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Influence of Enhanced Rock Weathering of Nepheline-Syenite Tailings on Major and Trace Elements Accumulation in Wheat

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ABSTRACT

Soil nutrient depletion and quality are critical challenges facing agriculture and have been exacerbated by the long-term use of chemical fertilisers. A 14-week pot experiment was conducted, with nepheline-syenite tailings (NST) serving as the sole non-nitrogen nutrient source for wheat, to determine the potential of NST to improve the soil nutrient status. The impact of NST on plant health was examined at five application rates (0, 1.25, 5, 10, and 20 g/kg of artificial soil). At the end of the experiments the pH, major and trace elements (e.g., Ca, Mg, P, S, K, Fe, Mn, Zn, Si, Cu, Mo) in both the rhizosphere and the bulk soil, and wheat biomass (both above and belowground) were measured, and used to calculate nutrient uptake. These parameters generally increased with higher NST application rates. Wheat biomass increased with increasing NST doses up to 10 g/kg of artificial soil. Potentially toxic elements (PTEs) such as Al, As, Sr, Rb, and Ba increased in the soil; however, their concentrations remained 52.5% to 91.7% below the world soil average, suggesting minimal environmental risk. The P and K nutrient use efficiency (NUE) decreased with increasing application, indicating that NUE may not be effective for evaluating slow-releasing amendments where the elemental totals do not represent the bioavailable fraction. The findings improve our understanding of how NST can be used to enhance soil fertility and agricultural yield, providing valuable insights for its effective use as soil amendments, particularly in regions with readily available silicate rocks of this type and nutrient-depleted soils.

1 | Introduction

To feed a growing global population, agriculture faces the dual challenges of increasing production and reducing soil/environmental degradation (Mrabet 2023; Saikanth et al. 2023; Khatri et al. 2024). The drive for high crop yields has led to the long-term use of soluble chemical fertilisers, which can result in the runoff of excess macronutrients (e.g., nitrogen (N), phosphorus (P)) causing environmental issues such as eutrophication. Additionally, high doses of N and P have led to soil degradation (Withers et al. 2014; Liu et al. 2019) through the depletion of

medium- and micronutrients (e.g., zinc [Zn], iron [Fe], sodium [Na], and calcium [Ca]; Jones et al. 2013; Abbasi et al. 2014).

Silicate rock dust (SRD), a by-product of quarrying or mining, contains Ca, magnesium (Mg), and potassium (K), and could be a readily available, cost-effective, and sustainable alternative to soluble chemical fertilisers (Dalmora et al. 2020). SRD can be used as a soil remineralizer to replenish a range of soil nutrients (Swoboda et al. 2022; Manning and Theodoro 2020). Silicate minerals occur widely and contain many of the essential elements required by plants, except for nitrogen (Nunes

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Highlights

- Investigated major and trace elements accumulation in wheat following nepheline-syenite tailings application.
- NST increased wheat biomass due to major and trace elements (e.g., Mg, Ca, Cu, Mo, B) uptake.
- Potentially toxic elements (e.g., Ba) were below the world soil average.
- Conventional NUE metrics are unsuitable for evaluating slow-release silicate amendments.

et al. 2014). Through the process of enhanced rock weathering (ERW), SRD has the potential to ameliorate soil nutrient depletion by releasing a range of major (P, K, Ca, Mg, and sulphur [S]) and trace elements (e.g., Fe, manganese [Mn], copper [Cu], Zn, Na, boron [B], cobalt [Co]; Harley and Gilkes 2000; Swoboda 2016; Plata et al. 2021).

SRDs such as basalt, phonolite, syenite, and granite have been studied to evaluate their potential as soil remineralizers, to increase soil fertility, and improve crop yield (Van Straaten 2007; Mohammed et al. 2014; Panhwar et al. 2016; Manning et al. 2017; Chiwona et al. 2020). ERW is also a promising carbon dioxide removal technology that involves spreading SRD on agricultural land; mineral weathering is accelerated by grinding silicate rocks to increase their surface area (Vandeginste et al. 2024). ERW has the potential to sequester an estimated 0.5–2 billion tonnes of CO₂ annually (Guo et al. 2023; Sokol et al. 2024). The efficiency of ERW depends on environmental factors (e.g., pH, water saturation; Deng et al. 2023). Mining and quarrying produce large amounts of low-cost and readily available fine-grained silicate rocks for ERW (Bian et al. 2012; Kinnunen et al. 2022). This approach reduces possible negative environmental impacts such as dust emissions, habitat/vegetation loss, water pollution, and land degradation, minimises waste, and creates novel economic opportunities (Tayebi-Khorami et al. 2019; Cacciuttolo et al. 2023; Kafu-Quvane and Mlaba 2024).

