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

by

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1. BACKGROUND OF THE STUDY

Sustainable agriculture is becoming increasingly important due to global challenges such as soil nutrient depletion, climate change, and food security concerns. Improving soil fertility through the efficient use of natural mineral resources is considered one of the key approaches for maintaining agricultural productivity while reducing environmental impacts.

In Egypt, agriculture faces several environmental and economic challenges, including declining soil quality, water scarcity, erosion, and the increasing cost of agricultural inputs such as fertilizers and pesticides (Jena, 2020). Although Egypt produces nitrogen and phosphate fertilizers locally, it still depends heavily on imported potassium fertilizers (Ahmed, 2023). The extensive use of conventional fertilizers may also lead to environmental problems because plants cannot absorb all applied nutrients, resulting in nutrient losses and contamination of soil and water resources (Wang et al., 2017). In the case of potassium fertilizers, only a small proportion of the applied potassium is absorbed by plants during a single growing season, while the remaining portion may become fixed in soil minerals or leach into groundwater (Basak et al., 2017).

In response to these concerns, increasing attention has been directed toward slow-release fertilizers as environmentally sustainable alternatives. Among these materials, glauconite has emerged as a promising natural potassium source because of its ability to gradually release nutrients while minimizing nutrient losses (Liang et al., 2019; El-Habaak et al., 2016). Glauconite is a greenish iron-potassium phyllosilicate mineral commonly found in marine sedimentary deposits and is considered a potential alternative or supplementary potassium fertilizer (Rakesh et al., 2020a).

The agricultural importance of glauconite is related not only to its potassium content, but also to the presence of essential macro- and micronutrients such as iron, magnesium, calcium, and trace elements required for plant growth (Rudmin et al., 2017; Franzosi et al., 2014; Oze et al., 2019). Due to its slow nutrient release behavior, glauconite can provide a long-term nutrient supply, reduce leaching losses, and improve nutrient use efficiency. In addition, glauconite may improve soil physical and chemical properties, including cation exchange capacity and water retention (Rakesh, 2020a; Rudmin et al., 2019a).

Glauconite commonly occurs as greenish pellets or grains in marine sedimentary rocks and is widely distributed in several countries, including Egypt (Rubio & López-Pérez, 2024; Mohammed et al., 2025; Wilmsen et al., 2024; Baldermann et al., 2025). In Egypt, significant glauconite deposits occur in the Western Desert, particularly in the Bahariya Oasis and Abu-Tartur regions (Hassan & Baioumy, 2007). These deposits have attracted attention due to their potential agricultural and economic importance. As a naturally occurring potassium-bearing mineral, glauconite may contribute to reducing dependence on imported potash fertilizers and support sustainable agricultural practices (Torqueti et al., 2016; Rudmin et al., 2017).

Despite its potential, the agricultural use of glauconite is still insufficiently investigated, especially regarding nutrient release behavior, environmental safety, and its agronomic performance under different cultivation conditions. In particular, limited information is available concerning the mobility of potentially toxic elements (PTEs) in glauconite and their possible environmental impacts. Sequential extraction techniques, especially the BCR sequential extraction procedure, have been widely applied for evaluating the mobility and bioavailability of elements in soils and sediments (Rauret et al., 1999; Filgueiras et al., 2004; Pueyo et al., 2008), but their application to glauconite deposits remains limited.

In addition, several studies have demonstrated that acid treatment can enhance potassium release from glauconite by increasing mineral dissolution and nutrient solubility (Yadav & Sharma, 1992; Pessoa et al., 2015; Shekhar et al., 2017a; Schimicoscki et al., 2020). However, the effectiveness of different acids and the influence of particle size on nutrient release require further investigation.

Therefore, evaluating glauconite as a sustainable potassium fertilizer requires an integrated approach involving mineralogical and chemical characterization, environmental assessment, nutrient release studies, and agronomic evaluation under both controlled and field conditions. Such investigations are particularly important for Egypt and other arid and semi-arid regions where improving fertilizer efficiency and reducing dependence on imported fertilizers are national priorities.

2. AIM AND OBJECTIVES OF THE STUDY

The main aim of this doctoral research was to evaluate the potential of Egyptian glauconite as a sustainable slow-release potassium fertilizer and soil amendment suitable for agricultural application.

To achieve this aim, the study focused on the following objectives:

1. To characterize the elemental composition of glauconite deposits collected from the El-Gedida area in the Western Desert of Egypt and evaluate their suitability as a source of plant nutrients, particularly potassium.
2. To investigate the nutrient release behavior of glauconite under different acid leaching treatments using inorganic and organic acids.

3. To evaluate the effect of glauconite particle size on elemental release efficiency under acid treatment conditions.
4. To compare the effectiveness of different extractants, including single extractants and the BCR sequential extraction procedure, for evaluating nutrient and potentially toxic element mobility in glauconite.
5. To assess the presence and mobility of potentially toxic elements in glauconite deposits in order to evaluate their environmental safety for agricultural use.
6. To study the effects of glauconite application on soil nutrient availability and plant nutrient uptake under controlled pot experiments and field conditions.
7. To evaluate the residual effect of glauconite application on soil potassium availability and plant potassium uptake in successive crops without additional potassium fertilization.
8. To provide a scientific basis for recommending glauconite as an alternative potassium fertilizer that supports sustainable agriculture and reduces dependence on imported potash fertilizers.

3. MATERIALS AND METHODS

3.1. Research Methodology

This study was designed to evaluate the agronomic potential and environmental safety of Egyptian glauconite as a sustainable slow-release potassium fertilizer. The research focuses on chemical characterization, extraction studies, laboratory modification treatments, pot experiments, and field experiments. The methodology included the determination of nutrient and potentially toxic element (PTE) contents in glauconite deposits, assessment of nutrient mobility using sequential and single extraction techniques, investigation of nutrient release under acid treatment, and evaluation of the agronomic performance of glauconite under controlled and field conditions.

The experimental work was conducted through integrated laboratory and agricultural investigations. Chemical analyses were carried out using extraction methods and instrumental analysis, while agronomic evaluation involved both greenhouse pot experiments in Hungary and field trials in Egypt.

3.2. 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 1) 28°28′26″.11 N and 29°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.

The collected glauconite samples were air-dried, crushed, and homogenized prior to analysis. 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) in order to evaluate the effect of particle size on nutrient release and extraction efficiency. The prepared samples were stored in clean polyethylene containers until further laboratory analysis. The size-fractionated samples were subsequently used in the following chemical analysis.

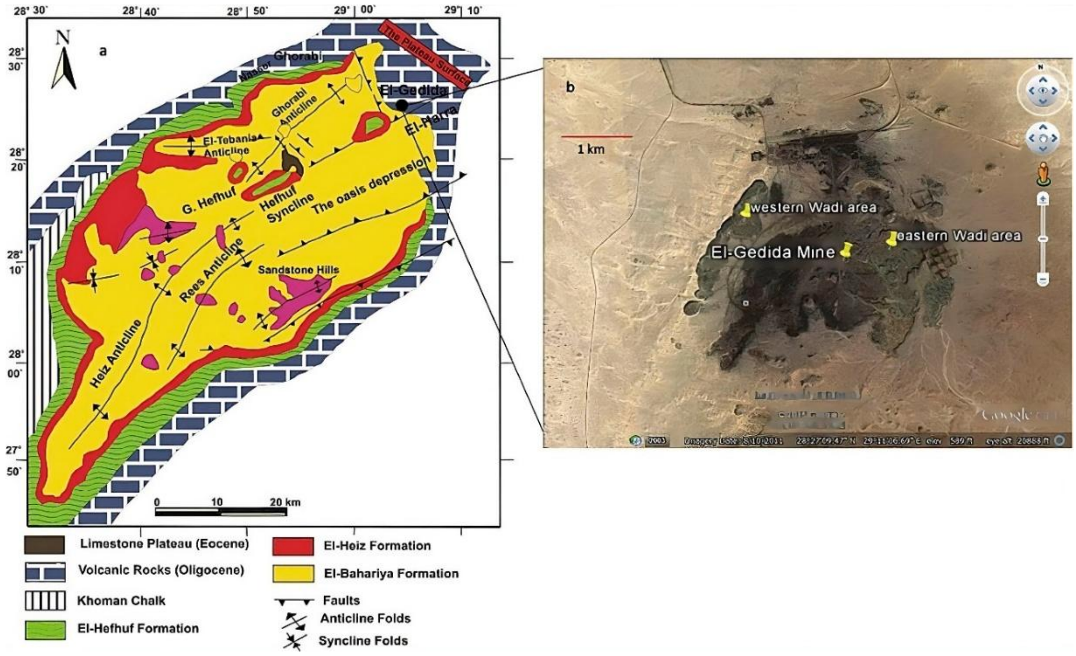


Figure 1. Geological map showing the glauconite sampling area at El-Gedida Mine, El-Baharia Oasis, Western Desert, Egypt.

