



Kinetic and Thermodynamic Analysis for the Transformation of Poorly Albite-kaolin from Gaya (Niger) into Metakaolin for sodalite synthesis

**MAMANE SOULEY. ABDOUL AZIZ^{*1,2}, MAHAMANE SANI OUSMANE²,
SEYBOU YACOUBA ZAKARIYAOU³, ABDOULAYE DAN MAKAOU OUMAROU¹
and BENJAMIN KOUASSI YAO¹**

¹Laboratoire des Procédés Industriels de synthèse, de l'Environnement et des Energies nouvelles (LAPISEN), Institut National Polytechnique Félix Houphouët-Boigny, Yamoussoukro, BP 1093, Côté d'Ivoire

²Département Géoressources et Procédés, Ecole Nationale d'Ingénieries et des Sciences des Energies, Université d'Agadez, Agadez, BP 199, Niger

³School of Chemistry and chemical Engineering, Central South University, Changsha, BP 410083, China

*Corresponding author E-mail: asouley2020@gmail.com

<http://dx.doi.org/10.13005/ojc/420311>

(Received: March 27, 2026; Accepted: May 18, 2026)

ABSTRACT

Selecting the kaolin calcination temperature is critical for producing amorphous products while minimizing energy use. This study applied the Coats–Redfern model to analyze the kinetic and thermodynamic behavior of poorly-crystalline albite-kaolin from Gaya, Niger, identifying four distinct transformation phases. Phase 1 (45–337°C) involved dehydration with minimal mass loss (0.40%), moderate activation energy ($E_a = 0.33$ eV), and negative entropy ($\Delta S = -234.5$ J/mol•K). Phase 2 (337–460°C) showed substantial mass loss (4.66%), slightly lower E_a (0.30 eV), and more negative ΔS (-243.0 J/mol•K), indicating increased structural ordering. Phase 3 (460–626°C) exhibited a comparable mass loss (4.42%) but distinct kinetics: the highest E_a (0.50 eV), the least negative ΔS (-215.8 J/mol•K), and a 32-fold increase in the pre-exponential factor ($A = 100.5$ s⁻¹). Phase 4 (626–884°C) displayed minimal loss (1.05%), the lowest E_a (0.18 eV), and the most negative ΔS (-267.4 J/mol•K) during eutectic melt formation. Optimal sodalite crystallization occurs in Phase 3, where maximum reaction frequency aligns with active chemical transformation.

Keywords: Albite-kaolin clay, Sodalite, kinetic, Thermodynamic, Model of Coats and Red-fern.



INTRODUCTION

Aluminosilicates are minerals composed of aluminum, silicon, oxygen and other elements such as sodium and calcium¹. Due to their physicochemical properties, abundance and low cost, Aluminosilicate clays have several industrial applications. They are used in the production of tiles, sanitary ware, heat resistant materials, catalysts, absorbents, paper, cosmetics and environmental protection²⁻⁴. Kaolin, a type of aluminosilicate mineral, has several properties that influence its industrial applications⁵. Kaolin's chemical composition, thermal stability and plasticity make it a crucial component in ceramic production. Its whiteness, brightness and particle size make it an ideal coating material for paper and paints. These properties to which one can add its surface area, porosity and acidity influence also its catalytic applications. Physicochemical properties of kaolin can vary depending on its deposition and location. Several kinds of minerals including quartz, Albite, Muscovite, orthoclase, halloysite, nacrite and dickite occur in natural kaolin⁶. These impurities may influence the characteristics of kaolin and impair its utility for industrial applications such as ceramics paper and zeolite. Zeolites, encompassing various forms such as types A, Y, P, cancrinite, and sodalite, can be synthesized from either chemical precursors or natural kaolin. While synthesis using chemical precursors yields pure products, the process is costly, underscoring the need for affordable, abundant alternatives like kaolin. The transformation of kaolin into metakaolin is a crucial step in the synthesis of sodalite. Kaolin, a naturally occurring clay mineral, undergoes a thermal treatment process known as calcination to produce metakaolin, an amorphous aluminosilicate phase. To produce metakaolin, kaolin is typically calcined at temperatures between 500°C to 850°C, where dehydroxylation occurs, and the crystalline structure is transformed into an amorphous phase⁷. Recently, Abdoul Aziz *et al.* synthesized sodalite via calcination of kaolin at 600°C⁸. Multiple studies have demonstrated the synthesis of metakaolin at temperatures reaching up to 800°C⁹⁻¹². To date, no studies have investigated the kinetics and thermodynamics of kaolin-to-metakaolin transformation using the model of Coats-Redfern. The kinetics and thermodynamics of this transformation play a significant role in determining the properties of the resulting metakaolin and its suitability for sodalite synthesis. This study focuses