Despite its promise, the widespread adoption of ERW with SRDs by farmers is held back by the lack of systematic studies that quantify the benefits and identify the key nutrients in SRD that provide crop benefits, whilst also assessing possible consequences such as the accumulation of potentially toxic elements (e.g., chromium [Cr], aluminium [Al], arsenic [As], strontium [Sr], rubidium [Rb]) in the soil. One challenge for determining the effectiveness of SRD at improving soil fertility and crop yield is the variability between studies, including numerous rock/mineral types, a mixture of pot and field trials, various crop types, climates, and differences in soil type.

ERW using SRD has been found to improve several soil properties, including nutrient retention, soil pH, available P, K, Ca, Mg, silicon (Si), cation exchange capacity, microbial biomass, and exchangeable bases (Manning 2010; Belliard et al. 2014; Anda et al. 2015; da Silva Mendes et al. 2015), however, few studies have measured trace elements (Table S1). Experiments have used a wide range of crops, including soybean (Cunha et al. 2022), tomatoes (Badr 2006), cocoa (Shamshuddin et al.

2011), maize (Boniao et al. 2002), rice (Panhwar et al. 2014), leeks (Manning et al. 2017), watermelon (Atungwu et al. 2014), and arabica coffee (Mancuso et al. 2014). For example, in pot experiments with leeks and the source of K limited to mica (phlogopite), the K uptake increased with increasing mica additions by 2%, 138%, and 648% compared to the negative control (Manning et al. 2017).

Trials have shown mixed results for improving crop productivity, with many studies showing yield increases (e.g., Sanz Scovino and Rowell 1988; Mohammed et al. 2014; Anda et al. 2015; Manning et al. 2017; Cunha et al. 2022). However, other trials have found no change in yield (e.g., Bolland and Baker 2000; Harley and Gilkes 2000; Campbell 2009; Ramezani et al. 2013; Celimar Dalmora et al. 2020) or even a decrease in yield (Bolland and Baker 2000). For example, Ramezani et al. (2013) in field trials using a commercially available 'volcanic' SRD, found no observable effect on wheat biomass, nutrient status, or soil microbial activity due to the inability of the SRD to increase the soil nutrient bioavailability. Similarly, Hinsinger et al. (1995), found that for sandy soil with a pH of 4.7, the diorite treatment had no observable impact on wheat growth or soil fertility. Additionally, fields amended at rates of 2 and 20 t/ha with granite reduced grain biomass by 22% and 66% compared to the control (Bolland and Baker 2000). The unique conditions of each trial, including the silicate minerals used, make it difficult to determine the mineralogical and environmental differences between 'successful' and 'unsuccessful' SRD trials. Local conditions are likely to cause some variability due to changes in SRD weathering rates and initial soil nutrient bioavailability. A consistent methodology, including SRD mineralogy, soil mineralogy, crop type, and growing conditions, is needed to enable cross-study comparisons. Standardised controlled experiments are required, designed to isolate and quantify the direct nutrient contributions of SRDs and to be free from the confounding effects of natural soil variability and environmental conditions.

In this study, we address this gap by testing the effect of enhanced rock weathering using nepheline-syenite tailings (NST) in nutrient-limiting pot experiments, where SRD was the sole non-nitrogen nutrient source for wheat plants. Using a controlled experimental design based on Manning et al. (2017), which eliminates natural variability in soil mineralogy, we applied NST—also known as 'lurgi' (Bakken et al. 1997)—to artificial soil to evaluate the effects on (i) soil nutrient status, (ii) plant biomass and morphological characteristics, and (iii) macro- and micronutrient uptake. NST was selected as a commercially available mining by-product with distinct alkali-rich mineralogy, which remains underexplored compared to more commonly used materials such as basalt. By standardising the soil matrix (monomineralic high purity quartz), nutrient inputs, and environmental conditions, this study provides a reproducible baseline for assessing SRD performance under controlled conditions. Using this approach, the results relate specifically to the weathering behaviour of NST. We have focused on the first 14 weeks of growth, during which wheat is highly responsive to nutrient availability, and nutrient uptake and biomass accumulation are highest. Our findings improve the understanding of how SRDs enhance soil fertility and agricultural productivity, while also informing their potential role in climate-smart and sustainable agriculture.