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

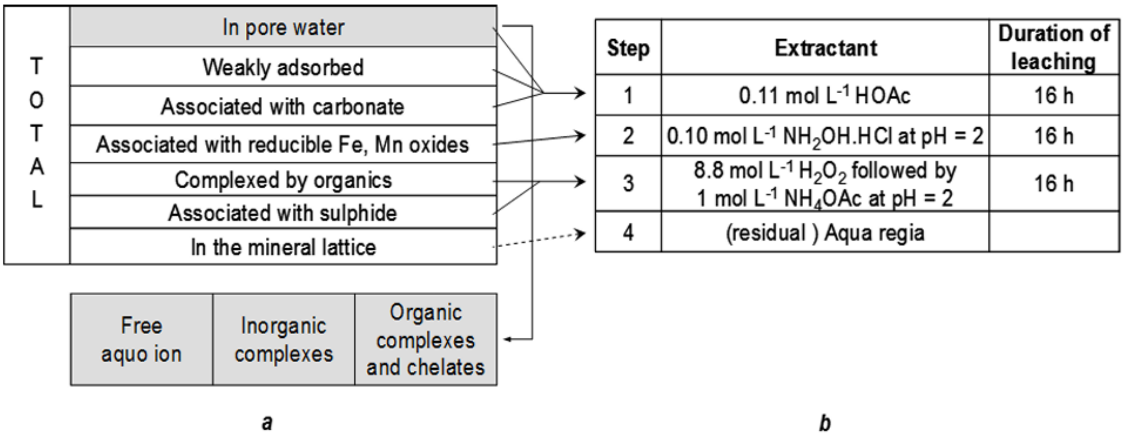
3.3. Chemical and Elemental Analysis

BCR Sequential Extraction Procedure

The mobility and fractionation of elements in glauconite were investigated using the Community Bureau of Reference (BCR) sequential extraction procedure. This method was selected because it provides detailed information regarding the chemical forms, mobility, and potential bioavailability of nutrients and potentially toxic elements.

The BCR procedure consisted of three sequential extraction steps in addition to a residual fraction as shown in Figure 2. The first extraction step was carried out using acetic acid in order to release exchangeable and carbonate-bound elements. The second step involved hydroxylamine hydrochloride extraction for reducible fractions, while the third step involved hydrogen peroxide oxidation followed by ammonium acetate extraction for oxidizable fractions. The residual fraction was determined after digestion with concentrated acids.

Following each extraction step, the samples were centrifuged and filtered before elemental analysis. The concentrations of major nutrients and potentially toxic elements were measured in each fraction.



Step	Extractant	Duration of leaching
1	0.11 mol L^{-1} HOAc	16 h
2	0.10 mol L^{-1} $NH_2OH.HCl$ at pH = 2	16 h
3	8.8 mol L^{-1} H_2O_2 followed by 1 mol L^{-1} NH_4OAc at pH = 2	16 h
4	(residual) Aqua regia	

Figure 2: The Developed sequential extraction scheme

Quality Control

Quality control procedures were applied throughout the analytical work to ensure the reliability and accuracy of the results. Reagent blanks, duplicate samples, and standard reference materials were used during extraction and instrumental measurements. All glassware and laboratory equipment were carefully cleaned to minimize contamination.

Pseudo-Total Elemental Content

Pseudo-total elemental concentrations were determined to evaluate the total potentially available nutrient and metal contents in glauconite samples. The samples were digested using concentrated acid mixtures under controlled laboratory conditions. The obtained solutions were analyzed instrumentally for elemental determination.

Single Extraction Methods

Two single extractants were used to compare their efficiency with the first step of the BCR sequential extraction method:

Ammonium Lactate (AL) Extraction

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.

Potassium Chloride (KCl) Extraction

Potassium chloride (1 M KCl) extraction was performed to determine exchangeable nutrient fractions in glauconite samples. The samples were mixed with the extractant solution and shaken under standardized laboratory conditions. After filtration, the extracted elemental concentrations were measured.

3.4. Modification of Glauconite by Acid Treatment

Washing Procedure

A washing treatment was applied to glauconite samples using distilled water in order to remove readily soluble salts and evaluate the influence of washing on nutrient release behavior. 50 grams of material from each size fraction were washed with 250 mL of d H_2O. 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 (ICP-OES).

Acid Leaching Experiments

Acid leaching experiments were conducted to investigate the release behavior of nutrients from glauconite under different chemical conditions. Both inorganic and organic acids were used as extractants. The investigated acids included hydrochloric acid , nitric acid, phosphoric acid , acetic acid.

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.

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.

Instrumental Analysis

Elemental concentrations in all extracts and digested samples were measured using inductively coupled plasma optical emission spectrometry (ICP-OES). The instrument was calibrated using certified standard solutions, and analytical measurements were performed according to standard laboratory procedures.

pH and Electrical Conductivity Measurements

The pH and electrical conductivity (EC) of glauconite suspensions and acid-treated extracts were measured to evaluate the chemical changes associated with glauconite dissolution and nutrient release. Measurements were conducted using calibrated laboratory instruments.

3.5. Pot Experiment

Experimental Design

A pot experiment was conducted in Hungary to evaluate the effects of glauconite application on soil nutrient dynamics and plant nutrient uptake under controlled conditions.

Two crops were used in the experiment: lettuce and tomato. 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 (H_3PO_4)

The glauconite used in T2 and T3 was thoroughly mixed into the soil before planting.

Soil and Plant Sampling

After harvesting, soil and plant samples were collected for chemical analysis. Soil samples were air-dried, homogenized, and prepared for digestion and extraction analysis.

Plant samples were cleaned, dried, and ground before digestion. Nutrient concentrations in plant tissues were determined to evaluate nutrient uptake efficiency.

Chemical Analysis of Soil and Plant Samples

Soil and plant samples were digested using acid digestion procedures. The resulting solutions were analyzed using ICP-OES to determine concentrations of potassium, calcium, magnesium, phosphorus, iron, manganese, and zinc.

The effects of glauconite application on soil nutrient availability and plant nutrient accumulation were evaluated by comparing treated and untreated samples.

3.6. Field Experiment

Experimental Site and Design

The field experiment was conducted in Egypt to evaluate the agronomic performance of glauconite under field conditions. The field study included two successive crops grown on the same soil.

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

1. 100% Potassium sulfate (150 kg K_2SO_4/feddan)
2. 75% Potassium sulfate + 25% acidified glauconite
3. 50% Potassium sulfate + 50% acidified glauconite
4. 25% Potassium sulfate + 75% acidified glauconite
5. 100% acidified glauconite (1.5 ton/feddan)
6. 100% raw glauconite (unacidified) (1.5 ton/feddan)

The potassium sulfate rate was based on the recommended dose for the local soil and crop conditions. The acidified glauconite was prepared by mixing natural glauconite 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.

Potato was cultivated as the first crop, followed by maize as the second crop without additional potassium fertilization. This approach was designed to evaluate both the direct and residual effects of glauconite application.

Plant and Soil Sampling

During harvesting, plant, tuber, and soil samples were collected from the experimental plots. Plant growth parameters and yield characteristics were measured.

Soil samples were collected after harvesting in order to evaluate residual potassium availability and nutrient dynamics following glauconite application.

Chemical Analysis

Collected soil and plant samples were subjected to digestion and elemental analysis using ICP-OES. The concentrations of potassium were determined in both plant tissues and soil samples in both crops.

3.7. Statistical Analysis

Statistical analyses were conducted to evaluate the significance of differences among treatments. Mean values and standard deviations were calculated for all measured parameters.

Analysis of variance (ANOVA) was applied to determine statistically significant differences between treatments. Least significant difference (LSD) tests at $P < 0.05$ were used for mean comparison where appropriate.

The obtained results from chemical analyses, pot experiments, and field experiments were statistically evaluated in order to assess the effectiveness of glauconite as a sustainable potassium fertilizer and soil amendment.

4. RESULTS AND DISCUSSION

4.1. 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 1, 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 2). 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.

Table 1: Element concentration in the BCR steps compared with pseudo-total element content (mg kg^{-1}, dry weight basis; mean ± 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 ($P < 0.05$).

Element	*Sample*	*BCR 1*	*BCR 2*	*BCR 3*	*BCR 4*	*(1+2+3+4)*	*Pseudo Total*
	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
	LSD %5	*21*	*36*	*9.6*	*3.6*	*44*	*38*
	Extractable (%)	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.
	LSD %5						
	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
	LSD %5	*0.07*	*0.1*	*0.1*	*1.7*	2.33	n.s.
	Extractable (%)	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
	LSD %5		*0.48*		0.22	0.76	0.3
	Extractable (%)	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
	LSD %5	*26*	*88*	*13*	*1223*	1033	85
	Extractable (%)	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

	LSD %5	*15*	*42*	*6*	*400*	366	218
	Extractable (%)	2.29	8.71	1.37	87.79	100.16	100
	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
	LSD %5	*181*	*17*	*5.7*	*9*	180	175
	Extractable (%)	129.32	1.92	0.58	2.84	134.67	100
	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
	LSD %5				*0.6*	1.6	2.3
	Extractable (%)	0.00	0.00	0.00	89.80	89.80	100
	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
	LSD %5		*0.5*		*0.79*	0.99	0.2
	Extractable (%)	0.00	12.00	0.00	101.08	113.08	100
	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
	LSD %5	*1.14*	*2.5*		*3.7*	4.6	2.7
	Extractable (%)	1.97	7.07	0.00	91.62	101	100

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

Table 2. 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

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 3, 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.