on the kinetic and thermodynamic analysis of the transformation of kaolin from Gaya into metakaolin, with the aim of optimizing the calcination process for the production of high-quality metakaolin for sodalite synthesis. First, many characterization techniques were used to determine its physical, chemical and mineralogical properties. X-ray fluorescence (XRF) was used to determine the chemical composition including major and minor elements. The mineralogical composition and crystal structure were investigated using the X-Ray Diffraction (XRD) technique¹³. The thermal stability and mass loss were assessed using the Thermogravimetric Analysis. Then, to investigate the kinetic and thermodynamic behavior of this kaolin, the model of Coats-Redfern was employed to calculate the key parameters for each zone of mass loss section. The molecular structure and functional groups of Gaya kaolin assessed using Fourier Transform Infrared spectroscopy was used. Finally, the X-ray diffraction spectroscopy (XRD), the Fourier transform infrared spectroscopy (FTIR), the scanning electron microscopy (SEM) and were used to characterize the synthesized zeolite.

MATERIALS AND METHODS

Kinetic and thermodynamic analysis

The thermal stability and mass loss of the raw kaolin were assessed using thermogravimetric Analysis. To investigate the kinetic and thermodynamic behavior of the present sample, the model of Coats-Redfern was employed to calculate the key parameters for each zone previously discussed in the mass loss section. Assuming that all zone conversions are first-order reactions, the following equation and the constants of Planck and Boltzmann is used:

$$\ln [-\ln (1 - x)] = \ln \left(\frac{A R T^2}{\beta E_a} \right) - \frac{E_a}{R T}$$

where

$$x = \frac{W_i - W_t}{W_i - W_f}$$

w_i : initial weight,

w_t : weight of sample at particular temperature T,

w_f : final weight.

A: pre-exponential factor,

β : heating rate (10 °C/min),

R: gas constant (8.3143 J mol⁻¹ K⁻¹),
 Ea: activation energy,
 T: temperature (K) at the peak of the DTG curves.

The slope and intercept values of each zone were calculated from the plot $\ln[-\ln(1-x)]$ versus $1000/T$, then further used to calculate the apparent activation energy and other thermodynamic parameters listed in Table 4, such as the pre-exponential factor (A), Gibbs free energy (ΔG), Entropy Change (ΔS), and Enthalpy change (ΔH) [27,82,83,84].

$$E_a = \text{slope} \times 8.3143$$

$$A = \frac{\beta E_a}{RT^2} e^{\frac{E_a}{RT}}$$

$$\Delta S = R \times \ln\left(\frac{Ah}{KT}\right)$$

$$\Delta H = E_a - RT$$

$$\Delta G = \Delta H - T \cdot \Delta S$$

where k is Boltzmann's constant (1.381×10^{-23} J·K⁻¹), and h is Planck's constant (6.626×10^{-34} J·s).

Synthesis of sodalite

Sodalite was synthesized by first extracting the fraction less than 2 μm from the starting material using a centrifuge. The resulting product was then subjected to calcination at 620°C to produce metakaolin which contained quartz, orthoclase and albite as associated minerals. The fraction less than 2 μm from the starting material was subsequently treated with hydrochloric acid for 96 hours. The treated kaolin was calcined at 620°C to produce metakaolin without albite. The resulting metakaolin was mixed with sodium hydroxide and reacted in an autoclave at 200°C for 2 hours to produce sodalite. The obtained product was filtered, washed with distilled water to eliminate excess alkali.