2 | Materials and Methods

2.1 | Glasshouse Experiment

The effects of NST on wheat growth were investigated in 14-week closed-system pot experiments conducted in a glasshouse at Cockle Park Farm, Newcastle University, UK (latitude: 55.2144° N; longitude: -1.6854° W). The average glasshouse conditions were 19.0°C temperature, 57% humidity, and a dew point of 10.0°C. The experiment was designed so that NST served as the sole non-nitrogen nutrient source to quantify the release of macro- and micronutrients from the NST without interference from other fertiliser inputs or inputs from minerals naturally present in the soil. To minimise nutrient loss through drainage, pots were maintained as a closed system, and irrigation was carefully controlled using measured volumes of deionised water to avoid leaching. Each of the 40 cm diameter × 30 cm high pots contained 4 kg of well-mixed artificial soil, composed of 3.2 kg of silica sand (Lochaline Silica Sand L30: >99% quartz and >99% 90–500 µm grain size; <https://www.lochalinequartzsand.co.uk/>) and 0.8 kg organic matter (Clover Fine Grade Irish Moss Peat, East Riding Horticulture, www.eastridinghorticulture.co.uk). The artificial soil was analysed by inductively coupled plasma optical emission spectroscopy (ICP-OES) (ICP-OES analytical method; Section 2.4) and contained small amounts of essential elements including Ca (390 mg/kg), Mg (180 mg/kg), Fe (140 mg/kg), Na (120 mg/kg), and extractable Si (95 mg/kg); the full elemental composition is detailed in Table S2. Throughout the study, 'bulk soil' refers to the portion of the artificial soil not in direct contact with plant roots, while 'rhizosheath' refers to the soil adhering to the roots, which is directly influenced by root exudates and microbial activity.

The NST (Sibelco, Antwerp) was from Stjernøy, Norway, and its mineralogical composition has been previously given in detail (Barth 1963; Heier 1964; Mena Silva et al. 2018); <https://www.sibelco.com/en/materials/nepheline-syenite>. The primary mineralogy is orthoclase (a potassium feldspar), nepheline, biotite, and amphibole (Bakken et al. 1997). The NST was sieved to select the predominant particle size, 125–355 µm, which composed 54.5% of the total NST by mass (Gee and Or 2018). XRF analysis was used to determine the oxide composition of the NST (Table S3).

2.2 | Experimental Design and Plant Growth Measurement

A randomised experiment was used to test the impact of five NST application rates (0, 1.25, 5, 10, and 20 g/kg, equivalent to 0, 2.5, 10, 20, and 40 t/ha, respectively), with eight replicates per treatment, on the growth of the globally significant crop, wheat (*Triticum aestivum* L. var. 'KWS Zyatt'). Each pot had an individual saucer to prevent the transfer of water or nutrients between pots. Three wheat seeds were sown per pot, and 14 days after sowing (DAS), plants were thinned to one per pot. To limit external nutrient inputs and maintain consistent moisture, deionised water (<https://www.chemicals.co.uk/deionised-water>) was used for irrigation. Soil moisture was initially adjusted to 70% of pot water-holding capacity, and plants were then watered twice weekly with 400 mL on Mondays and 300 mL on Fridays

to sustain near-optimal growing conditions. Ammonium nitrate (32.4 mM; 200 mL) was used to provide nitrogen at 30 and 40 DAS, at a rate equivalent to 180 kg N ha⁻¹ based on UK agronomic recommendations (Department for Environment, Food & Rural Affairs 2015). Other major nutrients such as P and K were not applied and intended to be supplied through the NST treatments. From 30 DAS, stem diameter was assessed using a stainless steel vernier calliper, and the number of tillers and leaves was counted every 2 weeks.

