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Health Effects of Lithium (Spodumene) Concentration by Froth Flotation: A Case Study of Udawa Lithium Pegmatite, Kaduna State, Nigeria

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Abstract

The rapid expansion of renewable energy technologies, electric vehicles, and large-scale energy storage systems has significantly increased global demand for lithium resources. Spodumene-bearing pegmatites represent one of the most important hard-rock lithium sources; however, their relatively low lithium content requires effective beneficiation before commercial utilization. This study investigates the metallurgical performance and occupational health implications associated with the concentration of spodumene from the Udawa lithium pegmatite deposit located in Kaduna State, Nigeria. Representative run-of-mine ore samples were subjected to crushing, grinding, and froth flotation processing. The feed material contained an average lithium oxide (Li_2O) grade of 1.12 wt.%. Following flotation concentration, a spodumene concentrate grading 4.35 wt.% Li_2O was obtained with an overall lithium recovery of 78.6%. The results demonstrate that froth flotation provides an effective upgrading route for the beneficiation of Nigerian spodumene resources. In addition to metallurgical evaluation, occupational health risks associated with lithium processing were assessed through airborne dust monitoring and evaluation of reagent handling practices within the processing circuit. Measured respirable dust concentrations ranged from 0.18 to 0.32 mg/m^3 , with the highest values recorded in the crushing and grinding sections due to increased mineral liberation and particle generation. Although observed reagent exposure conditions were within acceptable occupational limits under controlled laboratory conditions, prolonged exposure to mineral dust remains a potential respiratory health concern. The study highlights that successful lithium beneficiation should not only focus on recovery efficiency but also incorporate occupational safety strategies. Effective dust suppression, improved ventilation, personal protective equipment, and routine worker health surveillance are recommended to support safe and sustainable lithium processing operations in Nigeria.

Keywords:

Lithium beneficiation; Spodumene; Froth flotation; Pegmatite; Occupational health; Respirable dust; Sustainable mining

1. INTRODUCTION

Lithium has become one of the most strategically important elements in modern industrial development due to its essential role in rechargeable battery technologies, electric vehicles, portable electronic devices, and grid-scale energy storage systems. The rapid transition toward low-carbon energy systems has significantly increased global lithium demand, making lithium-bearing minerals important components of future critical mineral supply chains (Kesler et al., 2012; Flexer et al., 2018; Ali et al., 2025).

Lithium occurs mainly in two geological environments: continental brines and hard-rock deposits. Among hard-rock resources, spodumene ($\text{LiAlSi}_2\text{O}_6$) is considered the most commercially important lithium mineral because of its relatively high lithium content and suitability for industrial extraction processes (Garrett, 2004; Meshram et al., 2014). Other lithium-bearing minerals include petalite, lepidolite, and amblygonite; however, spodumene remains the dominant feedstock for conventional lithium chemical production (Chagnes and Światowska, 2013).

The global increase in demand for lithium-ion batteries has stimulated exploration and development of new lithium resources worldwide. Countries including Australia, Canada, China, Brazil, Zimbabwe, and Portugal have developed significant hard-rock lithium operations based on spodumene-bearing pegmatites (Tadesse et al., 2019). Nigeria has recently emerged as a potential lithium-producing country due to widespread occurrences of lithium-bearing pegmatites within the Precambrian Basement Complex.

The Nigerian Basement Complex contains numerous rare-element pegmatite fields associated with Pan-African tectono-magmatic activity. These pegmatites occur mainly within Kaduna, Nasarawa, Plateau, Oyo, and other regions of Nigeria and host economically significant minerals including feldspar, quartz, mica, tantalite, and lithium-bearing minerals (Garba, 2003; Matheis, 1987). The Udawa pegmatite deposit in Kaduna State represents one of the emerging lithium occurrences within northern Nigeria and contains spodumene mineralization associated with quartz-feldspar pegmatite assemblages.

However, naturally occurring spodumene ores generally require beneficiation because lithium grades in run-of-mine material are insufficient for direct industrial utilization. Mineral processing techniques are therefore necessary to increase lithium concentration and produce marketable spodumene concentrates (Kesler et al., 2012).