Characterization of Gaya kaolin and the resulted products

In this study, the physicochemical properties of Bana kaolin, the resulting metakaolin and synthesized sodalite were investigated using several instrumental techniques: The chemical

composition of the raw kaolin including major and minor elements, was determined using the X-ray fluorescence (XRF) (Panalytical Axios series Phillips). The mineralogical composition and crystal structure of Bana kaolin, the resulting metakaolin and synthesized sodalite were investigated using the Rigaku Miniflex X-Ray Diffraction. The Goniometer has Bragg-Brentano geometry with 150 mm radius, and has a measurement range 2θ of 2° to 145°. The x-ray source is a copper anode ($\lambda_{\text{Cu K}\alpha} = 1.5418 \text{ \AA}$). The obtained sodalite was also characterized using the Fourier transform infrared spectroscopy (FTIR) and the scanning electron microscopy (SEM).

RESULTS AND DISCUSSION

DSC/TGA Analysis of Gaya Kaolin

The TGA-DTA curve of the kaolin sample heated from 30 to 950 °C at 10.00 °C/min is shown in Fig. 1. The first endothermic mass loss between 30–265 °C is due to the evaporation of adsorbed water. The maximum weight loss occurs above 580 °C. The dehydroxylation above 580 °C with a significant mass loss of around 11 % is due to the loss of structural water to produce disordered metakaolin ($\text{Al}_2\text{Si}_2\text{O}_7$)¹⁴.

Kinetic and thermodynamic analysis

The kinetic and thermodynamic parameters for metakaolin formation, combined with weight loss data (Fig.2), reveal a four-phase transformation mechanism with important insights for synthesis optimization. Phase 1 (45-337°C) shows minimal weight loss (0.40%) with moderate activation energy (0.33 eV) and negative entropy ($\Delta S = -234.5 \text{ J/mol}\cdot\text{K}$), corresponding to dehydration and structural reorganization. Phase 2 (337-460°C) exhibits substantial weight loss (4.66%) with slightly decreased activation energy (0.30 eV) and more negative entropy ($\Delta S = -243.0 \text{ J/mol}\cdot\text{K}$), indicating carbonate and hydroxide decomposition with chloride volatilization that increases order in the remaining solid matrix. Phase 3 (460-626°C) demonstrates comparable weight loss (4.42%) but distinctly different kinetic behavior: the highest activation energy (0.50 eV), the least negative entropy ($\Delta S = -215.8 \text{ J/mol}\cdot\text{K}$), and a dramatically increased pre-exponential factor ($A = 100.5 \text{ M}\cdot\text{s}^{-1}$, a 32-fold increase over Phase 2). This combination indicates a pre-melt activated state where the system achieves maximum crystallization efficiency

despite requiring substantial energy input, with active decomposition providing the chemical driving force. Phase 4 (626-884°C) shows minimal weight loss (1.05%) and the lowest activation energy (0.18 eV) as a sodium-aluminosilicate eutectic melt forms, but it has the most negative entropy ($\Delta S = -267.4$ J/mol·K) and a severely reduced pre-exponential factor ($A = 0.26$ M·s⁻¹, a 387-fold decrease from Phase 3) reveal that despite enhanced diffusion in the melt, the

entropic penalty for ordering from a fully disordered liquid severely hinders successful crystallization. The R² values for Phases 1-3 (0.9422-0.9585) validate the kinetic analysis, while the lower correlation in Phase 4 (0.7244) suggests greater mechanistic complexity (Table 1). These findings demonstrate that optimal sodalite crystallization will occur not in the fully developed melt but in the activated decomposition region (Phase 3), where maximum

Table 1: Kinetic and thermodynamic parameters summary

phase	T°C	T°K	Ea J/mol	ΔS	ΔH	ΔG	A(M.s ⁻¹)	R2	Loss
1	45.46-337.14	538	31839.61	-234.458	1.62E+08	1.62E+08	7.193767187	0.9422	0.40
2	337.14-460.12	823	28512.23	-242.964	1.74E+08	1.74E+08	3.107426758	0.9585	4.66
3	460.12-626	1157.14	48418.33	-215.755	3.62E+08	3.62E+08	100.5135959	0.9488	4.42
4	626-884.14	1157.14	17332.82	-267.422	1.67E+08	1.67E+08	0.258869587	0.7244	1.05

