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Mineralization Potential of the Lithium-Bearing Micas in the St Austell Granite, SW England

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Abstract:- **The St Austell Granite, located in southwest England, represents a geologically significant area for the study of lithium-bearing micas and their mineralization potential. This paper investigates the geochemical properties, spatial distribution, and extraction feasibility of lithium from micas, such as zinnwaldite and lepidolite, which are hosted within this granite complex. Through a combination of field sampling, petrographic analysis, and advanced geochemical characterization techniques, the study explores the factors influencing lithium enrichment, including magmatic processes and hydrothermal alterations. The findings reveal that the lithium-bearing micas in the St Austell Granite possess high concentrations of lithium, often associated with rare earth elements, making them a promising resource for sustainable lithium extraction. Moreover, the research highlights the environmental and economic implications of developing these deposits, particularly in the context of increasing global demand for lithium in energy storage technologies. This study contributes to the growing body of knowledge on unconventional lithium sources, providing insights into their viability as a strategic resource for the renewable energy transition. Key recommendations for future exploration and processing strategies are proposed, emphasizing the role of innovation in unlocking the full potential of lithium-bearing micas in the St Austell Granite.**

Keywords:- *Lithium-Bearing Micas, St Austell Granite, Mineralization Potential, Geochemical Analysis, Sustainable Lithium Extraction.*

I. INTRODUCTION

➢ *Background and Significance of Lithium-Bearing Micas*

Lithium-bearing micas, such as zinnwaldite and lepidolite, have garnered significant attention due to their potential as strategic mineral resources in renewable energy applications. Lithium plays a critical role in energy storage technologies, particularly in rechargeable lithium-ion batteries used in electric vehicles and renewable energy storage systems (Bradley et al., 2017). Unlike traditional lithium sources such as brine pools or spodumene, lithium-bearing micas offer an unconventional yet promising alternative, particularly in granitic systems like the St Austell Granite in southwest England (Onifade et al., 2021).

The St Austell Granite is part of the Cornubian Batholith, a well-known geological formation enriched with rare elements, including lithium, tin, and tungsten. The lithium enrichment in this granite is closely associated with hydrothermal alterations and magmatic processes that facilitate the crystallization of lithium-bearing minerals, particularly micas. These minerals not only host significant lithium concentrations but also occur in geologically stable formations, making them more accessible for sustainable extraction compared to other sources (Gorman & Holness, 2020).

Globally, the demand for lithium is projected to rise exponentially due to its critical role in decarbonizing energy systems. For instance, lithium-bearing micas in granitic formations are increasingly being considered as viable resources for meeting this growing demand, especially in regions with limited access to brine pools (Aborode et al., 2024). The St Austell Granite serves as an exemplary site for studying the mineralization of lithium-bearing micas, offering insights into innovative extraction strategies while supporting the global transition to renewable energy.

➢ *Overview of the St Austell Granite and its Geological Importance*

The St Austell Granite, part of the Cornubian Batholith in southwest England, is a significant geological formation renowned for its enrichment in lithium-bearing minerals and other rare metals. This granite is a late-Variscan intrusion characterized by its diverse mineralogy, including quartz, feldspar, topaz, and lithium-bearing micas like zinnwaldite and lepidolite. Its genesis is closely linked to fractional crystallization and hydrothermal processes, which facilitated the concentration of rare elements (Simons et al., 2016).

Geologically, the St Austell Granite is distinguished by its greisenized and kaolinized zones, which resulted from pervasive hydrothermal alteration. These processes played a pivotal role in enriching the granite with rare metals, including lithium, tin, and tungsten. For instance, the lithium-bearing micas in this granite crystallized under conditions of low pressure and high fluorine activity, creating mineral assemblages that are critical for rare-metal exploration and extraction (Manning & Hill, 1990).

The geological significance of the St Austell Granite extends beyond its mineralization potential. It serves as a model for understanding the evolution of peraluminous granites and the role of magmatic-hydrothermal systems in rare-metal enrichment (Ayobami et al., 2024). Notably, its extensive kaolin deposits, derived from feldspar alteration,

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have economic importance in ceramics and paper industries. Additionally, the presence of lithium-bearing micas makes the granite a valuable resource amidst growing global demand for lithium, positioning the St Austell Granite as a cornerstone for research into sustainable rare-metal extraction strategies.

- *Increasing Global Demand for Lithium and its Role in Renewable Energy*

Lithium has emerged as a critical mineral in modern energy systems due to its indispensable role in energy storage technologies. As nations worldwide transition towards renewable energy to combat climate change, lithium-ion batteries have become the dominant choice for storing energy from solar, wind, and other renewable sources. These batteries are essential for electric vehicles (EVs), grid-scale energy storage systems, and portable electronic devices, driving an unprecedented surge in lithium demand (Harper & Wafai, 2022).

The global push for decarbonization and electrification has significantly accelerated lithium consumption. For instance, the International Energy Agency (IEA) estimates that demand for lithium will increase 40-fold by 2040 to meet the needs of electric vehicles and renewable power storage. This growing demand underscores the urgency of identifying alternative and sustainable lithium sources, such as lithium-bearing micas in granite formations, including those found in the St Austell Granite (Vikström et al., 2013).

Lithium's lightweight, high-energy density, and rechargeability make it integral to clean energy solutions, offering superior performance compared to other battery materials. (Aborode et al., 2024) This has shifted focus to unconventional resources, such as lithium-bearing micas, which hold significant potential for meeting the rising global demand. The St Austell Granite, enriched with lithium-bearing minerals, offers a strategic opportunity to bridge the gap between resource availability and the growing requirements of the renewable energy sector (Ekundayo et al., 2020).

- *Research Objectives and Scope of the Study*

This study aims to assess the mineralization potential of lithium-bearing micas within the St Austell Granite, a known peraluminous granite in southwest England. The primary objective is to investigate the geochemical properties, spatial distribution, and lithium enrichment mechanisms of micas such as zinnwaldite and lepidolite. The study seeks to understand how magmatic and hydrothermal processes influence lithium-bearing mineral formation and their economic viability for sustainable extraction.

To achieve these objectives, the research incorporates advanced mineralogical and geochemical analyses, including petrographic microscopy, X-ray diffraction (XRD), and inductively coupled plasma mass spectrometry (ICP-MS). Through these methods, the study will characterize lithium concentrations and trace elements associated with micas across different zones of the St Austell Granite.

The scope of this research extends to evaluating the feasibility of extracting lithium from unconventional sources, particularly lithium-bearing micas, in response to growing global demand for lithium in renewable energy technologies. This assessment includes comparisons of the St Austell Granite's lithium resource potential with traditional sources such as brine pools and spodumene ores.

By focusing on the St Austell Granite, the study aims to provide a detailed understanding of its lithium-bearing mineral deposits, contributing to the broader effort of identifying alternative and sustainable lithium resources. Furthermore, this research highlights the role of geoscientific innovation in supporting clean energy transitions while promoting environmentally responsible resource extraction.

- *Organization of the Paper*

The paper, titled *"Mineralization Potential of the Lithium-Bearing Micas in the St Austell Granite, SW England"*, is organized into seven sections. Section 1 introduces the study, providing the background and significance of lithium-bearing micas, an overview of the St Austell Granite, the increasing global demand for lithium, and the research objectives and scope. Section 2 explores the geological setting of the St Austell Granite, emphasizing its mineralogical composition and the processes contributing to lithium mineralization. Section 3 details the materials and methods employed, including field sampling, petrographic analysis, and geochemical characterization techniques. Section 4 focuses on the characteristics, distribution, and lithium enrichment of micas such as zinnwaldite and lepidolite within the granite. Section 5 assesses the economic and environmental implications of lithium extraction, addressing feasibility and sustainability concerns. Section 6 presents a discussion of the findings, highlighting the broader significance of the study for lithium supply chains and clean energy solutions. Finally, Section 7 provides key conclusions and recommendations for future research, emphasizing the role of the St Austell Granite as a potential resource for sustainable lithium extraction.

II. GEOLOGICAL SETTING

- *Overview of the St Austell Granite Formation*

The St Austell Granite, located in southwest England, forms part of the larger Cornubian Batholith, a significant geological feature that intruded during the late Carboniferous to early Permian period (Awaji et al., 2024). This granite complex is renowned for its diverse mineralogical and geochemical composition, particularly its enrichment in rare metals, including lithium, tin, and tungsten. The St Austell Granite is classified as a peraluminous granite, characterized by high concentrations of quartz, feldspar, and topaz, along with lithium-bearing micas such as zinnwaldite and lepidolite, which are key to its mineralization potential as shown in Figure 1 (Stone et al., 1993).