Froth flotation is one of the most widely applied beneficiation methods for upgrading spodumene due to its ability to exploit differences in mineral surface properties. The process involves selective adsorption of collectors onto spodumene surfaces, rendering the mineral hydrophobic and allowing attachment to air bubbles while gangue minerals remain in the pulp phase (Wills and Finch, 2016). Fatty acid collectors such as oleic acid and tall oil fatty acids have been widely investigated for spodumene flotation because of their ability to enhance mineral recovery (Cook et al., 2023).

The efficiency of spodumene flotation depends on several operational parameters including particle size distribution, mineral liberation, pulp pH, collector dosage, depressant selection, and surface chemistry interactions. Poor liberation or inappropriate reagent conditions may reduce flotation selectivity and lithium recovery (Moon and Fuerstenau, 2003; Cook et al., 2023).

Although lithium beneficiation research has mainly focused on improving recovery performance, occupational health considerations associated with lithium mineral processing require greater attention. Crushing, grinding, and material handling operations generate airborne mineral dust containing fine silica-bearing particles that may create respiratory hazards for exposed workers (International Labour Organization, 2009).

Respirable crystalline silica exposure is recognized as a major occupational health concern in mining and mineral processing industries. Long-term exposure may result in silicosis, chronic respiratory impairment, and increased risk of other pulmonary diseases (Leung et al., 2012). Recent investigations have also demonstrated that respirable spodumene particles may possess biological activity capable of contributing to inflammatory responses in occupational environments (Gardner et al., 2022).

Flotation operations involve chemical reagents including collectors, frothers, modifiers, and pH regulators. Although these chemicals are generally used at controlled concentrations, improper handling practices may result in occupational exposure through skin contact, inhalation, or accidental ingestion (Wills and Finch, 2016).

Therefore, sustainable lithium processing requires an integrated approach that combines metallurgical efficiency with occupational health management. Cleaner production principles emphasize minimizing workplace hazards while maximizing resource recovery and operational efficiency (Geng et al., 2010).

Nigerian lithium resources have largely concentrated on geological characterization and economic evaluation, while limited research has examined occupational health implications associated with lithium beneficiation. This study addresses this gap by investigating the flotation performance of Udawa spodumene ore and evaluating potential workplace health risks associated with dust generation and reagent handling.