Table 2: Elemental composition of Gaya kaolin

Oxide	SiO ₂	Al ₂ O ₃	V ₂ O ₅	MnO	Fe ₂ O ₃	K ₂ O	CaO	TiO ₂	Cl	ZrO ₂	H ₂ O	Na ₂ O
Percent (%)	52.06	29.8	0.17	0.03	4.96	0.70	1.77	2.93	0.73	0.22	8.2	0.2

Table 3: 2 θ Values for Kaolin, Quartz, and Sodalite

Mineral	Kaolin	Quartz	Albite	Sodalite
2 Theta	12.678, 20.56, 25.091, 38.62,	21.38, 26.878,	35.40	14.01 20.07 24.54 31.78 38.05, 42.11

Table 4: FTIR band(cm⁻¹) for Gaya kaolin and the resulting Sodalite

Assignment	Raw kaolin Band(cm ⁻¹)	mineral	Sodalite Band (cm ⁻¹)	mineral
OH-for Al-OH and Si-OH	3693.8	kaolin	3458.8	Sodalite
Si-O-Si and Si-O-Al	1002.7	Kaolin, albite	1036.2	Sodalite
Surface of OH bends	909.5	Kaolin, albite	913.2	Sodalite
Si-O-Si bonds	771.6	Kaolin, albite	775.3	Sodalite
Bending vibration -OH	1633	Water adsorption		Sodalite
Symmetry stretching vibration of T-O-T (T = Si of Al)			682.1	Sodalite
Si-O et Al-O	689,6	Kaolin, albite		Sodalite

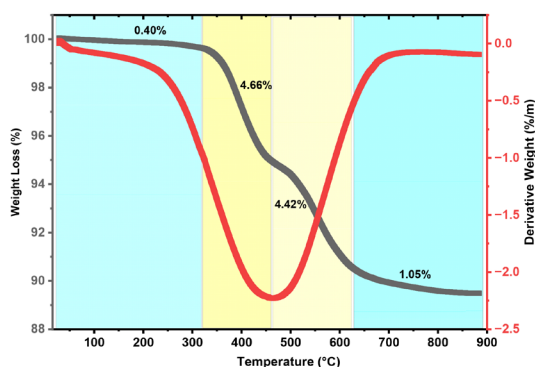


Fig. 1: Thermogravimetric and Differential Thermal Analysis (TG-DTA) Curves of Gaya Kaolin