The formation of the St Austell Granite involved complex magmatic and hydrothermal processes, which significantly influenced its mineralogical diversity. Initial crystallization of the granite magma produced feldspar-rich

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assemblages, while late-stage magmatic differentiation and volatile-rich fluids led to the development of lithium-bearing micas and other rare-metal minerals (Aborode et al., 2024). The pervasive greisenization and kaolinization of the granite, resulting from extensive hydrothermal alteration, further enhanced its economic significance. These processes replaced primary feldspar and mica with secondary minerals, enriching the granite with lithium and associated rare elements (Müller & Halls, 2005).

The granite's structural setting also plays a pivotal role in its formation. The intrusion was emplaced during extensional tectonic events, which facilitated magma ascent and crystallization. The associated fractures and faults served as conduits for hydrothermal fluids, promoting the deposition of lithium-bearing minerals in distinct zones (Ijiga et al., 2024). The St Austell Granite's mineralized zones provide a model for understanding granite-hosted lithium systems and highlight its potential as a valuable resource for sustainable lithium extraction in a growing renewable energy market. Its formation history and unique geochemical characteristics make it an essential focus for rare-metal exploration and research (Anyebe, et al., 2024).

A

B

Fig 1 A Picture Showing the Visual Insights into the St Austell Granite's Geological Formation (Granite in Focus, 2017).

Figure 1 highlight key geological and mineralogical characteristics of the St Austell Granite, supporting its classification as a significant lithium-bearing granitic system. The coastal outcrop showcases the granite's natural exposure, with visible structural features such as fractures and joints that facilitated hydrothermal fluid migration—key to lithium enrichment. Close-up views reveal its mineralogical diversity, including interlocking grains of quartz and feldspar, indicative of its peraluminous nature, alongside lithium-bearing micas like zinnwaldite and lepidolite, which reflect late-stage magmatic differentiation and hydrothermal alteration. Evidence of greisenization, where feldspar is replaced by quartz and muscovite, underscores the role of volatile-rich fluids in enriching the granite's lithium content. Additionally, pegmatitic textures highlight zones of extreme magmatic fractionation, often hosting economically significant minerals. These visual elements provide tangible evidence of the geological processes that shaped the St Austell Granite, reinforcing its potential as a strategic lithium resource.

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➢ *Geological Features and Mineralogical Composition*

The St Austell Granite, part of the Cornubian Batholith, exhibits a diverse range of geological features and a distinctive mineralogical composition that highlight its importance as a rare-metal-enriched granite system (Aborode et al., 2024). Emplaced during the late-Variscan orogeny, the St Austell Granite is characterized by extensive greisenization and kaolinization, processes resulting from late-stage hydrothermal alteration. Structurally, it comprises multiple phases of intrusion, with clear evidence of magmatic differentiation and subsequent hydrothermal fluid activity that enriched it with economically significant minerals (Shail & Wilkinson, 1994).

Mineralogically, the granite is composed predominantly of quartz, feldspar (both orthoclase and albite), and topaz, with accessory lithium-bearing micas, notably zinnwaldite and lepidolite. These micas are critical to the granite's rare-metal mineralization potential, as they host significant lithium concentrations, often accompanied by rubidium, cesium, and fluorine (Ijiga et al., 2024). Additionally, the pervasive presence of greisenized zones, where feldspar is replaced by muscovite, quartz, and lithium micas, further emphasizes the granite's complex mineralogical evolution (Manning, 1995).

The granite's structural and textural variations are equally notable. It is subdivided into multiple lithological units, including coarse-grained granite, fine-grained granite, and pegmatitic bodies. These units display varying degrees of mineralization, with lithium-bearing micas often concentrated in pegmatites and hydrothermal veins. Furthermore, fractures and faults associated with late-stage extensional tectonics facilitated the movement of hydrothermal fluids, contributing to localized enrichment of rare metals in the granite (Enyejo et al., 2024).

The St Austell Granite's unique combination of magmatic and hydrothermal features, coupled with its significant lithium-bearing mineralogy, underscores its geological importance. It serves as a valuable model for understanding rare-metal enrichment in peraluminous granites and highlights its potential as a strategic resource for sustainable lithium extraction (Idoko, et al., 2024).

➢ *Occurrence and Distribution of Lithium-Bearing Minerals in the Region*

The occurrence and distribution of lithium-bearing minerals in the St Austell Granite are strongly influenced by magmatic differentiation and hydrothermal processes. These processes have led to the formation of lithium-rich micas, predominantly zinnwaldite and lepidolite, which are found in pegmatites, greisenized zones, and hydrothermal veins within the granite. Lithium is preferentially incorporated into these micas due to their affinity for volatile elements such as fluorine and boron, which are abundant in the late stages of granite crystallization (Banks et al., 1994).

Spatially, lithium-bearing minerals in the St Austell Granite are not uniformly distributed but occur in specific zones where late-stage hydrothermal fluids enriched with lithium precipitated minerals under favorable conditions (Eguagie et al., 2025). Greisenized regions, which are characterized by the replacement of feldspar with quartz and muscovite, frequently host lithium-bearing micas. These zones are particularly concentrated along fractures and fault systems, which acted as conduits for lithium-rich fluids during the granite's cooling and alteration phases. Pegmatites within the granite, formed through extreme magmatic fractionation, also contain high concentrations of lepidolite and other rare-metal-bearing minerals (Wall & Naden, 2012).

The distribution of lithium-bearing minerals is often accompanied by other rare metals, such as cesium, rubidium, and tin, indicating the granite's geochemical enrichment. For example, the lithium concentrations in the greisenized zones of the St Austell Granite are notably higher than in other Cornubian Batholith regions, making it a prime target for rare-metal exploration. These occurrences demonstrate the granite's potential for sustainable lithium resource development, aligning with the increasing global demand for lithium in renewable energy applications. Understanding the spatial patterns and geological controls of lithium mineralization is critical for assessing the economic viability of this resource as represented in Table 1 (Ijiga et al., 2024).

Table 1 Spatial Patterns and Geological Features of Lithium-Bearing Minerals in the St Austell Granite

Lithium-Bearing Minerals	Geological Features	Spatial Distribution	Significance
Zinnwaldite and Lepidolite	Found in pegmatites, greisenized zones, and hydrothermal veins.	Concentrated along fractures, faults, and greisenized zones within the granite.	Indicate late-stage magmatic differentiation and hydrothermal enrichment; key sources of lithium in the region.
Greisenized Zones	Characterized by replacement of feldspar with quartz and muscovite.	Found near structural features such as faults and fractures where lithium-rich fluids precipitated.	Host higher lithium concentrations than other areas of the Cornubian Batholith.
Pegmatites	Formed through extreme magmatic fractionation.	Distributed within the granite, often containing high concentrations of lepidolite and rare metals.	Associated with rare-metal enrichment, including cesium, rubidium, and tin, enhancing economic potential.
Rare Metals (e.g., Cesium, Rubidium, Tin)	Associated with lithium-bearing micas in enriched zones.	Accompany lithium deposits in greisenized zones and pegmatites.	Highlight geochemical enrichment, enhancing resource diversity and economic viability.

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➢ *Role of Magmatic and Hydrothermal Processes in Mineralization*

The mineralization of lithium-bearing micas in the St Austell Granite is fundamentally controlled by magmatic differentiation and hydrothermal processes, which act in tandem to concentrate lithium and other rare metals. During the magmatic stage, lithium is enriched in the residual melt as fractional crystallization proceeds. This process depletes early-crystallized phases, such as feldspar and biotite, of lithium, leading to the eventual crystallization of lithium-bearing micas like zinnwaldite and lepidolite in the late magmatic stages (Sirbescu & Nabelek, 2003). These micas preferentially incorporate lithium due to their structural compatibility and the presence of volatile elements, particularly fluorine, which stabilizes lithium-rich phases.

The role of hydrothermal processes is equally significant in enhancing lithium mineralization. As the granite cools, volatile-rich fluids exsolve from the melt, becoming enriched in lithium, boron, and fluorine. These fluids migrate along fractures, faults, and other permeable zones, causing pervasive hydrothermal alteration known as greisenization. During greisenization, feldspar and primary micas are replaced by quartz, muscovite, and lithium-bearing micas, which are deposited under conditions of low temperature and high fluid activity. This process is particularly evident in the greisenized zones of the St Austell Granite, where lithium-bearing minerals are concentrated. (Enyejo et al., 2024)

Hydrothermal processes also play a role in redistributing lithium within the granite system. Pegmatitic and vein deposits, formed by highly evolved magmatic fluids, exhibit localized enrichments of lepidolite and other rare-metal-bearing phases. The interplay between magmatic and hydrothermal processes ensures that lithium is efficiently concentrated in specific geological settings, enhancing the economic potential of the St Austell Granite. This dual-process mechanism highlights the importance of understanding fluid-rock interactions and magmatic evolution in rare-metal granite systems.