II. GEOLOGICAL SETTING OF THE STUDY AREA

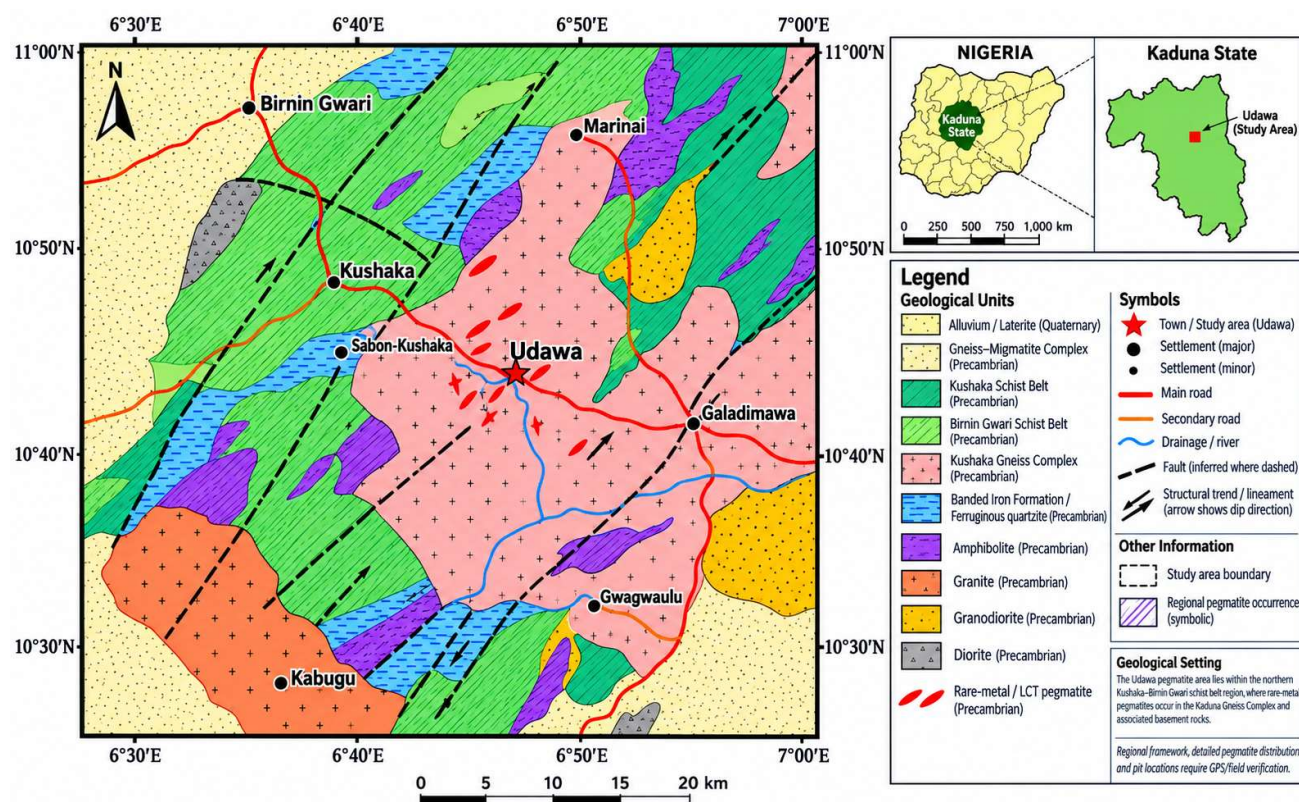


Figure 1. Geological Map of the Study Area

2.1 Regional Geological Framework

The Udaawa lithium pegmatite deposit is located in Kaduna State, north-central Nigeria, within the geological framework of the Nigerian Basement Complex. The Nigerian Basement Complex represents a segment of the Pan-African mobile belt of West Africa and consists mainly of migmatites, gneisses, schists, quartzites, and granitoid intrusions formed during multiple tectono-metamorphic events (Rahaman, 1988; Obaje, 2009).

The Basement Complex experienced intense deformation, metamorphism, and magmatic activity during the Pan-African orogeny (~600 Ma), resulting in widespread emplacement of granitic rocks and associated rare-element pegmatites. These pegmatites represent late-stage differentiated products of granitic magmatism and commonly host economically important minerals including tantalum, niobium, tin, beryl, feldspar, mica, and lithium-bearing minerals (Garba, 2003; Matheis, 1987).

Rare-element pegmatites in Nigeria occur mainly within the north-central and southwestern parts of the country. Important pegmatite fields have been documented in Kaduna, Nasarawa, Plateau, Kwara, Oyo, and parts of the Federal Capital Territory. These deposits have historically supported artisanal mining activities for gemstones and industrial minerals, while recent exploration has focused increasingly on lithium resources due to global demand for battery minerals (Garba, 2003; Kesler et al., 2012).

The Udaawa pegmatite occurrence forms part of this rare-element pegmatite province. The deposit is hosted within metamorphic country rocks consisting mainly of mica schists and gneisses intruded by coarse-grained granitic pegmatite bodies. The pegmatites display typical characteristics of highly evolved granitic systems, including coarse crystal size, mineral zoning, and enrichment in incompatible elements such as lithium, tantalum, and niobium.

2.2 Geological Characteristics of Udaawa Lithium Pegmatite

The Udaawa pegmatite body is characterized by a coarse-grained mineral assemblage typical of lithium-bearing pegmatites. The major minerals identified within the deposit include;

Spodumene occurs as elongated prismatic crystals commonly associated with quartz and feldspar minerals. The intergrowth relationship between spodumene and gangue minerals influences the liberation characteristics of the ore and determines the grinding requirements before flotation concentration.