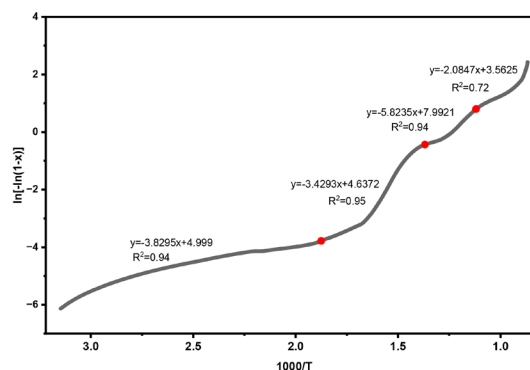


Fig. 2: plot of $\ln [-\ln (1 - x)]$ over $1000/T$

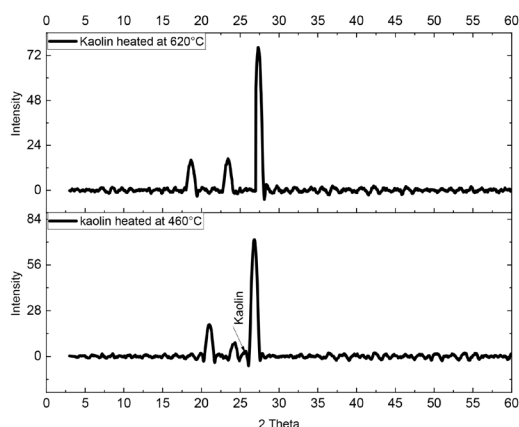


Fig. 3: XRD Patterns of Gaya Kaolin Heated at 460 °C and 620 °C

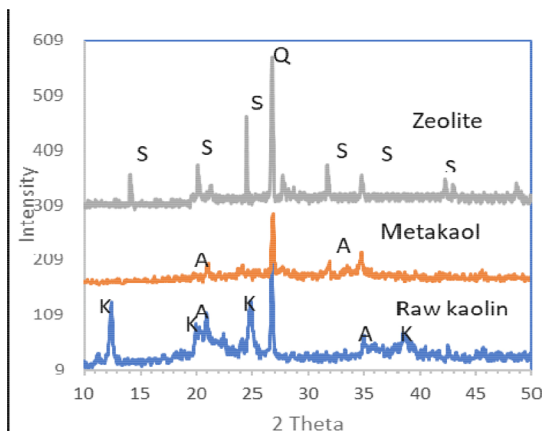


Fig. 4: XRD patterns of Gaya raw kaolin, metakaolin and the synthesized sodalite (Q=quartz, K=Kaolin, S=Sodalite)

reaction frequency coincides with active chemical transformations. Indeed, the kaolin peaks heated at 460 °C had considerably decreased, but a very weak intensity peak is observed at the 2 position of 25.091°. At 620 °C, all kaolin peaks have completely disappeared, indicating complete dehydroxylation and transformation into an amorphous phase (Fig 3).

Oxide composition of Gaya Kaolin

Table 2 summarizes the oxide composition of the studied clay. The material consists primarily of SiO_2 (52.06 wt%), Al_2O_3 (29.8 wt%), and H O (8.2 wt%), indicating a high kaolinite content. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio of 1.74 is close to that of commercial kaolin (1.69)¹⁵. The high SiO_2 and Al_2O_3 contents meet the requirements for applications in zeolites,

pharmaceuticals, ceramics, porcelain, and paper coatings. Impurities such as Fe_2O_3 and TiO_2 influence mullitization kinetics and grain morphology. The Fe_2O_3 content of 4.96 wt% likely results from oxidation of Fe-bearing silicates like muscovite in the parent rock¹⁶. XRF detects Fe incorporated via isomorphic substitution in clay structures, which is not observable by XRD. The overall composition is comparable to Tamazert kaolin (Algeria), previously evaluated as a substitute for commercial kaolin in mullite-based ceramics¹⁷. Quartz and Fe impurities significantly affect zeolite formation and performance in detergent applications¹⁸. High CaO_2 content can clog pores and block active sites on the zeolite surface, therefore, CaO_2 should be removed prior to synthesis. Na_2O , Cl, and TiO_2 are also present. Na and Cl are essential for stabilizing the sodalite

structure during synthesis, while the low K_2O content originates from muscovite.

X-ray diffraction analysis of Gaya Kaolin the resulted metakaolin and the synthesized sodalite

The XRD pattern (Fig. 4) of the raw kaolin is dominated by kaolinite, with characteristic peaks at $2\theta = 12.44^\circ$, 24.86° , 38.48° , and 62.32° . Quartz and albite are the main impurities, identified at $2\theta = 21.38^\circ$ and 26.88° for quartz. Albite likely formed through weathering of the parent rock and may exist either as the precursor that altered to kaolinite or as a minor associated phase¹⁹. It influences kaolin properties such as particle size distribution, brightness, and rheology. During zeolite synthesis, albite contributes both silica and Na ions, which act as a structure-directing agent. However, it also competes with kaolin for Al, altering the Si/Al ratio. Heat treatment eliminated kaolinite peaks, while quartz and albite peaks remained unchanged, confirming their thermal stability. The synthesized product exhibits sodalite peaks at $2\theta = 20.07^\circ$, 22.47° , 28.53° , 38.05° , and 42.11° , with only sodalite and residual quartz detected in the final pattern.

Fourier Transform Infrared Analysis of Gaya Kaolin

Fig. 5. shows the FTIR spectra of the raw kaolin. The FTIR peaks of Bana kaolin are summarized in Table 3. The FTIR spectrum of kaolin shows hydroxyl groups at 1633 and 3693.8 cm^{-1} associated with adsorbed and interlayer water. The band at 909.5 cm^{-1} , near 910 cm^{-1} , corresponds to surface OH bending vibrations. In addition to adsorbed, interlayer, and structural water, kaolinite exhibits active surface groups including Al-OH and