III. MATERIALS AND METHODS

➢ *Field Sampling Procedures*

Field sampling is a critical step in investigating the mineralization potential of lithium-bearing micas within the St Austell Granite. Proper sampling strategies ensure the collection of representative rock samples for subsequent mineralogical and geochemical analyses. To achieve this, systematic fieldwork was conducted across the St Austell Granite, focusing on regions with known occurrences of greisenized zones, pegmatitic bodies, and hydrothermal veins (Rollinson, 2014).

Sampling procedures began with detailed geological mapping to identify key lithological units and structural features, such as faults and fractures, that influence the distribution of lithium-bearing minerals. Hand specimens and bulk rock samples were collected using a grid-based approach, ensuring spatial coverage across different granite facies. This approach minimizes bias and ensures that variations in mineralization are captured. Particular attention was given to collecting samples from greisenized zones, where lithium-bearing micas like zinnwaldite and lepidolite are typically concentrated.

To maintain sample integrity, fresh and unweathered rock fragments were prioritized. Each sample site was georeferenced using a GPS, and field notes were recorded to document lithological characteristics, mineral assemblages, and visible signs of alteration. Duplicate samples were collected from select locations for quality control, ensuring that analytical results are reproducible and reliable (Chiaradia & Weis, 2016).

The collected samples were carefully labeled, packed, and transported to the laboratory for preparation and analysis. Representative thin sections were prepared for petrographic studies, while powdered rock samples were used for geochemical analyses. This comprehensive sampling methodology not only provides insights into the spatial distribution of lithium-bearing minerals but also establishes a robust dataset for evaluating the economic potential of the St Austell Granite as a sustainable lithium resource. Effective sampling strategies are thus indispensable for understanding the geological processes driving rare-metal enrichment.

➢ *Petrographic and Mineralogical Analysis Methods*

Petrographic and mineralogical analyses are fundamental for characterizing the composition, texture, and mineral associations within the St Austell Granite, particularly in its lithium-bearing micas. Petrographic analysis begins with the preparation of thin sections from collected rock samples. These sections are examined under a polarizing microscope to identify mineral assemblages, textural relationships, and alteration features. Specific attention is given to lithium-bearing micas, such as zinnwaldite and lepidolite, which are distinguished by their pleochroism, birefringence, and cleavage patterns (Barker, 2017).

In addition to optical microscopy, scanning electron microscopy (SEM) is employed for high-resolution imaging of mineral surfaces and microstructures. SEM, coupled with energy-dispersive X-ray spectroscopy (EDS), enables the identification of elemental compositions in lithium-bearing minerals, providing insights into their geochemical enrichment. For example, SEM-EDS analyses can confirm the presence of lithium, fluorine, and rare metals such as cesium and rubidium within mica grains, offering evidence of magmatic differentiation and hydrothermal alteration as shown in Figure 2 (Deer et al., 2013).

Mineralogical characterization is further refined using X-ray diffraction (XRD), which determines the crystalline structure and mineral phases present in the samples. XRD analysis is particularly effective for confirming the presence of lithium-bearing micas and distinguishing them from other silicates. Advanced techniques, such as Raman spectroscopy, are also applied to analyze the vibrational modes of minerals,

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providing complementary data on their structural composition.

These petrographic and mineralogical methods not only identify the distribution and characteristics of lithium-bearing micas but also reveal their association with other minerals, such as quartz, topaz, and feldspar, within the granite. This integrated approach ensures a comprehensive understanding of the mineralization processes and supports the evaluation of the St Austell Granite as a sustainable lithium resource.

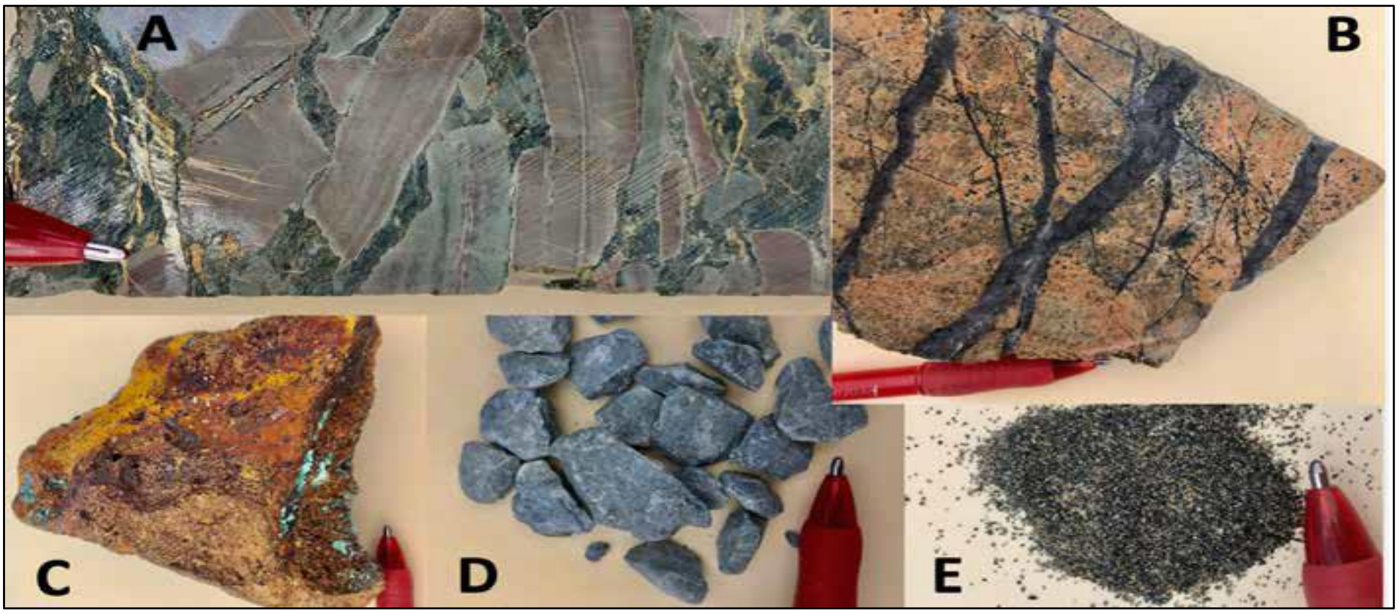

Fig 2 An Application of Petrographic and Mineralogical Analysis Methods to the Samples (Ashley P. 2023).

Figure 2 displays samples illustrating various stages and types of geological material relevant to petrographic and mineralogical analysis. Panel A shows detailed textural features of a rock, likely highlighting mineral alignment or cleavage patterns, critical for identifying structural deformation and mineral habit under petrographic microscopy. Panel B reveals fractures and vein systems, indicative of hydrothermal fluid activity, where mineralogical studies such as SEM-EDS would analyze vein composition for lithium-bearing minerals. Panel C depicts a weathered sample with vibrant colors, suggesting the presence of secondary alteration products or oxidized minerals, often examined using XRD to confirm crystalline phases. Panel D consists of angular rock fragments, likely representing bulk samples prepared for geochemical analysis, including ICP-MS, to determine elemental concentrations. Finally, Panel E shows finely ground material, typical of samples used in XRD or chemical digestion for detailed compositional and structural analysis. These samples represent the diverse material types used in the study of the St Austell Granite, showcasing how petrographic and mineralogical methods provide insights into texture, composition, and alteration processes essential for understanding lithium mineralization.

- *Geochemical Characterization Techniques (e.g., XRD, ICP-MS, SEM-EDS)*

Geochemical characterization techniques are essential for understanding the mineralogical and chemical properties of lithium-bearing minerals in the St Austell Granite. X-ray diffraction (XRD) is a primary method used to determine the crystalline structure of minerals in the samples. XRD analysis identifies mineral phases such as zinnwaldite and lepidolite, allowing differentiation between lithium-bearing micas and other silicates. This technique is invaluable for quantifying the mineralogical composition and confirming the presence of lithium-rich phases critical to the granite's economic potential (Pyle et al., 2002).

Inductively coupled plasma mass spectrometry (ICP-MS) is employed to quantify trace elements, including lithium, rubidium, and cesium, which are essential for evaluating the granite's rare-metal enrichment. ICP-MS offers high sensitivity and precision, enabling the detection of elemental concentrations at parts-per-billion levels. For example, lithium concentrations in samples from greisenized zones of the St Austell Granite can be accurately determined, providing insights into the granite's magmatic evolution and hydrothermal alteration processes. This data is critical for assessing the economic viability of lithium extraction.

Scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS) is used to visualize mineral textures and analyze elemental compositions at the microscale. SEM-EDS provides high-resolution imaging of mica grains, revealing structural details such as exsolution textures and compositional zoning. This technique also confirms the distribution of lithium within mica structures and its association with fluorine and other volatiles.

Together, these geochemical characterization methods provide a comprehensive understanding of the mineralization processes within the St Austell Granite. They ensure accurate identification and quantification of lithium-bearing minerals,

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supporting efforts to evaluate the granite as a sustainable source of lithium for the renewable energy sector.

➢ *Data Analysis and Interpretation Approach*

The data analysis and interpretation for the study of lithium-bearing minerals in the St Austell Granite involved a multi-faceted approach that integrated petrographic, mineralogical, and geochemical datasets. Analytical results from techniques such as XRD, ICP-MS, and SEM-EDS were first compiled and standardized to ensure consistency and reliability. Key data processing steps included baseline correction for XRD patterns, calibration of elemental concentrations in ICP-MS, and compositional mapping of mineral phases using SEM-EDS (Rollinson, 2019).

Quantitative analyses were conducted to identify correlations between lithium concentrations and associated trace elements, such as rubidium and cesium, within the mineral samples. For instance, geochemical trends observed in greisenized zones of the granite were mapped to identify enrichment patterns that could indicate areas of higher economic potential. Statistical tools, including principal component analysis (PCA), were applied to highlight geochemical relationships and differentiate mineralization styles. This method provided insights into the partitioning behavior of lithium during magmatic and hydrothermal processes.

Spatial data from field samples were integrated into a geographic information system (GIS) to visualize the distribution of lithium-bearing minerals across the St Austell Granite. This spatial analysis allowed the identification of zones with elevated lithium concentrations and their alignment with structural features such as faults and fractures.

Interpretation of the combined datasets focused on understanding the processes responsible for lithium mineralization. The results confirmed that late-stage magmatic differentiation and hydrothermal alteration were the primary drivers of lithium enrichment in micas as presented in Table 2. These findings were contextualized within the broader geological framework of the Cornubian Batholith, providing a detailed understanding of the St Austell Granite's potential as a sustainable lithium resource. This robust data analysis approach ensures the accuracy and relevance of interpretations for evaluating mineralization potential.

Table 2 Data Analysis and Interpretation of Lithium Mineralization in St Austell Granite

Analytical Techniques	Key Processing Steps	Insights Gained	Applications
XRD, ICP-MS, SEM-EDS	Baseline correction for XRD patterns, calibration of elemental concentrations in ICP-MS, compositional mapping with SEM-EDS.	Identification of lithium concentrations, associated trace elements (e.g., rubidium, cesium), and mineral phases.	Determined lithium enrichment zones, ensuring reliable and consistent dataset integration for further interpretation.
Quantitative Geochemical Analysis	Statistical tools like principal component analysis (PCA) were used to highlight geochemical relationships.	Correlations between lithium and trace elements, differentiation of mineralization styles, and enrichment patterns.	Enabled identification of high-potential zones for economic lithium recovery and assessment of partitioning behavior during geological processes.
GIS Integration of Spatial Data	Field samples mapped into a GIS for spatial visualization of lithium-bearing mineral distribution.	Visualized lithium concentration hotspots and their alignment with structural features like faults and fractures.	Facilitated the targeting of exploration zones, improving resource identification and aiding regional-scale geological studies.
Integrated Data Interpretation	Synthesized results from all techniques to contextualize lithium mineralization within the Cornubian Batholith.	Late-stage magmatic differentiation and hydrothermal alteration identified as primary drivers of lithium enrichment.	Provided a robust framework for evaluating the St Austell Granite's economic potential as a sustainable lithium resource.

IV. LITHIUM-BEARING MICAS: CHARACTERISTICS AND DISTRIBUTION

➢ *Types of Lithium-Bearing Micas (e.g., Zinnwaldite, Lepidolite) and Their Properties*

Lithium-bearing micas are a significant group of minerals commonly found in granitic pegmatites and greisenized zones, where magmatic differentiation and hydrothermal processes concentrate lithium. The two most notable lithium-bearing micas, zinnwaldite and lepidolite, exhibit unique mineralogical and geochemical properties that make them vital for lithium enrichment studies. Their occurrences in the St Austell Granite highlight their economic importance as potential resources for sustainable lithium extraction (Černý & Novak, 2001).

Zinnwaldite, a member of the biotite-phlogopite series, is a Li-Fe-Al-rich mica typically found in greisenized zones and granitic pegmatites. It displays dark brown to black coloration, reflecting its iron content, and can be identified petrographically by its pleochroism and high birefringence. Chemically, zinnwaldite incorporates lithium into its octahedral sites, with typical $Li2O$ contents ranging between 1–4 wt%. Its association with quartz, topaz, and fluorite in

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mineralized zones highlights the role of late-stage magmatic fluids in its formation (Ijiga et al., 2024).

Lepidolite, on the other hand, is a lithium-rich mica belonging to the trilithionite-polylithionite series. It is easily recognized by its characteristic pink to purple color, which arises from trace amounts of manganese. Lepidolite typically contains higher lithium concentrations than zinnwaldite, with Li2O contents ranging from 3–7 wt%, making it a more desirable target for lithium extraction. Its formation is strongly linked to evolved pegmatitic fluids enriched in volatile elements, such as fluorine, boron, and phosphorus as shown in Figure 3.

The distinct properties of zinnwaldite and lepidolite—ranging from their structural features to geochemical composition—reflect their petrogenetic origins and importance in lithium mineralization systems. The occurrence of these micas in the St Austell Granite underscores their potential as valuable lithium sources, driven by increasing global demand for energy storage technologies (Ibokette et al, 2024).

Fig 3 An Image Showing the Visual Representation of Lithium-Bearing Micas and their Properties, (X-Ray Minerals. n.d.)

Figure 3 provides a comparative overview of key micas, highlighting their physical characteristics and mineralogical properties, with a specific focus on lithium-bearing varieties. Biotite and muscovite are shown as common mica types, where biotite is dark-colored and rich in iron and magnesium, while muscovite exhibits a lighter, transparent appearance due to its higher aluminum and potassium content. These serve as baseline examples of mica group minerals. Lepidolite and zinnwaldite, the lithium-bearing micas of interest, exhibit unique features critical to lithium mineralization. Lepidolite, characterized by its pink to purple hue, has a high lithium content, typically ranging from 3% to 7% Li2O, making it a prime candidate for extraction in renewable energy applications. Zinnwaldite, with its silvery-gray metallic luster, contains moderate lithium concentrations (1% to 4% Li2O) and is associated with hydrothermal processes in granitic systems. These micas crystallize under low-temperature, volatile-rich conditions and are key indicators of late-stage magmatic differentiation. The image visually emphasizes the structural differences and physical attributes of these micas, facilitating their identification during petrographic and mineralogical analyses, as discussed in the context of the St Austell Granite.

- *Geochemical Composition and Lithium Enrichment*

The geochemical composition of lithium-bearing micas, such as zinnwaldite and lepidolite, is a direct result of magmatic differentiation and hydrothermal processes that promote lithium enrichment in granitic systems. Lithium is typically hosted within the octahedral positions of these

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micas, where it substitutes for aluminum, magnesium, or iron, reflecting its affinity for late-stage, volatile-rich environments (London, 2008). These processes are crucial in forming the lithium-enriched zones observed within the St Austell Granite.

Lepidolite, the most lithium-rich mica, contains up to 7% Li2O and is often associated with other volatiles, including fluorine, rubidium, and cesium. The enrichment of lithium in lepidolite occurs during the advanced stages of magmatic crystallization when residual melts become saturated with rare elements. The presence of fluorine enhances lithium mobility and incorporation into lepidolite, stabilizing its formation under low-temperature, high-volatile conditions. This geochemical behavior reflects the highly evolved nature of the pegmatites and greisen zones within the St Austell Granite (Ayoola et al., 2024).

Zinnwaldite, in contrast, is slightly lower in lithium content (1–4% Li2O) but is enriched in iron and manganese. It forms under conditions where hydrothermal fluids interact with pre-existing granitic minerals, facilitating lithium redistribution and crystallization. The trace element composition of zinnwaldite often includes rubidium and tin, which further highlights its association with evolved granitic systems.

The lithium enrichment in these micas within the St Austell Granite is spatially and geochemically controlled, with the highest concentrations observed in greisenized zones and pegmatitic bodies. These zones demonstrate the granite's potential as a lithium resource, particularly given the global demand for lithium in renewable energy technologies. The systematic study of geochemical composition provides critical insights into the processes driving lithium mineralization and its economic implications.

