

Chemical Characteristics and Bibliometric Patterns of Indonesian Kaolin and Bentonite: An Exploratory Integrative Analysis

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ABSTRACT

Indonesia has diverse kaolin and bentonite resources, but national claims are often inferred from non-equivalent samples and incomplete bibliographic records. This exploratory study integrated traceable secondary XRF/XRD evidence from selected Indonesian clays with four keyword co-occurrence maps derived from Google Scholar records retrieved through Publish or Perish for 2000–2025. The objective was to identify material variability, visible research themes, and priorities for reproducible clay research. Reviewed studies showed strong deposit and treatment specificity. A commercial kaolin studied in Medan contained 46.66 wt% SiO₂ and 39.63 wt% Al₂O₃, whereas Badau kaolin formed metakaolin at ≥600 °C. Pacitan bentonite was identified as Ca-montmorillonite; Santrijaya bentonite was montmorillonite-dominant, contained about 80% silica, and had a surface area of 121.89 m²/g and cation-exchange capacity of 43.23 meq/100 g. Indonesian maps emphasized characterization, adsorption, catalysis, soil, and composites, while global-labelled maps also contained intercalation, molecular modelling, and geotechnical themes. Because the queries and corpus sizes were not normalized, the maps support thematic comparison only. Deposit-resolved characterization, standardized performance testing, and documented data archiving are therefore the immediate priorities.

Keywords: Bentonite, Bibliometric Mapping, Indonesian Clay, Kaolin, Vosviewer, X-Ray Characterization

1. INTRODUCTION

Kaolin and bentonite are widely investigated because their mineral structures support applications in ceramics, binders, zeolite synthesis, adsorption, catalysis, rheology, and engineered barriers. However, these commercial labels do not denote a single chemical composition or performance class. Deposit origin, mineral assemblage, exchangeable cations, accessory phases, particle characteristics, and processing history can substantially change the behavior of the material [1]-[4].

Indonesian studies already demonstrate this locality dependence. A commercial technical kaolin studied in Medan [1], kaolin from Badau in Belitung [2], activated Pacitan bentonite [3], and Santrijaya bentonite evaluated for radioactive-waste containment [4] were examined under different analytical and application contexts. Their results are valuable as traceable cases, but they cannot be combined into one national oxide range or one universal clay class.

Bibliometric mapping can complement material characterization by showing how research questions and applications are connected. VOSviewer is widely used to construct and display bibliometric networks [5], and recent mapping confirms that applied clay research spans multiple disciplines [6]. Nevertheless, defensible interpretation requires transparent search sources, screening decisions, network settings, and limitations [7].

This study asks two exploratory questions: what do traceable case studies reveal about the chemical and mineralogical variability of selected Indonesian kaolin and bentonite, and what thematic differences are visible between the available Indonesian and global-labelled keyword maps? The study contributes an integrative, non-causal comparison that separates verified material

evidence from bibliometric inference and converts the combined findings into a reproducible research agenda.

2. LITERATURE REVIEW

2.1 *Mineralogical and Chemical Variability*

Kaolinite is a 1:1 phyllosilicate, whereas bentonite is generally rich in smectite, commonly montmorillonite. Quantitative phase analysis of bentonite remains difficult because smectite, mixed-layer phases, and accessory minerals vary within and between sources [8]. In kaolin, iron can occur in the structure or as an accessory phase, and its form affects beneficiation and activation [9], [10]. Cross-deposit characterization therefore requires explicit sampling context, analytical methods, and reporting bases rather than broad geographic labels [11].

2.2 *Modification and Application of Clay Materials*

Adsorption performance depends on mineral type, surface modification, water chemistry, and target contaminant [12], [13]. For kaolin-derived zeolites and calcined-clay binders, impurity content, dehydroxylation, phase assemblage, and calcined-kaolinite content influence product formation and reactivity [14]-[16]. Bentonite performance is likewise sensitive to temperature-dependent bonding and swelling [17], while engineered-barrier evaluations require coupled mineralogical, hydraulic, thermal, and mechanical evidence [18].

2.3 *Bibliometric Mapping and Reproducibility*

Database selection affects bibliometric coverage and citation patterns. Google Scholar is broader than Scopus and Web of Science, but its source composition and control differ [19], [20]. Reproducible science mapping therefore requires documented data conversion, network construction, and analytical choices [21], together with a clear review purpose and synthesis method [22]. Search-system evaluations caution against treating Google Scholar as the sole basis of a systematic search [23], although Publish or Perish and VOSviewer can support a transparent workflow when queries and settings are archived [24]. Related bibliometric work on geopolymer research also demonstrates how thematic mapping can guide classification while remaining distinct from experimental validation [25].