Lithium pegmatites are generally classified as rare-element pegmatites because they contain elevated concentrations of incompatible elements that become concentrated during the final stages of granite crystallization (Cerný et al., 1996). Spodumene-bearing pegmatites represent one of the most economically important hard-rock lithium resources globally due to their high lithium content compared with many other lithium minerals (Garrett, 2004; Kesler et al., 2012).

2.3 Mineralogical Importance for Beneficiation

The mineralogical characteristics of spodumene ores strongly influence beneficiation performance. Effective flotation requires adequate liberation of spodumene particles from associated gangue minerals.

III. MATERIALS AND METHODS

Representative samples of lithium pegmatite ore were collected from the Udawa deposit using systematic channel sampling, with approximately 100 kg of run-of-mine material prepared for laboratory investigation. The samples were air-dried, homogenized, crushed, ground, and reduced to a flotation feed size of $P_{80} = 150 \mu\text{m}$ to achieve effective mineral liberation while minimizing slimes formation. Chemical and mineralogical characterization was carried out using X-ray fluorescence (XRF), X-ray diffraction (XRD), optical microscopy, and polished section analysis to determine lithium content, mineral phases, spodumene liberation, and mineral associations. Froth flotation experiments were performed using a mechanical flotation cell under controlled pulp density and pH conditions, with fatty acid-based collectors, modifiers, and depressants applied to enhance spodumene recovery and separation from gangue minerals. The resulting concentrate and tailings were analyzed for Li_2O grade, recovery, mass yield, and separation efficiency using standard metallurgical calculations. Occupational health risks associated with lithium beneficiation were also assessed by monitoring respirable dust exposure in crushing, grinding, flotation, and concentrate handling areas, while evaluating chemical handling practices, personal protective equipment usage, and workplace safety measures. The results were compared with established occupational exposure guidelines to determine potential health hazards related to mineral processing activities.

IV. RESULTS AND DISCUSSION

4.1 Chemical Composition and Characteristics of Udawa Spodumene Ore

The chemical analysis of the representative Udawa lithium pegmatite ore revealed that the material contains measurable lithium mineralization associated with silicate gangue minerals. The average lithium oxide content of the run-of-mine sample was determined as 1.12 wt.% Li_2O , indicating that the ore requires beneficiation before it can be considered suitable for lithium extraction.

The relatively low lithium grade observed in the feed material is consistent with hard-rock lithium deposits, where spodumene is commonly associated with quartz, feldspar, mica, and other aluminosilicate minerals. Similar characteristics have been reported for spodumene deposits worldwide, where beneficiation is required to increase lithium concentration and reduce gangue mineral content (Kesler et al., 2012; Tadesse et al., 2019).

The mineralogical association between spodumene and feldspar minerals represents a major challenge during processing because both minerals possess similar physical and surface characteristics. Therefore, efficient liberation through controlled grinding is essential for improving flotation selectivity (Moon and Fuerstenau, 2003).

4.2 Froth Flotation Performance

The flotation experiments demonstrated that spodumene from the Udawa pegmatite deposit responded positively to beneficiation by froth flotation. The lithium content increased from 1.12 wt.% Li_2O in the feed to 4.35 wt.% Li_2O in the concentrate, representing significant enrichment of the valuable lithium mineral.

The overall lithium recovery achieved was 78.6%, indicating that a substantial proportion of the lithium-bearing minerals were successfully recovered into the flotation concentrate.

Table 1: Flotation Performance of Udawa Spodumene Ore

Product	Mass Distribution (%)	Li_2O Grade (wt.%)	Lithium Recovery (%)
Feed	100	1.12	100
Spodumene Conc.	25.8	4.35	78.6
Tailings	74.2	0.32	21.4

The improvement in lithium grade demonstrates the effectiveness of selective flotation in separating spodumene from associated gangue minerals. Similar upgrading behaviour has been reported in previous studies investigating flotation concentration of lithium-bearing pegmatite ores (Amarante et al., 1999; Tian et al., 2018).

The achieved concentrate grade is within the range reported for commercial spodumene concentrates produced from hard-rock lithium operations. Industrial spodumene concentrates typically contain approximately 5–6% Li_2O ; however, the final grade depends on ore mineralogy, processing route, and economic requirements (Garrett, 2004).