Table 3. 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

Effect of Particle Size on Elemental Content

The effect of particle size on elemental content and nutrient extractability in glauconite was evaluated across different size fractions. The results presented in Table 1 showed that particle size had a limited and non-systematic influence on the release of most elements, particularly potassium, calcium, and magnesium. Similar observations were reported by Franzosi et al. (2014) and Dasi et al. (2024), indicating that glauconite behaves mainly as a structurally controlled mineral rather than a surface-reactive material.

A slight increase in elemental release was observed in the finer fractions (<0.1 mm), likely due to the larger specific surface area and enhanced mineral–solution interaction. Similar behavior was reported for silicate-based fertilizers by Duarte et al. (2023). However, the differences among particle size fractions were not statistically significant ($p > 0.05$) for most analyzed elements, suggesting that nutrient release is primarily controlled by the mineralogical structure of glauconite rather than particle size alone (Eldawwy et al., 2024).

Potassium availability showed only minor variation among particle sizes, reflecting its occurrence within interlayer and structural sites of the glauconite mineral, where release depends mainly on slow weathering processes (Costa Júnior et al., 2024). From an agronomic perspective, these results indicate that coarse glauconite fractions may be used without significantly reducing fertilizer performance, minimizing the need for intensive grinding processes (Rudmin et al., 2019b; Silveira et al., 2025).

Overall, the results confirm that particle size is not a dominant factor controlling nutrient availability from glauconite. Instead, nutrient release is mainly governed by mineralogical structure and geochemical stability, supporting the potential use of glauconite as a sustainable slow-release potassium fertilizer (Verma & Prakash, 2018; Dasi et al., 2024).

4.2. Glauconite 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 glauconite, across numerous industrial and environmental contexts (Jena, 2021). This section explores the influence of different acid extractants and particle size fractions of glauconite on the release behavior of essential plant nutrients: calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), and zinc (Zn).

Calcium:

The assessment of calcium release from glauconite showed clear differences depending on the acid used for extraction (Figure 3). Nitric acid (HNO_3) produced the highest calcium release, ranging from 1199 ± 17.6 to 1545 ± 71.0 mg·kg^{-1}, whereas acetic acid (CH_3COOH) resulted in the lowest values, ranging between 147 ± 4.9 and 254 ± 6.4 mg·kg^{-1}. The efficiency of calcium release followed the order: $HNO_3 > HCl > H_3PO_4 > CH_3COOH$.

Acid treatment significantly enhanced calcium release compared with deionized water extraction due to the formation of soluble calcium salts, including calcium nitrate, calcium chloride, calcium dihydrogen phosphate, and calcium acetate. The higher solubility of calcium nitrate (1212 g·L^{-1}) and calcium chloride (745 g·L^{-1}) compared with calcium dihydrogen phosphate (180 g·L^{-1}) and calcium acetate (347 g·L^{-1}) explains the greater extraction efficiency of nitric and hydrochloric acids (Kant & Kafkafi, 2013; Ropp, 2013).

Overall, nitric acid was identified as the most effective extractant for calcium release from glauconite, highlighting the importance of acid-mediated dissolution processes in nutrient mobilization.

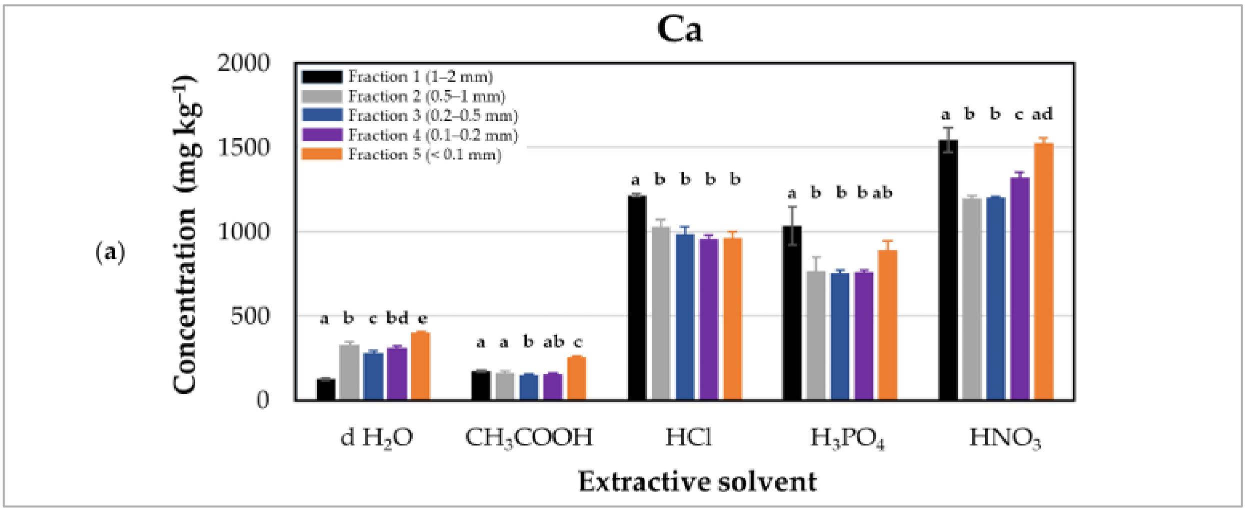


Figure 3. Calcium concentrations (mg. kg-1 dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants.

Potassium:

The release of potassium from glauconite varied significantly depending on the acid treatment applied (Figure 4). Nitric acid (HNO_3) showed the highest extraction efficiency, releasing between 1011 ± 11.0 and 1118 ± 10.8 mg·kg^{-1} potassium, while hydrochloric acid (HCl) produced nearly similar values. Both acids released approximately three times more potassium than deionized water extraction. In contrast, acetic acid (CH_3COOH) resulted in the lowest potassium release, ranging from 455.7 ± 16.6 to 551 ± 4.5 $mg \cdot kg^{-1}$. The effectiveness of potassium extraction followed the order: $HNO_3 \approx HCl > H_3PO_4 > CH_3COOH$.

The high efficiency of HNO_3 and HCl is related to the high solubility of potassium nitrate and potassium chloride, as also reported by Tro (2011). Conversely, the lower extraction efficiency of acetic acid reflects its weaker dissociation compared with strong inorganic acids. Potassium extraction using phosphoric acid showed relatively higher standard deviations, likely due to matrix effects influencing ICP-OES measurements.

The obtained results are consistent with previous studies. Shekhar et al. (2017a) reported less than 12% potassium recovery using HCl, while Praveen and Tomar (2019) also observed limited potassium extraction using acetic acid. Overall, the results confirm that strong inorganic acids are substantially more effective than weak organic acids for potassium release from glauconite.

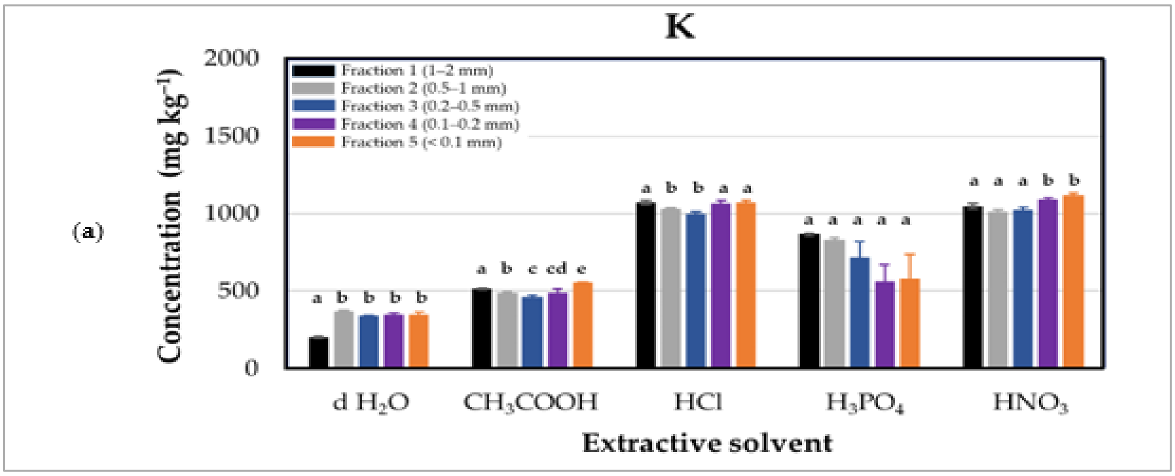


Figure 4. Potassium concentrations (mg. kg-1 dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants.

