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**Agronomic Evaluation and Environmental Assessment of Egyptian Glauconite
as a Sustainable Potassium Fertilizer**

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1. INTRODUCTION

1.1. Introduction (The importance of the topic, problems to solve)

Sustainable agriculture is becoming increasingly critical in light of escalating global challenges, including soil nutrient depletion, climate change, and food security concerns. Among the core strategies for promoting sustainability in agriculture is the efficient and judicious use of natural mineral resources to enhance soil fertility and support crop productivity.

In Egypt, the agricultural sector faces a combination of structural and environmental constraints, including declining soil quality, erosion, severe water scarcity, limited mechanization, and the rising cost of essential agricultural inputs such as fertilizers and pesticides (Jena, 2020). Enhancing soil fertility through alternative approaches has therefore become a national priority. While Egypt has domestic production of nitrogen and phosphate fertilizers, it continues to depend heavily on imports for potash and some nitrogen-based fertilizers (Ahmed, 2023). However, the extensive and conventional application of these fertilizers raises environmental concerns. Plants are often unable to absorb all of the released nutrients, leading to nutrient losses and subsequent soil and water pollution (Wang et al., 2017). For instance, only about 2% of applied potassium is typically absorbed by plants in a growing season, whereas the use of highly concentrated potassium salts can result in a buildup of non-exchangeable potassium in the soil, with the excess leaching into groundwater during off-seasons (Basak et al., 2017).

To address these inefficiencies, slow-release potassium fertilizers have been proposed as a more sustainable solution. Among these, glauconite stands out for its dual benefit: supplying essential plant nutrients and mitigating the risk of chemical overloading in the soil (Liang et al., 2019; El-Habaak et al., 2016). Glauconite, a greenish iron-potassium phyllosilicate mineral typically found in marine sedimentary deposits, has emerged as a promising candidate for use as an alternative or supplementary source of potassium in agriculture (Rakesh et al., 2020a).

The agronomic value of glauconite lies in its rich content of potassium and trace micronutrients, such as iron and magnesium, which are essential for plant growth (Rudmin et al., 2017; Franzosi et al., 2014; Oze et al., 2019). Its natural slow-release behavior supports long-term nutrient availability, reduces leaching losses, and aligns with principles of precision and environmentally sustainable agriculture. Moreover, glauconite contributes to improving soil physical and chemical characteristics, including enhancing cation exchange capacity and increasing water retention potential (Rakesh, 2020a; Rudmin et al., 2019a).

Geologically, glauconite is most commonly found in marine environments as greenish, pellet-shaped sediments, although it is also occasionally present in volcanic rocks (Rubio & López-Pérez, 2024; Mohammed et al., 2025; Wilmsen et al., 2024; Baldermann et al., 2025; Rudmin et al., 2023). Its use in soil science is well-established, particularly in the identification of green sands and the characterization of soil types (Obasi et al., 2011; Westgate et al., 2023). Glauconite's field identification is aided by its distinct color and morphology (Rudmin et al. 2017), while analytical techniques such as X-ray diffraction (Drits et al., 1997) and FTIR spectroscopy are commonly used for precise mineralogical analysis in laboratory settings (Singh et al., 2023).

Beyond its agronomic properties, glauconite holds strategic economic value. As a naturally occurring potassium-bearing silicate, it offers the potential to reduce dependency on imported fertilizers and contribute to national efforts in saving foreign exchange reserves (Torqueti et al., 2016; Rudmin et al., 2017).

Despite this potential, the effectiveness of glauconite in agriculture remains underexplored, particularly in relation to its nutrient release mechanisms, interaction with other soil components, and behavior under different environmental conditions.

This doctoral dissertation aims to address key knowledge gaps through an integrated research framework. The study includes a comprehensive characterization of the elemental composition of glauconite to evaluate its potential as a nutrient source, together with an assessment of potentially toxic elements to ensure its safe use in agricultural systems without environmental or human health risks. In parallel, acid leaching experiments were conducted to investigate the nutrient release behavior of glauconite under different chemical conditions.

To assess the agronomic effectiveness of glauconite, the study incorporates both controlled pot experiments conducted in Hungary and a field experiment conducted in Egypt. The pot experiments were designed to evaluate the influence of glauconite application on soil nutrient dynamics and plant nutrient uptake under controlled conditions. The field experiment involved two successive crops grown on the same soil, allowing for the evaluation of both the direct agronomic response to glauconite application and its residual effect on soil potassium availability and plant uptake in the subsequent crop, without additional potassium inputs.

Collectively, these complementary experimental approaches provide a scientifically grounded evaluation of glauconite as a sustainable potassium source and soil amendment, with particular relevance to enhancing agricultural productivity in Egypt's semi-arid soils and other arid and semi-arid regions with similar agro-environmental conditions.

1.2. Objectives

Today, the world faces growing pressure to adopt sustainable practices to combat environmental pollution and the effects of climate change. One of the major contributors to these problems is the excessive and unmodified use of chemical fertilizers, which often results in nutrient loss from agricultural soils and increased emissions of greenhouse gases. This contributes directly to global warming, climate instability, and worsening food insecurity. In response, there is a rising interest among farmers and researchers in sustainable alternatives, particularly in the use of slow-release or controlled-release fertilizers that improve nutrient use efficiency and minimize environmental impact. While many studies have investigated different types of slow-release fertilizers, there remains considerable potential in exploring other natural, cost-effective mineral sources that can serve this purpose. Among these is glauconite - a potassium-rich, iron-bearing phyllosilicate mineral - which has shown promise as a slow-release potassium fertilizer due to its nutrient content and gradual solubility.

The overarching aim of this doctoral research is to evaluate the potential of glauconite as a sustainable potassium fertilizer and soil amendment suitable for application in Egyptian agricultural systems. The study is structured around the following specific objectives:

1. To characterize the mineralogical and elemental composition of glauconite deposits collected from the El-Gedida area, Western Desert of Egypt, to assess their suitability as a source of essential plant nutrients, particularly potassium.
2. To investigate the nutrient release behavior of glauconite under various acid leaching treatments, using a range of inorganic and organic acids, with the goal of simulating possible activation strategies that enhance nutrient availability.
3. To evaluate the effect of glauconite particle size on elemental release efficiency under acid treatment, to determine whether particle size fractionation influences the dissolution rate and nutrient solubility.
4. To compare the effectiveness of different extractants in solubilizing essential nutrients and potential toxic elements (PTEs) from glauconite, using both single extractants and the BCR sequential extraction procedure.
5. To investigate the presence and mobility of potential toxic elements in glauconite deposits in order to assess their environmental safety and ensure their suitability for use in agricultural applications.

6. To assess the effects of glauconite application on soil nutrient content and plant nutrient uptake under both controlled pot conditions and field conditions using different crops.
7. To evaluate the residual effect of glauconite application on soil potassium availability and plant potassium uptake in a successive crop grown without additional potassium fertilization.
8. To provide a scientific basis for recommending glauconite as an alternative slow-release potassium fertilizer that aligns with sustainable agriculture practices and supports national strategies to reduce dependence on imported potash fertilizers.

2. LITERATURE REVIEW

The literature review begins by providing a comprehensive overview of potassium fertilizers in agroecosystems, emphasizing their physiological role in plant growth, global and regional consumption trends, and the distinction between conventional and alternative sources. Particular attention is given to the use of potassium fertilizer in Egypt in the context of increasing agricultural demands and soil nutrient limitations. The environmental implications of potassium fertilizer production and application are also considered, highlighting concerns about sustainability and resource depletion. Building upon this foundation, the review then focuses in detail on glauconite as a potassium-bearing mineral and its potential for use as a slow-release fertilizer. It explores glauconite's structural and chemical properties, geological distribution with emphasis on Egyptian deposits, and previous studies on its nutrient content, extractability, and environmental safety. Finally, the chapter identifies key knowledge gaps related to glauconite activation, nutrient mobility, and agronomic performance, which this dissertation addresses through integrated chemical, environmental, and crop-based investigations.

2.1. Potassium Fertilizers

2.1.1. Potassium in Agriculture and Plant Physiology

Potassium (K) is a major macronutrient essential for plant growth. It is the most abundant inorganic cation in plant cells (Sardans and Peñuelas, 2021) and plays a crucial role in numerous vital functions. For example, adequate K^+ enhances photosynthesis and carbohydrate translocation, activates numerous enzymes, and regulates water relations and stomatal opening. (Sardans and Peñuelas, 2021) Sufficient K makes plants more resistant to drought, cold, and disease, while K deficiency stunts growth, reduces protein synthesis, and lowers crop yields. In leaves, K^+ (50–150 mM) maintains turgor and drives osmotic adjustment, and it is enriched in chloroplasts to support photosynthetic enzymes. In short, K helps transport water, nutrients and sugars, supports enzyme

and Rubisco activity, and enables efficient gas exchange through stomata (Sardans and Peñuelas, 2021).

Enzyme activation and metabolism: K^+ activates dozens of enzymes, influencing protein, starch and ATP synthesis (UMN Extension, 2018). Adequate K thus boosts photosynthetic CO_2 fixation and nutrient uptake.

Water relations: K^+ regulates osmotic balance and turgor. It controls stomatal opening/closing, modulating water use and cooling (Sardans and Peñuelas, 2021). Potassium sufficiency makes plants more drought- and wilting-resistant.

Stress tolerance: K promotes thick cell walls and root growth, improving hardiness. Well-K'd plants tolerate cold and resist pests better. In contrast, K deficiency leads to chlorosis, weak stalks, low yield and poor quality.

In agriculture, K (usually reported as K_2O) is widely applied as fertilizer. In 2021 about 95% of global K (≈ 45 Mt K) was used in agriculture, making up ~ 20 – 25% of all fertilizer nutrients (UNEP 2024). Demand was rising (annual growth $\sim 2.4\%$ from 2015–2020) (UNEP 2024) to feed growing crops and biofuel needs. Because K is so vital, its omission severely limits food production.

2.1.2. Global Trends in Potassium Fertilizer Use

Global K fertilizer use has generally increased over recent decades, though it fluctuates with prices and supply. FAO data show world K fertilizer (K_2O) use was about 40 million tonnes in 2021, but then declined by $\sim 12\%$ to 35 Mt in 2022. (FAO Statistics 2021, 2022)

(High prices and supply-chain issues drove the recent drop.) For context, global N and P use in 2022 was ~ 108 Mt and ~ 42 Mt, respectively (FAO Statistics 2022). Regional patterns vary: Asia (especially China and India) dominates K use, while Europe saw the largest recent cuts (-18% K use in 2022) (5). Over the last 2 decades, rising food demand kept K use growing, but short-term swings reflect market factors.

In 2021, FAOSTAT reports ~ 40 Mt K_2O applied globally (FAO Statistics, 2021) this is about 45 Mt of elemental K (UNEP, 2024).

In 2022, K_2O use fell to ~ 35 Mt (a 12% drop from 2021). By comparison, N and P use also fell by 4–8% (FAO Statistics, 2022).

Long-term growth averaged a few percent per year; demand grew $\sim 2.4\%/yr$ (2015–2020) (UNEP, 2024). Overall, K use roughly doubled from the 1990s to 2020.

Global trade is concentrated: five countries supply ~80% of potash exports (FAO Statistics, 2022). The majority of K fertilizer is applied in Asia and the Americas, with little domestic production in Africa and the Middle East. High-income regions still use large K inputs per hectare, although economic or policy shifts (e.g. 2022 fertilizer crises) cause volatility. (UNEP, 2024; FAO Statistics, 2022)

2.1.3. Potassium Fertilizer Use in Egypt

Egyptian soils are K-deficient, so farmers use potash to boost yield of cotton, wheat, rice and vegetables. However, Egypt produces no potash domestically, relying entirely on imports. (Abdel Hadi, 2004) Historically, Egyptian K use has lagged behind N and P due to cost and availability: one report shows the fertilizer ratio (N:P₂O₅:K₂O) declined from ~63:12:1 in 1981 to ~36:5:1 by 2002 (Abdel Hadi, 2004), meaning K made up only ~1–2% of the N applied. (By contrast, ideal crop ratios are often 4:2:1 or similar.)

In recent years Egypt's potash imports have been on the order of a few hundred thousand tons. For example, in 2022 Egypt imported ~224,000 tonnes of muriate-of-potash (KCl) and ~36,000 tonnes of sulfate-of-potash (K₂SO₄) (SPglobal, 2023). This roughly 0.26 Mt of potash (nutrient) meets national K demand. If spread over Egypt's 3.2 M ha arable land, the average K₂O application is on the order of 50 kg/ha (plus the area of very high-use crops like sugarcane). In summary, Egypt's fields are heavily fertilized, but K remains the least-applied macronutrient. (Abdel Hadi, 2004, SPglobal, 2023)

2.1.4. Conventional Potassium Fertilizers

Most agricultural K is supplied by mined potash salts. The dominant product is muriate of potash (MOP, KCl) – a cheap, water-soluble salt. Indeed, over 80% of global K fertilizer consumption is met by KCl (AMR, 2025). MOP provides K₂O (~60%) plus chloride. Sulfate of potash (SOP, K₂SO₄) is the next major type (about 15–20% of the market) – more expensive, but with no chloride and with sulfur (SO₄²⁻) beneficial to many crops. Other K fertilizers include potassium nitrate, potassium-magnesium sulfate (langbeinite), and blends (NPK formulations). In practice, most K is applied either as straight KCl or mixed NPK granules containing K₂O (UNEP, 2024).

Conventional K fertilizers have known characteristics:

Muriate of Potash (KCl) – Highly soluble, relatively cheap. Provides ~62% K₂O and a high salt index. Its chloride can be harmful to salt-sensitive crops (fruit trees, tobacco) and can build up in soils with intensive use (AMS, 2023).

Sulfate of Potash (K_2SO_4) – Soluble and chloride-free; provides ~50% K_2O plus sulfur. Preferred for high-value or chloride-sensitive crops (tomato, potato, fruits). More expensive than KCl, so used for specialty crops.

Others – Potassium nitrate (13–46–0 NPK) gives both K and N; potassium-magnesium sulfate ($K_2Mg_2(SO_4)_3$) supplies K and Mg; Langbeinite; blended NPK compounds. These fill niche roles but constitute a small share of total K (the bulk is KCl/SOP. (AMR, 2025)

2.1.5. Alternative Potassium Sources

Interest is growing in alternative and slow-release K sources to improve sustainability and reduce dependence on mined potash. Examples include certain K-rich minerals and organic amendments:

Glauconite (greensand): A natural K-mica (typically ~7–8% K_2O) found in some clays. Glauconite releases K slowly over time. Field trials show only ~25% of its total K_2O is released in the first year (Rudmin et al., 2020a), with continued release in subsequent seasons. Despite its low initial solubility, glauconite can raise soil K over the long term and has water-retention benefits. It has been proposed as an indigenous K source (e.g. in India) to replace some imported potash (Rudmin et al., 2020a)

Feldspar (potassium feldspar minerals): Crushed K-feldspars (e.g. orthoclase or sanidine; ~7% K_2O) can be applied as a slow-release K source. For example, a pasture trial using finely-ground sanidine (7% K_2O) found plants took up only ~10% of its K over 14 months, versus 25–68% from KCl (Sanz Scovino & Rowell, 1988). The authors noted that feldspar is most useful in low-input systems on highly weathered soils, acting as a long-term K reserve. Research is ongoing to “activate” feldspar (e.g. via hydrothermal treatment) to make its K more plant-available. (Sanz Scovino & Rowell, 1988).

Organic amendments (manure, compost, residues): Animal manures, composts, crop residues and even wood ash supply K as part of recycled nutrients. For example, wood ash (a byproduct of biomass burning) typically contains ~5% K_2O (Aytenuw & Bore 2020), along with Ca and P, and can raise soil pH. Similarly, composted plant residues and nut shells often have 2–5% K (as K^+) and can gradually release it as they decompose (Aytenuw & Bore 2020). However, organic sources generally have much lower K concentration and slower release than mineral fertilizers (Golden et al., 2023). They are best viewed as supplements that improve soil organic matter and provide modest K inputs (rather than as sole K fertilizers) (Golden et al., 2023).

Other recycled K: Industrial by-products such as spent biomass ash, acid whey (from cheese making), and brewery residues contain K and have been tested as fertilizers. Phosphate-rich

biochar and seaweed also contribute K when applied. These methods also recycle nutrients back into agroecosystems.

Each alternative source tends to release K more gradually than conventional salts. They can improve soil structure and provide secondary nutrients, but they rarely match the immediate availability or K content of synthetic KCl/SOP (Sanz Scovino & Rowell, 1988; Aytenuw & Bore, 2020). In many trials, yield responses to these materials are slower and smaller unless soils are very K-deficient or the materials are processed (e.g. calcined or composted) to enhance K release. Nevertheless, their use can reduce the need for imported potash and add resilience to fertilizer supply.

2.1.6. Environmental Impacts of Potassium Fertilizer Use

Potassium fertilizers pose fewer acute environmental risks than nitrogen or phosphorus, but several issues are noted:

Soil and water salinization: The biggest concern is salinity. Potassium chloride adds a large chloride load to soil. Over-application can raise soil salt levels, harming plant roots and soil microbiota. In irrigation, excess Cl^- from KCl can accumulate in groundwater or surface water, reducing water quality. A USDA technical report warns that KCl use “can contribute to soil salinity,” leading to toxic effects on a range of organisms. (By contrast, SOP does not add Cl^- , so it carries no salinity risk from chloride.) (AMS, 2023)

Leaching and runoff: Potassium ions (K^+) are generally less mobile in soil than nitrate or phosphate because they bind to clay and organic colloids. In typical soils, K^+ leaches slowly. However, in coarse sandy soils with low cation exchange capacity, or in very acidic soils with many competing cations (H^+ , Ca^{2+}), excess K^+ can become mobile (Briana et al. 2019). In such cases, K can be carried downwards with irrigation or rainfall. Nevertheless, K losses are usually far smaller than N losses; K is unlikely to cause eutrophication. (In fact, UNEP notes that unlike N or P, excess K losses have not been linked to specific ecological problems (UNEP, 2024); main “loss” of K is simply reduced fertilizer efficiency.)

Soil nutrient imbalance: Heavy K fertilization can in some cases imbalanced soil cations, reducing uptake of calcium or magnesium if not managed. Very high K levels may also alter soil pH and CEC over time. Moderately high KCl rates can lead to chloride accumulation, which inhibits certain crop species.

Mining and production footprint: Conventional potash production is energy and water intensive. Potash is mined by deep underground or solution methods, with large open pits or evaporation

ponds. Mining can disrupt landscapes and consume vast amounts of water (a concern in dry regions) (UNEP, 2001). For example, environmental reviews note that phosphate/potash extraction can lead to water contamination (e.g. brine spills), air pollution (dust, gases), and long-lived tailings (UNEP, 2001). Studies of mining impact have shown significant alterations of riverine ecosystems near potash mines. In sum, large-scale potash extraction poses sustainability challenges: it relies on finite deposits, often in ecologically sensitive areas, and involves substantial greenhouse gas emissions (from both mining and the Haber-Bosch process for byproducts like KNO_3).

Heavy metal contaminants: Natural potash ores often contain trace metals (arsenic, cadmium, lead, mercury, etc.). These are usually low, but multiple years of potash application can gradually add heavy metals to soil. For instance, a New York State report found food-grade “potash” salts contaminated with high levels of Pb and As (NY report, 2023). (While such salts were sold as seasoning, the same issue can apply to agricultural potash.) Thus, long-term KCl use may introduce toxic impurities.

Carbon footprint: Producing KCl and SOP requires significant fossil energy (mining, processing). However, the carbon intensity per kg of K_2O is generally lower than that of nitrogen fertilizers. Still, reducing reliance on chemical K (by using organics or recycling) can improve sustainability.

Given these issues, there is a push for more efficient K management: matching K applications to crop needs, using controlled-release products, and recycling biomass K. Integrated nutrient management (using both inorganic and organic K sources) can lessen the environmental burden. In particular, reliance on chloride-bearing K should be minimized on sensitive lands; alternatives like SOP or slow release sources help avoid salinity problems (AMS, 2023; Sanz Scovino & Rowell 1988)

Due to the increasing demand for potassium and the limitations of conventional fertilizers, attention has turned to alternative sources. Glaucinite, a natural potassium-rich mineral, offers promise as a sustainable, slow-release fertilizer. The following section explores glaucinite in detail, highlighting its properties, agronomic potential, and role in improving potassium use in agroecosystems.

2.2. Glaucinite: general properties (Structure, Nutrient Content, and Role in Sustainable Fertilization)

The rising global population, projected to reach 9 billion by 2050 (Pretty et al., 2010), is intensifying the demand for agricultural production and thereby increasing the need for essential

soil nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K). Among these, potassium is especially vital for plant metabolism, root development, and crop yield (Oosterhuis et al., 2014; Zörb et al., 2014). However, many countries rely heavily on imports of soluble potassium fertilizers, such as sylvite (KCl) and complex potassium–magnesium salts, due to a lack of domestic sources (Jena et al., 2014; Santos et al., 2015, 2017).

In this context, potassium-bearing alumino-silicate minerals commonly referred to as agro-minerals have garnered global interest as alternative sources of potassium (Van Straaten, 2002; Ciceri et al., 2017). Minerals such as glauconite have been investigated for their potential use as slow-release potassium fertilizers (Santos et al., 2015, 2017; Skorina & Allanore, 2015; Manning, 2010; Kuanysheva et al., 2014; Karimi et al., 2012; Rudmin et al., 2017; El-Habaak et al., 2016).

The direct agricultural application of such agro-minerals, particularly glauconite, has been proposed as an environmentally friendly solution to reduce reliance on imported fertilizers while also improving soil texture and water-holding capacity (Van Straaten, 2006, 2014). As a result, increased attention has been directed toward the exploitation of indigenous potassium-bearing deposits such as glauconitic sandstone (Rakesh et al., 2020a).

Glauconite is a hydrous iron potassium phyllosilicate mineral with the general chemical formula: $[(K, Na, Ca)(Fe^{3+}, Al, Mg, Fe^{2+})_2(Si, Al)_4O_{10}(OH)_2]$, typically containing 4–8% K₂O. It commonly occurs in loosely cemented sandstones, referred to as greensands. Structurally, glauconite belongs to the 2:1 phyllosilicate group, composed of one octahedral sheet sandwiched between two tetrahedral sheets (T–O–T structure), with octahedral positions generally dominated by Fe³⁺, followed by Al³⁺, Mg²⁺, and Fe²⁺ (Van Straaten, 2002; Huggett, 2013; Hassan & Baioumy, 2006).

Glauconite is classified as a dioctahedral micaceous phyllosilicate and is characterized by high interlayer potassium concentrations, often exceeding 6% in some deposits (Guggenheim et al., 2006; Odin & Matter, 2003; Meunier & El Albani, 2007). In addition to potassium, glauconite contains several essential macro- and micronutrients, including phosphorus, calcium, iron, manganese, copper, cobalt, and nickel (Rudmin et al., 2019a; 2020a; Franzosi et al., 2014; Oze et al., 2019). These nutrients are vital for plant growth and development, osmotic regulation, and overall metabolic functioning, thereby enhancing the agricultural value of glauconite (Shin et al., 2005).

Morphologically, glauconite typically forms as rounded, sand-sized pellets or aggregates embedded in sedimentary rocks or as unconsolidated grains with scaly textures. Despite its granular appearance, glauconite does not behave like quartz sand. Instead, its microporous

structure offers significantly higher water-holding capacity and cation exchange capacity (Heckman and Tedrow, 2004).

Internationally, glauconite has been employed as a soil conditioner and potassium source, particularly in Russia, for both agricultural and land reclamation purposes (Levchenko et al., 2008). In Egypt, glauconite deposits—particularly those in the El-Gedida region—have been studied across multiple scientific disciplines, including petrology, mineralogy, geochemistry, and agricultural science (Baioumy et al., 2012; Hassan & Baioumy, 2006; Eid, 2013; El-Habaak et al., 2016; Morsy et al., 2016).

2.3. Geological Setting and Occurrence of Glauconite Deposits in Egypt

In Egypt, glauconite deposits are predominantly located in the Western Desert, which covers over 65% of the country and extends from the Nile Valley to the Libyan border. This vast plateau desert includes several major oases such as Bahariya, Farafra, Dakhla, Kharga, and Beris, and it formed during the Lower Triassic and Lower Jurassic ages (Dercourt et al. 1993).

The two primary regions hosting glauconite deposits are the Bahariya Oasis and the Abu-Tartur Plateau. Within these regions, glauconite commonly occurs in association with iron ores and phosphorites, particularly in shallow-marine sedimentary formations from the Upper Cretaceous to the Late Eocene (Hassan & Baioumy, 2007).

Bahariya Oasis Deposits

The Bahariya Oasis, an oval depression spanning approximately 1,800 km², is located in the central Western Desert (27°48'–28°30'65" N, 28°35'–29°10'66" E), about 270 km southwest of Cairo and 180 km west of the Nile Valley (Said, 1971). This region is of particular geological significance due to its large iron ore reserves, estimated at 270 million metric tons (Said, 1990), which are mined extensively in areas like the El-Gedida mine. The glauconite deposits here often occur as overburden to iron ores and are exposed during mining activities (Hassan & Baioumy, 2007).

In the Hara area, the Bahariya Formation (Lower Cenomanian) is exposed and begins with grey to yellowish-grey clayey sediments, overlain by multiple glauconite-rich layers. These glauconitic beds, intercalated with ironstone layers and nodules, vary in thickness from a few centimeters up to 1 meter, and range in color from greyish green to pale green. The total thickness of glauconite-bearing units reaches approximately 4 meters, overlain by ~3 meters of laminated, yellowish-white claystone (Baioumy & Boulis, 2012).

Abu-Tartur Plateau Deposits

In the Abu-Tartur region, glauconite is found within the Upper Cretaceous Duwi Formation, primarily in association with phosphorite, black shale, and glauconitic sandstone. These rocks were deposited in a shallow-marine environment and are lithologically composed of phosphate beds intercalated with glauconite-bearing sandstones, siltstones, and black-grey claystones (Sediek & Amer, 2001).

The Abu-Tartur Plateau has been the focus of extensive geological investigations due to its massive phosphate reserves. Notable studies by Hermina and Wassef (1975), Garrison et al. (1979), and Uosif and El-Taher (2008) have provided detailed insights into the stratigraphy and economic potential of the region. Although phosphate mining is the primary activity, glauconite is also present in significant quantities and merits attention for its potential use as a natural fertilizer.

However, while the agronomic potential of glauconite is well recognized, relatively few studies have investigated its environmental safety. Specifically, the content and mobility of potentially toxic elements (PTEs) in glauconite deposits remain underexplored, raising important questions about their long-term impact on soil health and food safety when applied to agricultural field.

2.4. The elemental composition of glauconite deposits (the methods of investigation)

2.4.1. BCR sequential extraction

Research has established that total concentrations alone cannot adequately indicate the bioavailability of Potentially Toxic Elements (PTEs), necessitating the use of speciation as a valuable tool for obtaining this information (Geography and Labor, 2008; Sungur et al., 2014). Additionally, total metal content fails to provide comprehensive insights into the hazards posed by metals, as their accessibility to plants varies depending on their occurrence forms (Geography and Labor, 2008). (Okoro et al. 2017) emphasize the inadequacy of total PTE concentration in accurately representing their characteristics and toxicity. They suggest that analyzing individual soil fractions to which metals are attached can provide a better understanding of their actual and potential environmental effects. (Qasim and Motelica Heino 2014) assert that additional data on the concentrations of specific physicochemical forms of PTEs are necessary, as their behavior in the environmental system is contingent upon chemical speciation.