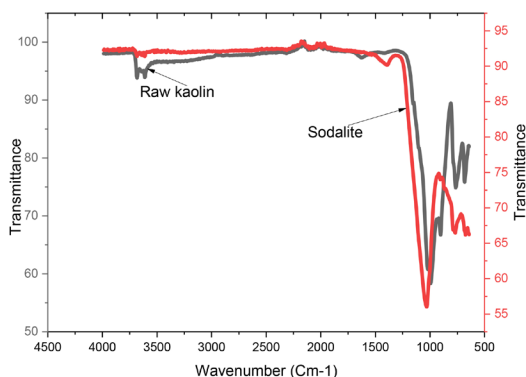
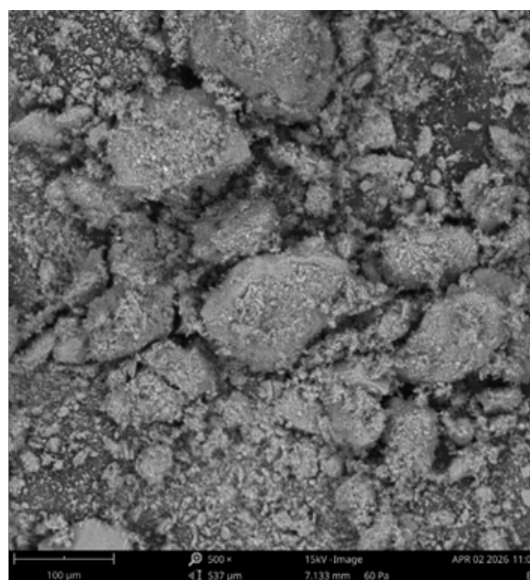


Fig. 5: FTIR Spectrum of Bana Kaolin and the resulting Sodalite

Si-O bonds. Si-O symmetric stretching appears in the $900\text{--}1200\text{ cm}^{-1}$ region. The peak at 1002.7 cm^{-1} is assigned to Si-O-Si and Si-O-Al lattice vibrations, while the band at 771.6 cm^{-1} corresponds to Si-O-Al inner-surface vibrations. Vibrations between 600 and 800 cm^{-1} are also observed; the peak at 689.6 cm^{-1} is attributed to Si-O and Al-O modes. The weak band at 2102.2 cm^{-1} is likely an artifact or background noise. For the synthesized sodalite, characteristic peaks occur at 682 cm^{-1} (sodalite cage vibration), 775 cm^{-1} (Si-O-Al vibration), 913 cm^{-1} (Al-O vibration), 1036 cm^{-1} (Si-O-Si vibration), and 3493 cm^{-1} (O-H vibration).



Element Number	Element Number	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminium	26.31	25.42
11	Na	Sodium	30.35	24.99
14	Si	Silicon	23.72	23.86
16	S	Sulfur	6.98	8.02
17	Cl	Chlorine	5.53	7.02
26	Fe	Iron	1.60	3.21
19	K	Potassium	1.96	2.75
20	Ca	Calcium	1.49	2.14
22	Ti	Titanium	0.96	1.65
12	Mg	Magnesium	1.08	0.94
15	P	Phosphorus	0.00	0.00
25	Mn	Manganese	0.00	0.00
23	V	Vanadium	0.00	0.00

Fig. 6. SEM Images and EDX of Synthesized Sodalite

Morphology of the synthesized sodalite

The EDX analysis (Fig.6.) of sodalite shows that the main detected elements are sodium (Na), aluminum (Al), silicon (Si), oxygen (O), and chlorine (Cl). The morphology of sodalite appears as aggregates of octahedral crystals characteristics of polycrystalline clusters of sodalite[8].

CONCLUSION

The kinetic and thermodynamic analysis of kaolin calcination from Gaya, Niger, reveals a four-phase transformation mechanism, highlighting the importance of optimizing calcination temperature for sodalite synthesis. The optimal conditions for sodalite crystallization occur in Phase 3 (460-626°C), where the highest activation energy and moderate entropy

changes facilitate active chemical transformations, rather than in the fully developed melt phase. These findings provide valuable insights for optimizing the calcination process to produce high-quality metakaolin for efficient sodalite synthesis.

Conflicts of interest

"There are no conflicts to declare".

