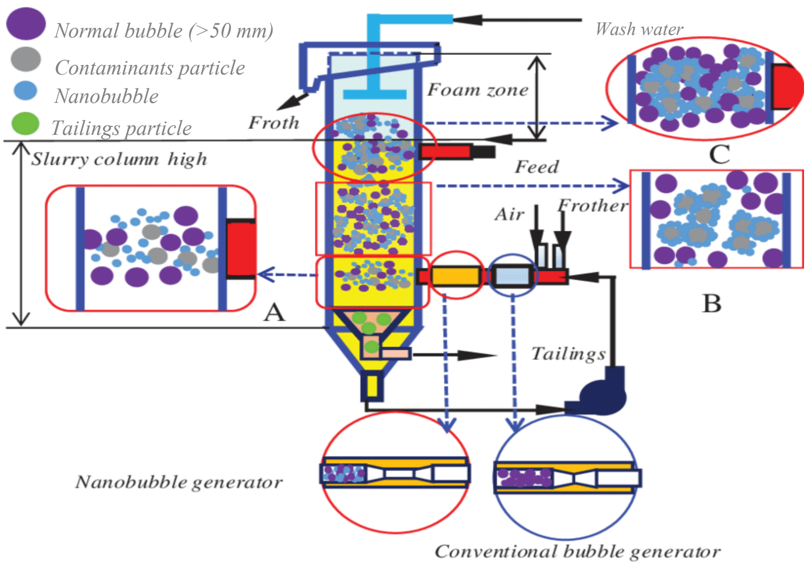

Figure 1. Illustration of the mechanism of nanobubble adsorption on the surface of contaminants particles (Ma *et al*., 2019)

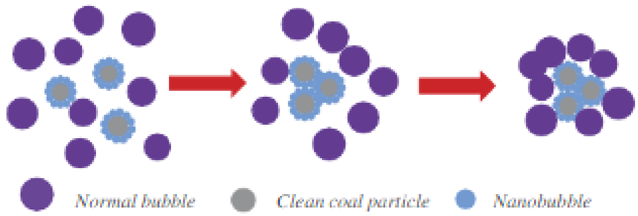

Figure 2. Illustration of enhanced flotation of contaminants particles by nanobubbles (Ma *et al*., 2019)

The application of nanobubble by flotation method utilizes the reaction arising from the addition of reagents such as collector, frother, and depressant. Collector serves to make the surface of mineral particles hydrophobic through attachment to the mineral surface so that it can attach to air bubbles. Frother serves to produce stable foam during the flotation process. Methyl Isobutyl Carbinol (MIBC) as a frother has the molecular formula $C_6H_{14}O$, is an alcohol-derived hydrocarbon that is often used as a frother in flotation because of its effectiveness in forming foam so that it is beneficial from a physical point of view to the continuity of flotation. Depressant functions for selectivity of transported minerals in order to suppress the flotation of unwanted minerals so that they do not flotate. The use of these reagents is a factor in the selectivity of bubbles transporting contaminants from tailings suspensions (Chipakwe *et al*., 2021).

Flotation with nanobubbles can affect the chemical properties of tailings. Several studies have shown that nanobubbles significantly increase the contact angle as the hydrophobicity of minerals also increases. The use of reagents is also interrelated with pH variations and can affect the final pH value of the tailings (Yan *et al*., 2025). Therefore, identification of chemical properties is necessary to determine the effect of nanobubbles on the chemical properties of tailings.

This study aims to explore the effect of applying nanobubble technology to the chemical properties of gold tailings, with the hope that tailings' chemical properties can be tolerated by soil and plants. It is hoped that this research can provide new insights in innovative mining waste management to develop more effective methods in remediating gold tailings, as well as evaluate the reutilization of tailings that have been treated through a series of flotation with nanobubble for an environment that is clean from contamination.

MATERIALS AND METHODS

A. Study Area and Sample Preparation

Tailing samples were collected from Gold Mining Business Unit (GMBU) Pongkor, PT Aneka Tambang, Tbk, Bogor, West Java and Artisanal and Small-scale Gold Mining (ASGM) in Kertajaya, Simpenan, Sukabumi, West Java, each with a composite of 4 points to represent the tailings area. These two sites were sampled to examine the significant properties of tailings from different processing methods, namely amalgamation and cyanidation. The tailings samples were air-dried at room temperature, pulverized and sieved to a size of 270 - 325 mesh.