Magnesium

As illustrated in Figure 5, 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 $HNO_3 > HCl > H_3PO_4 > CH_3COOH$, reaffirming the greater efficacy of strong acids in solubilizing divalent cations.

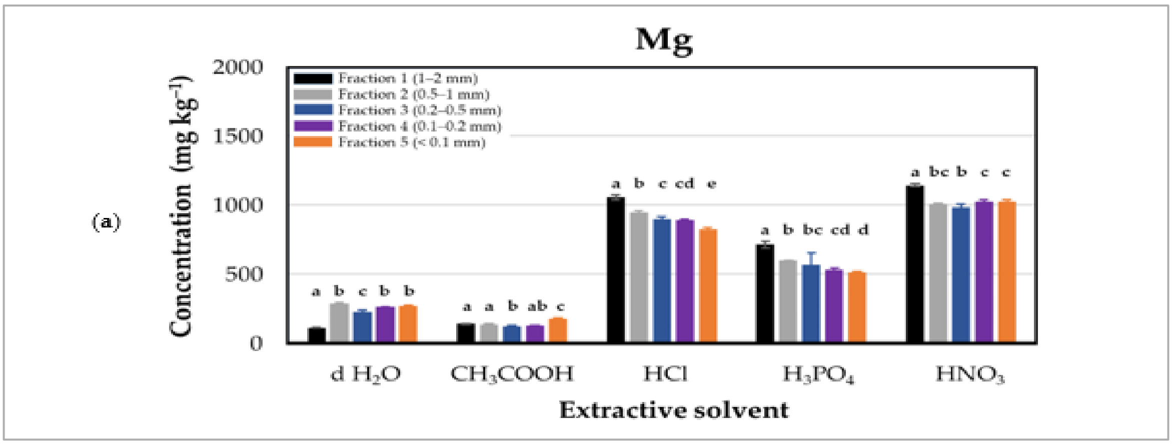


Figure 5. Magnesium concentrations (mg. kg-1 dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants.

Sodium

As illustrated in (Figure 6), the release of sodium (Na) from glauconite was highest when treated with deionized water (d H_2O), 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.

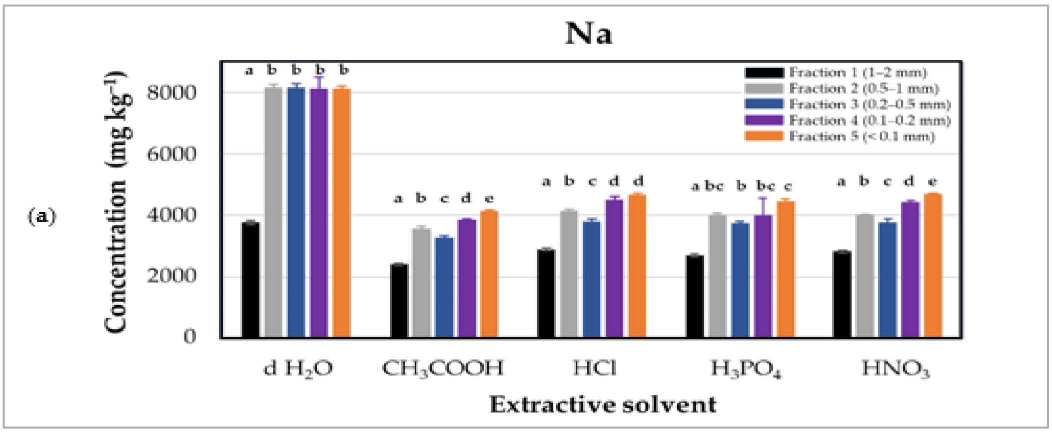


Figure 6. Sodium concentrations (mg. kg-1 dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants.

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).

Zinc

Among the acid treatments tested, nitric acid (HNO_3) 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 $mg \cdot kg^{-1}$, as shown in (Figure 7). Hydrochloric acid (HCl) followed closely in extraction efficiency. The overall descending trend for zinc release using different acids was established as: HNO_3 > HCl > H_3PO_4 > CH_3COOH.

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:

$$Zn^{2+}(\text{bound}) + 2H^+ \rightarrow Zn^{2+}(\text{aq}) + 2H^+(\text{in structure})$$

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 (H_3PO_4) is a triprotic acid that dissociates in a stepwise manner, with dissociation constants $pKa_1 \approx 2.15$, $pKa_2 \approx 7.20$, and $pKa_3 \approx 12.35$. 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, H_3PO_4 has a strong tendency to form insoluble metal-phosphate complexes, such as $Zn_3(PO_4)_2$, which may limit the amount of free Zn^{2+} 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 $mg \cdot kg^{-1}$.

Among all acids examined, acetic acid (CH_3COOH) 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.

(a)

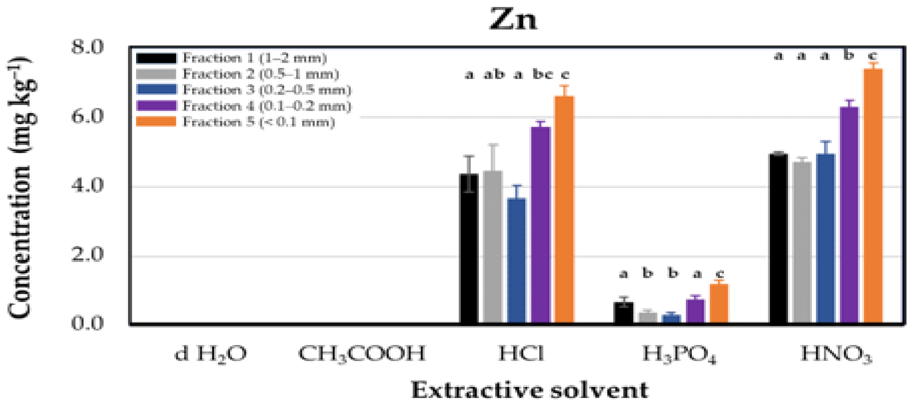


Figure 7. Zinc concentrations (mg. kg-1 dry matter) released from glauconite samples sieved for different particle sizes using distilled water and various acids as extractants

Changes in pH and Electrical Conductivity

Soil pH is an important factor controlling nutrient availability and element mobility in soil systems through dissolution–precipitation reactions, ion exchange, and metal complexation (Xia et al., 2024; Kalocsai et al., 2024). The pH results of glauconite samples are presented in and Figure 8.

Washing slightly increased the pH from 5.78 in the unwashed sample to 6.10 after washing, likely due to the removal of soluble acidic compounds and exchangeable ions. In contrast, acid-treated samples showed a considerable decrease in pH, ranging from 3.14 to 4.61 depending on the acid used. The effectiveness of the acids followed the order: HCl > HNO_3 > H_3PO_4 > CH_3COOH. This trend reflects the stronger dissociation and proton activity of mineral acids, which enhanced mineral dissolution and nutrient release. Similar observations were reported by Eldawwy et al. (2025).

Electrical conductivity (EC) varied markedly among treatments. The unwashed glauconite showed the highest EC value (12.59 mS cm^{-1}), indicating the presence of soluble salts and exchangeable ions. Washing reduced EC to 4.32 mS cm^{-1} due to the removal of soluble ionic species, consistent with the findings of El-Sharkawy et al. (2025).

After acid treatment (Figure 9), EC increased again to 7.48 mS cm^{-1} for HCl and 7.24 mS cm^{-1} for HNO_3, while lower values were recorded for H_3PO_4 (5.28 mS cm^{-1}) and CH_3COOH (4.93 mS cm^{-1}). This increase resulted from enhanced mineral dissolution and greater ion release into solution under acidic conditions, similar to trends reported by Dasi et al. (2024) and Eldawwy et al. (2025).

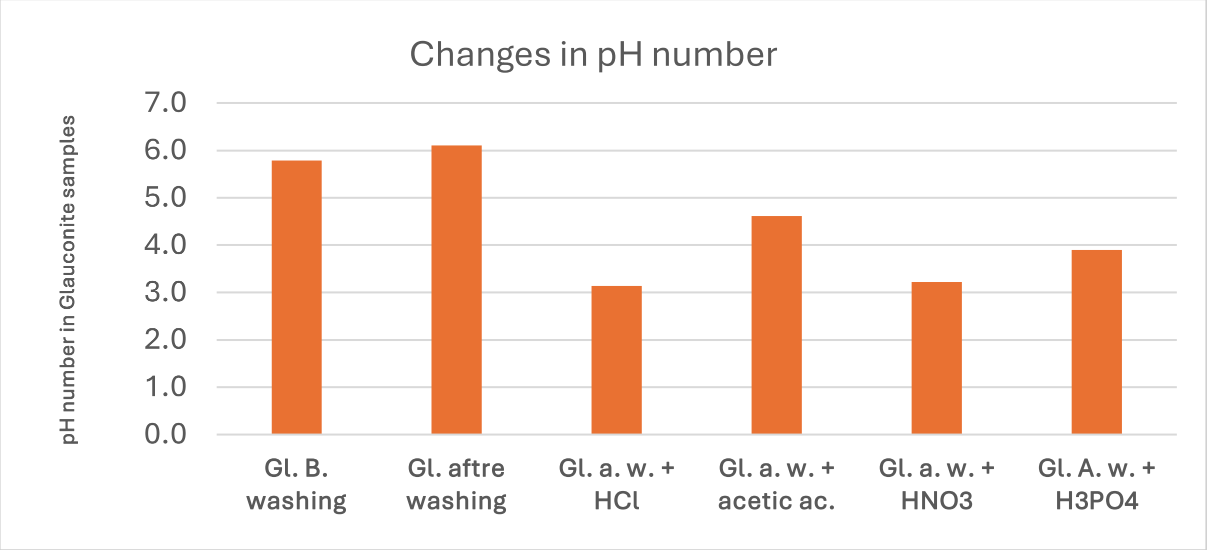


Figure 8. PH values detected in 0.4 kg. L^{-1} glauconite solution.