- *Spatial Distribution of Lithium-Bearing Micas within the Granite*

The spatial distribution of lithium-bearing micas, such as zinnwaldite and lepidolite, within the St Austell Granite is strongly influenced by magmatic differentiation and hydrothermal processes. These micas are primarily concentrated in highly evolved zones of the granite, including pegmatitic bodies, greisenized regions, and hydrothermal veins, where late-stage fluids enriched in lithium and other volatiles precipitate minerals under favorable conditions (Breiter et al., 2017).

Lithium-bearing micas are not uniformly dispersed throughout the granite; instead, they occur preferentially in structurally controlled areas, such as faults, fractures, and brecciated zones, which served as conduits for fluid migration. Greisenized zones, where feldspar and biotite have been altered to quartz and lithium-rich micas, represent significant sites of lithium enrichment. These zones commonly occur near the granite's roof contact and along structural weaknesses, indicating the influence of hydrothermal processes on lithium distribution (Ijiga et al., 2024).

Pegmatitic bodies, which form during the extreme fractionation of residual melts, are another key host for lithium-bearing micas. Lepidolite, with its higher lithium content, is particularly abundant in these pegmatitic environments. Its formation reflects the crystallization of volatile-rich fluids, which enhance lithium mobility and concentration in localized regions (Müller & Groves, 2019).

Mapping studies of the St Austell Granite have shown that lithium mineralization correlates with zones of increased alteration and proximity to late-stage fluid pathways. This spatial relationship emphasizes the importance of understanding the structural and geochemical controls on mineral distribution for identifying high-potential lithium zones. Such insights are essential for targeted exploration and the sustainable development of the St Austell Granite as a lithium resource, aligning with global demands for renewable energy technologies (Enyejo et al., 2024).

- *Factors Influencing the Mineralization Potential of these Micas*

The mineralization potential of lithium-bearing micas, such as zinnwaldite and lepidolite, in granitic systems is influenced by a combination of magmatic, geochemical, and structural factors. The St Austell Granite, like many lithium-enriched granites, underwent extensive magmatic differentiation and hydrothermal alteration, which facilitated the concentration of lithium in specific zones (Černý & Ercit, 2005).

One key factor is *magmatic differentiation*, where lithium becomes enriched in the residual melt during fractional crystallization. As early-formed minerals such as feldspars and biotite deplete the melt of major elements, incompatible elements like lithium, rubidium, and cesium remain concentrated. The formation of lithium-bearing micas occurs in the final stages of crystallization, when volatile-rich fluids stabilize minerals like lepidolite under low-temperature, high-fluorine conditions (Evensen et al., 2018).

Volatile content is another critical factor. Elements such as fluorine and boron enhance lithium mobility by reducing the viscosity of magmatic fluids, facilitating its incorporation into micas. Fluorine, in particular, plays a vital role in stabilizing lepidolite during crystallization, explaining its prevalence in highly evolved pegmatites and greisenized zones.

Structural controls, such as fractures, faults, and greisenized zones, significantly influence the spatial distribution of lithium-bearing micas. These features provide pathways for hydrothermal fluids enriched in lithium to migrate and interact with existing granitic minerals, leading to secondary mineralization.

Additionally, the temperature and pressure conditions during the late magmatic and hydrothermal stages dictate the crystallization of specific mica types. Zinnwaldite tends to form under higher iron activity, while lepidolite crystallizes in more evolved, lithium-rich systems with high fluorine content as presented in Table 3 (Idoko et al., 2024).

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Understanding these factors highlights the intricate processes driving lithium enrichment in micas, emphasizing the importance of magmatic evolution, fluid-rock interactions, and structural settings for assessing the mineralization potential of granitic systems like the St Austell Granite.

Table 3 Key Factors Driving Lithium Mica Mineralization in St Austell Granite

Factor	Description	Impact on Mineralization	Examples from St Austell Granite
Magmatic Differentiation	Fractional crystallization enriches lithium in residual melts as early-formed minerals deplete major elements.	Concentrates lithium, rubidium, and cesium, enabling the formation of lithium-bearing micas in the final crystallization stages.	Facilitated the crystallization of lepidolite and zinnwaldite under low-temperature, volatile-rich conditions.
Volatile Content	High levels of fluorine and boron reduce melt viscosity, enhancing lithium mobility and incorporation into micas.	Stabilizes lepidolite and promotes lithium enrichment in evolved pegmatites and greisenized zones.	Greisenized zones and pegmatites exhibit lithium enrichment due to high fluorine content during late magmatic stages.
Structural Controls	Faults, fractures, and greisenized zones act as pathways for lithium-rich hydrothermal fluids to migrate and interact with host rocks.	Localizes lithium-bearing micas in specific structural zones, leading to secondary mineralization.	Concentration of lithium-bearing micas along fractures and faults in greisenized regions of the St Austell Granite.
Temperature and Pressure Conditions	Late magmatic and hydrothermal conditions influence the crystallization of specific mica types based on available elements.	Zinnwaldite forms in higher iron environments, while lepidolite forms in lithium- and fluorine-rich systems.	Variability in mica types reflects the changing thermal and geochemical environment during the granite's evolution.

V. ECONOMIC AND ENVIRONMENTAL IMPLICATIONS

➢ *Assessment of Lithium Extraction Feasibility and Resource Potential*

Assessing the feasibility of lithium extraction from the St Austell Granite requires evaluating both the geological resource potential and the economic and environmental implications of developing lithium-bearing micas. Lithium extraction from unconventional sources, such as zinnwaldite and lepidolite, presents unique challenges and opportunities compared to traditional brine and spodumene deposits. These challenges are particularly relevant given the increasing global demand for lithium in energy storage technologies (Jaskula & Bradley, 2020).

The lithium content in lepidolite and zinnwaldite, ranging from 1% to 7% Li_2O, is competitive with many traditional resources. However, the relatively low abundance of these micas within the granite necessitates an efficient processing approach. Recent advancements in hydrometallurgical techniques, including sulfuric acid leaching and alkali digestion, have improved the economic feasibility of extracting lithium from micas. For instance, selective leaching methods target lithium while minimizing the dissolution of other elements, enhancing the efficiency and reducing environmental impacts (Xu et al., 2019).

The resource potential of the St Austell Granite is further supported by its proximity to existing infrastructure and markets, which lowers logistical costs compared to remote deposits. Additionally, the presence of associated rare metals, such as rubidium and cesium, offers opportunities for by-product recovery, further improving the economic viability of the project (Igba et al., 2024).

From an environmental perspective, the relatively low water consumption and the absence of extensive evaporation ponds, as required in brine extraction, position mica-based lithium extraction as a more sustainable option. However, the energy intensity of some processing methods remains a concern. Life-cycle assessments are crucial to quantifying the carbon footprint and comparing it with other lithium sources (Ayoola et al., 2024).

Overall, the St Austell Granite presents a viable lithium resource, contingent on continued advancements in extraction technologies and comprehensive feasibility studies that balance economic and environmental factors.

➢ *Environmental Considerations of Lithium Mining in the St Austell Region*

Mining lithium-bearing micas, such as zinnwaldite and lepidolite, in the St Austell Granite presents unique environmental considerations. Although lithium extraction from unconventional sources offers opportunities for reducing reliance on traditional brine and spodumene resources, the ecological footprint of mining and processing these micas requires careful evaluation to ensure long-term sustainability (Valenzuela & Billi, 2020).

One of the primary environmental concerns in the St Austell region is the potential impact of mining activities on land use and biodiversity. The region’s rich ecological landscape could face disruptions from surface mining operations, including habitat destruction and soil erosion.

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Implementing practices such as progressive land rehabilitation and minimizing the mine's spatial footprint can mitigate these impacts (Ijiga et al., 2024).

Another significant consideration is the environmental footprint of mica processing. Conventional hydrometallurgical techniques, such as acid leaching, may generate chemical waste and tailings that need proper management to prevent contamination of nearby water sources. Recycling process water and incorporating zero-waste strategies could reduce these risks and align the project with environmental best practices as shown in Figure 4 (Ali &order, 2019).

The relatively lower water requirements for mica-based lithium extraction compared to brine extraction offer an advantage, especially in regions where water scarcity is a critical issue. However, the energy-intensive nature of lithium extraction and processing contributes to greenhouse gas emissions. Utilizing renewable energy sources for mining and processing operations could offset these emissions and improve the project's sustainability profile (Idoko et al., 2024).

Finally, community engagement and stakeholder consultation are crucial in addressing public concerns and ensuring that mining activities deliver local benefits without compromising environmental integrity. Developing a comprehensive environmental management plan will be essential to balance the region's resource potential with its ecological preservation.