Traditional methods such as fractional leaching are applied to investigate the migration of PTEs in soil, involving soil processing with various reagents to determine mobile forms such as water-soluble, exchangeable, acid-soluble, and firmly fixed (Kuterbekov, 2019). Sequential extraction, proposed by Tessier et al. (1979) and widely adopted, is highlighted by Gleyzes et al. (2002) as

one of the most utilized procedures for this purpose. Sequential extraction studies have proven effective in assessing metals associated with the main accumulative phases in sedimentary deposits (Filgueiras et al., 2002).

due to the complex nature of solid environmental samples. As a compromise, fractionation of heavy metal content based on environmental mobility and estimation of biological availability through sequential extraction procedures have become primary tools for risk assessment of heavy metal contamination in soil, water, and the atmosphere. This approach involves sequentially applying solvents containing increasingly aggressive reagents to estimate element mobility based on different binding classes, as recommended by the IUPAC in 2000 (Templeton et al., 2000).

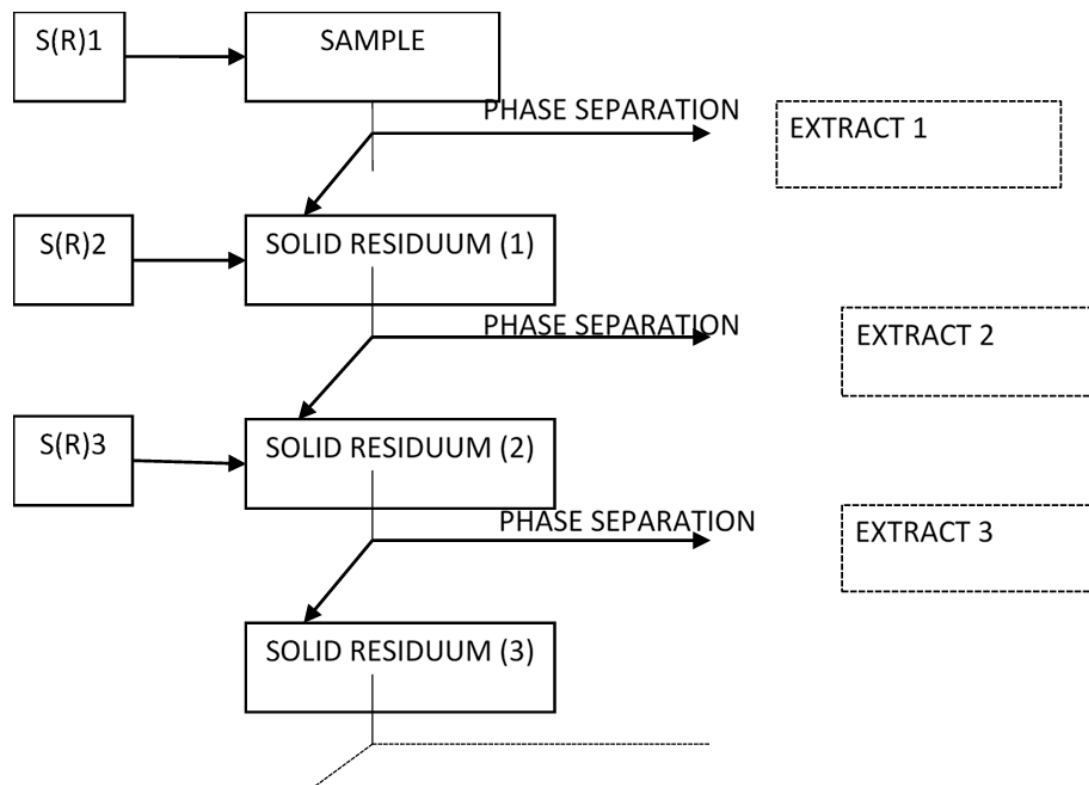


Figure 1. The strategy of sequential extractions

The mobility of an element, determined by the solubility of various binding classes, can be estimated through the sequential application of solvents containing increasingly aggressive reagents (Caroli, 1996; Kersten and Förstner, 1995). The strategy of sequential extractions can be illustrated through the following scheme (Figure 1), where the expression of SOLVENT(REAGENT) is abbreviated as S(R).

The first sequential extraction procedure for characterizing the mobility of heavy metals in aquatic sediments was developed by Tessier et al. (1979). They classified the metal content of sediments

based on the solubility and binding forms of metallic species, as depicted in the scheme (Figure 2, part "a"). Building upon this foundational work, several 5-8-step sequential extraction schemes were subsequently developed, gradually dissolving and/or decomposing the original chemical structures (binding forms) (Gleyzes et al., 2002). These procedures typically require 5-6 days to complete, with the duration of batch leaching steps determined by the time needed for partition and other heterogeneous equilibria to establish.

In 1993, the EU Community Bureau of Reference (BCR) proposed a simplified 3(+1)-step sequential extraction procedure (Ure et al., 1993), depicted in (Figure 2, part b) of the scheme. Despite its simplification, this method remains time-consuming and labor-intensive. In this procedure, the water-soluble, weakly adsorbed, and carbonate-associated metal fractions are simultaneously extracted in the first leaching step using acetic acid. The second step involves determining the metal fractions associated with reducible Fe and Mn oxides after reduction by hydroxylamine, while the fraction of metals complexed with organics and associated with sulphides is extracted after oxidation by H_2O_2 . In the additional (+1) step, the residual fraction can be obtained through digestion with aqua regia or HNO_3/H_2O_2 .

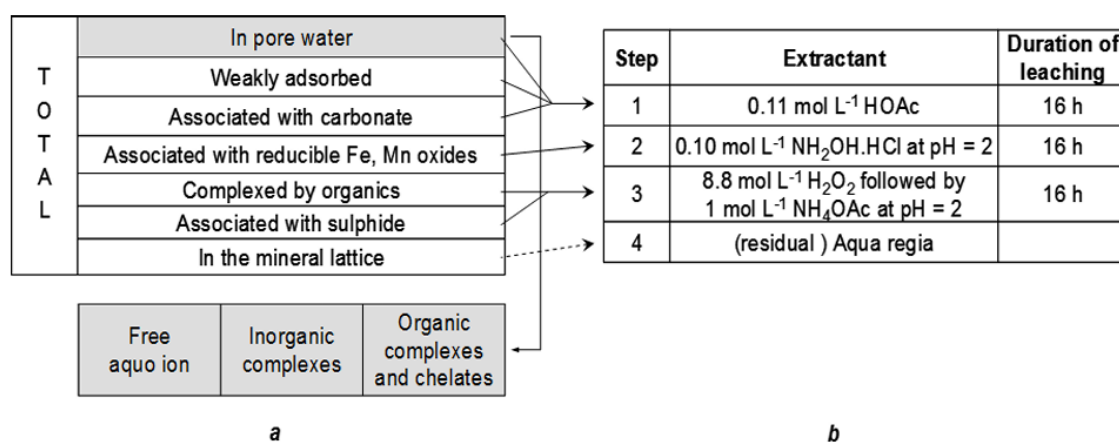


Figure 2. The Developed sequential extraction scheme

The re-adsorption of extracted metals during phase separation poses a risk of analyte losses, while high reagent concentrations in extracts can lead to strong matrix effects during spectrochemical element detection (López-Sánchez et al., 1998; Quevauviller et al., 1997). To address these concerns, the development of sequential extraction techniques has been pivotal. Tessier et al. (1979) introduced the first sequential extraction procedure, classifying sediment metal content based on solubility and binding forms, which laid the foundation for subsequent schemes (Gleyzes et al., 2002). Despite its effectiveness, sequential extraction can be time-consuming, with batch

leaching steps taking several days due to the time needed for equilibria to establish (Rauret et al., 1999).

The BCR (BCR) proposed a simplified 3(+1)-step sequential extraction procedure to address analyte losses during the second leaching step (Ure et al., 1993; Rauret et al., 1999). This technique, though labor-intensive, has been widely adopted and successfully applied in soil and sediment analysis (Sutherland, 2010; Rosado et al., 2016). However, concerns remain regarding the lack of specificity in element removal, re-adsorption issues, and variability between studies (Rauret et al., 1999). Despite these challenges, sequential extraction methods provide valuable information on metal fractionation, mobility, and bioavailability (Filgueiras et al., 2004; Pueyo et al., 2008). Tlustos et al. (2005) emphasize the importance of these techniques in understanding soil pollution and the long-term effects of soil amendments, despite their time-consuming nature. Moreover, the BCR technique fulfills criteria for widespread implementation due to its ease of use and cost-effectiveness (Rosado et al., 2016).

However, there is a need for certification of other environmental matrices beyond freshwater sediments (Heltai et al., 2019). Despite its time-consuming nature, sequential extraction offers comprehensive information on trace metal origin, occurrence, and availability (Filgueiras et al., 2002). Understanding the bioavailability and ecotoxicological impacts of PTEs requires consideration of chemical speciation (Violante et al., 2010). Methodological issues persist, but the BCR sequential extraction remains a traditional technique for evaluating PTE pollution risks (Heltai et al., 2018). Ultimately, sequential extraction procedures are critical for assessing environmental risks and understanding the mobility and bioavailability of PTEs in soils and sediments (Rauret et al., 1999; Ogundiran and Osibanjo, 2009). They offer essential knowledge for environmental management and are applicable across a broad range of terrestrial and aquatic fields (Sungur et al., 2014; Rosado et al., 2016).

The study of sequential extraction techniques on glauconite deposits is relatively scarce in the literature, yet it offers invaluable insights into the geochemistry of groundwater systems. Glauconite, a mineral commonly found in aquifer sediments, can significantly influence the distribution and behavior of rare earth elements (REEs) due to its unique properties. Sequential extraction techniques provide a systematic approach to understanding the distribution, speciation, and mobility of various elements within geological materials. This is particularly relevant to the study of glauconite-rich aquifer sediments, as demonstrated by the investigation of the Aquia aquifer in Maryland, USA conducted by Willis and Johannesson in (2011). By sequentially extracting different fractions of elements from solid phases, researchers can unravel complex geochemical processes, such as sorption, precipitation, and dissolution, which govern the behavior

of elements in natural environments. Therefore, the application of sequential extraction techniques offers crucial insights into the geochemistry of REEs within groundwater systems, enhancing our understanding of the role of glauconite in influencing REE distribution patterns and environmental processes.

In the Aquia aquifer study, sequential extraction procedures were instrumental in elucidating the association of REEs with different mineral phases, including glauconite pellets. Analysis revealed an overall enrichment of heavy REEs (HREEs) relative to light REEs (LREEs) in glauconite compared to shale, highlighting the importance of this mineral in influencing REE distribution patterns.

By applying sequential extraction techniques, researchers identified glauconite as a key reservoir for HREEs within the aquifer sediments. This finding suggests that the dissolution of glauconite contributes to the enrichment of HREEs in groundwater, particularly in regions where glauconite-rich sediments are prevalent.

Furthermore, the sequential extraction data indicated that REEs associated with glauconite exhibit distinct behavior compared to those associated with other mineral phases. Glauconite may preferentially sorb certain rare earth element (REE) species, leading to differential mobility and distribution within the aquifer system.

Overall, the application of sequential extraction techniques provides crucial insights into the geochemical processes governing REE mobility and availability in glauconite-rich aquifer sediments. Understanding the role of glauconite in REE cycling enhances our ability to assess groundwater quality and environmental impacts, ultimately informing resource management and conservation efforts.

2.4.2 Single Extractions: AL and KCl extractants

Assessing the mobile fractions of potentially toxic elements (PTEs) in soils is essential for evaluating their environmental risks, including their bioavailability to plants, potential leaching into groundwater, and broader ecological impacts. With the increasing number of contaminated sites worldwide, understanding the behavior of these elements in the soil environment has become a critical component of environmental risk assessment (Rao et al., 2008). In this context, both single and sequential extraction methods have proven to be valuable analytical tools. These techniques provide insights into the distribution and mobility of elements within various soil matrices. Single extraction methods, while less selective, offer a quick and practical approach for estimating the readily available fraction of elements. However, they are limited by their tendency to extract elements from multiple binding phases and may not fully capture the target fraction (Rao

et al., 2008; Jakubus, 2020). To address these limitations, Rao et al. (2008) proposed a classification of ideal single extractants based on their ability to mobilize elements from specific soil phases, thereby supporting the study of metal binding mechanisms, transformation pathways, and release behavior in soils.

Glaucinite is an iron-potassium phyllosilicate mineral commonly found in marine sedimentary rocks. It has garnered interest as a natural potassium (K) source for use in agriculture, particularly as a slow-release fertilizer (Rudmin et al., 2020a). However, the potassium in glauconite is partly locked within its crystal structure, rendering it less bioavailable unless treated with suitable extractants or activation methods (Shekhar et al., 2017a). Among the mild extractants evaluated for glauconitic potassium release, ammonium lactate (AL) and potassium chloride (KCl) are frequently used due to their relevance in soil testing protocols and their environmentally friendly nature (Eldawwy et al, 2024).

2.4.2.1. Ammonium Lactate (AL) as a single Extractant

Ammonium lactate (AL) is a widely used chemical extractant in soil science, primarily applied to evaluate the concentration of plant-available potassium. It consists of a mixture of lactic acid, acetic acid, and ammonium hydroxide, carefully adjusted to a pH of 3.75. Used in the Egner–Riehm–Domingo method, AL has been validated by Zebec et al. (2017) as a reliable and effective extractant for determining available potassium across various soil types. With a soil-to-solution ratio of 1:20 and mild acidity, AL facilitates the displacement of exchangeable potassium through ammonium ions (NH_4^+), accurately representing the potassium fraction accessible to plants. Its effectiveness on both calcareous and acidic soils has made AL the standard method in Croatia and several other European countries. In comparison with other extractants such as ammonium acetate (KAA), ammonium acetate with EDTA (KAAEDTA), Bray, and barium chloride (BaCl_2) AL showed strong statistical correlations, particularly with KAAEDTA ($r = 0.973$), reinforcing its credibility. While BaCl_2 extracted slightly higher potassium levels (on average 12.9% more), AL remains preferred due to its consistent performance and relevance to plant uptake. The findings emphasize AL's practical value for soil fertility evaluation and for making accurate, site-specific fertilizer recommendations in intensive agricultural systems.

The mechanism of extraction using ammonium lactate (AL) is based on the displacement of exchangeable potassium (K^+) ions from the surfaces of soil particles by ammonium ions (NH_4^+), under mildly acidic conditions (pH 3.75). This places AL in the third category of extractants, which utilize similar cations to replace potassium from the exchange complex (Zebec et al., 2017). The solution, composed of lactic acid, acetic acid, and ammonium hydroxide, facilitates potassium

desorption by weakening the electrostatic bonds between potassium and soil colloids. The presence of weak acids helps in mobilizing potassium without significantly extracting non-available mineral-bound forms. According to Lončarić (2009), AL is particularly effective on both calcareous and acidic soils and is widely used in countries such as Croatia and Sweden for nutrient diagnostics and fertilizer recommendations. The method targets the plant-available fraction of potassium, which closely correlates with crop uptake and growth responses. Römer et al. (1999) emphasized the importance of choosing an appropriate extractant, as different methods even if producing similar potassium values can lead to significantly different fertilizer recommendations. Therefore, the mechanism of AL extraction ensures high agronomic relevance and accuracy in estimating potassium availability in diverse soil types.

The efficiency of potassium extraction from soils is critical for accurately assessing nutrient availability. Recently, Eldawwy et al. (2024) conducted a comparative study using Egyptian glauconite samples and demonstrated that the ammonium acetate–lactate (AL) extraction method recovered 2–3 times more potassium than the commonly used KCl method under identical conditions. This enhanced extraction efficiency was attributed to the mild dissolution of the glauconite lattice facilitated by the lactate’s complexing action, in addition to ammonium ion (NH_4^+) exchange. These findings suggest that the AL method can access a broader potassium pool beyond the readily exchangeable fraction, highlighting its potential as a more effective tool for soil potassium analysis.

In another study, the ammonium acetate–lactate (AL) extraction method proved to be an efficient and reliable approach for estimating the availability of potassium (K) and phosphorus (P) in pseudogley soils. According to Teklić et al. (2009), AL-extractable K_2O and P_2O_5 values showed strong correlations with electro ultrafiltration (EUF) fractions and key soil properties such as pH and selective mineral clay content. The predicted AL values deviated by only 4% for potassium and 9% for phosphorus from the actual extracted amounts, demonstrating the method’s accuracy. These results highlight the AL method's suitability for assessing bioavailable nutrients in complex soil matrices.

2.4.2.2. Potassium Chloride (KCl) as a single Extractant

Potassium chloride (KCl) is a widely used extractant in soil science, particularly in the form of 1 M KCl solution (Kachurina et al., 2000). Bortolon et al. (2011) evaluated the effectiveness of a 1.0 mol L^{-1} KCl solution for soil testing and found it to be a reliable extractant for exchangeable calcium (Ca) and magnesium (Mg). The results obtained using KCl showed high correlation with those from the Mehlich-1 and Mehlich-3 extractants, with coefficients of determination (R^2) of

0.96 and 0.94, respectively. These findings are consistent with earlier research (Sims, 1989; Gartley et al., 2002), confirming the suitability of KCl for assessing Ca and Mg availability in soils.

Despite its effectiveness, KCl poses operational challenges in laboratory settings, particularly due to salt deposition on the atomizer of atomic absorption spectrophotometers, leading to increased maintenance. While the resin method extracted significantly lower amounts of Ca and Mg (70% and 52% less, respectively), KCl demonstrated higher extraction efficiency, making it a preferred option for routine soil testing. Therefore, despite some technical drawbacks, KCl remains a dependable extractant for evaluating exchangeable cations in agricultural soils.

Regarding potassium (K) extraction, the study primarily focused on Mehlich-1, Mehlich-3, and resin methods. Mehlich-3 was the most efficient, extracting 25% more K than Mehlich-1, while the resin method extracted 50% less. Although 1.0 mol L⁻¹ KCl was assessed for its performance with Ca and Mg, its specific efficiency in extracting K was not addressed in detail. Generally, KCl is known to effectively extract exchangeable potassium by replacing adsorbed K⁺ ions with Cl⁻, but the study did not provide comparative data against Mehlich methods. The findings underscore the importance of using effective extractants like Mehlich-3 for potassium evaluation, particularly in Southern Brazilian soils, where accurate nutrient assessment is essential for crop productivity.

In this study, two single extractants were employed. The first was 1 M KCl, with 20.00 g of each sample extracted in 50 mL of solution. The second was an acid lactate (AL) solution, diluted 1:10 with distilled water, following the method by Egner et al. (1960). For the AL extraction, a glauconite-to-extractant ratio of 1:20 was used. All samples were agitated on a shaking system for 2 hours before filtration.

2.5 Potentially toxic elements in glauconite deposits

Glauconite has been widely utilized internationally as a chemical fertilizer and soil conditioner, particularly for agricultural and land reclamation purposes in countries such as Russia (Levchenko et al., 2008). In Egypt, comprehensive research has examined glauconite sediments across a range of scientific disciplines, including petrology, mineralogy, chemistry, agriculture, and geochemistry (Baioumy et al., 2012; Hassan & Baioumy, 2006; Eid, 2013; El-Habaak et al., 2016; Morsy et al., 2016).

El-Habaak et al. (2016) investigated the presence of potentially toxic elements (PTEs) in glauconite deposits from the El-Gedida mine in Egypt to evaluate their suitability as alternative

potassium fertilizers. Utilizing inductively coupled plasma optical emission spectrometry (ICP-OES), they measured concentrations of key PTEs including molybdenum (Mo), copper (Cu), lead (Pb), zinc (Zn), nickel (Ni), arsenic (As), cadmium (Cd), cobalt (Co), and chromium (Cr). The study found that all PTE concentrations were below the maximum allowable limits established by the Canadian Food Inspection Agency (CFIA, 1997), indicating a low risk of contamination to soil and food. For example, cadmium levels were below 0.1 ppm in both eastern and western Wadi samples, significantly lower than the CFIA limit of 3 ppm. Similarly, zinc concentrations remained well under the 700 ppm threshold. These findings support the environmental safety of using glauconite from El-Gedida as a fertilizer.

Kalinina et al. (2023) conducted a similar study assessing PTE concentrations in glauconite sourced from mining waste at the Egorievsk phosphorite deposit. Using inductively coupled plasma mass spectrometry (ICP-MS), the researchers analyzed both bulk and concentrated glauconite samples for elements such as chromium (Cr), nickel (Ni), zinc (Zn), arsenic (As), and cadmium (Cd). Despite glauconite's strong sorption capacity for PTEs, the results revealed that all measured concentrations were well below international regulatory limits, including standards from Russia, Europe, and the United States. For instance, cadmium was detected at only 0.2 mg/kg in the concentrate, compared to the Russian threshold of 20 mg/kg. The study also noted that apatite micro inclusions in glauconite contributed to immobilizing PTEs by reducing their solubility and bioavailability in acidic soils. This reinforces the conclusion that glauconite from the Egorievsk deposit is environmentally safe and suitable for use as a slow-release fertilizer.

Although recent studies have explored the agricultural applications of glauconite, relatively few have examined its content of toxic elements and the potential environmental consequences associated with its use in farming. Evaluating the mobile fractions of toxic elements in soils is crucial for understanding their risks to the biosphere, groundwater quality, and plant availability. The growing prevalence of environmental contamination highlights the need for comprehensive assessments of such impacts (Rao et al., 2008).

To this end, single and sequential extraction methods have become valuable analytical tools in environmental science, particularly for investigating the behavior and fate of pollutants. Single extraction techniques, though less specific, provide a rapid assessment of elemental availability. However, they are limited by their tendency to extract multiple soil phases or incompletely release elements from target sites (Rao et al., 2008; Jakubus, 2020). Rao et al. (2008) categorized ideal single extractants based on their ability to target specific soil phases, contributing to a better understanding of soil chemistry and the mechanisms of metal binding, transformation, and release.

When assessing heavy metal contamination in environmental samples, two key factors must be considered: the chemical speciation of the metal, which affects its biological impact, and its solubility or availability. These aspects are closely interconnected in environmental media such as soil, water, or sediment (Templeton, 2000). Measuring “pseudo-total” concentrations—using strong acid or aqua regia digestion—helps determine the maximum potential hazard posed by metals not bound in silicates. This approach is useful for evaluating the long-term implications of incorporating materials like glauconite into soils (Rao et al., 2008; Ure & Davidson, 2002). While regulatory frameworks typically focus on total PTE content, these values do not necessarily reflect the actual environmental threat. The solubility and plant availability of metals, which are determined by their chemical fractions, are critical to understanding their mobility and ecological impact (Jakubus, 2020).

A variety of techniques exist for determining metal fractionation and evaluating their availability in solid matrices. One widely adopted method is the Community Bureau of Reference (BCR) sequential extraction procedure, known for its simplicity and ability to provide comprehensive data on metal mobility. The BCR scheme divides metals into four fractions: exchangeable, bound to iron and manganese oxyhydroxides, bound to organic matter and sulfides, and residual (Jakubus, 2020; Horvath et al., 2010; 2013; Heltai et al., 2015; 2018; 2019). Sequential extraction techniques offer detailed insights into the speciation of elements in soils, enabling more accurate predictions of their mobility, bioavailability, and environmental behavior. These methods offer a refined estimate of true environmental risks (Umoren et al., 2007; Yang et al., 2009; Saleem et al., 2018). However, to date, no study has applied the BCR sequential extraction method to glauconite sediments.

2.6. Acid treatment for glauconite

Several studies have explored the effectiveness of various acid treatments in enhancing potassium release from glauconite. Table 1 summarizes previous studies on extracting potassium from glauconite by different acid treatments. For example, Shekhar et al (2017a). used hydrochloric acid (HCl) to extract potassium from a concentrated glauconite sample, which resulted in a poor yield, with less than 12% of the potassium being recovered. Contrary to our results, HNO₃ was more effective, showing a trend similar to HCl. Praveen and Tomar (2019) investigated organic acids and found that the solubilizing efficiency followed the order: oxalic acid > malic acid > citric acid > acetic acid. Their findings also indicated a poor release of potassium using acetic acid, which aligns with our observations. This may generally reveal the poor extraction capacity of acetic acid compared to inorganic acids like HCl, HNO₃, and H₃PO₄, although variations can occur depending on factors such as temperature and the addition of coke, as demonstrated by Shekhar et al. (2017b).

Pessoa et al. (2015) demonstrated that organic matrices like coffee husk, humic acid, and citric acid influenced potassium solubilization, with coffee husk showing the highest efficiency. Mineral acids were also tested for their effectiveness; Yadav and Sharma (1992) reported that 6 M HCl achieved up to 96% potassium recovery under specific conditions, while other acids such as H₂SO₄, H₃PO₄, and HNO₃ yielded lower efficiencies. Furthermore, Schimicoscki et al. (2020) and Rao et al. (1993) showed that higher concentrations of H₂SO₄, especially when combined with fluoride salts, significantly improved potassium extraction, achieving recoveries exceeding 90% for fine glauconite particles. These findings underline the importance of both acid type and treatment conditions in optimizing potassium recovery from glauconite sources.

Table 1. Some acid treatments of Glaucosite are reported in the literature

Acid treatment	Concentration of acid	Effect on Glaucosite	Reference
oxalic acid acetic acid citric acid malic acid	15 mg/kg 40 mg/kg 60 mg/kg 30 mg/kg	the solubilizing order of different acids on the release of potassium from glaucosite nanoparticles is oxalic acid> malic acid> citric acid> acetic acid.	Praveen & Tomar, (2019).
humic acid citric acid coffee husk	Coffee husk was mixed with the two low-grade K rocks in the following doses: 0, 5, 10, 20, and 40% (w/w). Citric and humic acid were mixed with the modified glaucosite and syenite samples in the following doses: 0, 1, 2, 5, and 10% (w/w).	The organic matrices have different abilities to weather the incubated potassic rocks, with the decreasing order of solubilization capacity: coffee husk> humic acid> citric acid.	Pessoa et al., (2015).
HCl HNO ₃ H ₂ SO ₄ H ₃ PO ₄	(1 to 6) M 2M 2M (1 to 6) M	Results show the possibility of recovering 96 percent potassium by treatment of the glauconitic sandstone with 6 M HCl at 378 K (105°C) for 3 hours. a stirring speed of 450 rpm and leaching with other acids	Yadav & Sharma, (1992).

		(H ₂ SO ₄ , H ₃ PO ₄ , and HNO ₃) did not give appreciable results.	
HCl	30%(v/v)	Chemical leaching of enriched fraction with (HCl) yields very low recovery (<12%) of potassium, a combined reduction roasting-leaching method was developed to recover potassium chloride suitable for fertilizer application.	Shekhar et al., (2017a)
H ₂ SO ₄	(0.05, 0.1, 0.5, 1, 5) (mol L ⁻¹)	(0.27,0.38,0.33,0.49,0.44) of potassium recovery respectively to the concentrations of H ₂ SO ₄ . The reaction rate of K extraction was shown to be high, and K recovery was directly proportional to the acid concentration.	Schimicoscki et al., (2020)
H ₂ SO ₄	9 M	conducted tests on glauconitic sandstone with sulphuric acid (9 M) in the presence of fluoride salts NaF, NaH, HF, and LiF to obtain dissolution of potassium (>90%) for particle size below 75 mm.	Rao et al., (1993)

2.7 Glauconite in soil and plant systems

Glauconite is an iron potassium phyllosilicate mineral valued for its potential as a slow-release potassium (K) fertilizer. Naturally occurring in marine sedimentary deposits, glauconite contains essential plant nutrients such as potassium, magnesium (Mg), calcium (Ca), sodium (Na), and trace

elements like zinc (Zn), making it a multifaceted amendment in soil–plant systems (Ramesh et al., 2020). Its low solubility in water facilitates gradual nutrient release, aligning with plant uptake rates and reducing the risk of leaching -particularly in light-textured or degraded soils. Because of its mineralogical composition, glauconite also contributes to improving soil physical and chemical properties, including pH buffering, increased cation exchange capacity (CEC), and enhanced soil structure (Bakr et al., 2021).