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

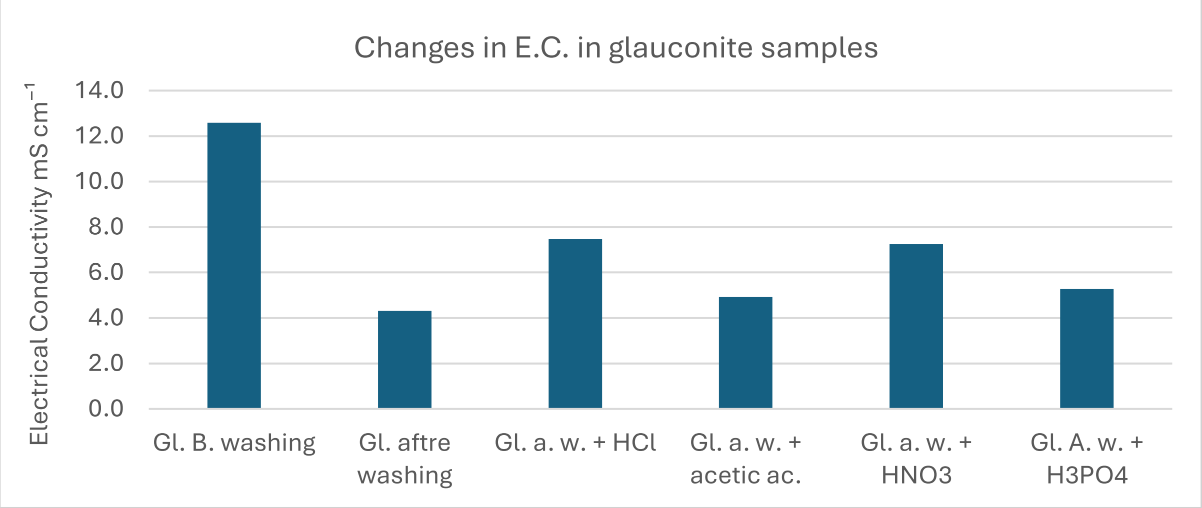


Figure 9. Electrical conductivity (EC) values detected in 0.4 kg L-1 glauconite solutions

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 H_2O, 7.53 in KCl) with high $CaCO_3$ (20.96%) and moderate organic matter (2.21% humus). Key nutrients included Al-P_2O_5 (269.5 mg/kg), Al-K_2O (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 $CaCO_3$ content likely influenced P fixation (Brady & Weil, 2016), but glauconite amendments particularly the H_3PO_4-treated form, were expected to alter nutrient dynamics, especially for K, Fe, and P (Rao et al., 2018).

Effects of Glauconite Treatments on Lettuce

As shown in Figure 10, the control treatment showed the highest concentrations of most soil nutrients (Ca, Fe, K, Mg, Mn, and P), while washed glauconite significantly reduced nutrient levels, particularly potassium, which decreased from 2406 to 1327 mg kg^{-1}. This reduction is mainly attributed to the removal of soluble and exchangeable nutrients during washing, similar to observations reported by Paramesh et al. (2023) and Hussain et al. (2026).

The application of washed glauconite + H_3PO_4 partially restored nutrient availability, increasing soil K to 1828 mg kg^{-1} due to enhanced mineral dissolution and cation exchange under acidic conditions (Shekhar et al., 2019; Hussain et al., 2026; Eldawwy et al., 2025). However, soil phosphorus decreased to 1027 mg kg^{-1}, likely due to phosphorus fixation reactions with Ca, Fe, and Al compounds, which reduce P availability (Stępień et al., 2025). Interactions between phosphorus and micronutrients such as zinc may also influence nutrient availability (Nadeem et al., 2024).

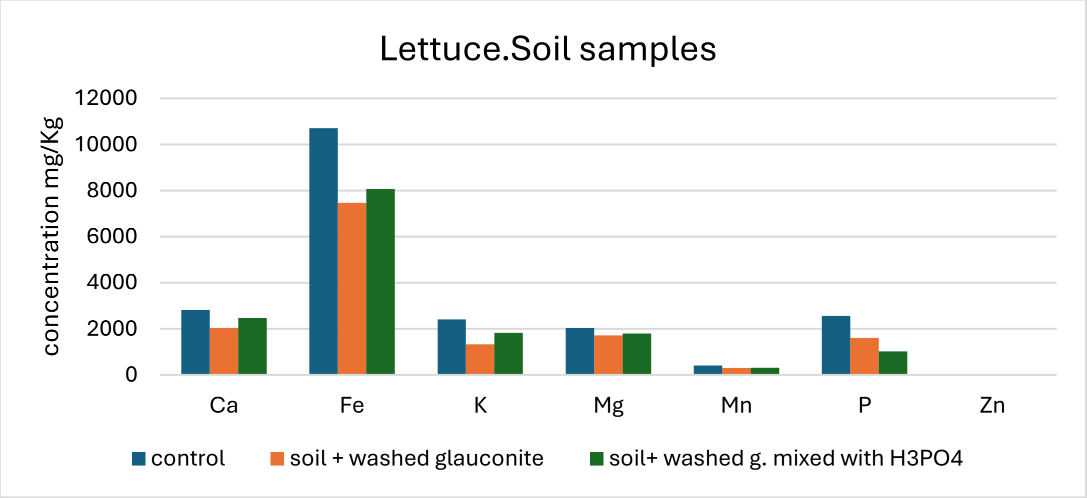


Figure 10. Nutrient Concentrations in Soil Samples After Harvest

In plant tissues (Figure 11), nutrient concentrations did not directly correspond to soil nutrient levels. The highest potassium concentrations in lettuce (~50,200 mg kg^{-1}) were recorded under glauconite treatments, exceeding the control, indicating that K uptake depends more on exchangeable K and root uptake efficiency than total soil K concentrations (Bhat et al., 2024).

Calcium and magnesium concentrations were highest in the washed glauconite treatment, suggesting that washing improved ionic balance and nutrient uptake efficiency by reducing soluble salts, particularly sodium (Paramesh et al., 2023). The highest Zn concentration in plants (33 mg kg^{-1}) was observed under H_3PO_4-treated glauconite, reflecting enhanced Zn mobility under acidic conditions and phosphorus–zinc interactions (Nadeem et al., 2024). Manganese uptake also increased after acid treatment due to higher Mn solubility at lower pH, whereas iron concentrations remained relatively stable because of limited Fe bioavailability under aerobic conditions.

Despite large variations in soil phosphorus, plant P concentrations remained relatively stable, suggesting physiological regulation of phosphorus uptake by lettuce plants (Stępień et al., 2025).

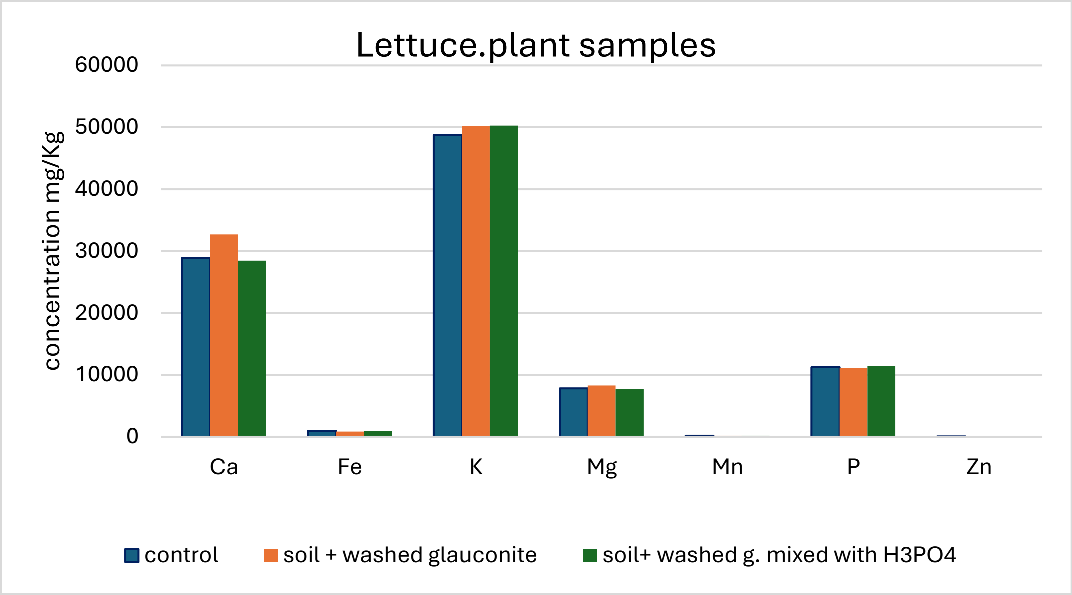


Figure 11. Nutrient Concentrations in plant samples after harvest

Effects of Glauconite Treatments on Tomato

As shown in Figure 12, glauconite application, particularly in the washed form, significantly increased nutrient concentrations in soil compared with the control treatment. The washed glauconite treatment recorded the highest concentrations 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}). These results indicate that washing removed excess soluble salts while enhancing the release of structurally bound nutrients from glauconite. Similar nutrient enrichment from silicate minerals has been reported by Ramos et al. (2015) and van Straaten (2006).