Although the Udawa concentrate grade is slightly below premium commercial specifications, the recovery performance indicates that further optimization of flotation conditions, including collector dosage, pH adjustment, and cleaning stages, could improve concentrate quality.

4.3 Effect of Flotation Parameters on Lithium Recovery

The flotation performance of spodumene is strongly influenced by several operational parameters, including:

- Particle size
- Pulp density
- pH conditions
- Collector concentration
- Conditioning time
- Mineral liberation

In this study, grinding to approximately 80% passing 150 μm provided adequate liberation of spodumene particles while limiting excessive production of fine slimes.

Excessive grinding may negatively affect flotation performance because very fine particles have reduced collision efficiency with air bubbles and may increase reagent consumption. Conversely, insufficient grinding may result in incomplete liberation and poor separation efficiency (Wills and Finch, 2016).

The use of fatty acid-based collectors contributed to improved spodumene recovery by increasing mineral surface hydrophobicity. Fatty acid collectors are widely used in spodumene flotation because lithium minerals exhibit favourable adsorption behaviour under controlled alkaline conditions (Bulatovic, 2015; Cook et al., 2023).

4.4 Occupational Dust Exposure Assessment

Mineral processing operations generate airborne particulate matter, particularly during crushing and grinding activities. The measured respirable dust concentrations within the Udawa beneficiation circuit are presented in Table 2.

Table 2: Airborne Dust Concentration During Lithium Beneficiation

Processing Area	Dust Concentration (mg/m^3)	Relative Exposure Level
Crushing Section	0.32	Highest
Grinding Section	0.28	High
Flotation Section	0.18	Low
Concentrate Handling	0.21	Moderate

The highest airborne dust concentration ($0.32 \text{ mg}/\text{m}^3$) was recorded in the crushing section, followed by the grinding section ($0.28 \text{ mg}/\text{m}^3$). These results are expected because mechanical size reduction processes generate significant quantities of fine mineral particles through impact and abrasion. The flotation section recorded the lowest dust concentration because the process occurs under wet conditions, which reduces airborne particle generation.

Although measured dust concentrations were within commonly accepted occupational exposure limits for general mineral processing environments, continuous exposure over extended periods may still represent a potential health concern, particularly where silica-bearing minerals are present. Respirable crystalline silica exposure remains one of the most significant occupational hazards in mining and mineral processing industries. Long-term exposure may result in pulmonary inflammation, fibrosis, and silicosis development (IARC, 2012; Leung et al., 2012).

4.5 Flotation Reagent Exposure Assessment

Flotation operations require the use of chemical reagents including:

- Collectors
- Frothers
- pH modifiers
- Depressants
- During laboratory evaluation, reagent exposure risks were mainly associated with:
- Manual preparation of reagents
- Chemical transfer operations

- Storage practices

No significant acute exposure was observed during the study; however, inadequate handling procedures could increase occupational risks.

Potential effects associated with improper reagent exposure include:

- Skin irritation
- Eye irritation
- Respiratory discomfort
- Chemical sensitivity

Therefore, appropriate personal protective equipment including gloves, safety glasses, protective clothing, and respiratory protection should be incorporated into lithium beneficiation operations.

4.6 Comparison with Other Spodumene Deposits

The flotation performance obtained from Udawa spodumene ore compares favourably with results reported from other lithium pegmatite deposits.

The Udawa deposit demonstrates significant potential because the flotation process achieved a lithium recovery of 78.6%, confirming that Nigerian lithium pegmatites can respond effectively to conventional beneficiation methods.

V. CONCLUSION AND RECOMMENDATION

Froth flotation successfully upgraded Udawa spodumene ore from 1.12 wt.% Li₂O to 4.35 wt.% Li₂O concentrate with 78.6% lithium recovery, confirming its suitability for lithium beneficiation. However, dust generation during crushing and grinding remains the major occupational health concern. It is recommended that lithium processing operations adopt effective dust control systems, proper ventilation, use of personal protective equipment, safe reagent handling practices, and regular health monitoring to ensure safe and sustainable lithium production.

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