Figure 4 highlights the environmental considerations of lithium mining in the St Austell region by focusing on two primary areas: land use and biodiversity, and processing and emissions. It illustrates how mining activities can lead to habitat destruction and soil erosion, which can be mitigated through habitat restoration and land rehabilitation. On the processing side, challenges like chemical waste generation and greenhouse gas (GHG) emissions are identified, with strategies such as recycling, zero-waste practices, and the use of renewable energy proposed to address these issues. The diagram underscores the need for sustainable practices to balance lithium extraction with environmental preservation.

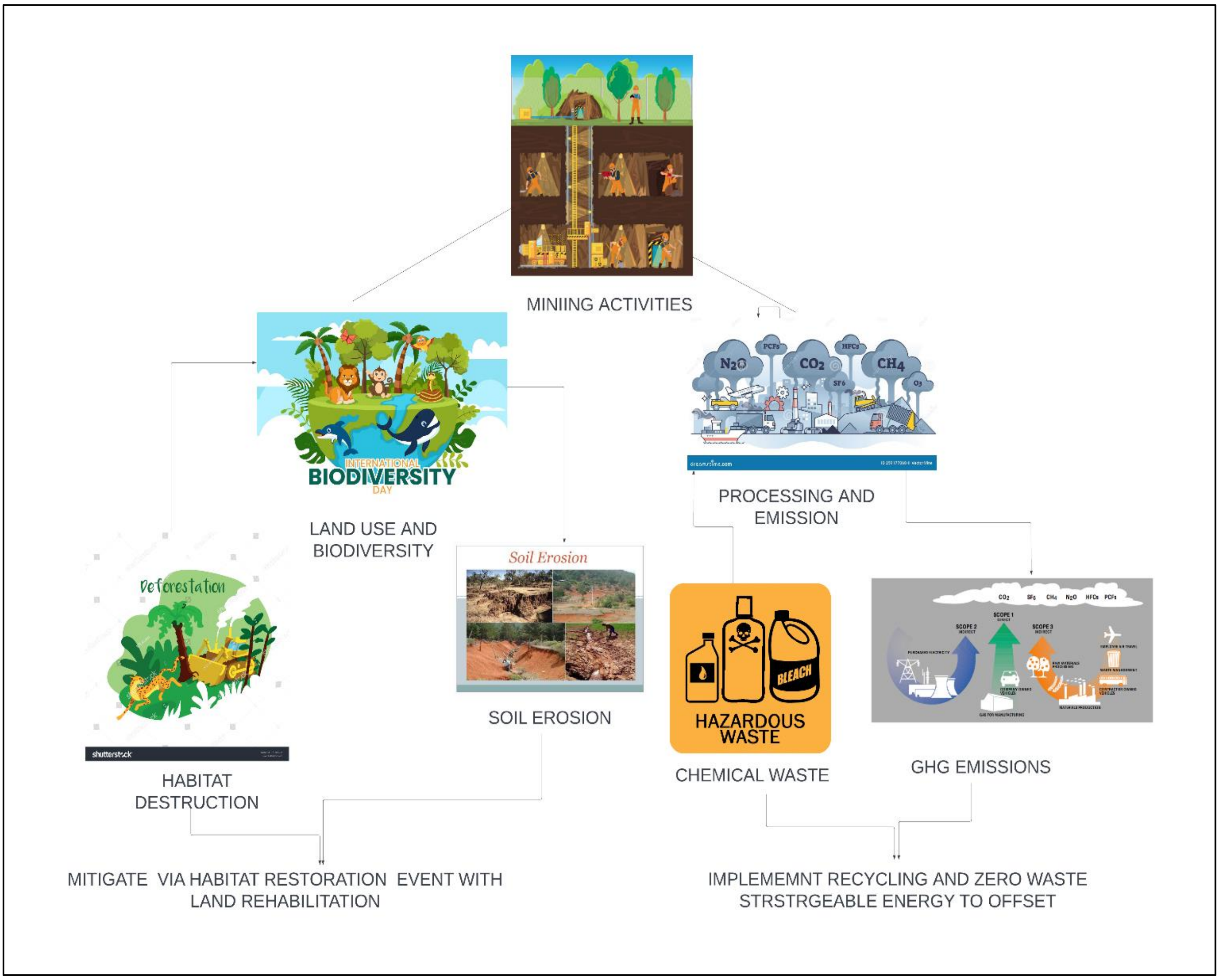

Fig 4 A Diagram Showing Environmental Challenges and Mitigation Strategies in Lithium Mining at St Austell

➢ *Economic Benefits and Challenges Associated with Developing the Deposit*

The development of lithium-bearing mica deposits in the St Austell Granite offers significant economic benefits, particularly in the context of the rapidly growing global demand for lithium in renewable energy technologies. The projected increase in electric vehicle (EV) production and energy storage systems positions lithium as a critical mineral in the energy transition. Deposits such as those in the St Austell Granite have the potential to reduce dependence on traditional lithium sources like brines and spodumene, creating opportunities for local economic growth (Vikström et al., 2013).

One key economic benefit lies in job creation, as mining and processing activities in the region could stimulate employment in both skilled and unskilled labor sectors. Additionally, the establishment of processing facilities and supporting infrastructure would contribute to the regional economy through local supply chains and increased economic activity. The potential for by-product recovery, including elements like rubidium and cesium, further enhances the economic viability of the deposit by diversifying revenue streams (Ijiga et al., 2024).

However, significant challenges must be addressed to realize these benefits. The capital investment required for mining and processing infrastructure is substantial, particularly for unconventional lithium sources such as micas. Advanced technologies are necessary to ensure efficient and cost-effective extraction, but their implementation may face technical and financial barriers (Enyejo et al., 2024).

Market volatility in lithium prices poses another challenge, as fluctuating demand and supply dynamics could impact the economic feasibility of the project. Additionally, stringent environmental regulations may increase operational costs, particularly for waste management and emissions control.

Despite these challenges, the economic potential of the St Austell Granite is significant. Strategic investments, technological innovations, and sustainable practices could position the deposit as a vital contributor to the growing global lithium market while fostering regional economic development.

➢ *Comparative Analysis with Other Global Lithium Sources*

The St Austell Granite represents an unconventional lithium resource compared to global sources such as brine pools in South America and spodumene deposits in Australia. Each type of deposit offers distinct advantages and challenges, influencing its viability in the global lithium supply chain. Brine deposits, such as those in the Lithium Triangle (Chile, Argentina, and Bolivia), dominate global lithium production due to their high lithium concentration and lower extraction costs. However, these operations are water-intensive, raising concerns about environmental sustainability in arid regions (Grosjean et al., 2012).

In contrast, hard-rock spodumene deposits, primarily located in Australia, provide higher lithium content but require energy-intensive processing methods, including roasting and chemical leaching, which increase operational costs and environmental impacts. These deposits are typically favored for their reliability and proximity to infrastructure, but they contribute significantly to the carbon footprint of lithium extraction.

The lithium-bearing micas in the St Austell Granite offer a unique alternative, combining moderate lithium concentrations with the potential for less water-intensive and environmentally sustainable extraction methods. Advances in hydrometallurgical techniques, such as alkali digestion and selective leaching, make mica-based lithium extraction increasingly competitive. Additionally, the granite's association with rare metals like rubidium and cesium adds economic value, distinguishing it from other sources (Grosjean et al., 2012).

Geographically, the St Austell Granite benefits from its location in a politically stable region with established infrastructure and proximity to European markets, reducing logistical challenges compared to remote brine or spodumene deposits. While the extraction process for micas remains more complex than for brines, ongoing technological developments could position the St Austell Granite as a viable contributor to the global lithium supply, offering a balance between environmental sustainability and economic feasibility as represented (Ijiga et al., 2024) in Table 4.

Table 4 Comparative Analysis of Global Lithium Resources

Lithium Source	Key Characteristics	Advantages	Challenges
Brine Pools (Lithium Triangle)	High lithium concentration, lower extraction costs.	Dominates global production; cost-effective for large-scale lithium extraction.	Water-intensive processes; environmental sustainability concerns in arid regions.
Spodumene Deposits (Australia)	Hard-rock deposits with high lithium content; requires roasting and chemical leaching.	Reliable resource with proximity to infrastructure; high lithium yield.	Energy-intensive extraction; significant carbon footprint and high operational costs.
Lithium-Bearing Micas (St Austell Granite)	Moderate lithium concentration in micas like zinnwaldite and lepidolite; potential for	Environmentally sustainable options due to less water-intensive methods; association with rare metals like rubidium.	More complex and costly extraction compared to brines; requires ongoing technological advancements for efficiency.