The washed glauconite + H_3PO_4 treatment also increased soil nutrient concentrations, although slightly lower values were observed for K and P compared with washed glauconite alone. This suggests that acid treatment enhanced mineral dissolution but also promoted nutrient fixation processes, particularly phosphorus precipitation with Ca and Fe compounds (Hinsinger et al., 2015; Penn & Camberato, 2019).

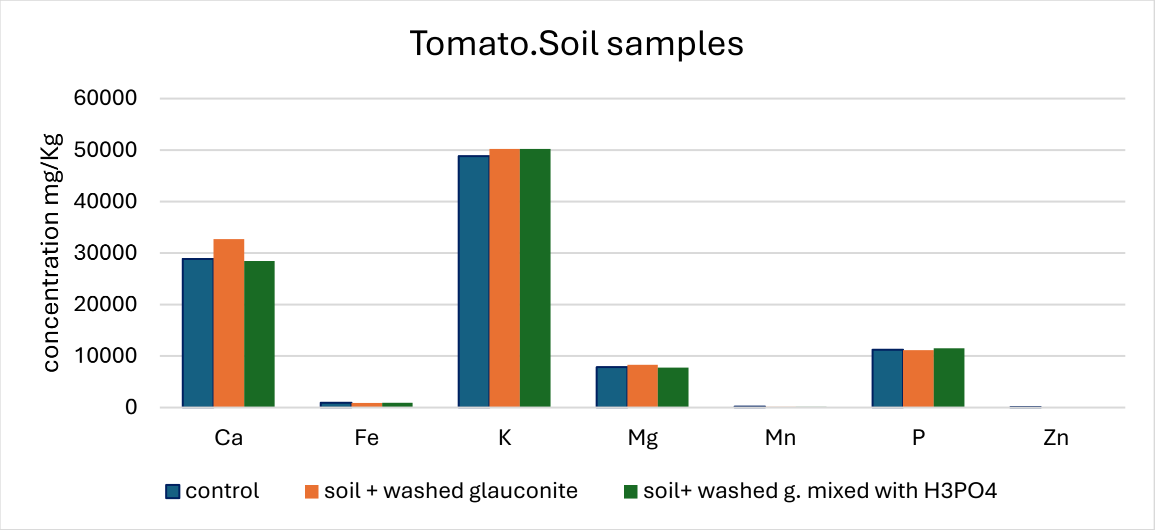


Figure 12. Nutrient Concentrations in Soil Samples After Harvest

In plant tissues (Figure 13), nutrient responses differed from soil trends. The highest potassium concentration in tomato plants (39756 mg kg^{-1}) was observed under washed glauconite treatment, indicating greater K availability for plant uptake compared with acid-treated glauconite. These results confirm that total soil nutrient concentrations do not necessarily reflect plant-available fractions (White & Greenwood, 2013; Gu et al., 2020).

Calcium and magnesium concentrations in plants showed no significant differences among treatments despite large variations in soil concentrations, suggesting physiological regulation of nutrient uptake (Maathuis, 2016). The highest Fe concentration in plants (187 mg kg^{-1}) was recorded under acid-treated glauconite, reflecting enhanced Fe solubility under acidic conditions (Marschner, 2012). Manganese concentrations also slightly increased under glauconite treatments.

In contrast, zinc concentrations were highest in the control treatment (39 mg kg^{-1}) and decreased after glauconite application, likely due to antagonistic interactions between phosphorus and zinc under high P conditions (Cakmak & Kutman, 2018). Plant phosphorus concentrations remained relatively stable across treatments despite large differences in soil P, indicating regulated phosphorus uptake controlled by root activity and rhizosphere processes (Hinsinger et al., 2015).

Overall, the results demonstrate that washed glauconite was more effective than acid-treated glauconite in improving plant nutrient uptake, while acid treatment mainly increased total soil nutrient concentrations. These findings emphasize the importance of nutrient availability and soil–plant interactions when evaluating glauconite as a multi-nutrient fertilizer.

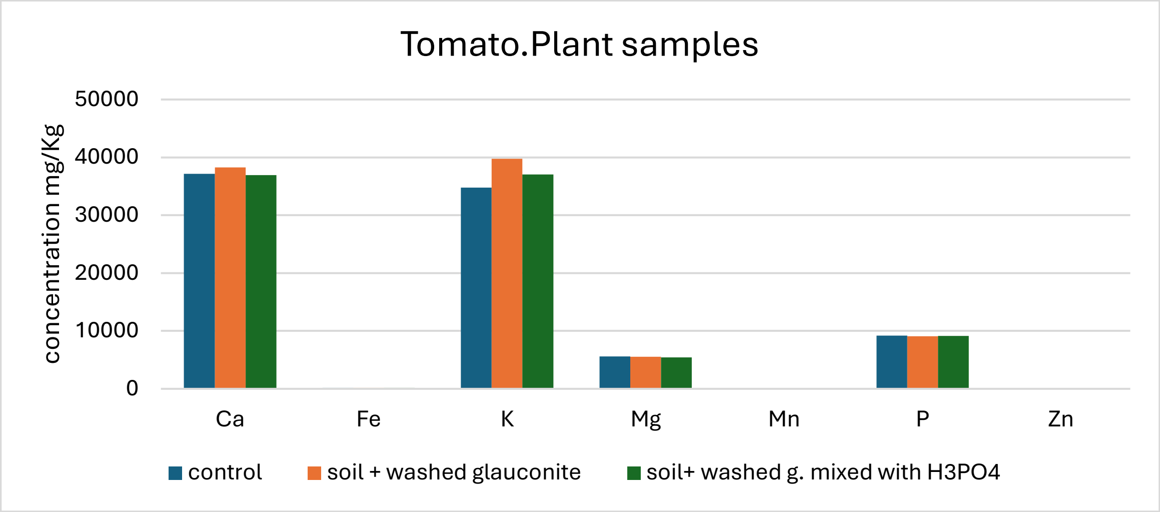


Figure 13. Nutrient Concentrations in plant Samples After Harvest

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

The field experiment evaluated the effectiveness of glauconite as a potassium source for potato and its residual effect on maize under sequential cropping conditions. Different combinations of potassium sulfate (SOP) and glauconite were tested to determine their influence on crop growth, potassium uptake, and residual soil fertility.

4.4.1. Potato Growth and Yield

The application of different potassium sources significantly affected potato vegetative growth and tuber yield (Figure 14). The 100% acid-treated glauconite treatment produced the highest vegetative biomass, with fresh and dry plant weights of 11.13 and 2.53 ton ha^{-1}, respectively, exceeding the 100% SOP treatment by approximately 38% and 40.5%. In contrast, the raw glauconite treatment recorded the lowest fresh and dry plant weights (7.50 and 1.87 ton ha^{-1}), reflecting the limited short-term potassium availability from untreated glauconite.

Tuber yield showed a similar trend. Treatments containing 50–75% glauconite produced tuber yields comparable to or slightly higher than the 100% SOP treatment (32.0 ton ha^{-1}). The 50% SOP + 50% glauconite treatment recorded the highest dry tuber weight (8.07 ton ha^{-1}), indicating a synergistic interaction between soluble potassium from SOP and the slow-release behavior of glauconite. In contrast, the raw glauconite treatment produced the lowest fresh tuber yield (30.0 ton ha^{-1}).

The improved performance of acid-treated glauconite was attributed to nitric acid activation, which enhanced the dissolution of K-bearing mineral phases and increased the availability of exchangeable potassium in soil solution. Similar observations were reported by Shekhar et al. (2019), Rakesh et al. (2020b), and El-Sharkawy et al. (2025).