Recent interest in glauconite's agronomic value has led to numerous pot experiments to investigate its efficiency under controlled conditions. Pot studies allow for close monitoring of nutrient dynamics and plant responses, enabling researchers to optimize application rates and compare its performance with conventional fertilizers. For instance, the application of glauconite nanoparticles (GNPs) in maize cultivation significantly improved potassium uptake, plant height, leaf area, and nitrate reductase activity compared to untreated and MOP-treated plants (Ramesh et al., 2020). These findings underscore glauconite's role not only as a K source but also as a soil amendment with the potential to support sustainable crop production.

2.7.1 Role in integrated nutrient management

Glauconite fits well within integrated nutrient management (INM) frameworks, which aim to combine organic, inorganic, and biological inputs for efficient and balanced plant nutrition. Its inclusion in such systems has several advantages. First, glauconite's slow-release behaviour complements the faster nutrient release of synthetic fertilizers. For example, when mixed with urea or MAP (monoammonium phosphate), glauconite can help regulate nutrient availability throughout the crop growth cycle. This synchronization reduces losses due to volatilization or leaching and enhances overall nutrient use efficiency. (Bakr et al. 2021) noted that the co-application of glauconite with compost not only enhanced available soil K but also stimulated microbial biomass and enzymatic activities, further aiding nutrient cycling.

The application of glauconite to soils has been shown to significantly improve cation exchange capacity (CEC), which enhances nutrient retention and helps protect plant roots from chemical stress. Unlike typical sand particles that exhibit minimal chemical reactivity, sand-sized glauconite particles possess a notably high CEC reaching up to 39 meq/100 g, thus playing a valuable role in soil chemistry and nutrient dynamics (Heckman and Tedrow, 2004). Beyond its chemical contributions, glauconite also improves soil physical properties, particularly in sandy soils, by forming soft and friable aggregates that enhance permeability, water retention, and the creation of beneficial micropore spaces. These structural improvements can lead to better plant growth, not

necessarily due to direct nutrient supply, but as a result of more favourable soil conditions, as demonstrated in field trials on sandy loam soils (Heckman and Tedrow, 2004).

Furthermore, glauconite is particularly attractive for organic and sustainable farming systems. As a naturally occurring, minimally processed mineral, it aligns with organic certification standards in many countries. According to the Technology Information, Forecasting and Assessment Council (TIFAC, 2018), India has significant glauconite reserves that can reduce the country's dependency on imported potash. The use of locally sourced glauconite thus offers economic and environmental benefits, supporting circular agriculture principles. It also contributes to long-term soil health by improving soil structure, enhancing moisture retention, and supporting beneficial microbial communities. Its multifunctional nature, supplying not only K but also Ca, Mg, Na, and micronutrients like Zn, makes glauconite an ideal amendment in nutrient-depleted or marginal soils. Due to its high specific surface area, glauconite serves as an advantageous substrate for the synthesis of nanocomposite fertilizers, facilitated by its efficient nutrient adsorption capacity and inherent antibacterial and antifungal properties (Dasi et al., 2024). Moreover, its application can be fine-tuned to crop demands, soil texture, and climatic conditions, making it versatile across different agroecosystems. As part of a broader nutrient management strategy, glauconite can help achieve both productivity goals and sustainability targets, particularly in systems aiming for reduced chemical input use, improved nutrient recycling, and enhanced soil quality. (Oze et al., 2019; Rudmin et al., 2019b). Glauconite acts as a sustainable, eco-friendly alternative to traditional inputs (Rudmin et al., 2016; Rudmin et al., 2023), whereas conventional potassium fertilizers offer specific advantages regarding immediate solubility and accessibility (Franzosi et al., 2014; Rudmin et al., 2019b, 2020a). A primary benefit of glauconite is its high cation-exchange capacity (CEC), which enhances the soil's ability to retain essential nutrients without the risk of iron or aluminum toxicity. Rudmin et al., 2019b found that incorporating glauconite into the soil matrix directly augments its CEC, thereby improving the retention of vital growth nutrients. Furthermore, its application can positively moderate soil acidity; for example, shifting pH levels from 6.0 to a near-neutral 6.7 (Rudmin et al., 2019b).

While glauconite demonstrates significant potential as a soil amendment, further empirical inquiry is required to determine optimal application rates and to establish economically sustainable methods for its extraction and industrial processing (Van Straaten, 2006). Additionally, a more rigorous evaluation of the environmental implications is necessary, specifically concerning the ecological hazards associated with nutrient runoff and leaching following the excessive application of glauconite in agricultural contexts (Zhang et al., 2005).

2.7.2. Previous pot/field experiments

Early investigations into glauconite have confirmed its potential for restoring soil fertility across diverse agricultural contexts (Castro and Tourn, 2003; Santos et al., 2016; Rudmin et al., 2017, 2019b, 2020a; Rakesh et al., 2020a). Numerous studies have evaluated the beneficial impact of glauconite-based fertilizers on the development of diverse botanical species, including olive trees (Karimi et al., 2012), sunflowers (dos Torqueti et al., 2016), various grasses (Franzosi et al., 2014), oats (Rudmin et al., 2017), coffee (de Dias et al., 2018), and durum wheat (Rudmin et al., 2019b). Nevertheless, further inquiry remains essential to evaluate its performance within specific local soil-crop systems (Morsy et al., 2016; Rakesh et al., 2020a; Rudmin et al., 2020a). Existing literature explores various agricultural applications for glauconite, including its utility as an alternative potassium-based fertilizer (Karimi et al., 2012; Franzosi et al., 2014; Rudmin et al., 2017; Hamed and Abdel Hafez, 2020), as a precursor for potassium salts (Rudmin et al., 2018; Shekhar et al., 2019; Duarte et al., 2022), and as a fundamental substrate for synthesizing nanocomposite fertilizers (Rudmin et al., 2019a, 2020b, 2022, 2023).

Numerous pot and field experiments have evaluated the role of glauconite in nutrient release, enhancement of plant growth parameters, and its effectiveness as a soil amendment. One prominent study by (Ramesh et al. 2020) assessed the release of K from glauconite nanoparticles (GNPs) in an Alfisol using maize (*Zea mays*) as a test crop. The GNPs were applied at rates equivalent to 100, 150, and 200 mg K₂O/kg of soil. Maize grown with 200 mg K₂O from GNPs showed the highest potassium content in plant tissues, improved nitrate reductase activity, increased electrical conductivity of the soil solution (an indirect measure of ionic activity), and greater biomass compared to the MOP treatment. These results suggest that finely ground glauconite, especially in nanoparticle form, can match or even surpass synthetic K sources in supplying potassium efficiently when applied in adequate doses.

(Bakr et al. 2021) Conducted a similar experiment in Egypt using glauconite mineral applied at 0, 3, 6, and 9 g/kg of sandy soil planted with wheat (*Triticum aestivum*). Their results indicated a dose-dependent improvement in available K, Ca, and Mg in the soil. Additionally, they observed a rise in soil cation exchange capacity (CEC) and moderate pH buffering, which positively influenced wheat shoot biomass and nutrient uptake. Notably, K uptake increased significantly without signs of toxicity or nutrient imbalance. In another experiment, (Jalali and Moradi 2012) evaluated glauconitic sandstone in olive (*Olea europaea*) cultivation under sand and hydroponic conditions. Although the glauconite contained only 2.24% K₂O, olive trees did not exhibit potassium deficiency symptoms, underscoring the material's suitability as a sustained K source.

Besides K, these studies confirmed plant uptake of other beneficial nutrients (Ca, Mg, Na, Zn), contributing to overall plant vigour and resilience.

The agricultural utility of glauconite is demonstrated globally, such as in the Republic of Congo, where it is deployed to enhance national crop outputs (Rakesh et al., 2020a). Research by Karimi et al. (2012) established that glauconitic sandstone (containing 2.2% K₂O) provides a steady release of potassium into the soil solution. This slow-release behavior positions it as both a sustainable and cost-effective fertilizer. Recent studies indicate that applying powdered glauconitic rock not only boosts potassium levels but also improves nitrogen and phosphorus profiles within the crop, potentially increasing yields by 10–47% (Dasi et al., 2024). From an industrial perspective, the use of primary glauconite rocks is economically advantageous due to the minimal processing required, often necessitating only basic grinding (Rudmin et al., 2017; Kalinina et al., 2023). However, to maximize its practical efficacy, evidence suggests that glauconitic sandstone should be integrated with alternative fertilizers to ensure a balanced nutrient supply (Rudmin et al., 2019b, 2020a).

Based on the above findings, glauconite plays a significant role in the agricultural sector, primarily as an alternative source of potassium. **Table 2** presents examples from different countries illustrating the use of glauconite in various crops and summarizes the main findings reported in these studies.

Table 2: The use of glauconite as a source of potassium in different countries on different crops, and the main findings of each study

Country of study	Crop studied	Main findings	References
Argentina	Grass	Greensands derived from the Salamanca Formation showed potential to reduce the use of conventional potassium-based fertilizers. However, their commercial application is economically feasible mainly within the Patagonia region due to transportation issues. Crop yield increased by approximately 16–27%.	(Franzosi et al., 2014)
Brazil	Calla lily	Powdered and granulated calcined glauconite, serving as calcium and nitrogen sources, positively influenced calla lily growth. These materials partially replaced KCl fertilization and improved plant health when combined with cattle manure. Crop yield increased by 10.9–11.6%.	(Boldrin et al., 2019)

Country of study	Crop studied	Main findings	References
Brazil	Urochloa brizantha (Brachiaria brizantha)	Glaucconitic siltstone application improved soil fertility and enhanced productivity in tropical pastures by supplying essential nutrients, thereby supporting sustainable agricultural practices. Crop yield increased by approximately 17.7%.	(Cristina et al., 2019)
Iran	Olive plants	Glaucconitic sandstone, characterized by high potassium oxide content, was identified as a sustainable and cost-effective alternative to conventional fertilizers. Its application improved soil nutritional status while reducing potential soil toxicity. Crop yield increased by approximately 11.5–16%.	(Karimi et al., 2012)
Russia	Durum wheat	Glaucconite functioned as an eco-friendly fertilizer, reducing initial soil K ₂ O concentration by 24% during the growing season, indicating sustained potassium release. This resulted in a crop yield increase of 18.4%.	(Rudmin et al., 2019b)
Russia	Potato	Application of glaucconite, a naturally occurring mineral, enhanced potato productivity, with yield increases ranging from 16–29%. Additionally, glaucconite reduced agricultural pollution by supplying essential trace elements and decreasing reliance on synthetic agrochemicals.	(Gasparyan et al., 2019)
Egypt	Sugar beet	A field experiment assessed the effects of different potassium sources, including glaucconite and its extracts, on soil properties, sugar beet yield, and sugar quality under saline soil conditions. Glaucconite extracted with humic acid (GH2) showed particularly strong positive effects.	(El-Sharkawy et al., 2025)

3. MATERIALS AND METHODS

The chapter outlines the experimental procedures employed to evaluate the chemical composition, nutrient release behavior, environmental safety, and agronomic performance of glauconite deposits collected from the El-Gedida mining area in Egypt. The methodology includes sample preparation and fractionation, multi-tier chemical analyses using pseudo-total digestion, BCR sequential extraction, and single extractants, as well as acid activation treatments. Additionally, the study involved pot experiments with lettuce and tomato to assess glauconite's effectiveness as a potassium fertilizer under controlled conditions. All laboratory procedures and experimental designs were conducted with rigorous quality control and statistical validation to ensure the reliability of the results.

3.1. Methodology Flow Chart

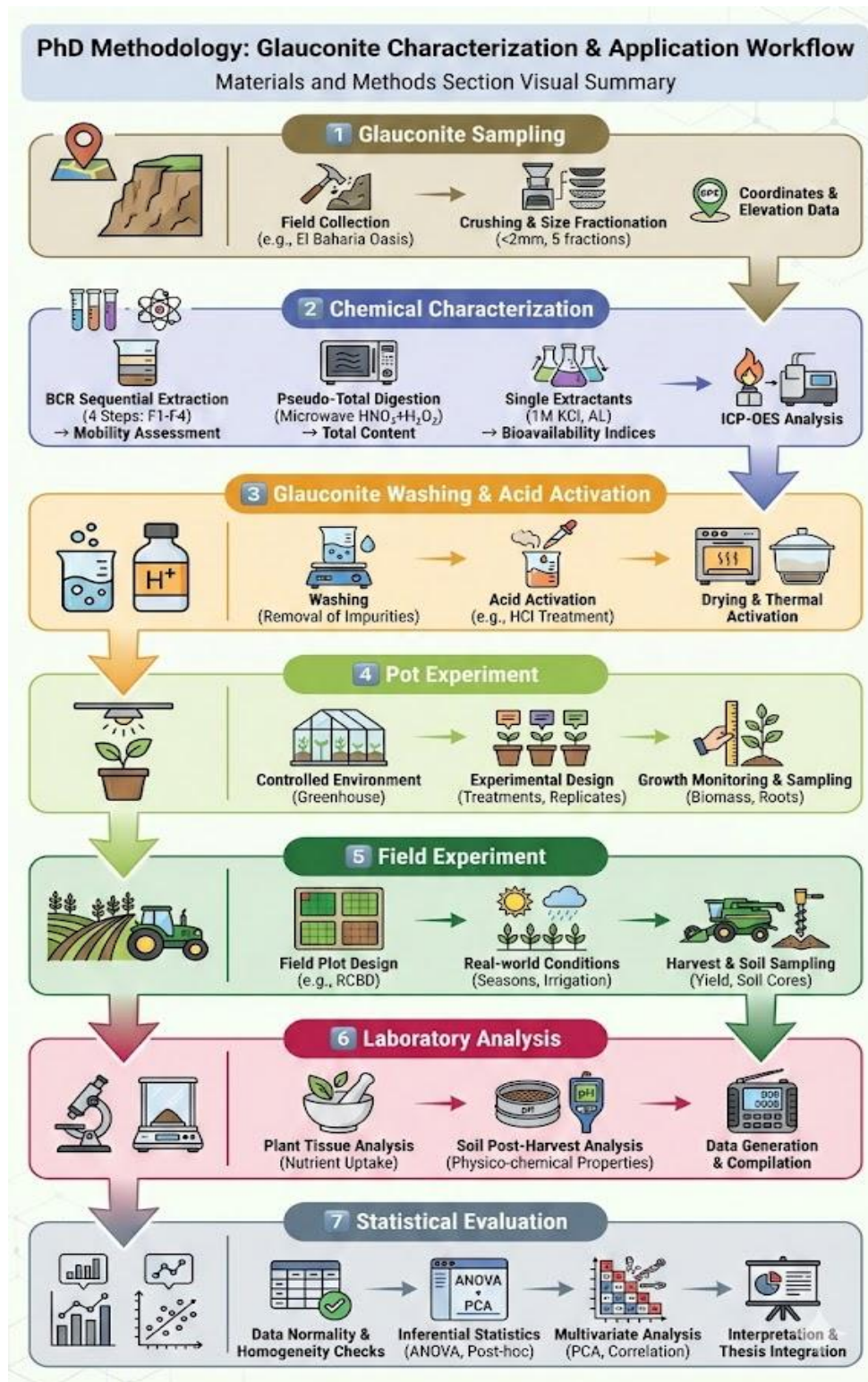


Figure 3. Flow chart summarising the Methodology of this research

3.2. Glauconite sampling area and sample preparation

Representative samples of Glauconite were collected from El Baharia Oasis in the Western Desert of Egypt, close to El-Gedida mining area (Figure 4) $28^{\circ}28'26''.11$ N and $29^{\circ}11'4.18''$ E at 187m above sea level. Egypt has abundant mineral resources, including significant ironstone reserves found in the El-Gedida mine (Salama et al., 2012). The mining area not only includes iron ores but also high amounts of glauconite sediments (Hassan & Baioumy, 2007). The sediments are mined as overburden and are removed to reach the commercial iron ore deposit. Glauconite sediments are widespread throughout many locations in the Western Desert.

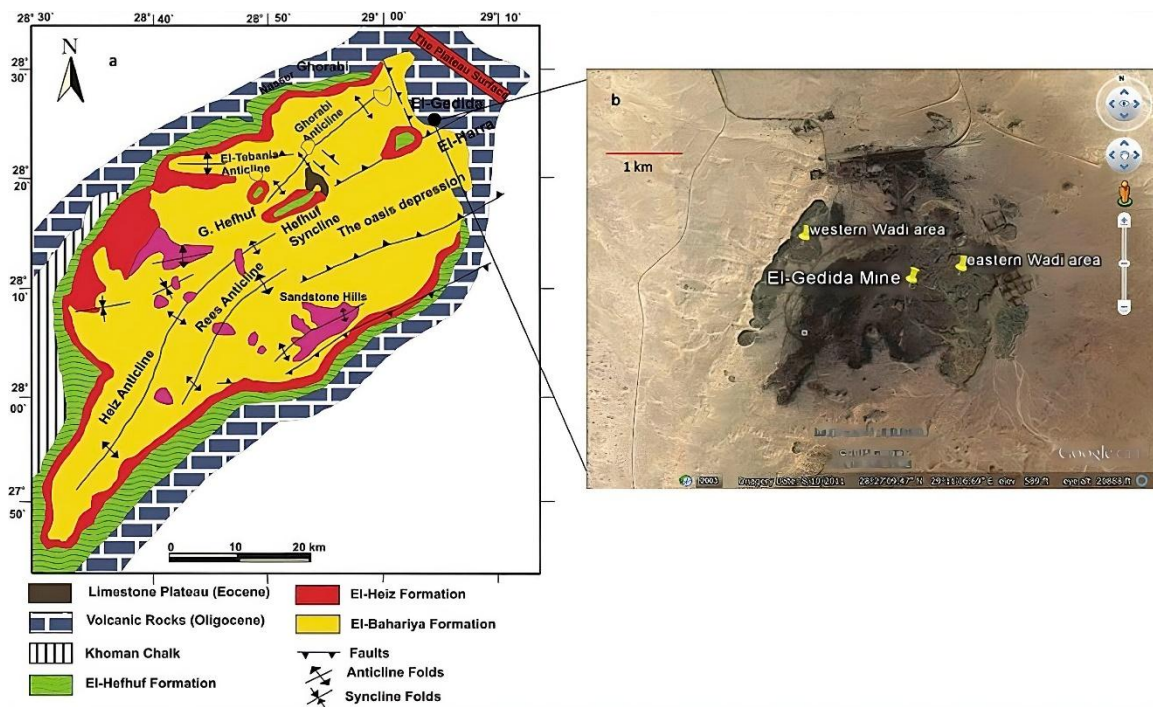


Figure 4. Geological map showing the glauconite sampling area at El-Gedida Mine, El-Baharia Oasis, Western Desert, Egypt.

(Elbassiony, 2005, El-habaak et al., 2016)

Glauconite is distinguished by its characteristic green color, which can range from olive-green to blue-green depending on the iron content and its oxidation state (Odin and Matter, 1981a, 1981b; Hegab and Abd El-Wahed, 2016). Although it crystallizes in the monoclinic system, glauconite rarely forms well-defined crystals in nature; instead, it commonly appears as small pellets or granules. In the field, glauconite can be identified by its distinctive green color, typical pellet-like morphology, and its frequent occurrence in marine sedimentary environments, with rarer associations in volcanic rocks (Rudmin et al., 2023a). Laboratory identification relies on its crystal structure and chemical composition, using a range of analytical techniques such as X-ray diffraction (XRD) (Drits et al., 1997), Fourier-transform infrared spectroscopy (FTIR) (Zviagina

et al., 2017; Singh et al., 2023), and transmission electron microscopy (TEM) (Amouric and Parron, 1985; Drief et al., 2002). Additionally, its elemental composition can be examined in detail using electron microprobe analysis (Rieder et al., 1988).

The first stage in sample preparation for analysis was to reduce the glauconite rock to particles smaller than 2 mm using a jaw crusher. The samples were dry sieved and divided into five size fractions (<2-1, < 1-0.5, < 0.5-0.2, < 0.2-0.1, and < 0.1 mm) as shown in (Figure 5). The size-fractionated samples were subsequently used in the following chemical analysis.

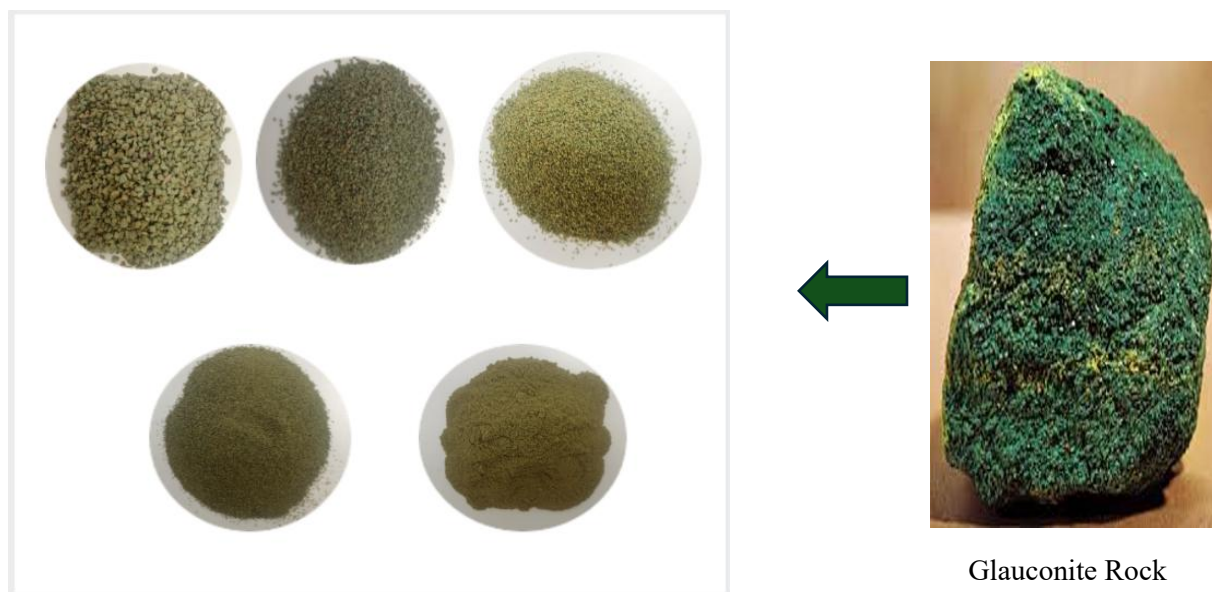


Figure 5. glauconite samples after grinding and fractionation by size

3.3. Chemical analysis (Extraction analysis measuring the elemental content)

Measuring the elemental content in glauconite samples by using two different methodologies and comparing with the pseudo-total content

3.3.1. BCR Sequential Extraction Procedure Protocol

Three independent replicates were performed for each glauconite sample. Blanks were measured in parallel for each set of analyses using the three-step BCR sequential extraction procedure with an additional (+1) aqua regia step. The Certified Reference Material BCR-701 was prepared in triplicate in parallel with the samples to ensure the accuracy of the analysis. The BCR three-step sequential extraction scheme was proposed by the European Community Bureau of Reference in 1992 (the Standards Measurement and Testing Program) (Zhu et al., 2015). The extractable contents of Cd, Ca, K, Na, Mg, Cr, Cu, Ni, Pb and Zn were determined using the procedure below (also refer to chapter 2.6.4) as described in detail by (Rauret et al., 1999; Rauret et al., 2001; Heltai et al., 2019).

Blanks

i. Vessel blank

To one vessel from each batch, taken through the cleaning procedure, 40 mL of solution A was added. This blank solution was analyzed along with the sample solutions from step 1 (described below).

ii. Reagent blank

A sample of each batch of solutions A (acetic acid, 0.11 mol/L), B (hydroxylammonium chloride, 0.5 mol/L), C (hydrogen peroxide, 300 mg/g, 8.8 mol/L) and D (ammonium acetate, 1.0 mol/L) was analysed.

iii. Procedural blank

With each batch of extractions, a blank sample (i.e., a vessel without a glauconite sample) was carried through the complete procedure and analyzed at the end of each extraction step.

Step 1

40 mL of solution A was added to 1 g Glauconite sample in an 80 to 100 mL centrifuge tube, then extracted by shaking for 16 h at 22 ± 5 °C (overnight) and at a speed of 30 ± 10 rpm. The delay did not occur between the addition of the extractant solution and the beginning of the shaking. The extract was separated from the solid residue by centrifugation at 3000 g for 20 minutes, and the supernatant liquid was decanted into a polyethylene container. The container was closed, and the extract was stored in a refrigerator at about 4 °C before analysis. The residue was washed by adding 20 mL of distilled water, shaken for 15 minutes on the end-over-end shaker, and centrifuged for 20 minutes at 3000 g. The supernatant was decanted and discarded while taking care not to discard any of the solid residues.

Step 2

40 mL of freshly prepared solution B was added to the residue from step 1 in the centrifuge tube and resuspended by manual shaking. The extraction was conducted by mechanical shaking for 16 hours at 22 ± 5 °C (overnight) and at a speed of 30 ± 10 rpm. No delay occurred between the addition of the extractant solution and the beginning of the shaking. The extract was separated from the solid residue by centrifugation and decantation as in step 1. The extract was retained in a polyethylene container, as before, for analysis. The residue was washed by adding 20 mL of distilled water, shaken for 15 minutes on the end-over-end shaker, and centrifuged for 20 minutes at 3000 g. The supernatant was decanted and discarded while taking care not to discard any of the solid residues.

Step 3

10 mL of solution C was added carefully to the residue in the centrifuge tube in small aliquots to avoid losses due to a possible violent reaction. The vessel was covered loosely with its cap and digested at room temperature for 1 hour with occasional manual shaking. The digestion continued for 1 hour at 85 ± 2 °C in a water bath, and then the volume was reduced to less than 3 mL by further heating of the uncovered tube. A further aliquot of 10 mL of solution C was added. The covered vessel was heated again to 85 ± 2 °C and digested for 1 hour. The cover was removed, and the volume of liquid was reduced to about 1 mL. Care was taken not to bring the residue to complete dryness. 50 mL of solution D was added to the cool, moist residue and shaken for 16 hours at 22 ± 5 °C (overnight) and at a speed of 30 ± 10 rpm. No delay occurred between the addition of the extractant solution and the beginning of the shaking. The extract was separated from the solid residue by centrifugation and decantation as in step 1 and retained as before for analysis.

+ 1 Step (Aqua regia)

Approximately 3 g of the residue from step 3 of the BCR sequential extraction of the air-dried material was weighed into the reaction vessel. 0.5 mL to 1.0 mL of water was added to obtain a slurry, and while mixing, 21 mL of 12.0 mol/L HCl was added, followed by 7 mL of 15.8 mol/L HNO₃, added drop by drop to reduce foaming. 15 mL of 0.5 mol/L HNO₃ was added to the adsorption vessel, and the vessel was connected to the reflux condenser, and both were placed on top of the reaction flask. The solution could stand for 16 h at room temperature to allow for slow oxidation of the organic matter of the sample. The temperature of the reaction mixture was raised slowly until reflux conditions were reached and maintained for 2 hours, ensuring that the condensation zone was lower than 1/3 of the height of the condenser. The reaction mixture could be cooled slowly to room temperature. After cooling down, the content of the absorption vessel was added through the condenser tube into the reaction vessel, and both were rinsed with 10 mL of 0.5 mol/L HNO₃. The extract was filtered using a cellulose-based membrane filter with a medium pore size of 8 µm to remove particulates (silicates and other insoluble materials) while collecting the filtrate in a 100 mL graduated flask. All the initial filtrate passed through the filter paper, then the insoluble residue was washed onto the filter paper with a minimum of 0.5 mol/L HNO₃. The graduated flask was filled up to the mark with 0.5 mol/L HNO₃ and homogenized by shaking. The elements could be determined by an appropriate ICP-OES method.