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	hydrometallurgical extraction.		
Geographical Considerations	St Austell Granite is in a politically stable region near European markets.	Reduced logistical challenges; alignment with European critical mineral strategies.	Requires investment in infrastructure and processing facilities; scalability remains a hurdle compared to global leaders.

VI. DISCUSSION

➢ *Implications of Findings for the Lithium Supply Chain*

The findings from the St Austell Granite highlight critical implications for the global lithium supply chain, emphasizing the potential of unconventional sources to mitigate current and future supply constraints. As demand for lithium continues to rise—driven primarily by the electric vehicle (EV) sector and energy storage systems—the reliance on traditional sources such as brine pools and spodumene deposits faces challenges, including geographic concentration, environmental impacts, and market volatility (U.S. Geological Survey, 2022).

Lithium-bearing micas in the St Austell Granite provide an alternative that could diversify the supply chain and reduce dependency on limited geographic regions like the Lithium Triangle. This diversification is crucial for stabilizing supply chains and ensuring that lithium resources are accessible to emerging markets, particularly in Europe, where demand is projected to increase significantly due to aggressive EV adoption policies. Furthermore, the co-extraction of rare metals such as rubidium and cesium in mica deposits could enhance economic sustainability by creating additional revenue streams.

From a sustainability perspective, the findings highlight that mica-based lithium extraction could offer environmental advantages over brine and spodumene sources. By utilizing advanced hydrometallurgical techniques with lower water consumption and a smaller environmental footprint, these methods align better with global efforts to achieve net-zero carbon goals in critical mineral supply chains (Ziemann et al., 2018).

Technological advancements in processing lithium-bearing micas are critical to unlocking their full potential. While current methods are costlier compared to brine extraction, the proximity of the St Austell Granite to infrastructure and European markets reduces logistical challenges, enhancing its competitiveness. The integration of such resources into the global supply chain could contribute to a more resilient, sustainable, and diversified lithium market, addressing both current needs and future growth.

➢ *Potential for Sustainable Extraction and Processing Technologies*

The St Austell Granite offers a promising opportunity to adopt sustainable extraction and processing technologies for lithium-bearing micas, addressing the dual challenges of resource efficiency and environmental responsibility. As global demand for lithium intensifies, driven by electric vehicle (EV) batteries and renewable energy storage, the implementation of sustainable methods becomes imperative to minimize the environmental footprint of lithium production (Kushnir & Sandén, 2020).

One key area of potential is the use of advanced hydrometallurgical techniques, such as selective acid leaching and alkali digestion, which allow the efficient extraction of lithium while reducing waste generation. These methods can be optimized to target lithium selectively within zinnwaldite and lepidolite, minimizing the dissolution of other elements and lowering reagent consumption. Additionally, by-products such as rubidium and cesium can be recovered, enhancing the economic viability of the process while reducing material waste.

Energy consumption remains a critical concern in lithium extraction, particularly for unconventional sources like micas. Transitioning to renewable energy for powering extraction and processing facilities could significantly lower greenhouse gas emissions. Furthermore, implementing closed-loop water systems and recycling reagents within the processing workflow can reduce water usage and the risk of environmental contamination as shown in Figure 5.

The geographic proximity of the St Austell Granite to European markets also presents a logistical advantage, reducing the transportation-related carbon footprint. This aligns with the EU's critical mineral strategy, which emphasizes local sourcing and sustainable supply chain development.

Integrating automation and digital technologies, such as process optimization through machine learning, could further enhance sustainability by improving operational efficiency and reducing resource use. These advancements position the St Austell Granite as a case study for sustainable lithium production, aligning with global goals for greener and more responsible critical mineral extraction.

Figure 5 visually represents the sustainable extraction and processing potential for lithium-bearing micas in the St Austell Granite. It outlines two main strategies: Advanced Techniques and Energy & Resource Efficiency, further detailing methods such as Selective Acid Leaching and Alkali Digestion for advanced extraction and Renewable Energy Use and Closed-Loop Systems for resource optimization. These methods aim to achieve goals like Targeting Lithium Selectively, Recovering By-products, Reducing GHG Emissions, and Recycling Reagents, aligning with sustainability objectives.

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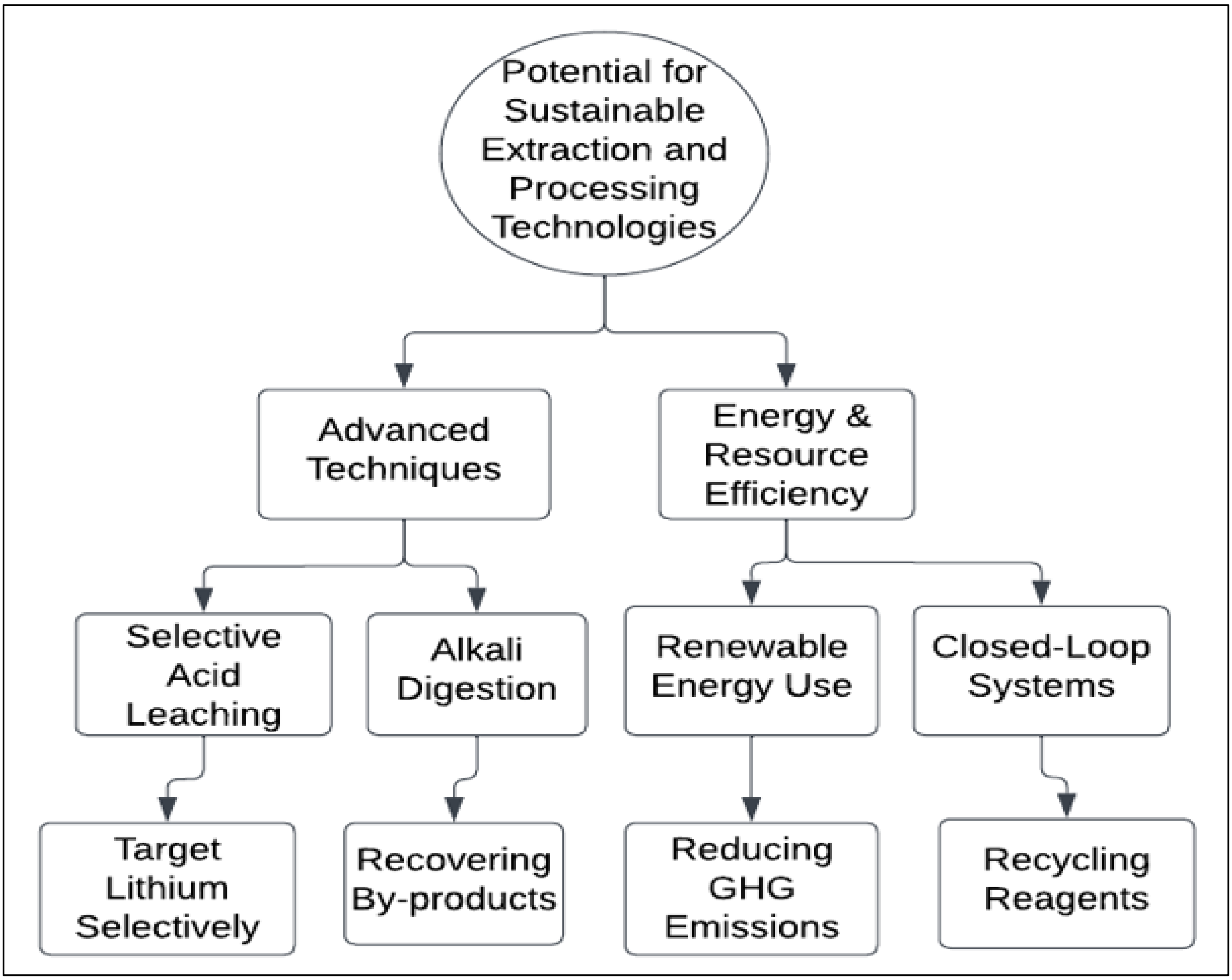

Fig 5 A Diagram Showing the Sustainable Extraction and Processing Strategies for Lithium Micas

➢ *Challenges Related to Grade, Extraction Costs, and Environmental Impacts*

The development of lithium-bearing mica deposits, such as those in the St Austell Granite, presents significant challenges related to ore grade, extraction costs, and environmental impacts. Unlike high-grade spodumene or brine resources, lithium-bearing micas typically contain lower lithium concentrations, with Li2O content ranging from 1% to 7%, requiring larger volumes of material to achieve comparable yields. This lower grade increases the cost per unit of lithium recovered, particularly when combined with the need for advanced extraction technologies (Flexer et al., 2018).