2.3 | Plant and Soil Sampling

Four pots per treatment were selected for plant and soil sampling, while the remaining four pots were reserved for a subsequent nutrient uptake gene expression study (Figure 1S for sampling workflow). The wheat plants were harvested at 100 DAS, washed to remove soil debris, and separated into aboveground and belowground biomass. The biomass was dried at 65°C for 72 h and then weighed. Due to the limited biomass obtained from individual pots, subsamples of aboveground and belowground biomass from the four pots within each treatment were finely milled and pooled. The composite plant samples were used for trace and minor element analysis.

To collect rhizosheath soil samples, wheat plants were uprooted, loose soil attached to the roots was removed by shaking, and firmly adhered soil was scraped off with a spatula. Soil not in direct contact with the roots was collected with a hand trowel as bulk soil. Soil samples were sieved using a 2-mm mesh to make composite bulk and rhizosheath soil samples for each. Soil samples for each treatment were dried at 65°C for 72 h.

2.4 | Plant, Artificial Soil, and Soil Analysis

The artificial soil, NST, plant samples, and NST-amended soil were digested for elemental analysis using U.S. Environmental Protection Agency method 3051a (US EPA 2007). Bulk soil and rhizosheath soil samples were analysed individually for each of the four pots within a treatment. An exception was made for the control, where the rhizosheath soil from the four pots was insufficient and therefore pooled. This pooling step was applied only to the control treatment, and only for aqua regia extraction, to ensure enough material for analysis. In this case, the pooled control sample was analysed in four technical replicates. Plant biomass samples (aboveground and belowground), which had been pooled from the four pots within each treatment, were treated as a single biological replicate and analysed in four technical replicates (Figure 1S for sampling workflow). In brief, approximately 0.2 g of material was microwave digested (MARS 6) in an amended aqua regia solution of 10 mL of 16.22 M nitric acid and 2 mL of 12.08 M hydrochloric acid, at 120°C for 45 min. Digestates were filtered through 0.45 µm Whatman-hardened filters and diluted to a final volume of 50 mL with ultrapure water. The same method was used for plant samples with half the sample mass, acid, and after dilution sample volume. The soil bioavailable nutrient fraction was extracted using a Mehlich-3 extraction solution composed of 0.2 M CH₃COOH, 0.25 M NH₄NO₃, 0.015 M NH₄F, 0.013 M HNO₃, and 0.001 M EDTA (Mehlich 1984). Both aqua regia and Mehlich-3 samples

were analysed using an Agilent 5800 inductively coupled plasma optical emission spectroscopy (ICP-OES) configured with a micromist nebulizer, and cyclonic spray chamber. During analysis, precision, accuracy, and drift were monitored through the analysis of blanks and repeat standards every 12 samples for the duration of the runs. Trace elements in aqua regia samples were measured using an Agilent 8900 Triple Quadrupole ICP-MS inductively coupled plasma mass spectrometry with a micromist nebulizer, a cooled double concentric spray chamber, and nickel cones. During analysis, a 10 ppb indium (In) internal standard was used to monitor and correct for drift. Additionally, analysis blanks and repeat standards were analysed every 12 samples for the duration of the run to determine detection limits, accuracy, and precision. A collision gas reaction cell was employed with helium gas to remove polyatomic interferences. A pH meter (HANNA HI 8424) was used to determine the pH using a ratio of 1:2.5 (w/v) soil/distilled water and measured after 15 min equilibration.

2.5 | Nutrient Uptake and Use Efficiency

The potassium and phosphorus content in the NST application rates (Table 1) were used to calculate the nutrient use efficiency (NUE). Nutrient uptake (mg/pot) was calculated as the product of dry biomass yield (kg/pot) and nutrient concentration in the plant tissue (mg/kg dry weight), determined separately for aboveground and belowground biomass. Nutrient use efficiency (NUE) indices such as partial factor productivity (PFP), agronomic efficiency (AE), recovery efficiency (RE), and physiological efficiency (PE) were employed for estimating nutrient utilization following the application of NST (Hong and Guanghuo 2004).

Partial factor productivity (PFP):

$$\text{PFP} = \frac{B_f}{F} \quad (1)$$

where B_f is the crop biomass with NST applied, and F is the quantity of the K or P applied from the NST.

Agronomic efficiency (AE):

$$\text{AE} = \frac{B_f - B_o}{F} (\text{mg} / \text{mg}) \quad (2)$$

TABLE 1 | Application rates of NST used in the pot trial experiment.