3.3.2. Quality control

The quality control for this study was conducted using the Certified Reference Material (CRM) BCR-701. This CRM is certified for ten elements (Ca, K, Na, Mg, Cd, Cr, Cu, Ni, Pb, and Zn).

The percentage recovery for each element was calculated. To validate the BCR sequential procedure, the sums of the cumulated concentrations for each element in Step 1 (F1) + Step 2 (F2) + Step 3 (F3) + Aqua regia step (F4) were compared to the pseudo total concentrations obtained from the same samples and given in mg/kg units.

3.3.3. Pseudo-total elemental content

Sample preparation:

Approximately 0.5 g of each sample was weighed into the Teflon vessel using an analytical balance. 5 mL of nitric acid (65 m/m%), 3 mL of hydrogen peroxide (30 m/m%), and approximately 2 mL of distilled water were added into the Teflon vessel containing the samples to make it up to 10 mL. The reaction could subside completely before capping the vessel.

Microwave digestive system

The microwave digestion method was conducted according to the Hungarian Standard MSZ 21470-50:2006 (2006). The microwave digestion vessels containing samples were assembled and placed in a CEM Mars 5 Extraction 230/60 Microwave Accelerated Reaction System 907501. The microwave digestion system was set at the following parameters: Ramp time – 20 minutes (450 PSI or 180 °C), Hold time – 18 minutes, Still time – 5 minutes (0 W), Hold time – 10 minutes (800 W, 450 PSI and/or 180 °C) and Cooling time – 20 minutes. (Figure 6) indicates the changes in parameters as the microwave operational time changes during the digestion. After digestion, each sample was filtered using a 90 mm Filter Discs (Quant.) Grade 389 into a 25 ml volumetric flask and made up to 25 ml with distilled water. Each sample was physically homogenised by shaking it and transferred into a centrifuge tube for the elemental analysis.

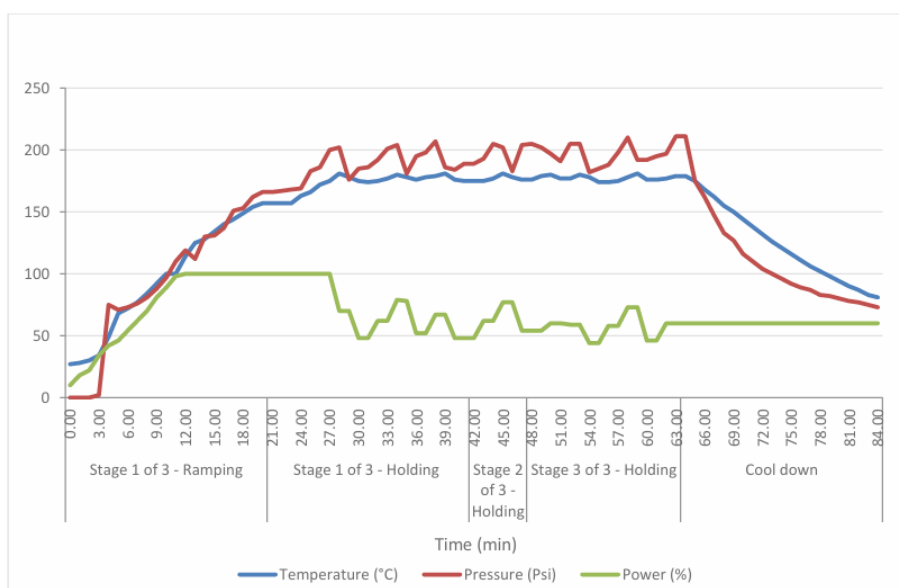


Figure 6. Microwave parameters

3.3.4. Extraction Using Single Extractants

This study utilized two distinct single extractants:

Potassium chloride (KCl)

The first single extractant was a 1M KCl solution, where 20.00 g of each sample was mixed with 50 mL of potassium chloride. The mixed samples with the extractant were placed on the shaking system for two hours before starting the filtration process.

Ammonium Lactate (AL)

The second extractant was an AL solution (diluted 1:10 with distilled water) using the AL method by EGNER et al. (1960). The glauconite sample ratio to extractant was 1:20. All samples were placed on the shaking system for 2 hours before starting the filtration.

Preparation of Ammonium Lactate (AL) Extractant

The ammonium lactate (AL) solution used in this study contained 0.1 mol of ammonium lactate and 0.4 mol of acetic acid per liter of solution. With a pH number of 3.70 ± 0.05 .

Hydrolysis of Lactic Acid

Commercial lactic acid typically contains dilactylic acid, which must be hydrolyzed before use. To perform the hydrolysis:

- 1,000 cm³ of commercial lactic acid was placed in a 5,000 cm³ round-bottom flask.
- Approximately 2,500 cm³ of distilled water was added.

- The mixture was placed in a drying oven and maintained at 95 ± 2 °C for 48 hours.
- Water loss due to evaporation was replenished regularly during the hydrolysis process.

Determination of Hydrolyzed Lactic Acid Concentration

After cooling, the concentration (normality) of the hydrolyzed lactic acid was determined by titration:

- 10 cm³ of the hydrolyzed sample was titrated with 1 mol/dm³ NaOH using 2–3 drops of phenolphthalein as the indicator.
- The hydrolyzed lactic acid factor (F) was calculated using the formula:

$$F = \frac{A \cdot f}{10}$$

Where:

- A = Volume of NaOH used in titration (cm³)
- f = Correction factor of the NaOH solution
- 10 = Volume of hydrolyzed lactic acid used for titration (cm³)

Preparation of Ammonium Lactate Stock Solution

Based on the calculated factor F, the required volume of hydrolyzed lactic acid for 1 litre of stock solution was calculated as:

$$V = \frac{1000}{F} \text{ cm}^3$$

To prepare 1,000 cm³ of the stock solution:

- The calculated volume V of hydrolyzed lactic acid was measured.
- 178.5 cm³ of 96% (m/m) acetic acid was added.
- Separately, 77.0 g of ammonium acetate was dissolved in approximately 50 cm³ of distilled water.
- This solution was added to the lactic-acetic acid mixture in a 1,000 cm³ volumetric flask.
- The volume was then made up to the mark with distilled water.

Preparation of Working Ammonium Lactate Solution

The working AL solution was prepared by diluting the stock solution 10-fold with distilled water.

- The pH of the diluted solution was measured.
- If necessary, the pH was adjusted to 3.70 ± 0.05 using either 3 mol/dm³ ammonium hydroxide or acetic acid solution.
- Finally, the solution was brought to the required final volume with distilled water.

3.4. Modification of Glauconite deposits by washing and mixing with acids

The same size-fractionated glauconite samples that were used in the first stage of extraction analysis (section 3.2.) were utilized in this section

3.4.1. Glauconite Washing

The initial analysis of the glauconite already used in this study unveiled a predominant water-soluble sodium fraction, constituting 96% of the total sodium content. Concurrently, the salinity quotient within the samples ranged approximately between 12-13 mS cm⁻¹. Recognizing the potential deleterious implications of elevated salinity levels and excessive sodium content on soil fertility and plant health, a pre-treatment protocol involving the washing of glauconite samples with distilled water (d H₂O) was implemented before adding acids to the samples, thereby enhancing the suitability of glauconite for agriculture usage as an alternative soil fertilizer without causing environmental harm.

50 grams of material from each size fraction were washed with 250 mL of d H₂O. The washing process involved shaking the mixture for two hours, followed by filtration. The resulting filtrate was collected for the determination of elemental composition by inductively coupled plasma optical emission spectrometry (ICP-OES). The residue of the glauconite samples after filtration was dried in an oven at a temperature of 105°C until it reached a constant mass.

3.4.2. Acidic Extraction

The acid activation process was carried out by mixing the washed and dried glauconite samples with 0.1 M of extractive solvents (nitric acid, hydrochloric acid, acetic acid, or phosphoric acid) separately into polyethylene bottles with a ratio of 1:40. Water was also taken as the control solubilizing medium. Acid treatment was performed by the Hungarian standard MSZ 1484-3:2006 protocol. The polyethylene bottles were placed on a rotary agitator. The acidified glauconite mixtures were rotated at 24 rpm for 16 h. After mixing, the eluate was filtered using a 0.45 µm filter paper. In this part of the study, we extracted five individual elements (potassium, calcium, magnesium, sodium, and zinc) from washed glauconite samples in five different size fractions using the mentioned four acids. The total released elemental content of the elute was

analyzed by ICP-OES. For each analyzed parameter, three replicates were made to ensure the accuracy of the work.

3.4.3. Instrumental analysis

The total elemental content of digested samples was determined by a HORIBA Jobin Yvon ACTIVA M Inductively Coupled Plasma – Optical Emission Spectrometer (ICP-OES) using operation parameters proposed by the manufacturer and yttrium internal standard. (Table 3.) indicates the ICP-OES operational parameters used to determine the following elements (with ICP-OES emission lines): Ca (315.887 nm), Cd (228.802 nm), Co (228.615 nm), Cr (205.571 nm), Cu (324.754 nm), Fe (240.489 nm), K (766.490 nm), Mg (279.078 nm), Mn (257.610 nm), Na (589.592 nm), Ni (231.604 nm), Pb (220.353 nm), and Zn (213.857 nm).

Table 3 ICP-OES operational parameters for trace elemental analysis

Operational parameters	Settings
Incident RF-power	1200 W
Outer gas flow (Argon)	16 L/min
Sheath gas flow (Argon)	0.3 L/min
Auxiliary gas flow (Argon)	0.6 L/min
Nebulizer gas pressure (Argon)	2.86 bar
Nebulizer solution uptake (Meinhardt-cyclonic spray chamber)	0.85 mL/min

3.5. pH and Electrical Conductivity Measurements

Under practical field conditions, glauconite may be pre-treated with acids prior to its application as a fertilizer to enhance nutrient availability. To simulate such environmental conditions, a separate set of glauconite samples was prepared by mixing the mineral with various acids until saturation was achieved. Following acid treatment, a 1:2.5 solid-to-liquid ratio was used to prepare glauconite extracts, corresponding to 10 g of glauconite per 25 mL of distilled water.

To assess the chemical changes resulting from treatment, pH and electrical conductivity (EC) measurements were performed on different sample groups:

- Unwashed (raw) glauconite
- Washed glauconite without acid treatment
- Washed glauconite treated with 0.1 M solutions of nitric acid (HNO₃), hydrochloric acid (HCl), acetic acid (CH₃COOH), and phosphoric acid (H₃PO₄).

Each acid was applied individually to separate samples until saturation was reached. Following acid treatment, the samples were allowed to dry completely. Subsequently, a glauconite–water suspension was prepared for analysis. pH measurements were conducted using a Jenway 3510 digital pH meter (Jenway–Cole Parmer Co., Stone, Staffordshire, UK). While Electrical conductivity (EC) and total dissolved solids (TDS) were measured using a Jenway 4510 conductivity meter (Jenway–Cole Parmer Co., Staffordshire, UK).

3.6. Plant experiment

3.6.1. Soil sampling and preparation

The soils were sampled from Mate Research Farm, Godollo, Hungary. The sampled soil was brought to the laboratory on the same day. The soil was spread on a sheet for air drying. All external materials, such as plant residues, roots, and stones, were removed. After drying, the soil was ground by using a mechanical grinder equipped with a 2 mm sieve. Following this, a pre-sowing physicochemical analysis of the soil was conducted.

3.6.2. Plant Experiment Design

A pot experiment was conducted to evaluate the effect of glauconite mineral application on the uptake and accumulation of potassium and other essential elements (Ca, Mg, P, Zn, Fe, and Cu) in two different crops: tomato (*Solanum lycopersicum*) and lettuce (*Lactuca sativa*). The experiment began on the 6th of May 2024 and was designed to assess the influence of Egyptian glauconite deposits on soil fertility and plant nutrient content under controlled conditions.

The study was conducted using plastic pots with a depth of 15 cm and a radius of 8 cm, each filled with 0.5 kg of soil. A total of three treatments were applied for each crop with three replicates for each treatment (n=3), as follows:

T1 – Control: Soil without any added glauconite

T2 – Washed Glauconite: Soil mixed with washed glauconite (unacidified)

T3 – Washed and Acidified Glauconite: Soil mixed with glauconite pre-treated with 0.1 M phosphoric acid (H₃PO₄)

The glauconite used in T2 and T3 was thoroughly mixed into the soil before transplanting. The application rate was based on the glauconite potassium content (approximately 3% total K) and the standard field recommendation of 200 kg K/ha, resulting in the addition of 1.6 g of glauconite per pot.

In each pot, three uniform seedlings (2 weeks old) of either tomato or lettuce were transplanted. The soil in all pots was irrigated with distilled water to reach field capacity and maintained under appropriate moisture conditions throughout the experiment.

3.6.3. Harvesting and Sample Collection

Plants were harvested 45 days after transplanted. After harvest, both plant and soil samples were collected from each pot. The plant tissues were dried, weighed, and stored for subsequent chemical analysis. Similarly, post-harvest soil samples from each treatment were air-dried, homogenized, and kept for further nutrient analysis.

3.6.4. Soil and Plant Sample Digestion

The total elemental content of soil and plant samples was determined after digestion in a mixture of nitric acid (HNO_3) and hydrogen peroxide (H_2O_2), following the Hungarian Standard MSZ 21470-50:2006. For each sample, between 0.3500 and 0.4500 g was accurately weighed using an analytical balance and transferred into a digestion tube. Subsequently, 5 mL of concentrated HNO_3 and 2 mL of H_2O_2 were added under a fume hood. The mixture was allowed to stand at room temperature for several minutes to release any vapors prior to commencing the digestion process. Upon completion of digestion, the resulting solution was filtered into a 50 mL volumetric flask and the volume was adjusted to 50 mL with Milli-Q water. The prepared solutions were then analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES).

3.7. Field Experiment

First crop (Potatoes)

A field experiment was conducted at the Agricultural Research Farm of Minia University, Egypt, to evaluate the effectiveness of glauconite as an alternative potassium source for potato (*Solanum tuberosum* L.) compared with the commonly used potassium sulfate (SOP). The experiment was established during the winter growing season of 2017/2018, where the potato crop was planted on 9 October 2017 and harvested on 22 January 2018. Different rates and combinations of glauconite and potassium sulfate were applied to assess their effects on plant growth, tuber yield, potassium uptake, and soil potassium availability after harvest.

Successive Crop (Residual Effect Study – *Zea mays*)

Following the harvest of the potato crop, a successive crop of *Zea mays* was grown in the same experimental plots without the addition of any potassium fertilizers. The purpose of cultivating maize as a second-season crop was to evaluate the residual effects of potassium fertilisers and

glaucanite applied during the potato season, particularly their contribution to soil-available K and subsequent plant uptake.

Zea mays was planted on 5 April 2018 and harvested on 25 June 2018. Standard agronomic practices were applied uniformly to all plots during the maize season, including irrigation, nitrogen and phosphorus fertilization, and pest management, but no potassium fertilizer was added to ensure that any observed effects were solely attributable to the residual K remaining from the first crop.

The experimental layout followed a randomized complete block design (RCBD) with six treatments and three replications. Each plot measured 2 * 3.5 meters (7 m²). The treatments were as follows:

1. 100% Potassium sulfate (150 kg K₂SO₄/feddan)
2. 75% Potassium sulfate + 25% acidified glaucanite
3. 50% Potassium sulfate + 50% acidified glaucanite
4. 25% Potassium sulfate + 75% acidified glaucanite
5. 100% acidified glaucanite (1.5 ton/feddan)
6. 100% raw glaucanite (unacidified) (1.5 ton/feddan)

The potassium sulfate rate was based on the recommended dose for the local soil and crop conditions. The acidified glaucanite was prepared by mixing natural glaucanite with 1 M nitric acid until saturation. The mixture was then left to air-dry for five days, followed by crushing with a jaw crusher to achieve a particle size of less than 2 mm.

All standard agronomic practices for potato cultivation were uniformly applied to all plots throughout the growing season. One week before harvest, representative plant and tuber samples were randomly collected from each plot for laboratory analysis. Fresh and dry weights were recorded for both tubers and aboveground plant parts to assess the biomass and yield components.

3.7.1. Plant and Tuber Sample Collection

Harvesting and Initial Handling

At harvest, for the potato crop, plant shoots and tubers were sampled. For the successive Zea mays crop, only plant shoots were collected.

All samples were placed into labelled paper bags and transported immediately to the laboratory. Soil particles and surface contaminants were gently removed manually, followed by washing with tap water and a final rinse with distilled water to ensure sample cleanliness.

Fresh Weight Determination

After cleaning, the fresh weight of each sample (plant shoots and tubers for potato, plant shoots for *Zea mays*) was measured using a digital analytical balance and recorded for each plot.

Drying and Dry Weight Determination

Clean plant tissues and tubers were cut into small, uniform pieces to facilitate proper drying. Samples were oven-dried at 70 °C until constant weight (typically 48–72 hours). After drying, samples were cooled in a desiccator to prevent moisture absorption, and the dry weight was recorded.

Grinding and Storage

Dried plant materials (potato shoots, potato tubers, and maize shoots) were ground using a stainless-steel Wiley mill and passed through a 0.5-mm sieve to obtain a uniform powder. The processed samples were stored in airtight polyethylene containers until subsequent chemical analysis to determine potassium concentration and nutrient uptake.

3.7.2. Soil Samples

Collection

After harvesting each crop, soil samples were collected from the root zone of each plot at a depth of 0–30 cm using a soil auger. Five subsamples were randomly taken from each plot, mixed thoroughly, and a composite sample was prepared.

Air-Drying and Sieving

Soil samples were air-dried at room temperature, gently crushed using a porcelain mortar and pestle, and passed through a 2-mm sieve. A portion of the soil sample intended for extractable potassium determination was further ground to pass through a 0.5-mm sieve when required.

3.7.3. Chemical Analysis

Wet Digestion of Plant and Tuber Samples

Total potassium in plant tissues and tubers was determined after wet digestion. Approximately 0.5 g of the ground dry sample was transferred into a digestion tube. A mixture of concentrated H_2SO_4 and H_2O_2 was added (5 mL H_2SO_4 + 2–3 mL H_2O_2). The samples were digested on a block digester until a clear, colourless solution was obtained. The digest was filtered and diluted to a known final volume with deionized water.

Potassium Measurement by Flame Photometer

Potassium concentration in plant digests, tuber digests, and soil samples was measured using a flame photometer. Before sample analysis, a calibration curve was prepared using standard K solutions of known concentrations. Each sample was aspirated into the flame photometer, and the K concentration was obtained directly from the instrument reading. All measurements were performed in triplicate, and quality-control samples were included to ensure instrument accuracy.

Potassium uptake was calculated using:

$$\text{K Uptake (kg/hectare)} = \left(\frac{\text{K concentration (\%)}}{100} \right) \times \text{Dry matter yield (kg/hectare)}$$

3.8. Statistical Analysis Methods

To fulfil the research objectives, the data obtained from various experiments were compiled in Microsoft Excel and subsequently analyzed using SPSS and R software. Before statistical analysis, data preprocessing was conducted to address missing values and outliers. Outliers were identified and removed using the interquartile range (IQR) method (Vinutha et al., 2018). The distribution of each dataset was examined using the Shapiro–Wilk test to determine normality. When necessary, data were normalized to meet the assumptions of parametric tests. The Levene’s or Bartlett’s test was used to assess homogeneity of variance at a significance level of $p < 0.05$.

Based on the results of these preliminary tests, appropriate statistical analyses were applied. For comparing more than two group means or evaluating multiple factors, one-way, two-way, or multifactorial ANOVA was used (Kim, 2014). If data did not meet parametric assumptions, the Kruskal–Wallis test was employed as a non-parametric alternative. For pairwise comparisons, a t-test was used when the data followed a normal distribution (Kim and Park, 2019), while the Wilcoxon test was applied for non-normally distributed data (Wadgave, 2019).

Post hoc analysis was conducted using Tukey’s Honest Significant Difference (HSD) or the Student–Newman–Keuls (SNK) test to determine significant differences among treatments ($p < 0.05$). The multcomp View package in R was used to generate grouping letters indicating statistical significance.

In particular, the effects of extractive solvents and glauconite particle size fractions on elemental release were statistically analyzed using Statistica 8.0 software (StatSoft, TIBCO Software Inc., Tulsa, OK, USA), and the results were grouped and compared accordingly.

4.RESULTS AND DISCUSSION

4.1. Glauconite elemental content

4.1.1. Elemental composition measurement using BCR sequential extraction procedure

The elemental content of the five glauconite sediment fractions was analyzed using the BCR sequential extraction protocol alongside pseudo-total content determination. As shown in Table 4, the samples consistently contained 3–3.3 wt% potassium, indicating their suitability as a natural potassium source. Notably, cadmium was absent across all samples, and other potentially toxic elements (PTEs) Cr, Cu, Ni, and Pb were all well below the permissible limits set by the EU Regulation (2019/1009) for fertilizers (Table 5). The descending order of element concentration was $K > Mg > Na > Ca > Zn > Cr > Ni > Cu > Pb$.

The summation of BCR fractions (1+2+3+4) was generally consistent with or slightly exceeded the pseudo-total contents, especially for elements such as Ca, Na, and Pb. This deviation is attributed to the accumulated procedural inaccuracy during multiple extraction steps, as previously discussed by Van Herreweghe et al. (2003). Elements like K, Mg, Cu, Cr, Ni, Pb, and Zn were predominantly present in the residual fraction (BCR 4), indicating their low mobility and potential for slow release in soil environments. Conversely, calcium was mainly associated with the reducible phase (BCR 2), and sodium was largely found in the exchangeable phase (BCR 1), confirming their higher potential mobility and availability.

4.1.2. Single Extractants vs. BCR Step 1

To evaluate more practical, low-cost extraction methods, two single extractants—1M KCl and ammonium lactate (AL) solution—were compared with BCR Step 1 (exchangeable fraction). As shown in Table 6, for elements such as Ca, Cu, K, Mg, and Zn, the concentrations extracted using AL or KCl exceeded those measured in BCR Step 1. Specifically, AL solution extracted up to three times more calcium than BCR Step 1 and captured quantities close to the reducible fraction for Mg. This enhanced efficiency is likely due to the formation of stable metal-acetate complexes, which improve ion exchange and prevent re-adsorption (Pickering, 1986).

Zinc showed notably higher extractability in AL solution compared to both KCl and BCR Step 1. The results for sodium, however, revealed higher extraction in BCR Step 1 than with single extractants, likely due to sodium's inherent water solubility and rapid dissolution.

In the case of lead and nickel, neither single extractant was effective, consistent with their strong association with the residual fraction in the BCR method. These findings reaffirm that single extractants like AL are efficient for estimating mobile and available forms of specific nutrients, but less suitable for immobile or tightly bound elements.

4.1.3. Effect of Particle Size on Elemental Content

The influence of particle size on the elemental content and extractability of nutrients in glauconite was systematically evaluated across the defined size fractions. The results presented in Table 4 indicate that particle size exhibited a limited and non-systematic effect on the distribution and release of most elements, particularly potassium, calcium, and magnesium. This observation aligns with previous findings indicating that glauconite behaves as a structurally controlled mineral rather than a surface-reactive material (Dasi et al., 2024). These findings also align with Franzosi et al. (2014), who reported negligible differences in nutrient release between glauconite particle sizes in Patagonia.

A slight tendency toward increased elemental release was observed in the finer fractions (e.g., <0.1 mm), which can be attributed to the increase in specific surface area and enhanced mineral–solution interaction. Finer particles provide a greater reactive surface, facilitating ion exchange and dissolution processes. Similar behavior has been reported in silicate-based fertilizers, where reduced particle size enhances short-term nutrient release due to improved contact with the extracting solution (Duarte et al., 2023).

However, despite this expected trend, the differences among size fractions were not statistically significant ($p > 0.05$) for most of the analyzed elements. This suggests that the majority of elements are not governed solely by surface-related processes but are instead structurally incorporated within the glauconite matrix. Sequential extraction results further confirm that a large proportion of elements are associated with stable mineral fractions, indicating low mobility and controlled release (Eldawwy et al., 2024).

For potassium specifically, which represents the primary nutrient of interest, the minimal variation across particle sizes indicates that its availability is predominantly controlled by its occurrence within interlayer and structural sites of the glauconite mineral. This behavior is characteristic of K-bearing silicate minerals, where potassium release is governed by slow weathering processes rather than physical disintegration alone (Costa Júnior et al., 2024).

From an agronomic perspective, these findings are highly relevant. The absence of significant differences between particle size fractions suggests that glauconite can be applied in relatively coarse forms without substantially affecting its performance as a potassium source. This has important economic implications, as it reduces the need for energy-intensive grinding processes. Similar conclusions have been reported in studies evaluating the use of glauconite and other silicate minerals as alternative fertilizers, where mineral composition and chemical reactivity were found to be more influential than particle size (Rudmin et al., 2019b; Silveira et al., 2025).

Overall, the results demonstrate that while finer particles may slightly enhance elemental release,

particle size is not a dominant controlling factor in nutrient availability from glauconite. Instead, nutrient release is primarily governed by mineralogical structure and geochemical stability, reinforcing the classification of glauconite as a slow-release, sustainable potassium source suitable for long-term soil fertility management (Verma & Prakash, 2018; Dasi et al., 2024).

Table 4. Element concentration in the BCR steps compared with pseudo-total element content (mg kg^{-1} , dry weight basis; mean \pm standard deviation). Samples 1–5 correspond to particle size fractions $<2-1$, $<1-0.5$, $<0.5-0.2$, $<0.2-0.1$, and <0.1 mm, respectively. n.d.: not detected. LSD (5%): least significant difference according to the Fisher test ($P < 0.05$).