The extraction process for micas is energy-intensive, requiring multiple steps, including crushing, grinding, and chemical leaching. Hydrometallurgical techniques, such as acid leaching, are effective but involve high reagent costs and the generation of chemical waste. While newer methods, such as alkali digestion, aim to improve efficiency and reduce costs, they remain economically viable only at scale. This poses a challenge for smaller or regionally concentrated deposits like those in the St Austell Granite.

Environmental concerns further complicate the feasibility of mica-based lithium extraction. Chemical processes often produce tailings and effluents that must be managed carefully to avoid contamination of local water sources. Additionally, the high energy requirements contribute to greenhouse gas emissions, particularly if renewable energy sources are not integrated into the extraction workflow.

The proximity of the St Austell Granite to ecologically sensitive areas adds another layer of complexity. Surface mining, the most feasible extraction method, could disrupt local biodiversity and land use, necessitating comprehensive environmental impact assessments and the adoption of mitigation strategies as presented in Table 5.

Despite these challenges, advancements in processing technologies, coupled with strict environmental regulations and community engagement, could help address these issues. Developing a cost-effective and sustainable framework is essential for realizing the potential of mica-based lithium resources as part of a diversified global supply chain (Enyejo et al., 2024).

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Table 5 Key Challenges in Developing Lithium-Bearing Mica Resources in St Austell Granite

Challenge	Description	Impact on Development	Potential Solutions
Low Ore Grade	Lithium concentrations range from 1% to 7% Li2O, requiring larger material volumes for comparable yields.	Increases the cost per unit of lithium recovered, reducing economic viability.	Focus on processing efficiency and high-yield techniques such as alkali digestion.
High Extraction Costs	Energy-intensive processes like crushing, grinding, and hydrometallurgical techniques.	Requires significant capital investment; high reagent costs and complex processing reduce profitability.	Scale operations to improve economic viability; invest in renewable energy for cost and emission reductions.
Environmental Impacts	Tailings and effluents from chemical processing risk contaminating water sources; high energy usage adds to emissions.	Threatens local ecosystems and contributes to climate change if unmanaged.	Implement closed-loop water systems, waste recycling, and integrate renewable energy into the workflow.
Proximity to Sensitive Areas	Surface mining disrupts biodiversity and land use near ecologically important regions.	Requires extensive environmental assessments and mitigation strategies, increasing project complexity and costs.	Develop progressive land rehabilitation plans; engage with local communities to ensure sustainable land management.

- *Future Opportunities for Exploration and Development in the Region*

The St Austell Granite offers significant future opportunities for exploration and development, particularly as the demand for lithium continues to rise due to its critical role in renewable energy technologies. The region's known enrichment of lithium-bearing micas such as zinnwaldite and lepidolite positions it as a potential resource for the European market, which is increasingly prioritizing local and sustainable sources of critical minerals (Wanger, 2011).

One key opportunity lies in leveraging advanced geological mapping and geochemical modeling to identify additional zones of lithium mineralization within the granite. Improved mapping techniques, such as drone-based remote sensing and machine learning algorithms, could refine the understanding of lithium distribution, enhancing exploration efficiency and reducing costs. These tools would help pinpoint high-potential areas, especially along structural features such as faults and greisenized zones where lithium-bearing micas are concentrated.

Another promising avenue is the development of pilot projects that integrate emerging extraction technologies, such as direct lithium extraction (DLE) methods tailored for mica-based deposits. These projects could demonstrate the feasibility of sustainable lithium recovery while addressing environmental concerns through the implementation of closed-loop water systems and renewable energy use.

The St Austell Granite's proximity to existing infrastructure and industrial hubs also presents logistical advantages. Establishing partnerships with local industries and governments could facilitate the construction of processing facilities, creating a vertically integrated supply chain that reduces transportation costs and environmental impact.

Furthermore, the region's potential for co-extraction of rare metals such as rubidium and cesium provides an opportunity to diversify revenue streams and enhance economic viability. Strategic collaboration with research institutions and the adoption of green mining policies could position the St Austell Granite as a model for sustainable critical mineral extraction. These efforts would not only support regional economic development but also contribute to the broader goals of a sustainable and resilient global lithium supply chain.

VII. CONCLUSION AND RECOMMENDATIONS

- *Summary of Key Findings*

This study highlights the mineralization potential of lithium-bearing micas within the St Austell Granite, identifying their role as a promising unconventional resource for lithium extraction. The investigation revealed that the St Austell Granite hosts significant quantities of zinnwaldite and lepidolite, primarily concentrated in greisenized zones, pegmatitic bodies, and hydrothermal veins. These minerals are enriched through magmatic differentiation and hydrothermal processes, with lithium content ranging from 1% to 7% Li2O, comparable to other global sources.

The spatial distribution of lithium-bearing micas is strongly influenced by structural controls such as fractures and faults, which facilitated the movement of lithium-enriched hydrothermal fluids. Advanced a nalytical techniques confirmed the geochemical associations of lithium with elements like fluorine, rubidium, and cesium, further emphasizing the economic potential of these deposits. The study also identified challenges such as the lower ore grade compared to traditional resources and the energy-intensive nature of extraction processes.

Despite these challenges, the proximity of the St Austell Granite to European markets and infrastructure enhances its strategic importance. The study underscores the potential for

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implementing sustainable extraction technologies, such as selective leaching and renewable energy-powered processing, to mitigate environmental impacts. Furthermore, the opportunity for co-extracting rare metals adds economic value, strengthening the case for development.

Overall, the findings position the St Austell Granite as a viable contributor to the global lithium supply chain, supporting the transition to renewable energy and aligning with global goals for sustainable resource development.

➤ *The Significance of the St Austell Granite as a Lithium Resource*

The St Austell Granite holds substantial significance as a lithium resource, offering a strategic opportunity to diversify the global lithium supply chain. Unlike traditional lithium sources, such as South American brine pools and Australian spodumene deposits, the St Austell Granite presents a sustainable and regionally significant alternative. Its lithium-bearing micas, including zinnwaldite and lepidolite, exhibit concentrations comparable to other globally recognized deposits, with the added advantage of occurring alongside rare metals like rubidium and cesium, which enhance the economic potential of the resource.

The geological characteristics of the St Austell Granite make it uniquely suited for sustainable lithium development. Lithium enrichment in the granite is driven by magmatic differentiation and hydrothermal processes, resulting in spatially concentrated deposits within greisenized zones and pegmatites. These zones are strategically located near fractures and faults, providing accessibility and reducing exploratory challenges. The proximity of the St Austell Granite to European markets and infrastructure further underscores its importance, offering logistical and economic advantages over more remote deposits.

From an environmental perspective, the St Austell Granite provides a model for sustainable mining practices. Its lower water demands and the potential for renewable energy-powered extraction methods align with global goals for reducing the carbon footprint of critical mineral production. The integration of advanced processing technologies, coupled with the co-recovery of associated rare metals, reinforces its economic and environmental appeal. As the demand for lithium intensifies, the St Austell Granite stands as a significant resource capable of supporting the transition to a sustainable, low-carbon energy future.

➤ *Recommendations for Future Research, Exploration, and Extraction Methods*

Future research into the St Austell Granite should prioritize advanced geological mapping and resource modeling to refine the understanding of lithium-bearing mica distribution and concentration. Incorporating geophysical techniques, such as ground-penetrating radar and resistivity surveys, alongside geochemical sampling, will allow for more accurate delineation of high-potential zones, particularly along structural features such as faults and greisenized areas. This will reduce exploratory costs and enhance the efficiency of future mining operations.

Further development of extraction methods tailored to lithium-bearing micas is crucial to improving economic viability and environmental sustainability. Research should focus on optimizing hydrometallurgical techniques, such as selective leaching, to maximize lithium recovery while minimizing chemical waste. Exploring innovative approaches like direct lithium extraction (DLE) and bioleaching could also provide scalable solutions that reduce reagent use and energy consumption. Pilot projects should be initiated to test these methods in real-world conditions, ensuring their adaptability to the mineralogical complexities of the St Austell Granite.

Environmental management must be integral to future extraction efforts. Studies should assess the potential impact of mining activities on local ecosystems and explore mitigation strategies, such as progressive land rehabilitation and water recycling systems. Developing a closed-loop processing framework will further reduce environmental risks while enhancing the sustainability of operations.

Finally, collaboration with academic institutions, industry stakeholders, and policymakers is essential to address technological, economic, and regulatory challenges. Establishing a transparent framework for community engagement will foster public trust and ensure that the benefits of resource development are equitably distributed. These recommendations will pave the way for responsible exploration and extraction, maximizing the potential of the St Austell Granite as a sustainable lithium resource.

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