Treatment	g/kg	g K/kg	g P/kg
Control			
Ctrl	0		
Nepheline-syenite tailings			
NST-1.25	1.25	0.008	0.0005
NST-5	5	0.032	0.002
NST-10	10	0.063	0.004
NST-20	20	0.126	0.008

where B_o is the biomass from the control treatment (without K or P from NST).

Recovery efficiency (RE):

$$\text{RE} = \frac{U_f - U_o}{F}, \quad (3)$$

where U_f is the K or P uptake by the biomass when NST is applied and U_o is the K or P uptake by the biomass in the control treatment.

Physiological efficiency (PE):

$$\text{PE} = \frac{B_f - B_o}{U_f - U_o} (\text{mg} / \text{mg}) \quad (4)$$

2.6 | Data Analysis

One-way ANOVA was used to evaluate the impact of NST on soil quality, wheat biomass, nutrient uptake, and nutrient use efficiency. For plant tissue analyses, samples within each treatment were composited and subdivided into four subsamples for laboratory measurement due to insufficient plant material from individual pots. Thus, the ANOVA results for plant nutrient concentrations represent treatment-level comparisons rather than variability among individual pots. For soil analyses, biological replicates were maintained, with bulk and rhizosheath soils analysed individually for four pots. An exception was made for the control, where rhizosheath soil was insufficient and therefore pooled for aqua regia extraction. Data normality was checked using the Shapiro–Wilk test. Significant differences ($p < 0.05$) between NST application rates for the rhizosheath and bulk soil were determined using Tukey's HSD test at the 0.05 significance level. Independent t -tests were used to determine statistically significant differences between rhizosheath soil properties and the corresponding bulk soil. Analyses were performed using R Statistical Software (v4.4.0; R Core Team 2024) and visualized with GraphPad Prism version 10.0.0 for Windows (GraphPad Software, Boston, Massachusetts, USA; www.graphpad.com). Pearson correlation analysis was conducted using Python 3.11.6 to examine relationships between bio-essential elements and total biomass, as well as inter-element correlations. Correlation coefficients and p values were calculated using the `pearsonr()` function from the SciPy library (v1.11.3), and correlation matrices were generated with the `corr()` method in the pandas library (v2.2.3).

3 | Results

3.1 | Soil pH

The soil pH of the NST-amended soil ranged from 4.12 to 4.99 in the bulk soil and 4.35 to 5.70 in the rhizosheath. It increased with increasing NST dose. The NST-20 rhizosheath soil pH was higher by 0.8 and 1.4 units than the NST-1.25 and the control, respectively (Figure 1). In contrast, for the bulk soil there was no significant difference ($p = 0.571$) in the soil pH between NST-5 and NST-10 or NST-10 and NST-20. The pH of rhizosheath soil was significantly greater ($p < 0.001$) than the bulk soil for all treatments.

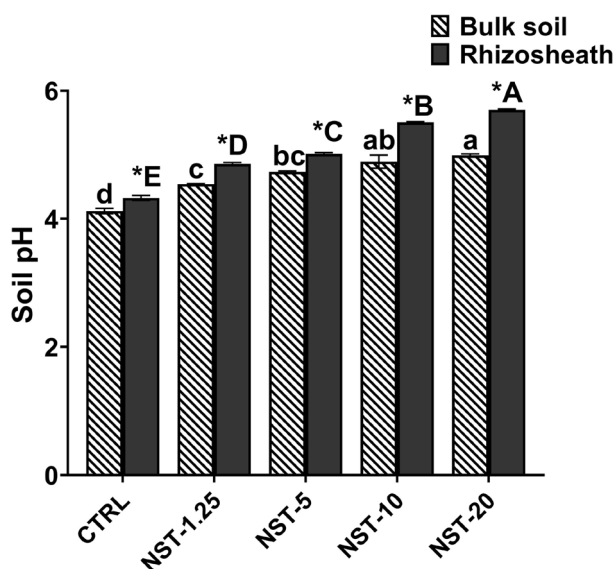


FIGURE 1 | The soil pH response to NST treatment. The values are the mean $\pm$ SE ($N=4$). Uppercase and lowercase letters indicate significant differences ($p < 0.05$) among the NST application rates within the rhizosheath and bulk soil. Significant differences between the rhizosheath and the corresponding bulk soil pH are indicated with asterisks at the $p < 0.05$ level. CTRL = Control, NST-1.25 = 1.25 g/kg, NST-5 = 5 g/kg, NST-10 = 10 g/kg, and NST-20 = 20 g/kg of nepheline-syenite tailings.