<i>Element</i>	<i>Sample</i>	<i>BCR 1</i>	<i>BCR 2</i>	<i>BCR 3</i>	<i>BCR 4</i>	<i>(1+2+3+4)</i>	<i>Pseudo Total</i>
	1	269 ±3	1214 ±15	57.5 ±6.4	46.8 ±0.3	1587	1410
	2	265 ±10	1191 ±20	47.4 ±3.1	41.0 ±2.1	1544	1238
Ca	3	276 ±11	1275 ±19	50.3 ±0.6	44.5 ±2.7	1645	1316
	4	250 ±14	1331 ±17	53.2 ±1.2	49.5 ±0.7	1683	1354
	5	254 ±1	1427 ±6	64.3 ±6.0	48.0 ±0.3	1793	1733
	<i>LSD %5</i>	21	36	9.6	3.6	44	38
	<i>Extractable (%)</i>	18.66	91.31	3.87	3.26	117.09	100
	1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cd	3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	<i>LSD %5</i>						
	1	0.091 ±0.022	0.110 ±0.200	0.70 ±0.00	45.3 ±1.0	46.2	51.27
	2	0.073 ±0.032	0.140 ±0.090	0.65 ±0.05	47.6 ±0.1	48.54	50.15
Cr	3	0.092 ±0.031	0.052 ±0.013	0.78 ±0.02	49.9 ±0.7	50.82	48.09
	4	0.120 ±0.100	0.081 ±0.012	0.98 ±0.07	52.1 ±1.0	53.28	52.11
	5	0.092 ±0.031	0.130 ±0.010	1.06 ±0.02	52.4 ±0.4	53.68	54.12
	<i>LSD %5</i>	0.07	0.1	0.1	1.7	2.33	n.s.
	<i>Extractable (%)</i>	0.18	0.20	1.63	96.79	98.81	100
	1	n.d.	0.40 ±0.40	n.d.	7.6 ±0.1	8	8.1
	2	n.d.	0.51 ±0.04	n.d.	7.7 ±0.1	8.2	8
Cu	3	n.d.	0.66 ±0.12	n.d.	8.0 ±0.4	8.7	8.4
	4	n.d.	1.05 ±0.20	n.d.	8.2 ±0.3	9.3	9.2
	5	n.d.	1.20 ±0.07	n.d.	8.5 ±0.1	9.7	15.9
	<i>LSD %5</i>		0.48		0.22	0.76	0.3
	<i>Extractable (%)</i>	0.00	8.31	0.00	86.67	94.98	100
	1	811 ±12	536 ±86	255 ±8	29561 ±257	31163	30690
	2	789 ±12	575 ±2	262 ±8	30553 ±301	32179	32323
K	3	782 ±12	573 ±4	269 ±3	31819 ±482	33443	32408
	4	789 ±12	567 ±4	263 ±3	31079 ±831	32698	33255
	5	801 ±8	550 ±8	263 ±5	29950 ±612	31564	33363
	<i>LSD %5</i>	26	88	13	1223	1033	85
	<i>Extractable (%)</i>	2.45	1.73	0.81	94.40	99.39	100
	1	272 ±4	983 ±27	164 ±3	9552 ±157	10971	10894
	2	264 ±5	1002 ±4	157 ±2	10068 ±153	11491	11500
Mg	3	256 ±3	1002 ±10	155 ±3	10345 ±71	11758	11115
	4	223 ±12	1003 ±17	144 ±3	10094 ±179	11464	11494
	5	282 ±4	951 ±22	158 ±3	9735 ±265	11126	11718

	<i>LSD %5</i>	<i>15</i>	<i>42</i>	<i>6</i>	<i>400</i>	<i>366</i>	<i>218</i>
	<i>Extractable (%)</i>	<i>2.29</i>	<i>8.71</i>	<i>1.37</i>	<i>87.79</i>	<i>100.16</i>	<i>100</i>
	1	9239 ±140	128 ±15	35.4 ±2.0	175 ±5	9577	7124
	2	9032 ±62	139 ± 0	39.0 ±2.0	189 ±6	9398	6821
Na	3	8514 ±29	131 ± 1	42.6 ±4.0	196 ±4	8882	6442
	4	8236 ±83	141 ± 4	38.9 ±1.0	200 ±1	8615	6267
	5	9109 ±25	119 ± 6	43.6 ±2.5	248 ±3	9520	7468
	<i>LSD %5</i>	<i>181</i>	<i>17</i>	<i>5.7</i>	<i>9</i>	<i>180</i>	<i>175</i>
	<i>Extractable (%)</i>	<i>129.32</i>	<i>1.92</i>	<i>0.58</i>	<i>2.84</i>	<i>134.67</i>	<i>100</i>
	1	n.d.	0.2	n.d.	13.9 ±0.3	14.1	16.2
	2	n.d.	n.d.	n.d.	14.6 ±0.2	14.6	15.9
Ni	3	n.d.	n.d.	n.d.	16.2 ±0.3	16.2	16.2
	4	n.d.	n.d.	n.d.	16.5 ±0.2	16.5	17.5
	5	0.1	0.4	n.d.	15.9 ±0.3	16.4	18.5
	<i>LSD %5</i>				<i>0.6</i>	<i>1.6</i>	<i>2.3</i>
	<i>Extractable (%)</i>	<i>0.00</i>	<i>0.00</i>	<i>0.00</i>	<i>89.80</i>	<i>89.80</i>	<i>100</i>
	1	n.d.	1.21 ±0.41	n.d.	6.50 ±0.42	7.7	6.8
	2	n.d.	0.52 ±0.21	n.d.	7.40 ±0.23	7.9	6.7
Pb	3	n.d.	0.63 ±0.12	n.d.	7.50 ±0.51	8.1	7
	4	n.d.	0.73 ±0.22	n.d.	7.37 ±0.28	8.1	6.8
	5	n.d.	1.40 ±0.10	n.d.	7.61 ±0.17	9	8.7
	<i>LSD %5</i>		<i>0.5</i>		<i>0.79</i>	<i>0.99</i>	<i>0.2</i>
	<i>Extractable (%)</i>	<i>0.00</i>	<i>12.00</i>	<i>0.00</i>	<i>101.08</i>	<i>113.08</i>	<i>100</i>
	1	3.0 ±0.01	7.2 ±1.9	n.d.	101.6 ±2.3	111.7	112.3
	2	3.1 ±0.18	7.8 ±0.5	n.d.	105.6 ±0.3	116.4	115.7
Zn	3	1.9 ±0.38	8.0 ±0.2	0.1	111.0 ±1.6	121	112.8
	4	1.2 ±0.40	8.3 ±1.1	n.d.	111.0 ±1.9	120.5	118.4
	5	2.4 ±0.96	10.1 ±0.7	0.8	107.8 ±1.3	121.2	127.1
	<i>LSD %5</i>	<i>1.14</i>	<i>2.5</i>		<i>3.7</i>	<i>4.6</i>	<i>2.7</i>
	<i>Extractable (%)</i>	<i>1.97</i>	<i>7.07</i>	<i>0.00</i>	<i>91.62</i>	<i>101</i>	<i>100</i>

*The mean percentage of extractable element content in each BCR step compared with pseudo-total content

Table 5. Comparison between the concentrations (mg kg⁻¹) of the PTEs in glauconite sediments and the limits in fertilizers in the guidelines in the EU REGULATION (2019/1009)

Potentially toxic elements	Cu	Cr	Pb	Ni	Cd
Glauconite	9.9	51.1	7.2	16.8	0
EU limits on Fertilizers	600	200	120	100	1.5

Table 6. Element concentration in the BCR step 1 compared with element content by using single extractants (mg·kg⁻¹ related to dry weight)

Element	Sample	BCR 1	KCl	AL
Ca	1	269	962	1019
	2	265	963	1297
	3	276	947	1300
	4	250	976	1270
	5	254	1022	1305
Standard Deviation		11	29	123
Cr	1	0.1	n.d.	n.d.
	2	0.1	n.d.	n.d.
	3	0.1	n.d.	n.d.
	4	0.1	n.d.	n.d.
	5	0.1	n.d.	n.d.
Standard Deviation		0		
Cu	1	n.d.	0.7	0.3
	2	n.d.	0.1	0
	3	n.d.	0	0.9
	4	n.d.	0.9	2.1
	5	n.d.	0.6	1.9
Standard Deviation			0.4	0.9
K	1	811	-	1197
	2	789	-	1029
	3	782	-	954
	4	789	-	936
	5	801	-	890
Standard Deviation		12		120
Mg	1	272	592	657
	2	264	568	679
	3	256	557	666
	4	223	531	661
	5	282	523	581
Standard Deviation		23	28	39
Na	1	9239	3515	7271
	2	9032	3509	7229
	3	8514	3491	6718
	4	8236	3550	6486
	5	9109	3539	6879
Standard Deviation		430	24	335
Zn	1	3	1.2	7.4
	2	3.1	1.3	11
	3	1.9	2	9.1
	4	1.2	1.4	9.9
	5	2.4	0.7	12.6
Standard Deviation		0.8	0.5	2.0

- not measured

4.2. Glaucosite modification by washing and mixing with different acids

The application of various acid solutions represents one of the most straightforward and commonly used methods for leaching elements from minerals, including glaucosite, across numerous industrial and environmental contexts (Jena, 2021). This section explores the influence of different acid extractants and particle size fractions of glaucosite on the release behavior of essential plant nutrients: calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), and zinc (Zn).

4.2.1. Calcium

The assessment of calcium release from glaucosite demonstrated distinct patterns that varied according to the type of acid applied for acidification (Figure 7). The greatest calcium release was recorded when nitric acid (HNO_3) was used, with concentrations ranging between 1199 ± 17.6 and $1545 \pm 71.0 \text{ mg}\cdot\text{kg}^{-1}$. In contrast, the application of acetic acid (CH_3COOH) yielded the lowest calcium release, with values ranging from 147 ± 4.9 to $254 \pm 6.4 \text{ mg}\cdot\text{kg}^{-1}$. These differences led to the establishment of the following descending order of calcium-releasing efficacy: $\text{HNO}_3 > \text{HCl} > \text{H}_3\text{PO}_4 > \text{CH}_3\text{COOH}$.

Upon acid treatment, calcium is released into solution and reacts with the corresponding acids to form soluble salts, such as calcium chloride (CaCl_2) with HCl , calcium nitrate ($\text{Ca}(\text{NO}_3)_2$) with HNO_3 , calcium dihydrogen phosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2$) with H_3PO_4 , and calcium acetate ($\text{Ca}(\text{CH}_3\text{COO})_2$) with CH_3COOH .

The formation of these salts plays a critical role in the efficiency of calcium release. In every case, acid treatment was significantly more effective than extraction using deionized water, underscoring the importance of acid-mediated dissolution processes. The solubility of the resulting calcium salts in water varies markedly, which helps explain the observed differences in calcium release. Calcium nitrate and calcium chloride are highly soluble, with solubility values of $1212 \text{ g}\cdot\text{L}^{-1}$ (Kant & Kafkafi, 2013) and $745 \text{ g}\cdot\text{L}^{-1}$ (Ropp, 2013) at 20°C , respectively. In contrast, calcium dihydrogen phosphate and calcium acetate show considerably lower solubility, at $180 \text{ g}\cdot\text{L}^{-1}$ and $347 \text{ g}\cdot\text{L}^{-1}$ (20°C), respectively—approximately 3 to 6 times lower than calcium nitrate.

These solubility characteristics directly influence the extent to which calcium is mobilized during acid leaching. The high solubility of calcium nitrate enhances the dissolution and release of calcium when nitric acid is used, making it significantly more effective than the other acids tested. These findings support the selection of nitric acid as the most suitable extractant for calcium from glaucosite, particularly in processes aimed at maximizing nutrient recovery.

This understanding of the underlying chemical dynamics of calcium release from glauconitic materials has practical relevance in multiple fields, particularly in mineral beneficiation, soil amendment formulation, and resource recovery technologies.

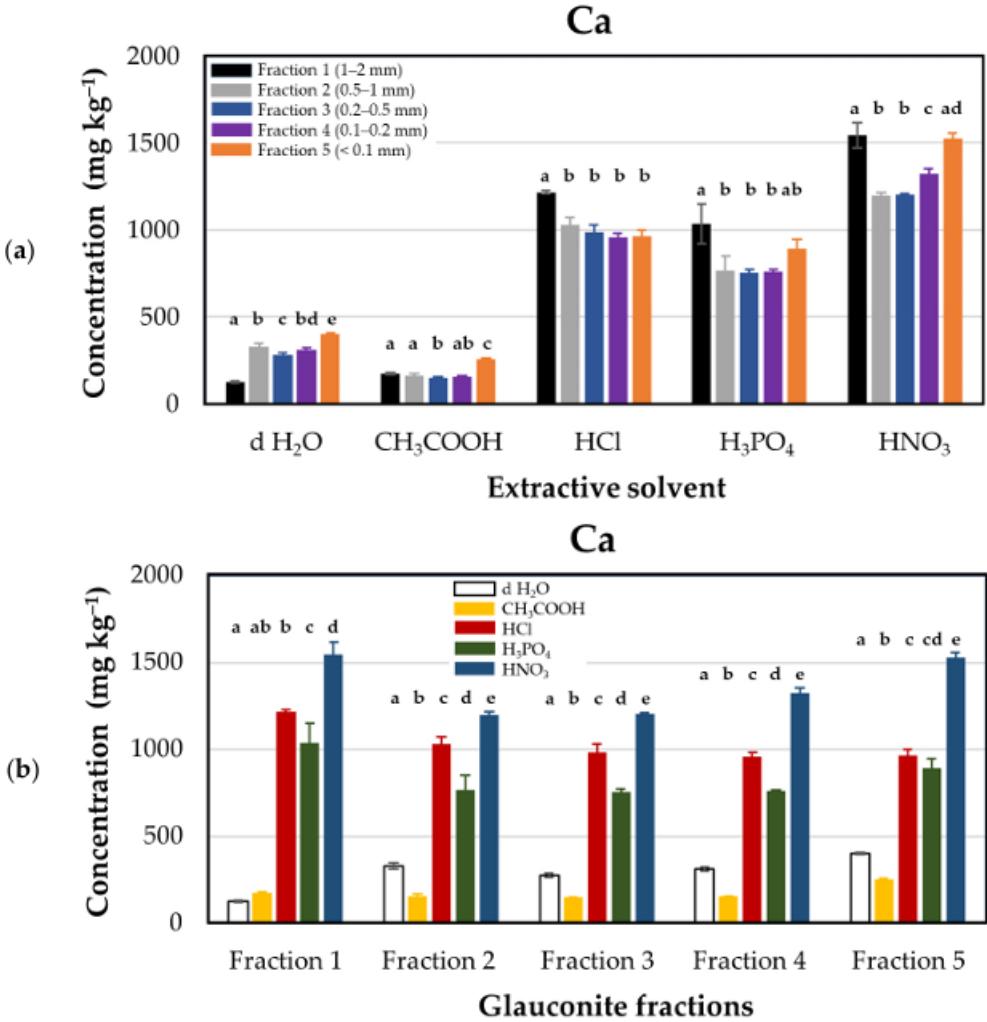


Figure 7. Calcium concentrations (mg. kg⁻¹ dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants.

(a) Extraction efficacies plotted by extractants in particle size fractions: Fraction 1 (1-2 mm), Fraction 2 (0.5-1 mm), Fraction 3 (0.2-0.5 mm), Fraction 4 (0.1-0.2 mm), and Fraction 5 (<0.1 mm). (b) Extraction efficacies plotted by fractions using extractants: distilled water (d H₂O), acetic acid (CH₃COOH), hydrochloric acid (HCl), phosphoric acid (H₃PO₄), and nitric acid (HNO₃). Lower case Latin letters above the corresponding columns on the graph indicate significant differences: different lower case letters designate statistically significantly different categories within the groups (but not among different groups) by extractant solvents on Figure a, and by glauconite fractions on Figure b. Statistical comparisons were performed on a group-by-group (groups by solvents or group by fractions) basis, thus, interpretations of significance for a given group do not represent any correlation with descriptors listed for other groups.

4.2.2. Potassium

The release behavior of potassium from glauconite was examined under the influence of various acid treatments, revealing distinct differences in extraction efficiency (Figure 8). Among the tested acids, nitric acid (HNO_3) exhibited the highest efficiency, with potassium concentrations ranging between 1011 ± 11.0 and $1118 \pm 10.8 \text{ mg}\cdot\text{kg}^{-1}$. Hydrochloric acid (HCl) produced similar results, with potassium release closely matching that of nitric acid. This similarity aligns with findings by Tro (2011), who reported that the solubilities of potassium chloride and potassium nitrate are essentially equivalent at approximately 23°C . The potassium released by these two acids was nearly threefold greater than that obtained through leaching with deionized water ($\text{d H}_2\text{O}$).

In contrast, acetic acid (CH_3COOH) yielded the lowest release of potassium, with values ranging from 455.7 ± 16.6 to $551 \pm 4.5 \text{ mg}\cdot\text{kg}^{-1}$. Accordingly, the descending order of potassium extraction effectiveness among the acids tested was as follows: $\text{HNO}_3 \approx \text{HCl} > \text{H}_3\text{PO}_4 > \text{CH}_3\text{COOH}$.

It is noteworthy that potassium extraction using phosphoric acid (H_3PO_4) was accompanied by relatively higher standard deviations. This variability is likely due to the unique chemical properties of phosphoric acid, which can interfere with the ionization balance of the plasma during analysis. Potassium, having a low ionization energy, is particularly susceptible to changes in matrix composition. Moreover, phosphoric acid can modify the viscosity of the solution, thereby affecting aerosol generation and transport efficiency into the plasma, which in turn impacts the accuracy and consistency of emission intensity measurements.

(Table 1) provides a summary of prior studies investigating potassium leaching from glauconite using different acid treatments. For instance, Shekhar et al. (2017a) employed HCl to extract potassium from concentrated glauconite samples. Their study reported a relatively low recovery rate, with less than 12% of potassium extracted. This contrasts with the current findings, where both HCl and HNO_3 demonstrated higher efficiency. Furthermore, the poor potassium release observed with acetic acid in this study is consistent with the results of Praveen and Tomar (2019), who also reported limited potassium extraction using this acid. These similarities reinforce the general understanding that acetic acid, as an organic acid with weaker dissociation, exhibits lower extractive capacity than strong inorganic acids like HCl , HNO_3 , and H_3PO_4 . However, it is essential to note that the leaching efficiency can also be influenced by external factors, such as temperature and the presence of coke, as demonstrated in the work of Shekhar et al. (2017a).

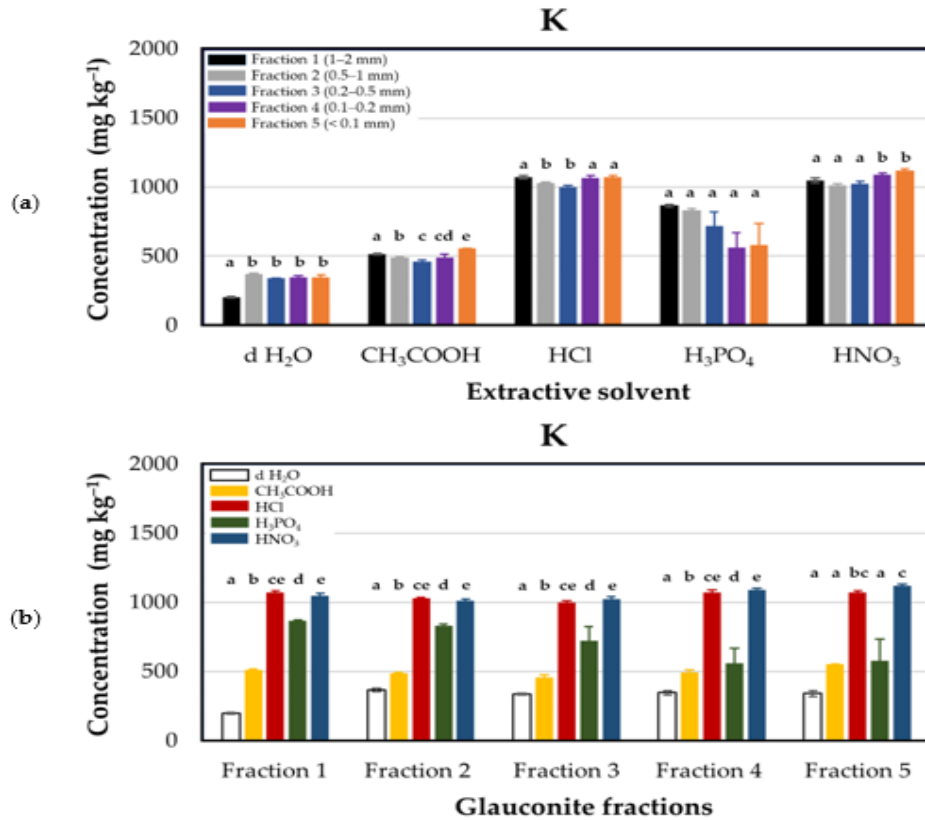


Figure 8. Potassium concentrations (mg kg^{-1} dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants.

(a) Extraction efficiencies plotted by extractants in particle size fractions: Fraction 1 (1-2 mm), Fraction 2 (0.5-1 mm), Fraction 3 (0.2-0.5 mm), Fraction 4 (0.1-0.2 mm), and Fraction 5 (< 0.1 mm). (b) Extraction efficiencies plotted by fractions using extractants: distilled water ($\text{d H}_2\text{O}$), acetic acid (CH_3COOH), hydrochloric acid (HCl), phosphoric acid (H_3PO_4), and nitric acid (HNO_3). Lower case Latin letters above the corresponding columns on the graph indicate significant differences: different lower case letters designate statistically significantly different categories within the groups (but not among different groups) by extractant solvents on Figure a, and by glauconite fractions on Figure b. Statistical comparisons were performed on a group-by-group (groups by solvents or group by fractions) basis, thus, interpretations of significance for a given group do not represent any correlation with descriptors listed for other groups.

(Table 1) summarizes previous findings. Shekhar et al. (2017a) observed less than 12% K recovery using HCl, highlighting its lower effectiveness relative to HNO_3 in certain settings. Acetic acid consistently showed poor extraction capacity (Praveen & Tomar, 2019), reinforcing its limited utility in glauconite processing unless assisted by thermal or catalytic methods.

4.2.3. Magnesium

As illustrated in Figure 9, nitric acid was also the most effective extractant for magnesium (Mg), with release levels ranging from 979 ± 29.3 to 1142 ± 7.7 mg·kg⁻¹. This was nearly three times higher than the release obtained with deionized water. Acetic acid, again, exhibited the weakest extraction, with values between 119 ± 4.7 and 173 ± 3.2 mg·kg⁻¹. The descending order of extraction was HNO₃ > HCl > H₃PO₄ > CH₃COOH, reaffirming the greater efficacy of strong acids in solubilizing divalent cations.

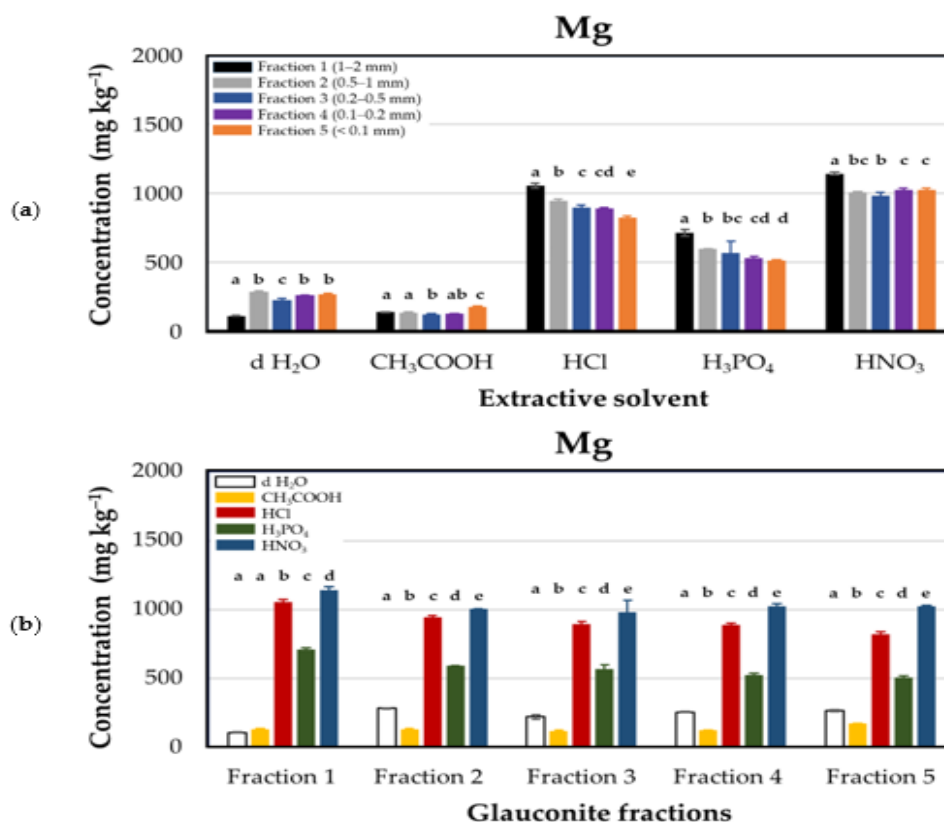


Figure 9. Magnesium concentrations (mg. kg⁻¹ dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants.

(a) Extraction efficacies plotted by extractants in particle size fractions: Fraction 1 (1-2 mm), Fraction 2 (0.5-1 mm), Fraction 3 (0.2-0.5 mm), Fraction 4 (0.1-0.2 mm), and Fraction 5 (<0.1 mm). (b) Extraction efficacies plotted by fractions using extractants: distilled water (d H₂O), acetic acid (CH₃COOH), hydrochloric acid (HCl), phosphoric acid (H₃PO₄), and nitric acid (HNO₃). Lower case Latin letters above the corresponding columns on the graph indicate significant differences: different lower case letters designate statistically significantly different categories within the groups (but not among different groups) by extractant solvents on Figure a, and by glauconite fractions on Figure b. Statistical comparisons were performed on a group-by-group (groups by solvents or group by fractions) basis, thus, interpretations of significance for a given group do not represent any correlation with descriptors listed for other groups.

4.2.4. Sodium

As illustrated in (Figure 10), the release of sodium (Na) from glauconite was highest when treated with deionized water (d H₂O), yielding concentrations between 3768 ± 61.2 and 8161 ± 135.0 mg·kg⁻¹. This substantial release indicates that more than 50% of the initial sodium content originally around 8000 mg·kg⁻¹ was removed during the water washing process alone. In contrast, the use of acid extractants had minimal impact on sodium release, with all tested acids producing relatively uniform and lower extraction values compared to deionized water.

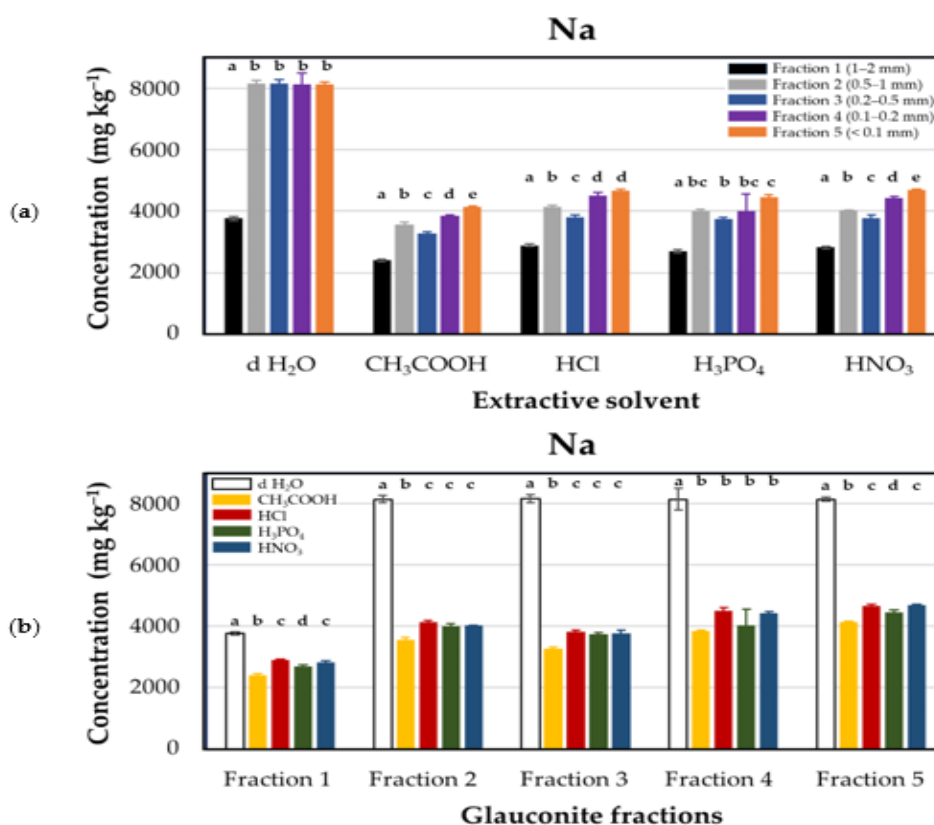


Figure 10. Sodium concentrations (mg. kg⁻¹ dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants.

(a) Extraction efficacies plotted by extractants in particle size fractions: Fraction 1 (1-2 mm), Fraction 2 (0.5-1 mm), Fraction 3 (0.2-0.5 mm), Fraction 4 (0.1-0.2 mm), and Fraction 5 (<0.1 mm). (b) Extraction efficacies plotted by fractions using extractants: distilled water (d H₂O), acetic acid (CH₃COOH), hydrochloric acid (HCl), phosphoric acid (H₃PO₄), and nitric acid (HNO₃). Lower case Latin letters above the corresponding columns on the graph indicate significant differences: different lower case letters designate statistically significantly different categories within the groups (but not among different groups) by extractant solvents on Figure a, and by glauconite fractions on Figure b. Statistical comparisons were performed on a group-by-group (groups by solvents or group by fractions) basis, thus, interpretations of significance for a given group do not represent any correlation with descriptors listed for other groups.