Formatting of funding sources

SONIDEP, SOS NIGER

ACKNOWLEDGMENTS

The authors would acknowledge Agadez University for facilitating the performance of this study in the laboratories of Genie de Procédés

REFERENCES

- Hartati; Prasetyoko, D.; Santoso, M.; Qoniah, I.; Leaw, W. L.; Firda, P. B. D.; Nur, H. A., *J. Chin. Chem. Soc.*, **2020**, 67 (6), 911-936.
- Comin, A. B.; Zaccaron, A.; Saviatto, E.; Acordi, J.; Raupp-Pereira, F.; Abrantes, J. C. de C.; Ribeiro, M. J.; de Souza, G. S., *J. South Am. Earth Sci.*, **2024**, 148, 105157.
- Al-Ameri, O. B.; Alzuhairi, M.; Bailón-García, E.; Carrasco-Marín, F.; Amaro-Gahete, J. *Appl. Sci.*, **2024**, 14(19).
- Mohammed, K. S.; Atlabachew, M.; Derby, G. W.; Berhie, B. A., *JCIS Open*, **2025**, 20, 100153.
- Bahgaat, A. K.; Hassan, H. E.-S.; Melegy, A. A.; Abdel Karim, A.; Mohamed, M. H., *Egypt. J. Chem.*, **2020**, 63(10), 3791–3800.
- Awad, A. M.; Shaikh, S. M. R.; Jalab, R.; Gulied, M. H.; Nasser, M. S.; Benamor, A.; Adham, S., *Sep. Purif. Technol.*, **2019**, 228, 115719.
- Liu, Y.; Zhang, B.; Fahimzadeh, M.; Yu, T.; Ou, Z.; Peng, Z.; Yuan, P. Mechanical., *Appl. Clay Sci.*, **2025**, 271, 107796.
- M.S. Abdoul Aziz, O.M. Sani, B.G. Henri Briton, A.K. Mahamane; Nassirou, and Y. K. Benjamin., *Rasayan J. Chem.*, **2026**, 19(1), 498-503.
- Li, J.; Zeng, X.; Yang, X.; Wang, C.; Luo, X., *Mater. Lett.*, **2015**, 161, 157–159.
- Bellucci, S.; Eid, M. H.; Fekete, I.; Péter, S.; Kovács, A.; Othman, S. I.; Ajarem, J. S.; Allam, A. A.; Abukhadra, M. R., *Inorganics*, **2023**, 11 (1), 14.
- Jang, K.; Nunna, V. R. M.; Hapugoda, S.; Nguyen, A. V.; Bruckard, W. J., *Minerals Engineering*, **2014**, 60, 14-22.
- Céleri, E. P.; da Silva, C. C. M.; Lacerda Jr, V.; Barañano, A. G., *Braz. J. Chem. Eng.*, **2025**, 42 (2), 637-645.
- Bahgaat, A. K.; Hassan, H. E.-S.; Melegy, A. A.; Abdel Karim, A.; Mohamed, M. H., *Egypt. J. Chem.*, **2020**, 63 (10), 3791-3800.
- Wang, H.; Li, C.; Peng, Z.; Zhang, S. J.Q., *Therm. Anal. Calorim.*, **2011**, 105 (1), 157-160.
- Zewdie, T. M.; Prihatiningtyas, I.; Dutta, A.; Habtu, N. G.; Van der Bruggen, B., *Mater. Res. Express.*, **2021**, 8(11), 115201.
- Sadli, N.; May, A.; Hamidouche, M.; Henniche, A.; Belhouchet, H.; Boudouh, H. Investigations on Kaolin Mixtures., *Int. J. Appl. Ceram. Technol.*, **2024**, 21(6), 3950-3966.
- Hartati; Prasetyoko, D.; Santoso, M.; Qoniah, I.; Leaw, W. L.; Firda, P. B. D.; Nur, H. A., *J. Chin. Chem. Soc.*, **2020**, 67 (6), 911-936.
- Yunusa, A.; Hong, H.; Salim, A.; Amam, T.; Liu, C.; Xu, Y.; Zuo, X.; Li, Z., *Minerals*, **2024**, 14 (9).
- Li, S.; He, H.; Liang, X.; Tao, Q.; Ji, S.; Yang, M.; He, Y.; Zeng, Q.; Yang, Y.; Zhu, J., *ACS Earth Space Chem.*, **2022**, 6(4).