Before use, the tailings samples were pretreated by homogenizing 500 g of it using 1 L of distilled water. The solution was added NaOH drop by drop until it had a pH ranging from 9-10 to obtain a well-dispersed and chemically stable slurry. This step ensures reproducible hydrodynamic and mass-transfer conditions similar to those applied in nanobubble-assisted flotation and flocculation studies (Shao *et al.*, 2023). Under alkaline conditions (pH 9–10), nanobubbles have a strong negative charge (approximately −59 mV at pH 10) and a stable electric double layer, thus maintaining the stability and dispersion of nanobubbles in solution (Xiao *et al.*, 2018). In addition, alkaline pH causes changes in the surface charge of particles, which reduces electrostatic repulsion and increases hydrophobic interactions, collector adsorption, and particle–bubble adhesion during the flotation process.

B. Nanobubble Flotation Treatment

Flotation was conducted with the modelling framework for the generation of Micro Nanobubbles (MNBs) Generator. It used Computational Fluid Dynamics combined with Population Balance Methods (CFD-PBM couple model). Flotation with nanobubbles was developed by combining collector, frother, and depressant reagents. The collectors used in this study were ethylene diamine tetra acetic acid or EDTA (Na_2-$C_{10}H_{14}N_2O_8$) and NaOH. The frother used is Methyl Isobutyl Carbinol (MIBC) thas has $C_6H_{14}O$ structure. The depressants used are Na_2SiO_3 and Na_2CO_3.

The flotation process with nanobubble began with mixing the tailings sample and the combination of 0,3 g collector with 0,05 g depressant in 500 mL aquadest, followed by adding 5 mL of frother reagent at the 5th minute of flotation running. A combination of four variations of reagent treatments was applied crosswise between collector and depressant on two tailings samples from different locations, with all four treatments still using the same MIBC as the frother. Therefore, in this study there were 8 tailings samples, of which 4 were taken from Pongkor GMBU and 4 from Sukabumi ASGM. The 4 treatment variations are

(1) Combination of reagent collector EDTA, frother MIBC, and depressant Na_2SiO_3;

(2) Combination of reagent collector EDTA, frother MIBC, and depressant Na_2CO_3;

(3) Combination of reagent collector NaOH, frother MIBC, and depressant Na_2SiO_3; and

(4) Combination of reagent collector NaOH, frother MIBC, and depressant Na_2CO_3. Therefore, the samples after flotation are symbolized P1, P2, P3, and P4 for the Pongkor site and S1, S2, S3, and S4 for the Sukabumi site, respectively. Details of the sample codes are presented in Table 1.

Table 1. Details of flotation reagent treatment on tailings samples

Tailings Sample	Treatment			Sample Code
	Collector	Frother	Depressant	
Pongkor (Cyanidation)	EDTA	MIBC	Na_2SiO_3	P1
	EDTA	MIBC	Na_2CO_3	P2
	NaOH	MIBC	Na_2SiO_3	P3
	NaOH	MIBC	Na_2CO_3	P4
Sukabumi (Amalgamation)	EDTA	MIBC	Na_2SiO_3	S1
	EDTA	MIBC	Na_2CO_3	S2
	NaOH	MIBC	Na_2SiO_3	S3
	NaOH	MIBC	Na_2CO_3	S4

Nanobubble formed by the reaction of reagents that carry heavy metals and gangue minerals flotation to the output of the generator. Mineral-loaded bubble cells like metal-colored detergent froth overflow from the output of the flotation machine into the mineral collection bin (Paradise and Nurkhamim, 2020). The flotation stage was stopped when the bubbles no longer appear to float towards the generator output, varied around 40 minutes to 2 hours for each treatment. Treated tailings (sediment fraction) were separated by centrifuge, dried by oven at 60°C, and stored for chemical analysis.

C. Analysis of Chemical Properties

The analysis of chemical properties was applied to each sample before and after flotation to measure those levels after separation from tailings. The results of the chemical properties before and after treatment were recorded for each treatment variation. Analysis of pH using a pH-meter for pH H_2O and KCl using a calibrated pH meter (ISO 10390:2005), and identification of the pyrite oxidation potential with H_2O_2 by adding 30% H_2O_2 (Sobecki and Ainsworth, 1991). Cation Exchange Capacity (CEC) analyzed with 1 N NH_4OAc 1 N extract at pH 7 (Soil Survey Laboratory Methods, USDA, 2017). Base saturation calculated from the proportion of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, Na^+) extracted using NH_4OAc and analyzed by AAS (Atomic Absorption Spectrophotometer).