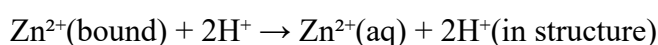
These findings highlight the effectiveness of water washing in reducing sodium levels in glauconite, outperforming even strong acids in this regard. Therefore, incorporating a washing step using deionized water is strongly recommended prior to the application of glauconite as a soil

amendment or fertilizer. This is especially important considering the potential risks associated with elevated soil salinity, which can negatively affect plant growth through mechanisms such as osmotic stress, ion toxicity, and disruptions in nutrient uptake (Oze et al., 2019; Liu et al., 2023).

4.2.5. Zinc

Among the acid treatments tested, nitric acid (HNO₃) proved to be the most effective in promoting zinc (Zn) release from glauconite, with concentrations ranging from 4.70 ± 0.12 to 7.38 ± 0.16 mg·kg⁻¹, as shown in (Figure 11). Hydrochloric acid (HCl) followed closely in extraction efficiency. The overall descending trend for zinc release using different acids was established as: HNO₃ > HCl > H₃PO₄ > CH₃COOH.

This trend can be attributed to the differing chemical properties and dissociation behaviors of the acids used. Nitric acid, a strong monoprotic acid with a pKa of approximately -1.4, completely dissociates in aqueous solutions, yielding a high concentration of protons (H⁺). These protons promote proton exchange reactions and contribute to the disruption of the glauconite matrix, thereby liberating zinc. The simplified chemical reaction illustrating this mechanism is:



This enhanced release suggests that nitric acid facilitates the breakdown of Zn-containing structural components within glauconite more efficiently than other acids.

On the other hand, phosphoric acid (H₃PO₄) is a triprotic acid that dissociates in a stepwise manner, with dissociation constants pK_{a1} ≈ 2.15, pK_{a2} ≈ 7.20, and pK_{a3} ≈ 12.35. Under the experimental conditions used in this study, the release of free protons from phosphoric acid is lower than that from nitric acid. In addition, H₃PO₄ has a strong tendency to form insoluble metal-phosphate complexes, such as Zn₃(PO₄)₂, which may limit the amount of free Zn²⁺ in solution. This is reflected in the significantly lower zinc concentrations measured in the phosphoric acid-treated samples, which ranged only from 0.31 ± 0.08 to 1.20 ± 0.11 mg·kg⁻¹.

Among all acids examined, acetic acid (CH₃COOH) exhibited the weakest ability to extract zinc, yielding concentrations even lower than those recorded with deionized water. As a weak monoprotic acid with a pKa of approximately 4.76, acetic acid undergoes limited dissociation in water, resulting in a lower availability of protons in solution. This reduced proton concentration is insufficient to disrupt the strong metal–oxygen bonds in the glauconite framework, thus hindering zinc solubilization. Consequently, acetic acid demonstrated a negligible effect on zinc release.

Taken together, these findings clearly indicate that nitric acid is the most chemically aggressive and effective acid for liberating zinc from glauconite. Its full dissociation, strong acidity, and lack

of metal-complexing or precipitating tendencies contribute to its superior performance in mobilizing Zn from glauconitic structures.

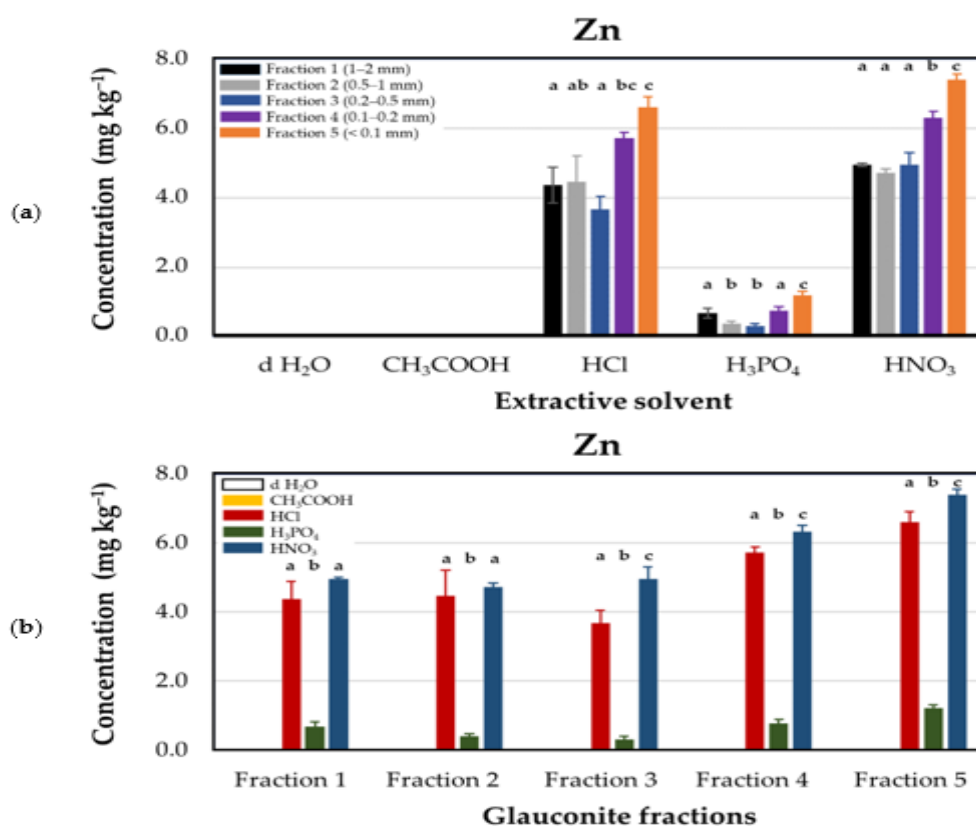


Figure 11. Zinc concentrations (mg. kg⁻¹ dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants

(a) Extraction efficacies plotted by extractants in particle size fractions: Fraction 1 (1-2 mm), Fraction 2 (0.5-1 mm), Fraction 3 (0.2-0.5 mm), Fraction 4 (0.1-0.2 mm), and Fraction 5 (<0.1 mm). (b) Extraction efficacies plotted by fractions using extractants: distilled water (d H₂O), acetic acid (CH₃COOH), hydrochloric acid (HCl), phosphoric acid (H₃PO₄), and nitric acid (HNO₃). Lower case Latin letters above the corresponding columns on the graph indicate significant differences: different lower case letters designate statistically significantly different categories within the groups (but not among different groups) by extractant solvents on Figure a, and by glauconite fractions on Figure b. Statistical comparisons were performed on a group-by-group (groups by solvents or group by fractions) basis, thus, interpretations of significance for a given group do not represent any correlation with descriptors listed for other groups.

4.2.6. Effect of Glauconite Fraction Size on Element Release

To assess the influence of particle size on nutrient release, glauconite was fractionated into five different size classes and subjected to acid leaching. While there was a general tendency for smaller particle sizes, particularly the <0.1 mm fraction to exhibit slightly higher nutrient release, this pattern was neither strong nor consistent across all tested elements and acid treatments. As shown in (Figures 7–11), the <0.1 mm fraction occasionally demonstrated marginally increased extraction

efficiencies. However, the differences in release among the five size classes were often small and lacked statistical or practical significance.

Specifically, elements such as potassium (K), zinc (Zn), and sodium (Na) showed minor enhancements in extractability with decreasing particle size. In contrast, the release of magnesium (Mg) and calcium (Ca) remained largely unaffected by particle size across all acid treatments. These findings suggest that fractionating glauconite to isolate finer particles does not yield significant benefits in nutrient release and therefore, may not be necessary in practical applications.

This outcome aligns with previous work by Eldawwy et al. (2024), who concluded that glauconite particles in the size range of <2.0–0.1 mm could be effectively utilized as a single unit without sifting, as size-based separation had a negligible impact on elemental availability. However, this contrasts with studies by Praveen and Tomar (2019), who found that reducing glauconite to nanoparticle size enhanced its nutrient release efficiency. Similarly, Shekhar et al. (2017a) observed a positive correlation between decreasing particle size and increased potassium extraction, attributing this effect to greater surface area and reactivity in finer fractions.

Taken together, the results indicate that particle size reduction can influence the release of certain elements such as Zn, Mg, and Ca; however, this effect is not consistent across all elements and has a limited impact on potassium availability. Therefore, from an agronomic perspective, extensive mechanical refinement may not be essential for optimizing glauconite as a potassium source.

4.2.7. Changes in pH and Electrical Conductivity

Soil pH is a fundamental parameter controlling nutrient availability, as it regulates key geochemical processes such as dissolution–precipitation reactions, ion exchange, and metal complexation. Variations in pH directly influence the mobility and bioavailability of elements in soil systems (Xia et al., 2024; Kalocsai et al., 2024). The pH values obtained from the glauconite samples in this study are presented in Table 7 and Figure 12.

The results show a slight increase in pH following washing, from 5.78 in the unwashed sample to 6.10 after washing. This increase can be attributed to the removal of soluble acidic components and exchangeable ions from the mineral surface. In contrast, acid-treated samples exhibited a pronounced decrease in pH, with values ranging from 3.14 to 4.61 depending on the acid used. The effectiveness of the acids followed the order:



This trend reflects the relative acid strength and dissociation behavior, where strong mineral acids promote greater proton activity and enhanced dissolution of mineral phases. Similar findings have

been reported in studies evaluating acid-treated glauconite, where stronger acids significantly increased element release and altered solution chemistry (Eldawwy et al., 2025).

Electrical conductivity (EC), which represents the total concentration of dissolved ions in solution, showed substantial variation among treatments. The unwashed glauconite exhibited the highest EC (12.59 mS cm^{-1}), indicating the presence of readily soluble salts and exchangeable ions. After washing, EC decreased markedly to 4.32 mS cm^{-1} confirming the removal of soluble ionic species. This behavior is consistent with previous findings indicating that washing processes reduce salinity by eliminating easily soluble fractions from mineral surfaces (El-Sharkawy et al., 2025).

Following acid treatment as presented in Figure 13 and Table 7, EC values increased again, reaching 7.48 mS cm^{-1} for HCl-treated samples and 7.24 mS cm^{-1} for HNO_3 -treated samples, while lower values were observed for H_3PO_4 (5.28 mS cm^{-1}) and CH_3COOH (4.93 mS cm^{-1}). This increase is attributed to the enhanced dissolution of mineral components and subsequent release of elements into solution, particularly under strong acid conditions. Similar trends have been observed in glauconite-based systems, where acidification significantly enhances nutrient solubilization and ionic concentration (Dasi et al., 2024; Eldawwy et al., 2025).

Importantly, the observed changes in pH and EC are attributed to chemical interactions between extractants and the mineral matrix, rather than any changes in grain size or mineralogical composition, which were not directly measured in this study. This clarification addresses the limitation of the current work and ensures that interpretations remain strictly within the scope of the experimental data.

From an agronomic perspective, these findings are highly relevant. The reduction in pH and increase in EC following acid treatment indicate improved nutrient solubility and potential short-term availability. However, the moderate EC values after treatment suggest that glauconite does not induce excessive salinity, supporting its role as a slow-release fertilizer capable of enhancing nutrient availability without adverse effects on soil properties (Rudmin et al., 2019; El-Sharkawy et al., 2025)

Table 7. Electrical conductivity (EC) and pH values detected in 0.4 kg L⁻¹ glauconite solutions (individual values reported as a mean ± standard deviation).

Sample	Gl. before washing	Gl. after washing	Gl. a.w. + HCl	Gl. a.w. + CH ₃ COOH	Gl.a.w.+HN O ₃	Gl.a.w.+H ₃ P O ₄
EC (mS cm ⁻¹)	12.59±0.36	4.32±0.01	7.48±0.01	4.93±0.11	7.24±0.09	5.28±0.07
pH	5.78±0.06	6.10±0.01	3.14±0.01	4.61±0.02	3.22±0.01	3.90±0.00

*Gl.: glauconite; Gl. B.: Glauconite before washing; Gl. a.w.: glauconite after washing with distilled water.

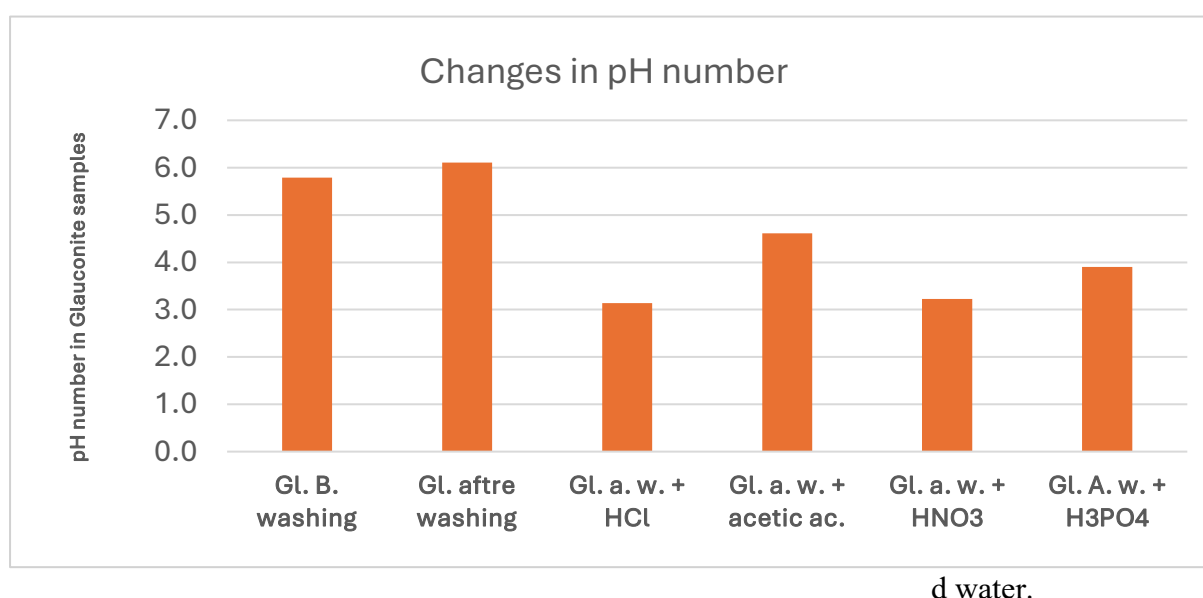


Figure 12. pH values detected in 0.4 kg. L⁻¹ glauconite solution.

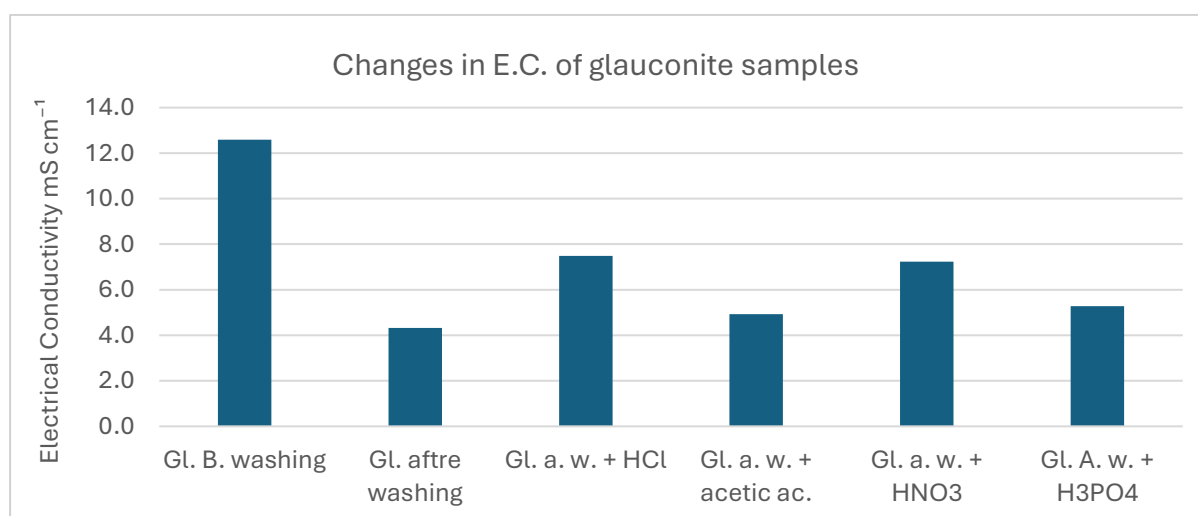


Figure 13. Electrical conductivity (EC) values detected in 0.4 kg L⁻¹ glauconite solutions

4.3. Pot Experiment using glauconite deposits as potassium fertilizer in two different crops

4.3.1 Soil Characteristics and Initial Conditions

The experimental soil was alkaline (pH 7.97 in H₂O, 7.53 in KCl) with high CaCO₃ (20.96%) and moderate organic matter (2.21% humus) (Table 8). Key nutrients included Al-P₂O₅ (269.5 mg/kg), Al-K₂O (139.4 mg/kg), and Al-Ca (9961.2 mg/kg), while micronutrients like Fe (1112.3 mg/kg), Mn (207.9 mg/kg), and Zn (7.8 mg/kg) were sufficient for plant growth (Kabata-Pendias, 2011). The high CaCO₃ content likely influenced P fixation (Brady & Weil, 2016), but glauconite amendments particularly the H₃PO₄-treated form, were expected to alter nutrient dynamics, especially for K, Fe, and P (Rao et al., 2018).

Table 8. soil description

pH (H₂O)	7.97
CaCO₃ %	21.0
K_A	31.2
Salt %	0.085
Humus %	2.21
AL-P₂O₅ (mg/kg)	269.5
Al-K₂O (mg/kg)	139.4
Al-Ca (mg/kg)	9961
Al-Na (mg/kg)	556
Al-Mg (mg/kg)	978.9
HNO₃-Cu (mg/kg)	5.40
HNO₃-Fe (mg/kg)	1112
HNO₃-Mn (mg/kg)	208
HNO₃-Zn (mg/kg)	7.8
SO₄²⁻ (mg/kg)	75.8
NH₄-N (mg/kg)	52.1
NO₃-N (mg/kg)	7.4
N [%]	0.093
C [%]	3.80
S [%]	0.01

4.3.2. Effects of Glaucanite Treatments on Lettuce

The results presented in Table 9 indicate that glaucanite treatments significantly affected nutrient concentrations in both soil and lettuce tissues, with statistically significant differences among treatments ($p < 0.05$). These variations reflect the influence of washing and phosphoric acid treatment on nutrient solubility, chemical speciation, and plant uptake mechanisms.

Table 9. Mean nutrient concentrations (\pm SD) in soil and plant samples of lettuce under different treatments

	Treatment	Ca (mg/kg)	Fe (mg/kg)	K (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	P (mg/kg)	Zn (mg/kg)
Nutrient concentrations in Soil samples	Control	2816 \pm 486 ^a	10712 \pm 998 ^a	2406 \pm 1316 ^a	2039 \pm 135 ^a	408 \pm 25 ^a	2558 \pm 311 ^a	19 \pm 6 ^b
	Washed glaucanite	2030 \pm 424 ^b	7470 \pm 423 ^b	1327 \pm 58 ^b	1708 \pm 137 ^b	296 \pm 24 ^b	1607 \pm 192 ^b	13 \pm 2 ^c
	Washed glaucanite + H ₃ PO ₄	2463 \pm 532 ^{ab}	8063 \pm 1313 ^b	1828 \pm 863 ^{ab}	1798 \pm 101 ^b	315 \pm 34 ^b	1027 \pm 185 ^c	21 \pm 1 ^a
Nutrient concentrations in Plant samples	Control	28896 \pm 5650 ^b	955 \pm 134 ^a	48799 \pm 2402 ^a	7820 \pm 1328 ^b	170 \pm 16 ^b	11239 \pm 801 ^a	23 \pm 4 ^b
	Washed glaucanite	32670 \pm 7297 ^a	854 \pm 230 ^b	50228 \pm 3227 ^a	8303 \pm 1207 ^a	168 \pm 24 ^b	11126 \pm 743 ^a	19 \pm 2 ^c
	Washed glaucanite + H ₃ PO ₄	28457 \pm 2780 ^b	909 \pm 116 ^{ab}	50268 \pm 2476 ^a	7734 \pm 979 ^b	187 \pm 4 ^a	11460 \pm 529 ^a	33 \pm 5 ^a

Different superscript letters (a, b, c) indicate significant differences ($p < 0.05$) between treatments within each column.

As shown in Table 9 and Figure 14. In soil samples after harvesting, the control treatment exhibited the highest concentrations of most elements (Ca, Fe, K, Mg, Mn, and P), while the washed glauconite treatment significantly reduced nutrient levels, particularly potassium (from 2406 to 1327 mg kg⁻¹). This reduction is primarily attributed to the removal of soluble and exchangeable elements during the washing process, which alters the equilibrium between solid-phase and solution-phase nutrients. Similar reductions in readily available nutrient pools following washing or leaching processes have been reported in soil systems where easily exchangeable ions are displaced or removed (Paramesh et al., 2023; Hussain et al., 2026).

The application of washed glauconite + H₃PO₄ partially restored nutrient availability, particularly for potassium and calcium. Soil K increased to 1828 mg kg⁻¹, indicating that phosphoric acid promoted the release of interlayer and structurally bound potassium. Acidification enhances mineral dissolution and cation exchange processes, increasing nutrient mobility in silicate minerals. This mechanism has been widely reported in studies showing that acidic treatments improve nutrient release from mineral sources through proton-promoted weathering reactions (Shekhar et al., 2019; Hussain et al., 2026; Eldawwy et al., 2025).

However, soil phosphorus decreased significantly under the H₃PO₄ treatment (1027 mg kg⁻¹) compared to the control. This apparent contradiction can be explained by phosphorus fixation processes, where added P reacts with Ca, Fe, or Al to form less soluble compounds. It is well established that a large proportion of applied phosphorus (up to 80–85%) becomes immobilized in soils shortly after application, reducing its measurable availability (Stępień et al., 2025). Additionally, strong interactions between phosphorus and micronutrients such as zinc may further influence nutrient distribution and availability (Nadeem et al., 2024)

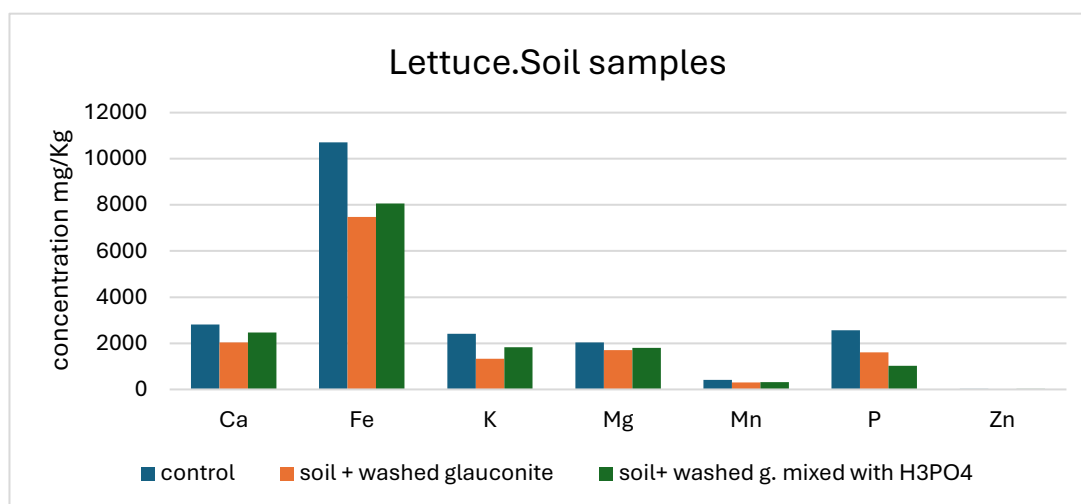


Figure 14. Nutrient Concentrations in Soil Samples After Harvest

In plant tissues as demonstrated in Figure 15 and Table 9, nutrient concentrations did not directly follow soil trends, highlighting the complexity of plant–soil interactions. The highest potassium concentrations in lettuce ($\sim 50,200 \text{ mg kg}^{-1}$) were recorded under glauconite treatments, with no significant difference between washed and acid-treated samples, both exceeding the control. This indicates that plant potassium uptake is not solely dependent on total soil K concentration but rather on the availability of exchangeable K and root uptake efficiency. Recent studies confirm that plant nutrient uptake is regulated by root transport systems and internal demand rather than bulk soil concentrations (Bhat et al., 2024).

Calcium and magnesium concentrations were highest in the washed glauconite treatment, suggesting that washing improved ionic balance and reduced competitive inhibition from excess salts. The removal of soluble salts, particularly sodium, enhances the selectivity of nutrient uptake by plant roots and improves overall nutrient acquisition efficiency. This effect has been observed in nutrient-deficient and saline-affected systems, where improved ionic balance leads to better uptake of divalent cations (Paramesh et al., 2023).

Micronutrient dynamics showed distinct responses to acid treatment. The highest Zn concentration in plants (33 mg kg^{-1}) was observed under H₃PO₄-treated glauconite, indicating enhanced Zn solubility and mobility under acidic conditions. Acidification promotes desorption of Zn from soil particles and increases its availability in soil solution. Furthermore, the interaction between phosphorus and zinc plays a critical role in regulating plant uptake, as both synergistic and antagonistic effects may occur depending on soil conditions (Nadeem et al., 2024).

Similarly, manganese uptake increased under acid-treated conditions, reflecting the well-established increase in Mn solubility at lower pH. In contrast, iron concentrations in plants did not

show a strong response, likely due to its tendency to form stable oxides and hydroxides under aerobic soil conditions, limiting its bioavailability despite relatively high total soil concentrations.

Interestingly, phosphorus concentrations in plant tissues remained relatively stable across treatments despite large variations in soil P. This suggests that lettuce plants regulated phosphorus uptake through physiological mechanisms such as root exudation and transporter activity. It is well known that plants can adapt to varying phosphorus availability by modifying rhizosphere chemistry and enhancing P acquisition efficiency (Stępień et al., 2025).

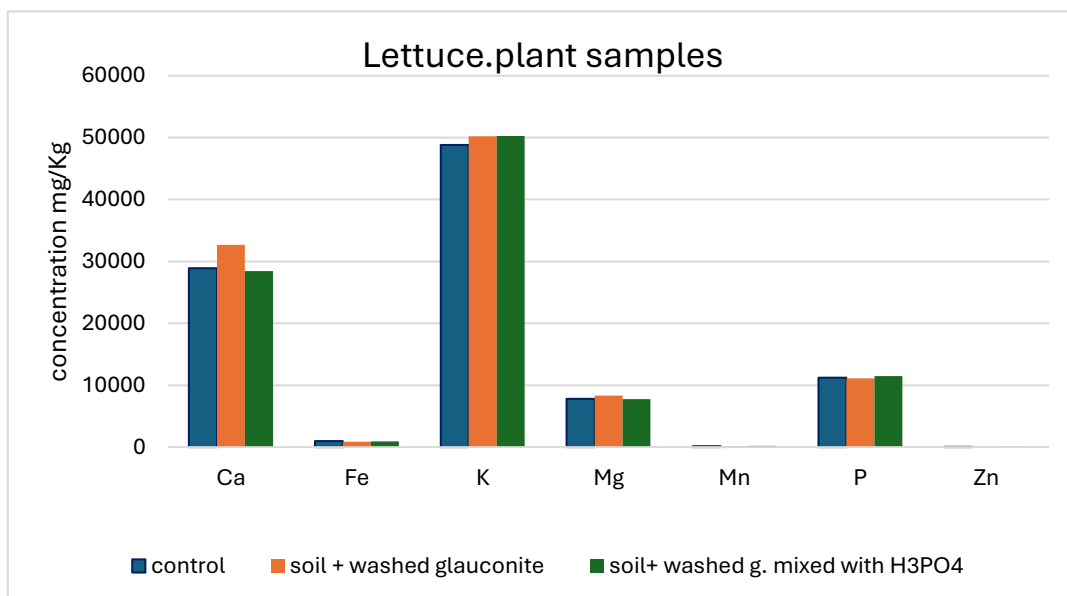


Figure 15. Nutrient Concentrations in plant samples after harvest

Overall, the results demonstrate that washing and phosphoric acid treatment of glauconite significantly modify nutrient dynamics, but their effects differ between soil and plant systems. Washing reduces readily available nutrient pools but improves ionic balance and uptake efficiency, while acid treatment enhances the release of specific nutrients, particularly potassium and micronutrients. However, it may also induce nutrient fixation processes, especially for phosphorus.