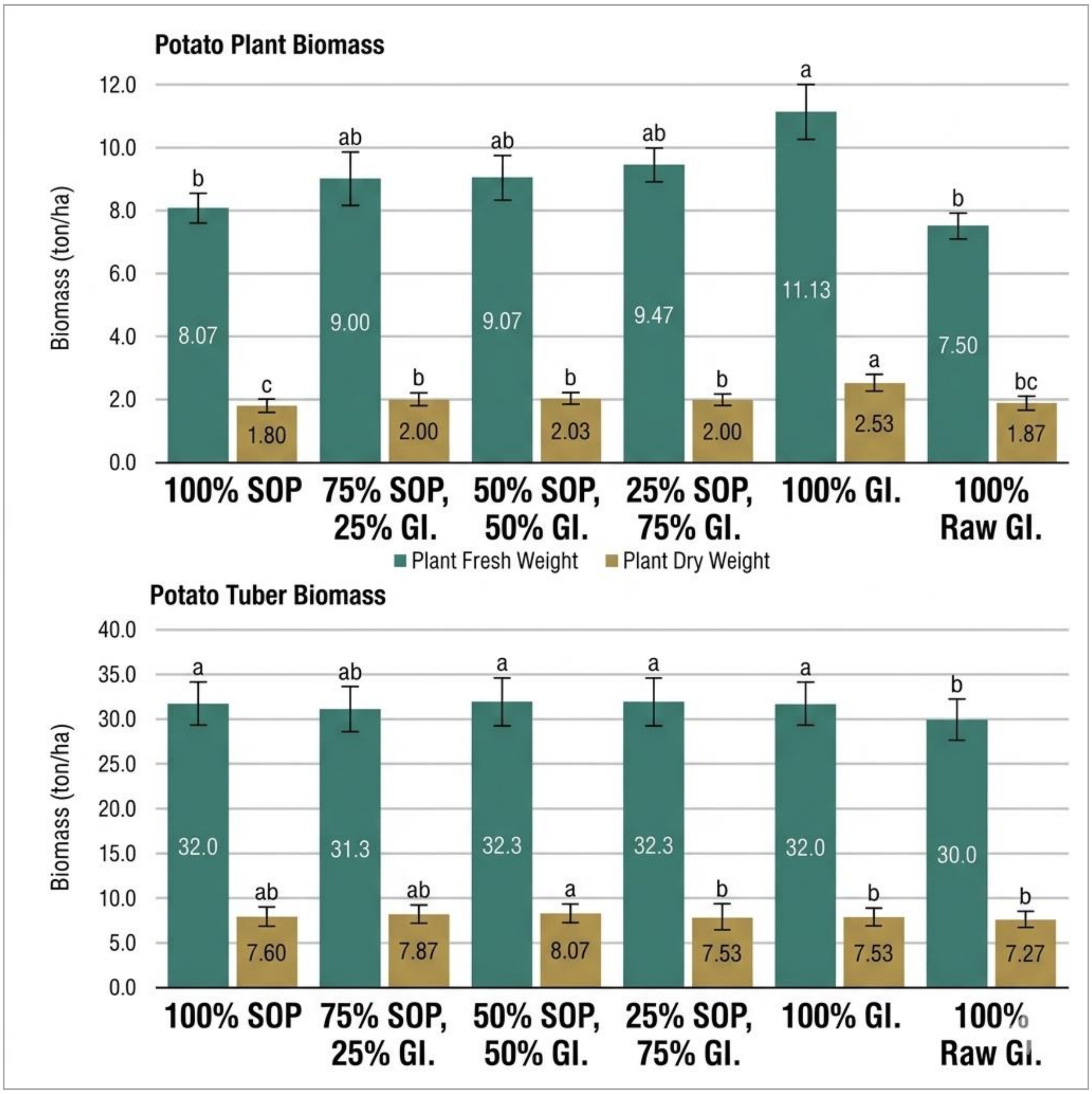


Figure 14. Fresh and dry biomass production of the potato crop

4.4.2. Potassium Uptake and Residual Soil K after Potato Harvest

Potassium uptake by potato plants and tubers varied significantly among treatments (Table 4). The highest K uptake in vegetative tissues (50 kg ha^{-1}) was observed under the 100% acid-treated glauconite treatment, whereas the raw glauconite treatment showed the lowest uptake (27 kg ha^{-1}). In tubers, the highest potassium uptake (154 kg ha^{-1}) was recorded in the 50% SOP + 50% glauconite treatment, followed by the 100% SOP treatment (151 kg ha^{-1}).

Table 4: Potassium Dynamics in Potato Tissues and Soil Residuals

All values are presented as means of three replicates ± 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 ± 0.6	151 ± 18.1	364 ± 80.8
75% SOP, 25% Gl.	40 ± 9.7	146 ± 11.3	370 ± 9.8
50% SOP, 50% Gl.	39 ± 2.1	154 ± 7.2	353 ± 40.7
25% SOP, 75% Gl.	43 ± 5.0	141 ± 34.9	310 ± 9.8
100% Gl.	50 ± 10.0	131 ± 12.3	291 ± 9.8
100% Raw Gl.	27 ± 2.1	111 ± 4.0	289 ± 7.8
LSD 5%	**0.018**	**0.092**	**0.061**

The enhanced uptake under acid-treated glauconite treatments reflects improved potassium release following mineral activation. The combined application of SOP and glauconite appeared to optimize potassium availability by providing both immediate and sustained K supply during the growth cycle (Rakesh et al., 2020b).

Residual soil potassium concentrations after potato harvest also differed among treatments. The highest residual soil K concentration was observed in the 75% SOP + 25% glauconite treatment (370 mg kg^{-1}), followed by the 100% SOP treatment (364 mg kg^{-1}). In contrast, the 100% glauconite and raw glauconite treatments recorded lower residual soil K values (291 and 289 mg kg^{-1}, respectively), suggesting a more gradual release and utilization of potassium during the growing season.

The 25% SOP + 75% glauconite treatment maintained moderate residual soil K (310 mg kg^{-1}) while supporting relatively high plant uptake, indicating balanced potassium release and utilization. Similar findings regarding the benefits of integrating soluble and mineral potassium sources were reported by Manning (2010), Shekhar et al. (2019), and Dasi et al. (2024).

4.4.3. Residual Effect on Maize Growth and Potassium Dynamics

The residual effect of potassium treatments applied during the potato season significantly influenced maize growth and potassium uptake in the following season (Table 5, Figure 15). Maize fresh and dry biomass increased with increasing proportions of glauconite in the initial treatments.

The highest fresh biomass (101.4 ton ha^{-1}) and dry matter yield (22.9 ton ha^{-1}) were recorded in the 25% SOP + 75% glauconite treatment, followed closely by the 100% glauconite treatment. The raw glauconite treatment produced the lowest fresh and dry biomass values (94.3 and 21.4 ton ha^{-1}, respectively).

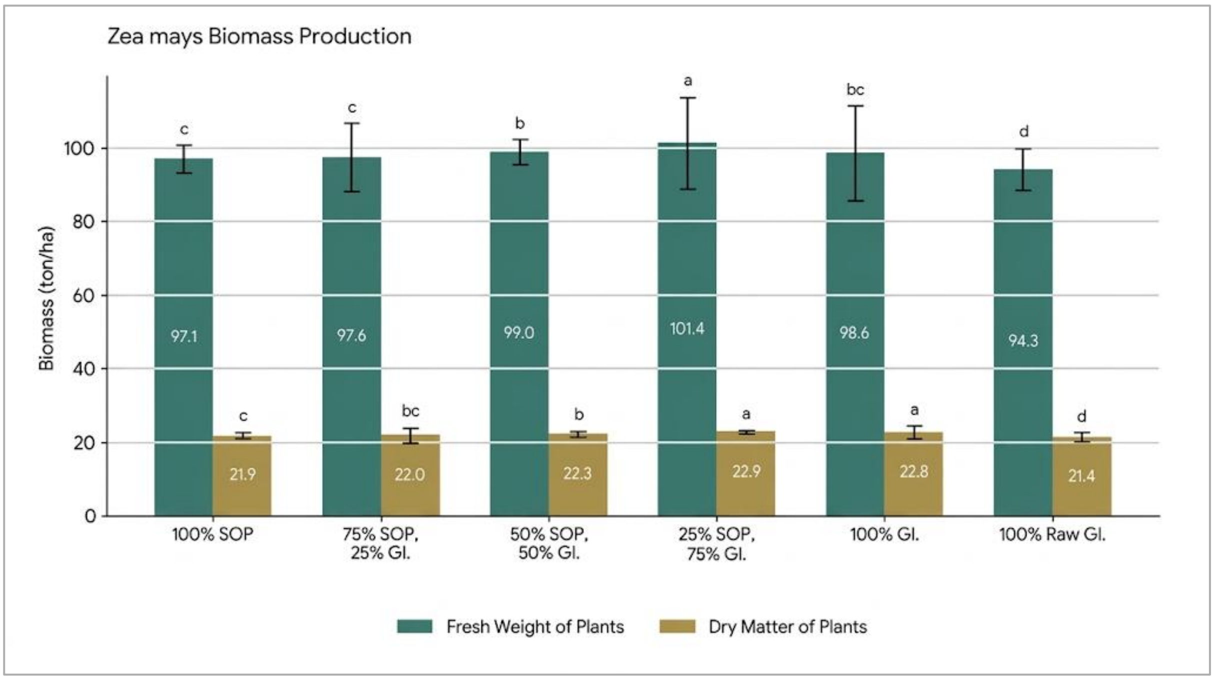


Figure 15. Fresh and dry biomass production of the Zea mays crop.