Comparative analysis was conducted by comparing the data pattern obtained from chemical properties in tailings, before and after flotation. It aims to determine changes in the properties of tailings.

RESULTS AND DISCUSSION

A. Geology and Mineralogy of Gold Tailings Samples

GMBU PT Aneka Tambang, Tbk. is geographically located at Mount Pongkor, Nunggul Village, Nanggung District, Bogor Regency, West Java. The lithology of the sampling area consists of lapilli tuff, breccia tuff, and andesite which are characteristic of the Cimapag Formation, as shown in Figure 3.

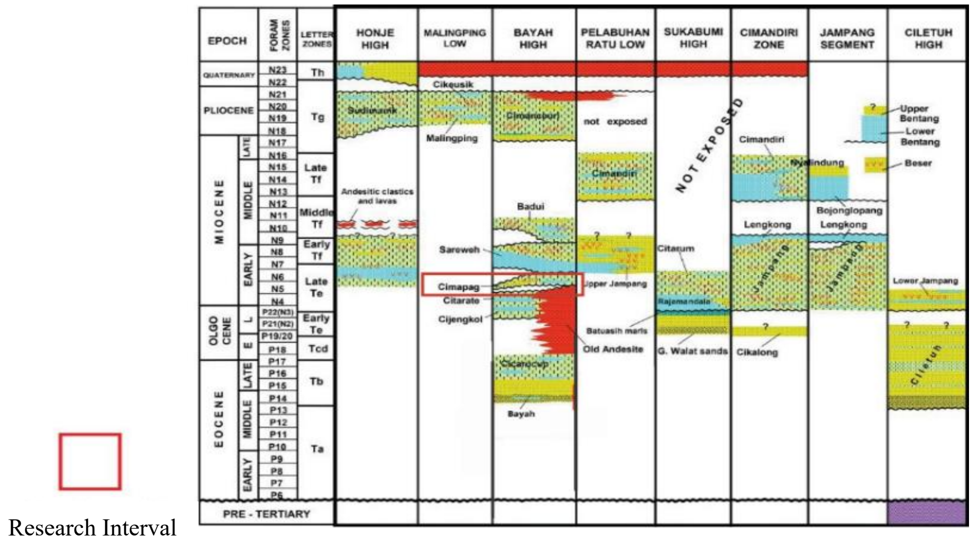

Figure 3. Regional stratigraphic column of southern West Java (Pertamina and Beicip, 1985).

Geographically, Sukabumi ASGM is located in Kertajaya Village, Simpenan Sub district, Sukabumi District, West Java Province. Geologically, the Kertajaya area belongs to the Jampang Formation which consists of fine to very coarse grained submarine volcanic rocks of Lower Miocene age, specifically the upper fan of the Jampang Formation as illustrated in Figure 4.