These findings highlight that soil nutrient concentration alone is not a sufficient indicator of plant nutrient availability, emphasizing the importance of considering nutrient speciation, soil chemistry interactions, and plant physiological regulation when evaluating fertilizer efficiency. The study confirms that modified glauconite can function as a multi-nutrient source, with its agronomic performance strongly dependent on the type of pre-treatment applied.

4.3.3. Effects of Glaucanite Treatments on Tomato

The results presented in Table 10 demonstrate that glaucanite treatments significantly influenced nutrient concentrations in both soil and tomato plant tissues, with statistically significant differences observed among treatments ($p < 0.05$). The data reveal a clear divergence between nutrient accumulation in soil and nutrient uptake by plants, reflecting the complex interactions among mineral amendments, soil chemistry, and plant physiological processes.

Table 10. Means of nutrient concentrations (\pm SD) in soil and plant samples after harvest (tomato under different treatments)

	Treatment	Ca (mg/kg)	Fe (mg/kg)	K (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	P (mg/kg)	Zn (mg/kg)
Nutrient concentrations in Soil samples	Control	2673 \pm 136 ^b	8407 \pm 1124 ^b	1161 \pm 94 ^c	1813 \pm 106 ^b	343 \pm 16 ^b	607 \pm 58 ^c	22 \pm 4 ^b
	Washed glaucanite	3906 \pm 103.8 ^a	13790.3 \pm 345 ^a	2288 \pm 585 ^a	2205 \pm 38 ^a	533.7 \pm 17.8 ^a	5580 \pm 127 ^a	27 \pm 0.8 ^a
	Washed glaucanite + H ₃ PO ₄	3624 \pm 63 ^a	12641 \pm 563 ^a	1643 \pm 316 ^b	2071.7 \pm 51 ^{ab}	490 \pm 18.9 ^a	5147 \pm 271.4 ^b	24 \pm 1 ^{ab}
Nutrient concentrations in plant samples	Control	37132 \pm 7121 ^b	159 \pm 49 ^b	34787 \pm 4127 ^b	5570 \pm 907 ^a	106 \pm 7 ^b	9187 \pm 743 ^a	39 \pm 7 ^a
	Washed glaucanite	38241 \pm 332 ^a	174 \pm 54 ^{ab}	39756 \pm 4053 ^a	5562 \pm 756 ^a	113 \pm 43 ^{ab}	9102 \pm 1508 ^a	34 \pm 5 ^b
	Washed glaucanite + H ₃ PO ₄	36917 \pm 3277 ^b	187 \pm 42 ^a	37037 \pm 3039 ^b	5437 \pm 55 ^a	111 \pm 13 ^{ab}	9152 \pm 655 ^a	31 \pm 8 ^b

Different superscript letters (^a, ^b, ^c) indicate significant differences ($p < 0.05$) between treatments within each column.

Nutrient Concentrations in Soil Samples After Harvest

In soil samples, as shown in Figure 16 and Table 10, the application of glauconite, particularly in the washed form, resulted in a substantial increase in nutrient concentrations compared to the control. The washed glauconite treatment recorded the highest levels of Most elements, including Ca (3906 mg kg⁻¹), Fe (13790 mg kg⁻¹), K (2288 mg kg⁻¹), Mg (2205 mg kg⁻¹), Mn (533 mg kg⁻¹), and P (5580 mg kg⁻¹). This indicates that washing effectively removed excess soluble salts while preserving and enhancing the release of structurally bound nutrients from glauconite. The increase in soil nutrient concentrations suggests that glauconite acts as a multi-element reservoir, gradually enriching the soil with both macro- and micronutrients. Similar behavior has been reported for silicate minerals, where mineral weathering contributes to sustained nutrient release and accumulation in soil systems (Ramos et al., 2015; van Straaten, 2006).

The washed glauconite + H₃PO₄ treatment also showed elevated nutrient levels, although slightly lower than washed glauconite alone for most elements such as K and P. This suggests that while acid treatment enhances mineral dissolution, it may also promote secondary reactions such as precipitation or fixation, particularly for phosphorus. The high soil P values (5147 mg kg⁻¹) indicate significant P input, but part of this phosphorus may exist in less available forms due to interactions with Ca and Fe, leading to the formation of stable phosphate compounds. Such fixation processes are well documented in soils receiving phosphate amendments, especially under conditions favoring Ca–P or Fe–P precipitation (Hinsinger et al., 2015; Penn & Camberato, 2019).

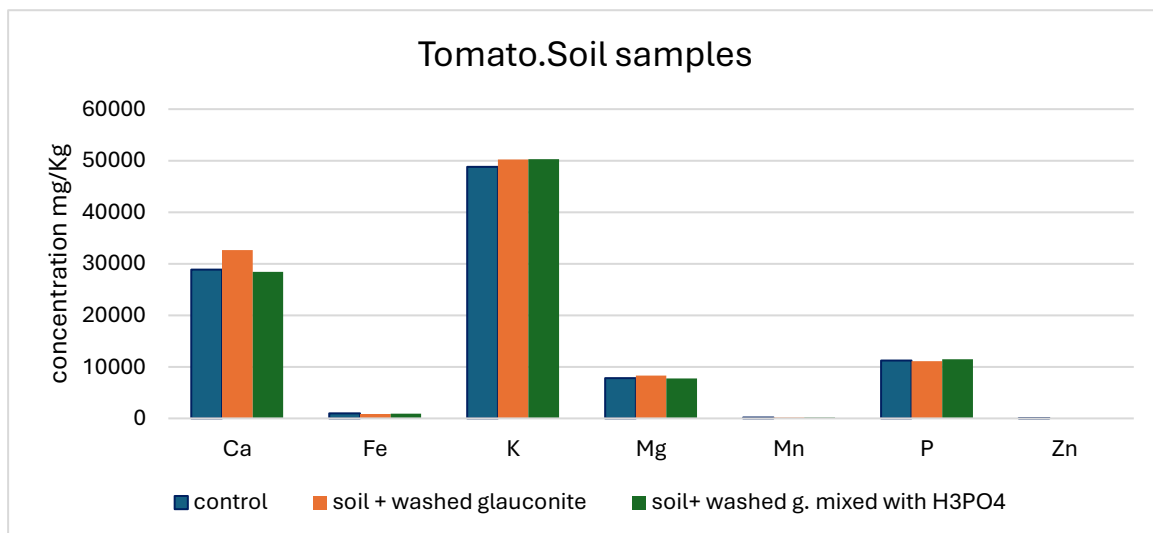


Figure 16. Nutrient Concentrations in Soil Samples After Harvest

Nutrient Concentrations in Plant Samples after harvest

In contrast to soil trends, plant nutrient concentrations, as presented in Figure 17 and Table 10 exhibited a more selective response. The highest potassium concentration in tomato plants (39756 mg kg^{-1}) was recorded under the washed glauconite treatment, significantly higher than both the control and the acid-treated treatment. This indicates that potassium released from washed glauconite was more effectively available for plant uptake compared to the acid-treated form. Although acidification increased total nutrient concentrations in soil, it may have altered nutrient speciation in a way that reduced immediate bioavailability, particularly through fixation or competition effects. This highlights that total soil nutrient content does not necessarily reflect plant-available fractions, a concept widely emphasized in soil fertility studies (White & Greenwood, 2013; Gu et al., 2020).

Calcium and magnesium concentrations in plant tissues did not show significant differences among treatments, despite their large variation in soil. This suggests that plant uptake of these elements is tightly regulated and may reach a physiological threshold beyond which additional soil supply does not translate into higher plant accumulation. Such regulation is consistent with the homeostatic control of nutrient uptake in higher plants, where internal demand governs absorption rates (Maathuis, 2016).

Micronutrient behavior revealed interesting patterns. The highest Fe concentration in plants (187 mg kg^{-1}) was observed under the acid-treated glauconite, indicating that acidification enhanced iron solubility and availability. Acidic conditions are known to increase Fe mobility by promoting dissolution of Fe oxides and hydroxides, thereby improving plant uptake (Marschner, 2012). Similarly, manganese concentrations were slightly higher under glauconite treatments, reflecting increased availability under modified soil chemical conditions.

In contrast, zinc concentrations were highest in the control treatment (39 mg kg^{-1}) and decreased under glauconite applications. This reduction may be attributed to antagonistic interactions between phosphorus and zinc, particularly in the acid-treated treatment where high P levels were recorded. Elevated phosphorus availability is known to suppress zinc uptake through both chemical interactions in soil and physiological mechanisms within the plant (Cakmak & Kutman, 2018).

Phosphorus concentrations in plant tissues remained relatively stable across treatments despite large differences in soil P content. This suggests that tomato plants maintained regulated P uptake, likely due to limitations in P mobility and diffusion in soil, as well as plant-controlled uptake

mechanisms. It is well established that phosphorus uptake is governed more by root activity and rhizosphere processes than by total soil P concentration (Hinsinger et al., 2015).

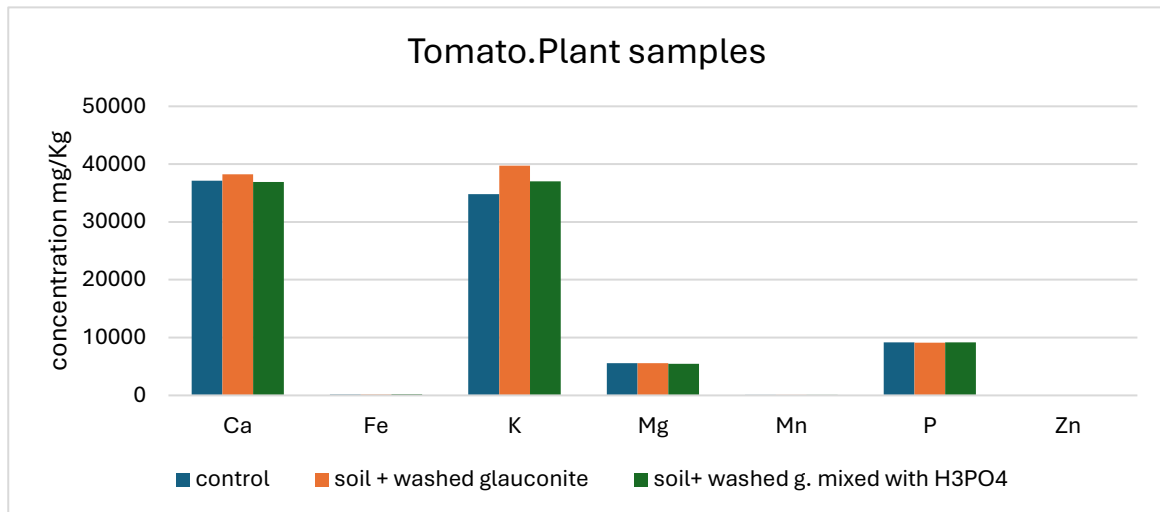


Figure 17. Nutrient Concentrations in plant Samples After Harvest

Overall, the results demonstrate that washed glauconite was more effective than acid-treated glauconite in enhancing plant nutrient uptake, despite the latter increasing total nutrient concentrations in soil. This indicates that washing improves nutrient availability by optimizing ionic balance and reducing inhibitory effects, while acid treatment may lead to partial nutrient fixation or altered speciation.

These findings highlight the importance of distinguishing between total nutrient content and bioavailable fractions, as well as the role of soil chemical processes in regulating nutrient transfer from soil to plant. The study confirms that glauconite can serve as a multi-nutrient fertilizer, but its effectiveness is strongly dependent on pre-treatment method and its influence on nutrient dynamics within the soil–plant system.

4.4. Agronomic Performance and Residual Effects of Glaucosite as a Potassium Source in a Potato–Maize Cropping System (Field Experiment)

The strategic management of soil fertility in Egypt represents a cornerstone of national food security, particularly given the intensive nature of agricultural production in the Nile Valley and the expansion into reclaimed sandy soils of the Western Desert. Potassium (K) is a critical macronutrient that governs a multitude of physiological and biochemical processes within plant systems, yet Egypt remains heavily reliant on the importation of commercial potassic fertilizers, such as potassium sulfate (K_2SO_4 , or SOP), to meet the rising demands of its agrarian sector (Morsy et al., 2016). The economic burden of these imports, coupled with the environmental risks of nutrient leaching and soil salinization in arid regions, has necessitated the exploration of indigenous mineral alternatives (Verma, 2018). Glaucosite, a green, iron-rich phyllosilicate mineral abundant in the Bahria Oasis of Egypt, presents a compelling solution as a slow-release potassium fertilizer (El-Sharkawy et al., 2025). This investigation evaluates the direct impact of glaucosite-SOP mixtures on the productivity of potatoes (*Solanum tuberosum* L.) and the subsequent residual efficacy on maize (*Zea mays* L.) in a sequential cropping system designed to maximize nutrient use efficiency and soil resilience.

Agricultural Potential of Egyptian Glaucosite

As mentioned previously in the Literature review section, glaucosite, commonly referred to as "greensand" in agricultural contexts, is a diagenetic sedimentary mineral of the mica group formed through marine authigenesis in shallow-water environments. In Egypt, significant deposits are localized in the Western Desert, particularly near the El-Gedida mining area within the Bahria Oasis (Morsy et al., 2016). The chemical structure of glaucosite is characterized by a 2:1 dioctahedral phyllosilicate framework with the generalized formula $[(K, Na, Ca)(Fe^{3+}, Al, Mg, Fe^{2+})_2(Si, Al)_4O_{10}(OH)_2]$. The substitution of Al^{3+} and Al^{2+} for Al^{3+} in the octahedral layers, and Al^{3+} for Si^{4+} in the tetrahedral layers, creates a negative charge that is primarily balanced by interlayer K^+ ions (Costa et al., 2024).

The agricultural value of glaucosite is derived from its unique slow-release mechanism. Unlike highly soluble potassic salts, the K in glaucosite is released gradually through weathering and cation exchange processes, which reduces the immediate risk of "salt burn" and minimizes leaching losses—a critical advantage in the sandy, porous soils typical of Egyptian reclamation projects (Rudmin et al., 2019a). Furthermore, glaucosite is a multi-nutrient mineral, containing essential trace elements such as Fe, Mn, Zn, Cu, B and Mo, as well as macronutrients like Mg and Ca (Eldawwy et al. 2024). These elements contribute to the overall fertility of the soil and support

the complex enzymatic functions required for optimal plant growth in stressed environments (Costa et al.,2024).

4.4.1. Experimental Results for Potato (Crop 1) Growth and Yield

The first phase of the field experiment focused on the primary crop, potatoes, which have a notably high requirement for potassium to support tuber bulking and starch accumulation (Torabian et al., 2021). The experimental design utilized different blending ratios of conventional SOP and Egyptian glauconite to determine the optimal balance between immediate and sustained nutrient availability.

Table 11: Growth Parameters of Potato Plants and Tubers

Table 11 presents the quantitative data regarding the fresh and dry biomass production of both the vegetative plant parts and the harvested tubers under varying K treatment regimes. All data are expressed as ton per hectare (ton/ha) and are accompanied by standard deviation (\pm) and the Least Significant Difference (LSD at 5%) for statistical comparison.

Treatments	Fresh weight of the plant (ton/ha)	Dry weight of the plant (ton/ha)	Fresh weight of the tubers (ton/ha)	Dry weight of the tubers (ton/ha)
100% SOP	8.07 \pm 0.21	1.80 \pm 0.10	32.0 \pm 1.0	7.60 \pm 0.36
75% SOP, 25% Gl.	9.00 \pm 1.44	2.00 \pm 0.10	31.3 \pm 2.1	7.87 \pm 0.74
50% SOP, 50% Gl.	9.07 \pm 1.04	2.03 \pm 0.35	32.3 \pm 3.5	8.07 \pm 0.55
25% SOP, 75% Gl.	9.47 \pm 0.42	2.00 \pm 0.10	32.3 \pm 5.7	7.53 \pm 1.48
100% Gl.	11.13 \pm 1.50	2.53 \pm 0.55	32.0 \pm 2.7	7.53 \pm 0.75
100% Raw Gl.	7.50 \pm 0.20	1.87 \pm 0.06	30.0 \pm 1.0	7.27 \pm 0.35
LSD 5%	0.01	0.08	0.933	0.86

The application of different potassium sources significantly influenced potato vegetative growth and tuber yield (Table 11 and Figure 18). The results demonstrate clear variations among treatments in terms of fresh and dry biomass production as well as tuber yield parameters, as indicated by the low LSD values, confirming that the observed differences among treatments were statistically significant.

Vegetative growth responded markedly to the application of glauconite-based treatments. The 100% acid-treated glauconite treatment recorded the highest fresh plant weight (11.13 ton.ha⁻¹) and dry plant weight (2.53 ton.ha⁻¹), exceeding the 100% potassium sulfate (SOP) treatment by approximately 38% and 40.5%, respectively. This substantial increase in vegetative biomass suggests that glauconite contributes to a more sustained nutrient supply and improved soil fertility conditions that favor canopy development (Morsy et al., 2016). In addition to its potassium content, glauconite contains micronutrients such as iron and magnesium, which play essential roles in chlorophyll synthesis and the stability of photosynthetic pigments. These elements likely contributed to the enhanced vegetative growth observed in glauconite-treated plots compared with the sole SOP treatment (Eldawwy et al., 2025).

From a soil chemistry perspective, the superior performance of acid-treated glauconite can be attributed to the activation process using nitric acid. Acid treatment likely promoted partial dissolution of the mineral structure and increased the release of exchangeable potassium from interlayer sites, thereby enhancing its bioavailability in the soil solution. This process improves the agronomic effectiveness of glauconite by transforming part of the structural potassium into more plant-accessible forms.

In contrast, the raw glauconite treatment exhibited the lowest vegetative growth, with fresh and dry plant weights of 7.50 and 1.87 ton.ha⁻¹, respectively. The relatively poor performance of this treatment can be explained by the limited solubility of potassium within the untreated mineral lattice, which restricts the short-term release of potassium required to sustain rapid vegetative growth in potato crops.

Tuber yield parameters showed a similar trend, although the differences among treatments were less pronounced. Treatments containing at least 50% glauconite produced tuber yields comparable to or slightly higher than the 100% SOP control (32.0 ton.ha⁻¹). The 50% SOP + 50% glauconite treatment produced the highest dry tuber weight (8.07 ton.ha⁻¹), indicating a synergistic interaction between the two potassium sources. In this case, the readily soluble potassium supplied by SOP likely supported early plant growth and tuber initiation, while the gradual release of potassium from glauconite maintained nutrient availability during the tuber bulking stage (Rakesh et al., 2020b). This balanced nutrient supply may enhance carbohydrate translocation and starch accumulation in developing tubers.

Conversely, the 100% raw glauconite treatment recorded the lowest fresh tuber yield (30.0 ton.ha⁻¹). This outcome is likely related to the limited solubility of potassium in untreated glauconite, which reduces its ability to meet the high potassium demand of potato plants during

the critical tuber bulking phase (El-Sharkawy et al., 2025). Without prior chemical activation, potassium release from glauconite depends mainly on slow mineral weathering processes, which may not provide sufficient K availability during the relatively short potato growth cycle.

The superior performance of acid-treated glauconite compared with raw glauconite highlights the importance of mineral activation in improving the agronomic effectiveness of silicate-based potassium fertilizers. Acid leaching likely removed surface impurities and partially disrupted the mineral structure, increasing the exposure of exchangeable potassium and enhancing its dissolution into the soil solution. This mechanism explains the higher plant biomass and tuber yield observed under the activated glauconite treatments.

Overall, these findings indicate that acid-treated glauconite is an effective alternative potassium source capable of supporting both vegetative growth and tuber development in potato. Moreover, the results demonstrate that partial substitution of potassium sulfate with glauconite, particularly at 50–75% substitution levels, can maintain or even enhance crop productivity while introducing a slow-release potassium source. Such a strategy not only improves fertilizer efficiency during the current crop but may also contribute to improved residual soil potassium availability for the subsequent maize crop grown in the same experimental plots.

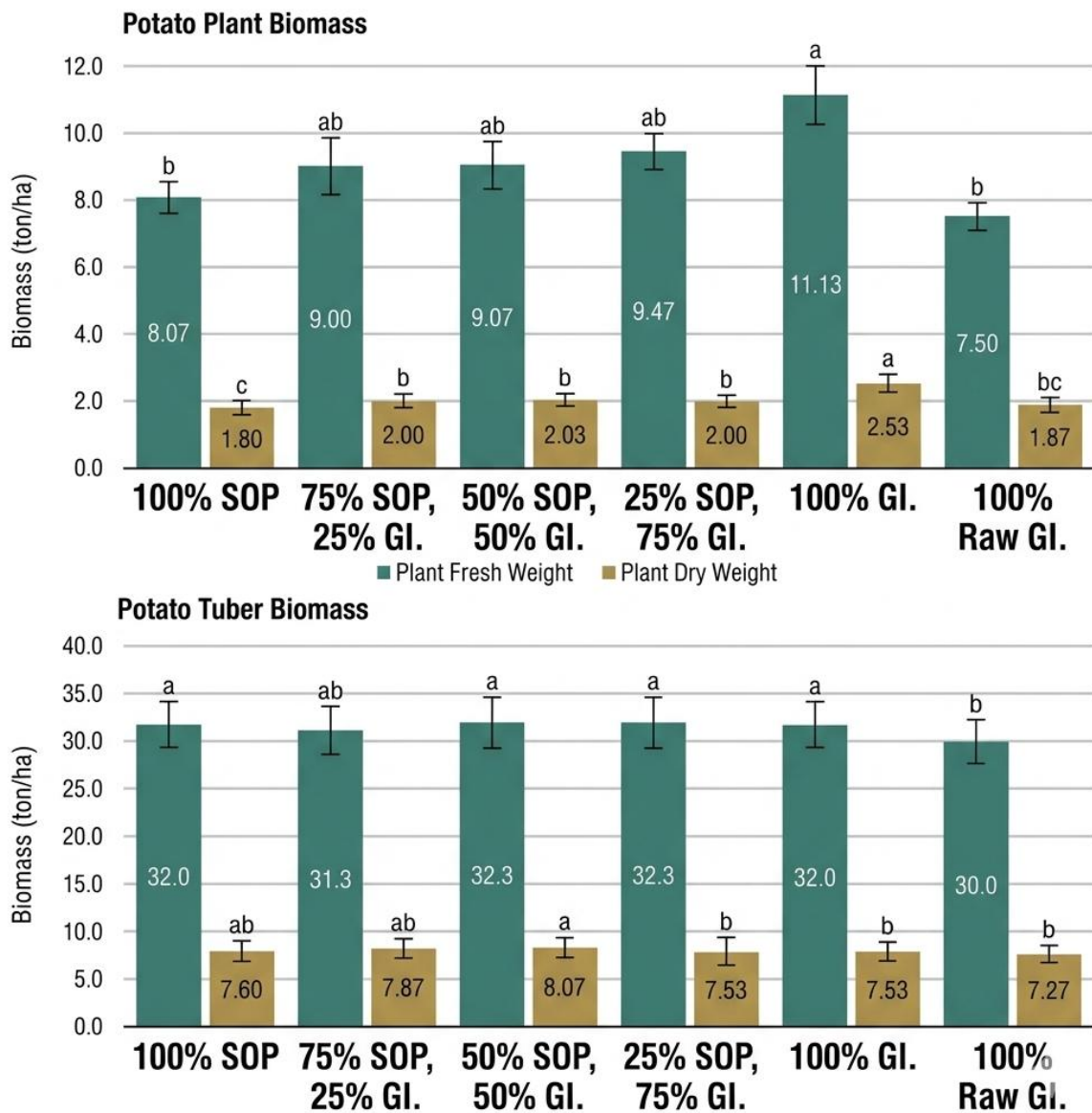


Figure 18. Fresh and dry biomass production of the potato crop

Fresh and dry biomass production of potato plant parts and harvested tubers under varying K treatment regimes. All data are expressed as tons per hectare (ton/ha) and are accompanied by standard deviation (\pm) error bars. The different letters show a significant difference between treatments at $\alpha=0.05$, $n=3$, derived from the Least Significant Difference (LSD 5%) values provided in Table 11.

Table 12: Potassium Dynamics in Potato Tissues and Soil Residuals

Table 12 delineates the total potassium uptake within the plant and tubers, alongside the residual K concentration in the soil profile after the potato harvest. These parameters are essential for understanding the efficiency of K utilization and the remaining fertility available for subsequent crops. All values are presented as means of three replicates \pm standard deviation (SD), and treatment differences were evaluated using the least significant difference (LSD) test at the 5% significance level.

Treatments	K uptake in plant (kg/ha)	K uptake in tubers (kg/ha)	K concentration in soil (mg/kg)
100% SOP	42 \pm 0.6	151 \pm 18.1	364 \pm 80.8
75% SOP, 25% Gl.	40 \pm 9.7	146 \pm 11.3	370 \pm 9.8
50% SOP, 50% Gl.	39 \pm 2.1	154 \pm 7.2	353 \pm 40.7
25% SOP, 75% Gl.	43 \pm 5.0	141 \pm 34.9	310 \pm 9.8
100% Gl.	50 \pm 10.0	131 \pm 12.3	291 \pm 9.8
100% Raw Gl.	27 \pm 2.1	111 \pm 4.0	289 \pm 7.8
LSD 5%	0.018	0.092	0.061

Potassium Uptake and Soil Residual K after Potato Harvest

The data presented in Table 12 reveal significant variations in potassium uptake by potato plants and tubers, as well as in residual soil K concentration, in response to different potassium sources. These parameters provide critical insight into potassium use efficiency, partitioning within the plant, and the sustainability of K supply for subsequent crops.

Potassium uptake by the vegetative parts ranged from 27 to 50 kg ha⁻¹, with the highest value recorded under 100% acid-treated glauconite (50 kg ha⁻¹), followed by the 25% SOP + 75% glauconite treatment (43 kg ha⁻¹). In contrast, the lowest uptake (27 kg ha⁻¹) was observed in the

raw glauconite treatment, indicating a clear limitation in K availability when glauconite is applied without prior activation. The enhanced K uptake in the acid-treated glauconite treatments can be attributed to increased dissolution of K-bearing mineral phases and improved release of exchangeable K into the soil solution, thereby enhancing plant availability. Similar findings have been reported where acid activation of silicate minerals significantly increased potassium release and uptake efficiency (Shekhar et al., 2019).

In tubers, potassium uptake was substantially higher than in vegetative tissues, reflecting the strong role of K in carbohydrate translocation and storage organ development. The highest tuber K uptake (154 kg ha^{-1}) was recorded in the 50% SOP + 50% glauconite treatment, followed closely by the 100% SOP treatment (151 kg ha^{-1}). This indicates that the combined application of soluble and slow-release potassium sources optimizes K availability throughout the growth cycle. The rapid availability of K from SOP supports early physiological processes, while glauconite ensures a sustained supply during tuber bulking, resulting in efficient nutrient partitioning toward storage organs (Rakesh et al., 2020b).