3. METHODS

3.1 *Study Design and Scope*

An exploratory integrative design was used. The first evidence stream was a focused secondary review of published Indonesian clay-characterization studies. The second was a descriptive reading of four existing keyword co-occurrence maps: Indonesian kaolin, Indonesian bentonite, global-labelled kaolinite, and global-labelled bentonite. The streams were integrated only at the level of research themes and future hypotheses. No pooled national chemical mean, meta-analysis, causal model, publication-growth rate, average citation indicator, or collaboration index was calculated. The explicit scope and extraction logic follow methodological guidance for integrative literature work [22].

3.2 *Selection and Extraction of Material Evidence*

Sources were retained when the publication could be verified by title, authors, outlet, year, and DOI, and when it reported an Indonesian sampling or procurement context plus at least one relevant method: XRF, XRD, FTIR, SEM, BET surface area, or cation-exchange capacity. Values were transcribed as reported and were not normalized across studies because sample preparation, loss-on-ignition treatment, instruments, and analytical objectives were not equivalent. General methodological studies informed the interpretation of phase identification, impurity effects, and cross-deposit comparison [8]–[11].

3.3 Bibliometric Data and Mapping

The available maps were generated from Google Scholar records retrieved through Publish or Perish for 2000–2025, exported in RIS format, cleaned in Mendeley, and visualized in VOSviewer. The documented search labels were “Indonesia kaolin,” “Indonesia bentonite,” “kaolin global,” and “bentonite global.” The working manuscript reported approximately 60 Indonesian records and more than 400 global-labelled records across the four corpora. Networks were interpreted by node prominence, proximity, links, and color-coded clusters, consistent with VOSviewer mapping [5] and published Publish or Perish-VOSviewer workflows [24].

Three restrictions were applied. First, the four queries were not symmetrical or exhaustive: “Indonesia” was a geographic qualifier, whereas “global” was a literal search term rather than a database scope. Second, the exact retrieval date, full record-level files, thesaurus file, counting method, and minimum-occurrence threshold were not preserved in the manuscript package. Third, Google Scholar coverage is broader and less controlled than curated citation databases [19], [20], [23]. The maps were consequently treated as legacy exploratory outputs and not as evidence for normalized productivity, impact, collaboration, or temporal comparisons.

3.4 Interpretation Framework

Integration used a cautious concordance approach. A material property was paired with a mapped theme only when a plausible research question could be stated; the pair was not interpreted as evidence that the property caused the theme. For example, an adsorption cluster and a site-specific cation-exchange result jointly motivate standardized sorption tests, but they do not prove that Indonesian bentonite as a class has superior adsorption performance.

4. RESULTS AND DISCUSSION

4.1 Deposit- and Treatment-Specific Material Evidence

Table 1. Traceable Indonesian material evidence included in the integrative analysis

Material and context	Methods	Reported evidence used here	Interpretive boundary
Commercial technical kaolin purchased in Medan	XRF, XRD, SEM, FTIR	SiO ₂ 46.66 wt%; Al ₂ O ₃ 39.63 wt%; K ₂ O 0.84 wt%; Fe ₂ O ₃ 0.55 wt%; TiO ₂ 0.274 wt%. Kaolinite dominant with minor accessory phases.	Commercial sample; mine origin was not established, so it is not a national or deposit average [1].
Badau kaolin, Belitung	XRF, XRD, FTIR; NH ₄ Cl treatment and calcination	Metakaolin was produced at calcination temperatures ≥600 °C; no optimum NH ₄ Cl concentration was identified in the tested range.	Treatment study aimed at zeolite raw material; values cannot be transferred to untreated kaolin from other deposits [2].

Material and context	Methods	Reported evidence used here	Interpretive boundary
Pacitan bentonite, East Java	XRF, XRD, FTIR, SEM, BET; acid and thermal activation	Ca-montmorillonite was identified; activation changed characteristics and supported further radionuclide-adsorption study.	Characterization of raw and modified material; the paper did not establish a national bentonite class [3].
Santrijaya bentonite, Tasikmalaya	XRF, XRD, SEM, surface area, CEC, Cs-137 sorption	Montmorillonite dominant; about 80% silica; surface area 121.89 m ² /g; CEC 43.23 meq/100 g; site-specific Cs-137 sorption reported.	Application-specific barrier study; results depend on sample, ionic conditions, and test protocol [4].

Source: Authors' Compilation from [1]-[4].

Note: All numerical values remain in the units and basis reported by the original studies. No cross-study oxide normalization was performed.

The verified evidence contradicts an overly simple "Indonesian clay composition." The Medan commercial kaolin closely reflects a kaolinite-rich aluminosilicate in its dominant oxides and contains low Fe₂O₃ in that particular sample [1]. This result cannot justify either a national high-iron or low-iron claim. Iron may occur in kaolin structures or accessory phases, and its location affects beneficiation and activation response [9], [10]. Brightness, ceramic suitability, and catalytic behavior therefore require deposit-level mineralogical and speciation evidence.