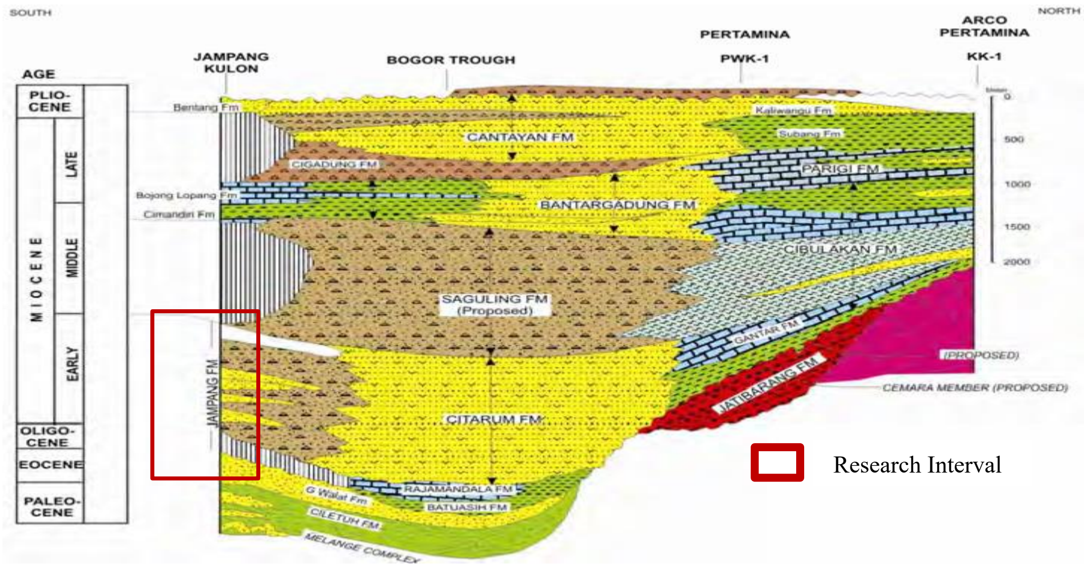

Figure 4. Regional Stratigraphic Column of the West Java region (Martodjojo, 1984)

B. Chemical Properties of Gold Tailings After Flotation with Nanobubble

Nanobubble application was at risk of causing changes in the physical and chemical properties of the tailings. Therefore, several characteristic parameters of the tailings were analyzed before and after treatment to determine the effect of nanobubble application on the chemical properties of the tailings. The chemical properties of the tailings analyzed were pH (potential of Hydrogen), CEC (Cation Exchange Capacity), and Base Saturation.

Table 2. pH, CEC, and base saturation in tailings samples before and after flotation

Sample Code*	pH H_2O	pH KCl	pH H_2O_2	CEC (cmol(+)/kg)	Base Saturation (%)
Pongkor	8,19	7,44	4,10	28,49	10,67
P1	8,20	8,12	4,92	27,89	5,38
P2	8,18	8,01	4,88	31,03	8,44
P3	8,16	7,95	5,28	6,01	40,76
P4	8,23	8,11	5,41	18,95	21,84
Sukabumi	6,79	6,52	3,11	4,55	48,57
S1	8,29	7,83	5,21	9,49	9,90
S2	8,22	8,06	5,14	8,68	17,16
S3	8,38	7,54	4,82	8,83	9,63
S4	8,50	7,96	4,51	9,49	16,33

*) Sample codes based on flotation treatment can be seen in Table 1

1. pH of Tailings

The determination of pH in tailings samples both before and after flotation with nanobubbles aims to determine the effect of flotation and the reagents used on changes in acidity levels in each sample. Gold tailings that have undergone various stages of mining certainly have the potential to have high acidity levels, especially with the presence of pyrite in each sample. Additionally, pH values influence nutrient availability, making pH determination a critical parameter for optimizing the potential of tailings as a sustainable growing medium. Determination of pH in tailings shown in Figure 5.

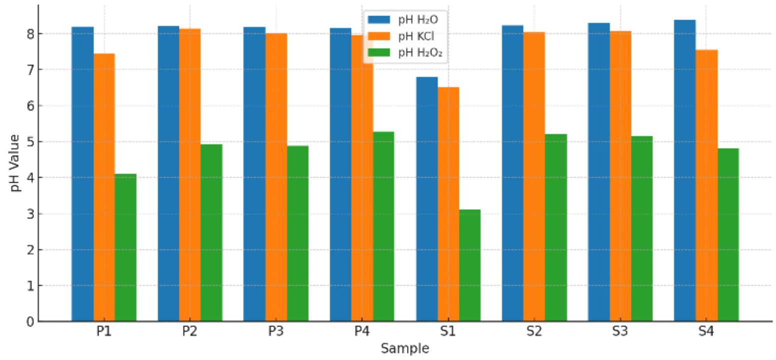

Figure 5. Interpretation of pH values in tailings samples after flotation

Based on the analysis results presented in Table 2, the pH of H_2O in the Pongkor GMBU tailings before treatment was 8,19, classified as moderately alkaline according to the USDA Soil Taxonomy (2017), which defines neutral soils as pH 6,6–7,3 and alkaline soils as >7,3. The relatively high pH is associated with the presence of calcite ($CaCO_3$) and other carbonate-bearing minerals that buffer acidity and maintain alkalinity. It came from the origin materials from the soil. Similar findings were reported by Mendez and Maier (2008), who stated that carbonate minerals in mine tailings can neutralize acid generation and stabilize pH within the alkaline range.