Table 5: Growth and Potassium Parameters of Zea Mays

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 ± 3.8	21.9 ± 0.9	325 ± 56	282 ± 4
75% SOP, 25% Gl.	97.6 ± 9.3	22.0 ± 2.1	351 ± 23	313 ± 25
50% SOP, 50% Gl.	99.0 ± 3.4	22.3 ± 0.8	367 ± 93	313 ± 4
25% SOP, 75% Gl.	101.4 ± 12.5	22.9 ± 0.6	391 ± 31	332 ± 24
100% Gl.	98.6 ± 12.9	22.8 ± 1.7	348 ± 16	297 ± 13
100% Raw Gl.	94.3 ± 5.7	21.4 ± 1.3	300 ± 17	298 ± 26
LSD 5%	**0.95**	**0.824**	**0.322**	**0.074**

Potassium uptake by maize followed a similar trend. The highest K uptake (391 kg ha^{-1}) was observed in the 25% SOP + 75% glauconite treatment, followed by the 50% SOP + 50% glauconite treatment (367 kg ha^{-1}). These values exceeded the 100% SOP treatment (325 kg ha^{-1}), indicating improved potassium use efficiency under glauconite-based treatments. In contrast, the raw glauconite treatment recorded the lowest K uptake (300 kg ha^{-1}).

Residual soil potassium after maize harvest remained highest in the 25% SOP + 75% glauconite treatment (332 mg kg^{-1}), followed by the 50% SOP + 50% glauconite and 75% SOP + 25% glauconite treatments (313 mg kg^{-1}). These results indicate that glauconite contributed to maintaining a stable pool of available potassium in soil while supporting crop uptake.

The improved residual performance of glauconite treatments was attributed to the slow-release behavior and high cation exchange capacity of glauconite, which reduced potassium losses and synchronized nutrient release with plant demand (Rudmin et al., 2019a; Oze et al., 2019). Furthermore, glauconite likely contributed additional micronutrients and improved soil physical properties, enhancing crop growth and nutrient utilization (Costa et al., 2024; Eldawwy et al., 2024).

Overall, the results demonstrate that acid-treated glauconite can serve as an effective slow-release potassium source capable of improving crop productivity, potassium uptake efficiency, and residual soil fertility. The combination of SOP and glauconite, particularly at 25–75% substitution ratios, provided the most balanced system for sustaining nutrient availability across sequential cropping cycles.

5.CONCLUSION AND RECOMMENDATIONS

Conclusion

This study evaluated glauconite from the El-Gedida region in Egypt as a sustainable potassium fertilizer and soil amendment through mineralogical characterization, chemical extraction studies, acid activation experiments, pot trials on lettuce and tomato, and field experiments on potato and maize.

The investigated glauconite contained 3.0–3.3% potassium together with important macro- and micronutrients including Ca, Mg, Na, Fe, Zn, Cu, and Ni, confirming its potential as a slow-release multi-nutrient fertilizer. The pseudo-total analysis and BCR sequential extraction results demonstrated that potentially toxic elements such as Cd, Pb, Ni, and Cr were either absent or present at concentrations below international safety limits. Most potentially toxic elements were associated with the residual fraction, indicating low mobility and minimal environmental risk.

This work represents the first application of the BCR sequential extraction method to glauconite sediments. The results showed that most potassium and associated nutrients were structurally bound within stable mineral fractions, confirming the slow-release behavior of glauconite and emphasizing the importance of nutrient fractionation in evaluating fertilizer efficiency.

The comparison between single extractants showed that ammonium lactate (AL) was more effective than KCl in extracting potassium, calcium, magnesium, and zinc, indicating that AL is more suitable for estimating plant-available nutrients from glauconite.

Acid activation experiments demonstrated that inorganic acids, particularly HCl and HNO_3, significantly enhanced potassium release compared with organic acids. However, increased nutrient solubility did not always result in improved plant uptake. Acid-treated glauconite increased total nutrient concentrations in soil but also promoted nutrient fixation in some cases, especially for phosphorus. These findings confirmed that nutrient bioavailability and soil chemical interactions are more important than total nutrient concentration alone.

Particle size reduction had only a limited effect on nutrient release, indicating that extensive grinding is not necessary for agricultural application. This finding supports the economic feasibility of using glauconite on a large scale.

The pot experiments demonstrated that glauconite significantly affected soil–plant nutrient dynamics. Washed glauconite improved potassium uptake and nutrient balance in lettuce and tomato, whereas acid-treated glauconite mainly increased total soil nutrient concentrations. Crop responses differed according to nutrient demand, with tomato showing greater sensitivity than lettuce.

Field experiments confirmed the agronomic potential of glauconite under practical conditions. Glauconite combined with potassium sulfate maintained or improved potato yield and biomass production while providing both immediate and sustained potassium availability. The successive maize crop demonstrated a clear residual effect, where treatments containing higher proportions of glauconite maintained greater soil potassium availability and improved potassium uptake without additional fertilization.

Overall, glauconite improved soil fertility, reduced nutrient losses through slow nutrient release, and enhanced nutrient use efficiency. Washing treatment also reduced salinity risks associated with sodium. The results highlight the strong potential of glauconite as a locally available alternative to imported potassium fertilizers in Egypt, particularly for sustainable agriculture in arid and semi-arid regions.

Recommendations

Based on the obtained results, washing is recommended as the most suitable pre-treatment method for glauconite because it improves nutrient bioavailability and reduces salinity effects associated with sodium. Acid treatment may enhance nutrient release; however, its application should be carefully controlled due to the possibility of nutrient fixation and reduced plant uptake efficiency.

Glauconite is recommended for use in combination with conventional potassium fertilizers such as potassium sulfate (SOP) to provide both immediate and long-term nutrient supply. Partial substitution of conventional fertilizers with glauconite can improve nutrient use efficiency while maintaining crop productivity.

Due to its slow-release behavior and residual effect, glauconite is recommended for long-term soil fertility management, particularly in soils with low potassium availability or high nutrient loss potential. Application strategies should also consider crop nutrient demand, as crops with high nutrient requirements showed greater responses to glauconite application.

The use of glauconite supports sustainable agricultural practices by reducing nutrient leaching, improving nutrient retention, and decreasing dependence on highly soluble imported fertilizers. Therefore, further industrial and agricultural development of Egyptian glauconite deposits is strongly recommended to support sustainable fertilizer production and long-term soil health management.

6. NEW SCIENTIFIC RESULTS

1. Glauconite 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 glauconite to evaluate nutrient release behavior and environmental safety. Most elements were associated with stable residual fractions, confirming the predominantly slow-release nature of glauconite. 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 glauconite for agricultural application.

3. Different physical and chemical treatments influenced elemental release from glauconite. 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 glauconite 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 glauconite as a sustainable local potassium source for improving long-term soil fertility and nutrient use efficiency under arid and semi-arid conditions.

The related Publications

Publication (Journal Article)

Nada Eldawwy, Miklós Gulyás, Heba Naser, Anita Takács, Éva Lehoczky, Márk Horváth .Investigating the elemental composition of Egyptian glauconite sediments by applying BCR sequential extraction procedure and some single extractants. AGROKÉMIA ÉS TALAJTAN 73 (2024) 1, 42–58 DOI: 10.1556/0088.2024.00170

2.Publication (Journal Article)

Nada Eldawwy, Márk Horváth, Heba Naser, Éva Lehoczky, Eszter Takács, Gábor Halász, Abdulrahman Maina Zubairu, András Székács and Miklós Gulyás.. Elemental Release from Egyptian Glauconite Sediments: An Extraction Study by Various Acids. Soil System 2025, 9, 50. https://doi.org/ 10.3390/soilsystems9020050

3. Publication (Review Article)

Abdulrahman Maina Zubairu, Jana Marjanović, Mustapha Abdulkadir, Anita Takács, Nada Eldawwy and Miklós Gulyás. Transformation of Agricultural Waste into Biochar and Its Potential for Soil Fertility Restoration in Arid Areas of Borno State, Nigeria .Journal: Discover Sustainability.2026 7.7. https://doi.org/10.1007/s43621-025-02008-9

4. Poster (Abstract) .Nada Gamal Eldawwy, Márk Horváth and Miklós Gulyás .The Followed Strategies to Face the Limitation of Water Resources in Egypt :A Look at Some Major National Projects . The 6th International Scientific Conference on Water (6th ISCW) was held on June 15-16 in Szarvas, Hungary.