Badau kaolin demonstrates the importance of processing history. Metakaolin was produced at 600 °C or above under the reported three-hour calcination conditions [2]. The observation supports zeolite and alkali-activated precursor research, but optimum processing must still be established for each feedstock. Impurities can modify zeolite synthesis and catalytic output [14], while dehydroxylation, phase assemblage, and calcined-kaolinite content influence reactivity [15], [16]. Temperature alone is therefore not a sufficient predictor.

The two bentonite cases also differ in purpose. Pacitan material was evaluated after acid and thermal activation and identified as containing Ca-montmorillonite [3]. Santrijaya bentonite was evaluated directly for Cs-137 retention and paired mineralogical characterization with surface-area and cation-exchange measurements [4]. These cases show that source identity, phase analysis, physicochemical properties, and performance testing must be reported together. This requirement is consistent with temperature-sensitive montmorillonite behavior [17] and current engineered-barrier reviews [18].

4.2 Indonesia Keyword Networks

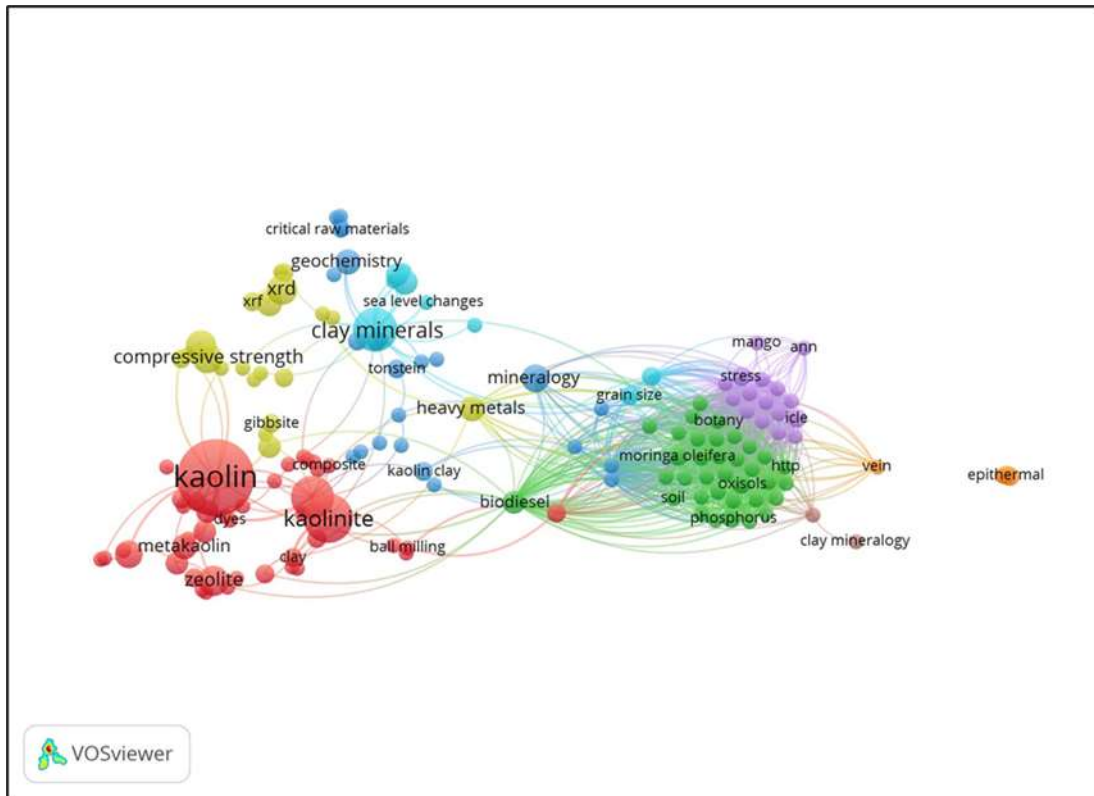


Figure 1. VOSviewer keyword co-occurrence network for the Indonesian kaolin corpus. Node and cluster patterns are interpreted descriptively; record-level parameters were unavailable for reanalysis.

Source: Authors' processing using Publish or Perish and VOSviewer.

The Indonesian kaolin map is organized around kaolin/kaolinite, clay minerals, mineralogy, XRD/XRF, compressive strength, soil, and several application terms. The left side groups mineral transformation and material use, including metakaolin, zeolite, dyes, and composites, while the central and right portions connect mineralogy with soil and biological or environmental topics. The retrieved corpus thus spans characterization, construction performance, soil studies, and applied treatment. Because some nodes are weakly connected and the selection threshold is unknown, cluster boundaries cannot be treated as formal disciplinary categories.