In contrast, the Sukabumi ASGM tailings exhibited a pH of 6,79, classified as neutral, likely due to the oxidation of pyrite (FeS_2), which produces sulfuric acid upon exposure to air and water. XRD analysis confirmed the presence of pyrite peaks in the Sukabumi sample, supporting the observed acidity. Minor occurrences of oligoclase and calcite provide limited neutralization, but are insufficient to offset pyrite oxidation. These differences reflect contrasting ore mineralogy and processing methods between cyanidation (Pongkor) and amalgamation (Sukabumi).

After flotation, the pH of H_2O for the Pongkor samples (P1–P4) remained relatively stable, ranging from 8,16 to 8,23, while the Sukabumi samples (S1–S4) increased to 8,22–8,50. The stabilization of pH near alkaline conditions is attributed to sample preconditioning at pH 9 prior to flotation and to the alkaline nature of reagents (EDTA, NaOH, Na_2CO_3, and Na_2SiO_3). Similar results were observed by Zhang *et al.* (2020), who found that flotation reagents containing alkaline compounds can neutralize acid mine drainage and elevate tailings pH.

The pH KCl of the Pongkor GMBU sample before treatment was 7.44, while that of Sukabumi ASGM was 6,52. After flotation, pH KCl values in both sites remained within the slightly alkaline–moderately alkaline range (7,4–8,4). The difference between pH H_2O and pH KCl, often referred to as ΔpH, indicates the dominance of negative surface charge and potential exchangeable acidity in both tailings. A greater ΔpH suggests a risk of acid generation if sulfide oxidation continues, consistent with the characteristics of mine-derived materials.

In the peroxide oxidation test (pH H_2O_2), which simulates pyrite weathering, the initial pH of the Pongkor tailings was 4,10, increasing to 4,88–5,41 after flotation, whereas the Sukabumi tailings initially had a pH of 3,11, increasing to 4,51–5,21. According to Sobek *et al.* (1978), pH <2,5 during peroxide testing indicates very high pyrite content, while pH between

4–5 suggests moderate sulfide oxidation potential. Therefore, both tailings can still generate acidity under oxidizing conditions but show a reduced tendency after flotation. The increase in pH (H_2O_2) after treatment implies that alkaline reagents reacted with sulfate or ferric ions, forming neutral salts such as Na_2SO_4 or $Fe(OH)_3$, thus lowering acid reactivity.

Overall, the flotation process not only neutralized the acidity in ASGM tailings, but also maintained the stability of pH in the GMBU Pongkor samples. These results indicate that nanobubble flotation with alkaline reagents can suppress potential acid generation and create more favorable conditions for subsequent soil amendment or revegetation efforts.

2. Cation Exchange Capacity (CEC) of Tailings

Determination of Cation Exchange Capacity (CEC) was carried out to measure the ability of tailings to absorb and exchange back the cations in it. The result of CEC value of each sample after nanobubble treatment interpreted through the graph in Figure 6.

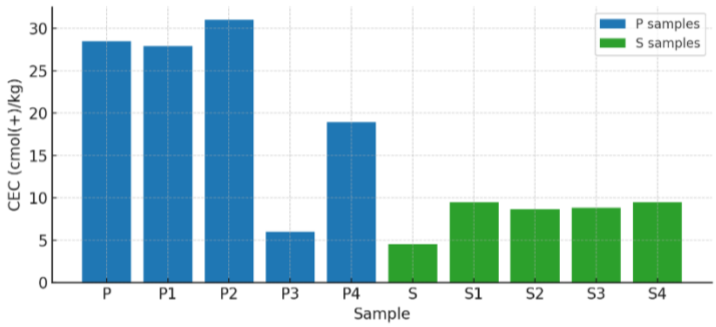

Figure 6. Interpretation of CEC values in tailings samples after flotation

Based on the data presented in Table 2 and Figure 6, the CEC value of the Pongkor GMBU tailings before treatment was 28,49 cmol(+)/kg, while the Sukabumi ASGM tailings showed a much lower value of 4,55 cmol(+)/kg. The high CEC of the Pongkor tailings can be attributed to the dominance of 2:1 clay minerals, particularly smectite and illite, as identified by X-Ray Diffraction. These minerals possess a large specific surface area and permanent negative charge that allow greater adsorption and exchange of cations. In contrast, the Sukabumi ASGM tailings were dominated by kaolinite and quartz, which are 1:1 and inert silicate minerals, respectively, resulting in limited cation exchange sites.