Despite the highest vegetative K uptake observed under the 100% glauconite treatment, tuber K uptake in this treatment (131 kg ha^{-1}) was lower than in the combined treatments. This suggests that although acid-treated glauconite enhances overall K availability, the absence of an immediately soluble K fraction may limit the synchronization between K supply and peak demand during tuber development. Such behavior is consistent with the slow-release nature of mineral-based potassium sources, which may not fully meet crop demand during critical growth stages (Manning, 2010).

The raw glauconite treatment exhibited the lowest K uptake in both plant (27 kg ha^{-1}) and tubers (111 kg ha^{-1}), confirming that potassium in untreated glauconite remains largely in non-exchangeable or structural forms with limited short-term bioavailability. This observation aligns with previous studies indicating that potassium in unprocessed glauconite is predominantly bound within the mineral lattice and released only through slow weathering processes (El-Sharkawy et al., 2025).

Residual soil potassium after harvest showed an inverse trend relative to plant uptake in some treatments. The highest residual soil K concentration (370 mg kg^{-1}) was observed in the 75% SOP + 25% glauconite treatment, followed by the 100% SOP treatment (364 mg kg^{-1}). This indicates that a portion of the applied potassium, particularly from highly soluble sources such as SOP, remained unused in the soil, potentially due to limited plant uptake efficiency or fixation within

soil mineral fractions. High residual K in such treatments may also suggest a risk of leaching losses under certain soil conditions, particularly in coarse-textured soils (Zörb et al., 2014).

In contrast, the lowest residual soil K values were observed in the 100% glauconite (291 mg kg⁻¹) and raw glauconite (289 mg kg⁻¹) treatments, suggesting a more gradual release and uptake of potassium throughout the growing season. The relatively lower residual K in the acid-treated glauconite treatment, despite higher plant uptake, indicates improved synchronization between K release and plant demand, which is a desirable characteristic of slow-release fertilizers. This controlled release behavior has been highlighted as a key advantage of glauconite-based fertilizers in improving nutrient use efficiency and reducing environmental losses (Dasi et al., 2024).

The 25% SOP + 75% glauconite treatment showed moderate residual soil K (310 mg kg⁻¹) combined with relatively high plant uptake, indicating a balanced system where potassium supply was efficiently utilized while still maintaining a residual pool for subsequent crops. This is particularly important in the context of the sequential cropping system employed in this study, where the residual potassium is expected to contribute to the nutrition of the following maize crop.

Overall, the results demonstrate that acid-treated glauconite enhances potassium uptake efficiency and promotes a more balanced distribution of K between plant tissues and soil reserves, compared to both conventional SOP and raw glauconite. The combination of SOP and glauconite, particularly at 50:50 ratios, appears to provide the most efficient strategy by ensuring immediate availability and sustained release of potassium. These findings are consistent with previous research emphasizing the benefits of integrating soluble and mineral potassium sources to optimize nutrient use efficiency and maintain soil fertility over time (Manning, 2010; Shekhar et al., 2019; Dasi et al., 2024).

Importantly, the observed residual soil potassium levels under glauconite treatments highlight their potential role in supporting the residual fertility required for the subsequent maize crop, thereby improving the sustainability of potassium management in intensive cropping systems.

4.4.2. Residual effect of potassium sources on *Zea mays* (maize) growth and K dynamics

The second year of the study evaluated the "carry-over" effect of the initial K treatments on maize, grown without any additional fertilization. This phase is critical for assessing the long-term agronomic value of slow-release minerals in Egyptian crop rotations.

Table 13: Growth and Potassium Parameters of Zea Mays

Table 13 summarizes the residual influence of the initial K treatments on maize fresh weight, dry matter, K uptake, and final soil K concentrations. All values are presented as means of three replicates \pm standard deviation (SD), and treatment differences were evaluated using the least significant difference (LSD) test at the 5% significance level.

Treatments	Fresh weight of plants (ton/ha)	Dry matter of plants (ton/ha)	K uptake in plants (kg/ha)	Soil K concentration post-harvest (mg/kg)
100% SOP	97.1 \pm 3.8	21.9 \pm 0.9	325 \pm 56	282 \pm 4
75% SOP, 25% Gl.	97.6 \pm 9.3	22.0 \pm 2.1	351 \pm 23	313 \pm 25
50% SOP, 50% Gl.	99.0 \pm 3.4	22.3 \pm 0.8	367 \pm 93	313 \pm 4
25% SOP, 75% Gl.	101.4 \pm 12.5	22.9 \pm 0.6	391 \pm 31	332 \pm 24
100% Gl.	98.6 \pm 12.9	22.8 \pm 1.7	348 \pm 16	297 \pm 13
100% Raw Gl.	94.3 \pm 5.7	21.4 \pm 1.3	300 \pm 17	298 \pm 26
LSD 5%	0.95	0.824	0.322	0.074

The results presented in Table 13 and Figure 19 clearly demonstrate that the residual effect of potassium sources applied during the potato season significantly influenced maize growth, potassium uptake, and soil K status. The observed differences among treatments were statistically significant, as indicated by the LSD values, confirming that the type and form of potassium fertilizer applied to the preceding crop had a measurable carry-over effect on the subsequent maize crop.

Maize growth, expressed as fresh and dry biomass, showed a consistent improvement with increasing proportions of glauconite in the initial treatments. The highest fresh weight (101.4 ton. ha⁻¹) and dry matter yield (22.9 ton. ha⁻¹) were recorded under the 25% SOP + 75% glauconite

treatment, followed closely by the 100% glauconite treatment. In contrast, the lowest values (94.3 and 21.4 ton. ha⁻¹ for fresh and dry weight, respectively) were observed under the raw glauconite treatment. This pattern indicates that acid-treated glauconite provided a sustained release of potassium that remained available for the second crop, thereby enhancing biomass production. Such residual effects are characteristic of slow-release mineral fertilizers, which gradually supply nutrients over extended periods (Manning, 2010).

The improved growth performance in glauconite-amended treatments can be attributed to the continued release of potassium from non-exchangeable and interlayer sites that were partially activated during the nitric acid treatment. This gradual release likely maintained an adequate level of potassium in the soil solution throughout the maize growing season, supporting physiological processes such as enzyme activation, osmotic regulation, and photosynthesis (Zörb et al., 2014). In addition, glauconite may have contributed secondary nutrients, further enhancing plant growth and metabolic activity.

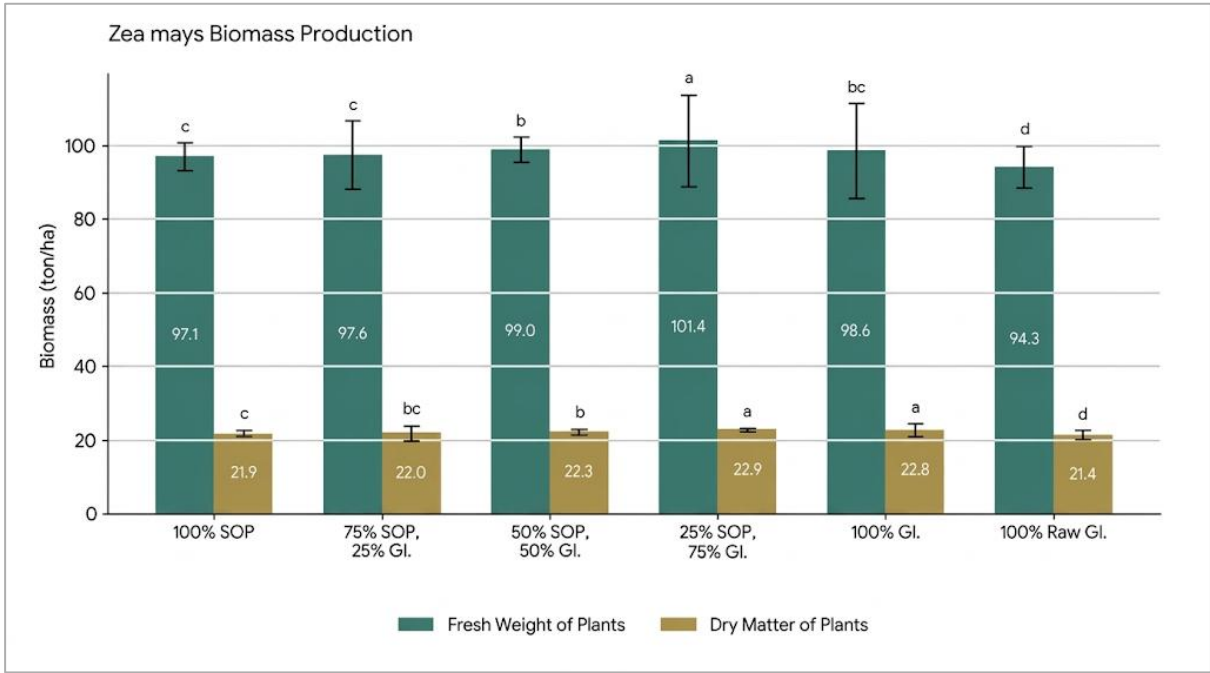


Figure 19. Fresh and dry biomass production of the Zea mays crop

Potassium uptake by maize plants followed a similar trend to biomass production. The highest K uptake (391 kg ha^{-1}) was recorded in the 25% SOP + 75% glauconite treatment, followed by the 50% SOP + 50% glauconite treatment (367 kg ha^{-1}). These values were notably higher than the 100% SOP treatment (325 kg ha^{-1}), indicating that the incorporation of glauconite improved potassium use efficiency in the residual phase. The enhanced K uptake in these treatments suggests that the combination of soluble and slow-release potassium sources not only benefits the primary crop but also ensures continued nutrient availability for subsequent crops. Similar observations have been reported in studies where mineral potassium sources such as glauconite contributed to sustained K supply and improved nutrient recovery over multiple cropping cycles (Dasi et al., 2024; Shekhar et al., 2019).

In contrast, the raw glauconite treatment showed the lowest K uptake (300 kg ha^{-1}), reflecting the limited residual availability of potassium from untreated glauconite. This result confirms that without prior chemical activation, the release of potassium from glauconite remains too slow to significantly contribute to crop nutrition within a short time frame. Comparable findings have been reported where untreated silicate minerals exhibited minimal contribution to plant-available potassium due to strong structural binding (El-Sharkawy et al., 2025).

Residual soil potassium concentrations after maize harvest further support these findings. The highest soil K values (332 mg kg^{-1}) were observed in the 25% SOP + 75% glauconite treatment, followed by the 50% SOP + 50% glauconite and 75% SOP + 25% glauconite treatments (313 mg kg^{-1}). These elevated residual levels indicate that glauconite not only supplied potassium to the maize crop but also contributed to maintaining a stable pool of available K in the soil. This behavior reflects the buffering capacity of glauconite, which can adsorb and release potassium depending on plant demand and soil conditions. (Oze et al., 2019).

In contrast, the 100% SOP treatment resulted in lower residual soil K (282 mg kg^{-1}), suggesting that potassium derived from highly soluble fertilizers is more prone to rapid uptake and potential losses, with limited contribution to long-term soil fertility. This observation is consistent with previous reports indicating that soluble potassium fertilizers may lead to inefficient nutrient use and reduced residual benefits in subsequent cropping systems (Zörb et al., 2014).

Interestingly, the 100% acid-treated glauconite treatment maintained moderate soil K levels (297 mg kg^{-1}) while supporting relatively high biomass and K uptake, indicating a balanced system in which potassium release was effectively synchronized with plant demand. This controlled release pattern is a key advantage of glauconite as a sustainable potassium source, as it reduces nutrient losses while ensuring prolonged availability (Dasi et al., 2024; Verma, 2018).

Overall, the results clearly demonstrate that acid-treated glauconite has a pronounced residual effect, enhancing maize growth, potassium uptake, and soil K availability compared to conventional potassium fertilization. The 25% SOP + 75% glauconite treatment emerged as the most effective strategy, providing an optimal balance between immediate nutrient supply and sustained release. These findings highlight the potential of glauconite as a long-term potassium source capable of improving nutrient use efficiency and supporting sustainable soil fertility management in sequential cropping systems.

Mechanisms of Synergistic and Residual Action

The data from this sequential cropping experiment provides compelling evidence for the integration of glauconite into Egyptian fertilization programs. The discussion that follows examines the underlying mechanisms that drive these results, the physiological role of potassium, and the broader implications for sustainable agriculture in Egypt.

Synergy Between Soluble and Mineral Potassium Sources

The superior performance of the 50/50 and 25/75 SOP-Glauconite mixtures in both potato tuber dry weight and maize residual growth suggests a potent synergistic interaction. Soluble fertilizers like SOP deliver a high concentration of K^+ ions immediately into the soil solution, which is essential for the early establishment of root systems and the high demand during the vegetative and tuber initiation phases of the potato (Sidhu et al., 2025). However, in Egyptian sandy soils, these ions are vulnerable to rapid leaching below the root zone (Costa et al., 2024).

Glauconite mitigates this vulnerability through its high cation exchange capacity (CEC) and its slow-release kinetics. The mineral particles act as a "sink" that can adsorb and retain K^+ ions from the soluble SOP, preventing their loss to leaching (Rudmin et al., 2019a). As the season progresses and the root system expands, the plant begins to draw on the K locked within the glauconite matrix. This release is further accelerated by the secretion of organic acids from the roots and the presence of potassium-solubilizing bacteria, which are often found in association with the nutrient-rich surfaces of glauconite pellets (El-sharkawy et al., 2025). This synchronized release maintains an optimal soil solution concentration throughout the growing season, preventing both deficiency and luxury consumption (Oze et al., 2019).

Physiological Drivers of Crop Response

Potassium is a highly mobile element within the plant and plays a central role in the translocation of carbohydrates from the "source" (leaves) to the "sink" (tubers or grains) (Sidhu et al., 2025). In potatoes, K is essential for the activation of starch synthase, and a steady supply is necessary to

maintain the osmotic pressure required for tuber cell expansion (Torabian et al., 2021). The fact that tuber dry weights were highest in the mixtures (Table 11) indicates that the combined K delivery system provided better support for starch accumulation than SOP alone.

In maize, K is vital for stomatal regulation and water-use efficiency, particularly in the arid conditions of Egypt where high temperatures and low humidity increase evapotranspiration rates (Shedeed , 2018).The residual K from glauconite, which supported a 391 kg/ha uptake in maize (Table 13), was critical for maintaining turgidity and preventing the "early senescence" that often limits yield in nutrient-depleted soils (Praveen et al.,2020). Furthermore, the micronutrients provided by glauconite, such as zinc and manganese, are known to enhance the plant's stress tolerance mechanisms, further explaining the robust growth of maize in the glauconite-treated plots (Costa et al.,2024).

Enhancing Soil Resilience and Physical Structure

Beyond its role as a nutrient source, glauconite functions as a significant soil amendment. The inclusion of glauconite has been shown to improve the physical properties of sandy and degraded soils by reducing bulk density and increasing porosity and moisture-holding capacity (Eldawwy et al., 2024). This is reflected in the superior vegetative growth of both potatoes and maize in this study. Improved soil structure allows for better root penetration and aeration, which in turn enhances the plant's ability to explore the soil volume for water and other nutrients (Costa et al.,2024).

Moreover, the use of glauconite helps to mitigate the salinization risks common in Egyptian agriculture. Traditional potassic salts can contribute to the accumulation of chloride or sulfate ions, which increase soil osmotic pressure and can be toxic to sensitive crops (Verma, 2018). Glauconite, being a mineral silicate, does not add to the soluble salt load in the same manner, making it an "eco-friendly" alternative that preserves the health of the soil ecosystem over multiple cropping cycles (Verma, 2018).

Economic and National Implications

For the Egyptian agricultural sector, the results of this study offer a clear pathway toward reducing the national dependence on imported fertilizers. With glauconite resources readily available in the Western Desert, the transition toward mineral-based K management could significantly lower the cost of production for high-value crops like potatoes (Morsy et al., 2016). The find that a 25/75 SOP-Glauconite ratio provides superior residual benefits for maize indicates that farmers can

reduce their total fertilizer applications over a two-crop rotation, further enhancing the profitability and sustainability of their operations.

5. CONCLUSION AND RECOMMENDATIONS

Conclusion:

This doctoral research presents a comprehensive assessment of glauconite deposits from the El-Gedida region in Egypt as a sustainable potassium fertilizer and soil amendment. The conclusions are drawn from mineralogical characterization, chemical extraction experiments, acid activation trials, controlled pot experiments involving tomato and lettuce, and field experiments conducted on successive crops (potato and maize). The results significantly contribute to the scientific understanding of glauconite's nutrient potential, environmental safety, and agronomic performance under both controlled and field conditions.

- Glauconite is a Potassium-Rich, Multi-Nutrient Source

The studied glauconite samples contain 3.0–3.3% potassium by weight, primarily in the form of K_2O embedded within the mineral lattice. In addition to potassium, glauconite also provides secondary macronutrients (magnesium, calcium, sodium) and micronutrients (iron, zinc, copper, nickel) that are essential for plant growth and soil fertility. These findings confirm glauconite's role as a slow-release, multi-nutrient agro-mineral capable of supporting long-term plant nutrition in both pot and field conditions.

- Environmental Safety Confirmed by Multi-Tier Chemical Assessment

The results of pseudo-total elemental content and the application of the BCR sequential extraction protocol revealed that all potentially toxic elements (PTEs), including cadmium, lead, nickel, and chromium, are either undetectable or present in concentrations well below internationally accepted agricultural safety thresholds (e.g., EU Regulation 2019/1009). Moreover, the majority of PTEs were found in the residual fraction, indicating low mobility and minimal environmental risk when applied to soil. These findings confirm that glauconite can be safely used in agricultural systems without adverse environmental impacts.

- First Application of BCR Sequential Extraction to Glauconite

This study is the first to apply the BCR sequential extraction method to glauconite sediments. The results provided critical insights into the binding forms of essential nutrients, demonstrating that most potassium and associated elements are retained in stable mineral fractions. This confirms the

slow-release nature of glauconite and highlights the importance of fractionation techniques in evaluating nutrient bioavailability rather than relying solely on total elemental content.

- Single Extractant Comparison Highlights Agronomic Accessibility

The comparison between ammonium lactate (AL) and potassium chloride (KCl) as single extractants showed that AL was significantly more effective in mobilizing potassium, magnesium, calcium, and zinc. The use of AL offers a practical and agronomically relevant method for estimating nutrient availability from glauconite. This reinforces its suitability as a diagnostic tool for soil fertility evaluations involving silicate-based fertilizers.

- Acid Activation Enhances Nutrient Release

The research demonstrated that inorganic acids, particularly HCl, are more effective than organic acids (e.g., citric, oxalic) in releasing potassium from glauconite. While HCl treatment yielded the highest release rates, the use of acids must be carefully considered in practice due to potential environmental and cost-related concerns. Nonetheless, this insight is valuable for developing enhanced formulations where rapid nutrient release is needed. In general, the results showed that inorganic acids significantly enhanced potassium release from glauconite. However, results from both pot and field experiments showed that increased total nutrient solubility does not necessarily translate into improved plant uptake. Acid-treated glauconite increased nutrient concentrations in soil, particularly phosphorus, but also promoted nutrient fixation and reduced bioavailability in some cases. This highlights that nutrient speciation and soil chemical interactions play a critical role in determining fertilizer efficiency.

- Particle Size Reduction Yields Limited Benefits

Although finer particles showed slightly increased nutrient release, the overall results confirmed that particle size reduction has a limited effect on nutrient availability. This indicates that glauconite can be applied without extensive mechanical processing, supporting cost-effective large-scale agricultural use.

- Pot Experiments Confirm the Importance of Nutrient Bioavailability

The pot experiments with lettuce and tomato demonstrated that glauconite significantly influences soil–plant nutrient dynamics. Washed glauconite improved potassium uptake and maintained balanced nutrient availability, while acid-treated glauconite increased total soil nutrient concentrations but did not consistently enhance plant uptake.

These results confirm that nutrient bioavailability, rather than total soil content, governs plant uptake, and that pre-treatment methods strongly influence the efficiency of glauconite as a fertilizer. Crop-specific responses were observed, with tomato showing higher sensitivity due to greater nutrient demand compared to lettuce.

- Field Experiments Validate Agronomic Performance under Practical Conditions

The field experiment on potato demonstrated that glauconite, particularly when combined with potassium sulfate, can maintain or improve crop yield and biomass production. The integration of glauconite with conventional fertilizers provided a balanced nutrient supply, combining immediate availability with sustained release throughout the growing season.

- Residual Effect Confirms Long-Term Fertility Benefits

The successive maize crop clearly demonstrated the residual effect of glauconite application. Treatments containing higher proportions of glauconite resulted in improved potassium uptake and higher soil K availability without additional fertilization. This confirms that glauconite contributes to long-term soil fertility and reduces the need for repeated fertilizer applications.

- Soil Improvement and Sustainability Benefits

Beyond nutrient supply, glauconite contributed to improving soil chemical properties and maintaining nutrient reserves after harvest. Its slow-release behavior reduces nutrient losses through leaching and enhances nutrient use efficiency. Additionally, washing treatment reduced salinity risks associated with sodium content, improving the suitability of glauconite for agricultural application.

- Strategic Relevance for Egyptian Agriculture

The findings of this study highlight the strong potential of glauconite as a locally available alternative to imported potassium fertilizers in Egypt. Its use can reduce production costs, enhance soil fertility, and support sustainable agricultural practices, particularly in arid and semi-arid regions. The combination of glauconite with conventional fertilizers offers a practical approach for improving both short-term productivity and long-term soil health.

- Alignment with Sustainable Agricultural Goals

The application of glauconite aligns with sustainable agriculture principles by reducing nutrient leaching, improving nutrient use efficiency, and offering a natural alternative to synthetic

fertilizers. It also supports circular resource use, particularly when combined with organic amendments.

Recommendations:

Based on the research outcomes, the following recommendations are proposed for agricultural application, policy, industrial development, and further study of glauconite as a sustainable potassium fertilizer:

- Optimization of Glauconite Pre-Treatment

Washing is recommended as the most suitable pre-treatment method to improve nutrient bioavailability and reduce salinity effects associated with sodium content.

Acid treatment may enhance nutrient release; however, it should be carefully controlled due to its potential to induce nutrient fixation and reduce plant uptake efficiency.

- Integration with Conventional Fertilization

Glauconite can be effectively used in combination with conventional potassium fertilizers (e.g., SOP) to provide both immediate and sustained nutrient supply.

Partial substitution of mineral fertilizers with glauconite is recommended to maintain yield while improving nutrient use efficiency.

- Soil Fertility and Residual Effect

Glauconite is recommended for long-term soil fertility management due to its slow-release characteristics and demonstrated residual effect in successive crops.

Its application is particularly suitable for soils with low potassium availability or high nutrient loss potential.

- Crop-Specific Considerations

Application strategies should consider crop nutrient demand, as higher responses were observed in crops with greater nutrient requirements (e.g., tomato and maize).

Moderate application rates are advised for low-demand crops to avoid unnecessary nutrient accumulation.

- Environmental and Sustainable Use

The use of glauconite supports sustainable agriculture by reducing reliance on highly soluble fertilizers and improving nutrient retention in soil.

6. NEW SCIENTIFIC RESULTS

1. Glaucosite from the Bahariya Oasis was comprehensively characterized and confirmed as a multi-nutrient source containing potassium (3.0–3.3%), Ca, Mg, and trace micronutrients. Laboratory, pot, and field experiments demonstrated its suitability as a potassium fertilizer and its ability to partially replace conventional soluble potassium fertilizers.
2. The BCR sequential extraction procedure was successfully adapted and applied to glaucosite to evaluate nutrient release behavior and environmental safety. Most elements were associated with stable residual fractions, confirming the predominantly slow-release nature of glaucosite. In addition, potentially toxic elements (Cr, Ni, Pb, and Cu) were mainly present in non-mobile fractions, while Cd remained below detection limits, supporting the environmental safety of glaucosite for agricultural application.
3. Different physical and chemical treatments influenced elemental release from glaucosite. Particle size reduction showed variable effects on nutrient release, while acid treatments increased elemental extractability without consistently improving plant uptake. In contrast, washing treatment improved nutrient uptake efficiency by reducing salinity effects, highlighting the distinction between elemental extractability and plant bioavailability.
4. Field experiments demonstrated that glaucosite produced potato yields comparable to conventional potassium fertilizers and exhibited a clear residual effect during the subsequent maize cultivation, as reflected by increased potassium uptake and soil K availability without additional potassium fertilization. These findings indicate the potential of glaucosite as a sustainable local potassium source for improving long-term soil fertility and nutrient use efficiency under arid and semi-arid conditions.

7. SUMMARY

This study provides a comprehensive evaluation of glauconite deposits from the El-Gedida area in the Bahariya Oasis, Egypt, as a sustainable alternative source of potassium for agricultural applications. The research integrates mineralogical and chemical characterization, advanced extraction techniques, material modification approaches, and both controlled pot and field experiments to assess nutrient availability, environmental safety, and agronomic performance.

The characterization of glauconite confirmed that it is a potassium-bearing mineral containing approximately 3.0–3.3% K, in addition to essential macro- and micronutrients such as calcium, magnesium, iron, and zinc. This multi-nutrient composition highlights its potential to function not only as a potassium source but also as a soil amendment capable of improving overall soil fertility. The application of the BCR sequential extraction procedure revealed that most elements are predominantly associated with stable mineral fractions, particularly the residual fraction, indicating low mobility and a slow-release nutrient behavior. Furthermore, the assessment of potentially toxic elements demonstrated that their concentrations are within safe limits and largely bound in non-bioavailable forms, confirming the environmental safety of glauconite for agricultural use.

The comparison of extraction methods showed that ammonium lactate (AL) is more effective than potassium chloride (KCl) in estimating plant-available nutrients, particularly potassium, calcium, and zinc. This finding emphasizes the importance of selecting appropriate analytical methods when evaluating nutrient availability from mineral sources. Additionally, the influence of particle size on nutrient release was found to be limited, suggesting that glauconite can be utilized without extensive grinding, thereby enhancing its economic feasibility for large-scale agricultural applications.

Modification treatments played a critical role in determining nutrient availability. Acid activation significantly increased the solubility of potassium and other elements; however, results from subsequent experiments demonstrated that higher solubility does not necessarily correspond to increased plant uptake. In contrast, washing treatment effectively reduced salinity associated with soluble sodium and improved nutrient bioavailability under soil conditions. These findings highlight that nutrient availability is governed by soil chemical interactions and speciation rather than total elemental content alone.

The pot experiments conducted on lettuce and tomato provided detailed insights into soil–plant nutrient dynamics. The results demonstrated that washed glauconite improved potassium uptake

and maintained a more balanced nutrient supply, whereas acid-treated glauconite increased total nutrient concentrations in soil without consistently enhancing plant absorption. These observations confirm that plant response is primarily controlled by nutrient bioavailability rather than total concentration, and that pre-treatment methods strongly influence the efficiency of glauconite as a fertilizer.

The field experiment on potato further validated the agronomic performance of glauconite under practical conditions. The results indicated that glauconite, particularly when integrated with potassium sulfate, can maintain or slightly improve crop yield and biomass production compared to conventional fertilization. This combined application provides both immediate nutrient availability and sustained release throughout the growing season.

Moreover, the residual effect of glauconite was clearly demonstrated in the successive maize crop. Soils treated with glauconite showed higher potassium availability and improved plant uptake without additional potassium fertilization, confirming its role in long-term soil fertility management.

Overall, the findings of this study demonstrate that glauconite is a promising, environmentally safe, and economically viable alternative potassium source. Its slow-release characteristics, multi-nutrient composition, and residual fertility effects make it particularly suitable for sustainable agricultural systems.

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9. Appendices

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