The bentonite network connects adsorption and kinetics with swelling pressure, permeability, microstructure, temperature, thermal conductivity, rheology, and modelling. This combination is consistent with bentonite serving both as a sorbent and an engineered barrier. It also shows why phase and exchangeable-cation characterization must accompany application testing: swelling and transport behavior cannot be inferred from the word “bentonite” alone [8], [11]. Machine learning appears as a small node, indicating presence in the retrieved corpus rather than dominance.

4.4 Integrative Interpretation and Research Agenda

The strongest cross-stream concordance concerns adsorption and barrier applications. Indonesian bentonite maps emphasize adsorption, while the Pacitan and Santrijaya studies provide site-specific mineralogical and sorption-related evidence. The appropriate next step is a comparative protocol across deposits that reports mineral phases, exchangeable cations, CEC, surface area, pore characteristics, water chemistry, kinetics, equilibrium, regeneration, and uncertainty. This protocol would allow material variables to be linked statistically to performance.

A second concordance concerns thermal transformation and aluminosilicate utilization. The Indonesian kaolin map includes metakaolin, zeolite, and compressive strength, while Badau kaolin has a documented thermal conversion pathway. A defensible research program would compare calcination windows, amorphous content, dissolution, reaction products, and mechanical performance for geographically resolved samples. Impurity effects should be measured rather than assumed [14]. Bibliometric classification of geopolymer research can inform the research taxonomy, but it cannot replace experimental validation [25].

The global-labelled maps additionally surface intercalation, molecular modelling, microstructure, and coupled geotechnical behavior. These are useful directions for Indonesian work only after reliable baseline characterization exists. Computation and machine learning require curated, machine-readable data; they cannot compensate for uncertain provenance or incompatible test methods. A national open clay dataset should record deposit identifiers, sampling depth, preparation, raw instrument files, phase-quantification method, full oxide tables including loss on ignition, physicochemical tests, and application outcomes

Table 3. Priority actions for a reproducible Indonesian clay research program

Priority	Minimum evidence	Recommended output	Decision enabled
Deposit-resolved baseline	Provenance; representative sampling; XRD with stated quantification method; XRF with LOI; FTIR/SEM where relevant	Versioned composition and phase dataset	Valid comparison across Indonesian sources
Application validation	CEC/BET or rheology as appropriate; controlled water chemistry; kinetics/equilibrium; replicate tests; uncertainty	Standard performance benchmark	Selection for adsorption, barrier, ceramic, or precursor use
Processing study	Temperature/time/chemical dose; raw and treated controls; phase and property change	Process–structure–property model	Optimization without extrapolating across deposits
Bibliometric reproducibility	Database; exact query; retrieval date; inclusion/exclusion; cleaned RIS; thesaurus; counting and threshold settings	Archived dataset, search log, and map files	Repeatable thematic and temporal analysis
Advanced modelling	Harmonized descriptors and sufficiently large labelled dataset	Validated statistical, molecular, or machine-learning model	Prediction with stated domain and uncertainty

Source: Authors' Synthesis.

4.5 Limitations

This study has four major limitations. First, the material evidence is a focused set of traceable case studies rather than a systematic review of every Indonesian clay deposit. Second, analytical conditions and reporting bases differ among sources, so oxide values were not pooled or normalized. Third, the bibliometric figures are legacy outputs: complete RIS datasets, the search log, VOSviewer thesaurus, counting method, and thresholds were unavailable. Fourth, the local and global-labelled queries are not equivalent. These constraints prohibit conclusions about national averages, temporal growth, citation impact, collaboration intensity, or direct chemical control of research themes.

5. CONCLUSION

Traceable studies show that selected Indonesian kaolin and bentonite materials have useful but site- and treatment-specific characteristics. The Medan commercial kaolin case cannot represent every deposit; Badau kaolin demonstrates a defined thermal pathway to metakaolin; Pacitan bentonite shows Ca-montmorillonite and activation response; and Santrijaya bentonite couples montmorillonite-rich mineralogy with measured surface and cation-exchange properties. The supplied keyword maps place Indonesian records mainly around characterization and applied themes, whereas the global-labelled maps also contain molecular, intercalation, geotechnical, and modelling vocabularies. Because the corpora are not normalized, this difference is thematic rather than a quantified gap.

Future studies should prioritize a deposit-resolved and reproducible dataset linked to standardized application tests. Complete search logs, cleaned bibliographic exports, thesaurus files, and mapping settings should be archived before temporal or impact comparisons are attempted. Causal comparisons and predictive modelling should follow only after compatible experimental data are available.

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