After nanobubble flotation, variations in CEC were observed across different reagent combinations. In the Pongkor samples, CEC increased slightly in P2 (31,03 cmol(+)/kg) but decreased in P1 (27,89 cmol(+)/kg), P3 (6,01 cmol(+)/kg), and P4 (18,95 cmol(+)/kg). These heterogeneous results suggest that the reagents used during flotation interact differently with mineral surfaces. The reagents containing EDTA acted as chelating agents capable of removing metal coatings from negatively charged sites, thereby reactivating the cation exchange capacity (Hossain *et al*., 2010). However, excessive use of Na-based reagents (e.g., NaOH, Na_2CO_3, Na_2SiO_3) can disperse clay aggregates, leading to structural collapse and a reduction in accessible surface area, which ultimately decreases the measured CEC. High sodium saturation can cause particle dispersion.

In the Sukabumi ASGM tailings, CEC values increased in all treated samples (S1–S4), indicating that nanobubble flotation enhanced the availability of exchange sites. This improvement likely resulted from the removal of exchangeable cations like Fe^{2+} and Pb^{2+} ions, which had previously occupied surface charge sites. The combination of alkaline reagents and nanobubbles promoted oxidation and dissolution of these metal cations, restoring the negative surface charge balance.

The contrasting response between Pongkor and Sukabumi tailings may also be explained by their mineralogical differences. The 2:1 clay-rich Pongkor sample is more sensitive to Na dispersion and structural alteration, while the kaolinite-rich Sukabumi sample, though having initially low CEC, responds more positively to surface cleaning and alkalinity. The strong correlation between mineral composition and reagent behavior demonstrates that flotation treatment can modify not only the metal content but also the surface reactivity of tailings.

Overall, these results indicate that nanobubble flotation influences the surface chemistry of tailings by modifying the accessibility of cation exchange sites. However, variations among treatments emphasize that reagent selection and dosage optimization are critical for improving the chemical quality of tailings without deteriorating their structure.

3. Tailings Base Saturation

The determination of base saturation value in tailings is related to the evaluation of the proportion of base cations that occupy cation exchange sites in tailings. High base saturation generally supports the availability of nutrients for plants. Base saturation also indicates the potential alkalinity that can affect the mobility of heavy metals and other elements in tailings. The result of base saturation concentrations of each sample after nanobubble treatment interpreted through the graph in Figure 7.

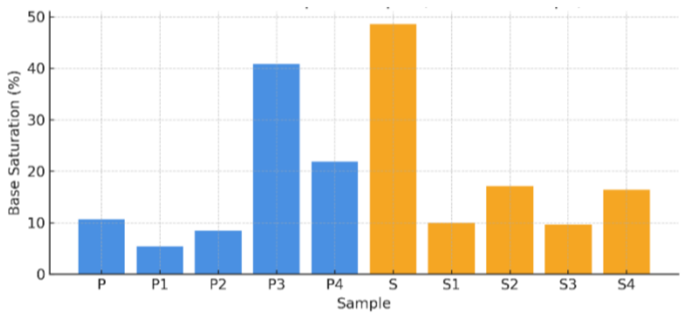

Figure 7. Interpretation of base saturation concentrations in tailings samples after flotation

The base saturation (BS) of tailings represents the proportion of total cation exchange sites occupied by base cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}). As shown in Table 2 and Figure 7, the BS of the Pongkor GMBU tailings before treatment was 10,67%, while that of the Sukabumi ASGM tailings was 48,57%. After nanobubble flotation, BS showed considerable variation depending on the reagent composition. BS of Pongkor tailings slightly decreased in P1 (5,38%) and P2 (8,44%), but increased drastically in P3 (40,76%) and moderately in P4 (21,84%). The substantial rise in P3 indicates that the reagents used in this treatment promoted replacement of exchangeable acidity (H^{+} and Al^{3+}) with base cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}), thus improving cation retention. This effect may be related to the balanced composition of depressants and collectors that enhanced dispersion without excessive Na^{+} accumulation, which otherwise could cause structure degradation.

In contrast, the Sukabumi ASGM tailings initially had a high BS value (48,57%), reflecting strong base saturation before treatment. However, after flotation, BS drastically decreased to 9,90% (S1), 17,16% (S2), 9,63% (S3), and 16,33% (S4). This decline suggests that the reagents and flotation process can mobilized or displaced base cations from the exchange complex, possibly through cation exchange reactions involving Na^{+} from alkaline reagents. The replacement of Ca^{2+} and Mg^{2+} by Na^{+} reduces cation increasing efficiency and can deteriorate the exchange surface, excessive sodium saturation leads to dispersion and reduced the structure stability.

The BS response patterns show the opposite between Pongkor and Sukabumi tailings. In Pongkor, BS increased markedly under certain reagent conditions, indicating chemical improvement from initially low base saturation. Meanwhile, the Sukabumi tailings experienced a strong decline, possibly due to reagent-driven desorption or dissolution of basic cations. These contrasting behaviors highlight the importance of reagent type, concentration, and mineral composition in determining the success of nanobubble flotation for chemical stabilization. Although some treatments enhanced BS substantially (e.g., P3), values below 60% still indicate that additional amelioration such as organic or gypsum application would be needed to restore full base balance and support plant growth.

D. Effectiveness of Gold Tailings Remediation with Nanobubble Application

The effectiveness of the nanobubble flotation treatment can be evaluated from the simultaneous changes in pH, CEC, and base saturation values. The treatment effectively stabilized the chemical properties of both tailings, particularly by neutralizing acidity and improving the buffering capacity. It was found to be site-dependent, reflecting differences in initial composition and reagent response.

In the Pongkor GMBU tailings, which initially had very low base saturation (10,67%) and moderate alkalinity, the treatment, particularly in P3 and P4, significantly improved chemical stability, as reflected by the increase in BS up to 40,76% and the maintenance of near-neutral pH. This suggests that nanobubbles enhanced reagent dispersion and promoted ion exchange, allowing the replacement of exchangeable acidity (H^+, Al^{3+}) by base cations (Ca^{2+}, Mg^{2+}, Na^+). The activation of these exchange sites indicates a partial remediation effect, improving the tailings' buffering capacity and cation retention potential.

In contrast, the Sukabumi ASGM tailings initially exhibited high BS, which decreased drastically after 4 treatments. This decline implies that the flotation reagents especially sodium-based ones caused excessive ion replacement and leaching of exchangeable bases. The introduction of excess Na^+ can induce dispersion and reduce structural stability, offsetting the chemical improvement achieved through pH neutralization. Hence, while nanobubbles facilitated the flotation process efficiently, the chemical quality of the treated tailings may decline if reagent concentration and composition are not properly balanced.

Nanobubble technology contributed significantly to enhancing flotation efficiency by providing high interfacial surface area and stable zeta potential, which improved the contact between reagents and mineral particles. Nanobubbles enhance oxidation–reduction reactions and promote the detachment of metal ions from mineral surfaces, thereby improving both metal separation and the chemical quality of tailings. In this study, such effects are reflected by the reduced acidity (higher pH H_2O_2) and the improved exchange capacity of the treated samples.

Although the nanobubble flotation treatment demonstrated potential for improving the chemical characteristics of gold mine tailings, the results also indicate that it should be regarded as a preliminary remediation step rather than a complete reclamation process. The remaining Na-rich conditions and moderate base saturation imply that post-treatment amelioration such as the addition of organic matter, gypsum, or biochar would still be required to enhance nutrient balance and structural aggregation before revegetation. Further assessment of heavy metal concentrations, plant growth response, and biological activity is therefore necessary to confirm the environmental safety and reclamation readiness of the treated tailings.

CONCLUSION

Based on the research that has been carried out, it is concluded that nanobubble technology affects different changes in the chemical properties of tailings, due to differences in initial mineral composition and reagents' interaction. The Pongkor GMBU tailings showed significant chemical improvement after treatment with increases in pH stability, CEC, and base saturation. These results indicate that nanobubbles enhanced reagent dispersion and ion exchange, effectively replacing exchangeable acidity with base cations and improving the buffering capacity of the tailings. Meanwhile, the Sukabumi ASGM tailings initially exhibited high base saturation but experienced a sharp decrease after treatment. This suggests that reagent optimization is crucial, as over-saturation by Na^+ may counteract the intended chemical remediation benefits.

Nanobubble flotation proved effective as a preliminary remediation step for tailings with low base saturation and poor buffering capacity, as observed in Pongkor. However, for tailings already rich in base cations, such as Sukabumi, careful reagent selection and post-treatment amelioration are necessary to restore ionic balance and improve the physicochemical conditions required for successful reclamation and revegetation. Future studies should include analyses of heavy metal concentrations, plant growth performance, and microbial activity to validate the environmental safety and sustainability of the treated tailings.

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