3.2 | Soil Nutrient Concentration

3.2.1 | Total Nutrient Concentration

3.2.1.1 | Bio-Essential Elements (BEE); Strong Acid Extraction. In general, the BEE concentrations were higher in the rhizosheath than bulk soil (Figure 2). In both soil fractions the elemental concentrations increased with increased NST application. While there was an overall increase, no significant differences were observed between the control, NST-1.25, and NST-5 treatments for many elements including P. While NST-20 resulted in the highest elemental concentrations, these were only significantly different from NST-10 for Mn, Mo, and Zn, for both the rhizosheath and bulk soil (Figure 2). The NST-20 rhizosheath concentrations of Mg, Ca, and K were 500%, 300%, and 5000% higher than control, while in the bulk soil, these elements were 100%, 100%, and 700% higher, respectively (Figure 2A–C). P, Mn, and S were 100%, 2000%, and 200% higher in NST-20 compared to the control in the rhizosheath. In the bulk soil P, Mn, and S were 90%, 600%, and 30% higher, respectively (Figure 2D–F). In the rhizosheath of NST-20 treatments, the Fe, Zn, and Mo concentrations were 500%, 70%, and 200% higher than in control, respectively, while in the bulk soil, these elements increased by 30% to 100% (Figure 2G–I). The concentrations of Co, Na, Si, boron (B), Cu, and selenium (Se) in NST-20 were significantly higher compared to the control, with increases of approximately 2000%, 1000%, 1000% for Co, Na, and Si, respectively, and 20%, 100%, and 200% for B, Cu, and Se in the rhizosheath. In the bulk soil, these elements also increased in NST-20 compared to control, with increases of 300% for Co, 400% for Na, 400% for Si, 100% for B, 100% for Cu, and 6% for Se (Figure 2J–O).

3.2.1.2 | Potentially Toxic Elements; Strong Acid Extraction. Increasing NST application rates increased the abundance of potentially toxic elements (PTE) in the soil, particularly in the rhizosheath. Al was higher in the rhizosheath bulk soil of NST-20 compared to the control (Figure 3A). Similarly, strontium (Sr) and titanium (Ti) were 8000% and 2000% higher in the bulk soil, respectively, in NST-20 than in the control (Figure 3B,C). Cr had a 200% increase in the rhizosheath at NST-20 compared to the control (Figure 3D). Ba and Rb increased by approximately 2000% and 500% in the rhizosheath and by 300% and 900% in the bulk soil, respectively, for NST-20 compared to the control (Figure 3E,F), while As increased by 40% in the rhizosheath at NST-20 compared to the control (Figure 3G).

3.2.2 | Available Nutrient Concentration (Mehlich-3 Extraction)

For both soil types, increasing NST application rates resulted in higher concentrations of bioavailable Ca, Mg, P, and Fe, particularly in the rhizosheath (Figure 4). The Ca and Mg concentrations at NST-20 were approximately 100% and 150%, respectively higher than the control (Figure 4A,B). The P concentration of NST-20 was approximately 200% higher in the rhizosheath compared to the control (Figure 4C). In contrast, S concentrations in both the bulk soil and rhizosheath exhibited no significant differences between the NST application rates and the control (Figure 4D). The Fe concentration in the rhizosheath of NST-20 was approximately 700% higher than the control (Figure 4E).

3.3 | Wheat Growth Characteristics and Biomass

Increasing NST application rates led to an increase in the number of tillers, leaves, and plant height (Figure 5). Despite the increase, no significant differences were found between NST-5, NST-10, and NST-20 for the number of tillers, leaves, or plant height (Figure 5). At 93 DAS, the number of tillers and leaves was approximately 100% greater for the NST-20 treatment compared to the control (Figure 5A,B). Plant height also increased; NST-20 was 14 cm taller than the control at 93 DAS (Figure 5C). Despite the increase, no significant differences were found between NST-5, NST-10, and NST-20 for the plant height at 93 DAS (Figure 5C). The application of NST led to an increase in wheat biomass compared to the control. However, no significant differences were observed in either aboveground or belowground biomass for NST-1.25, NST-5, and NST-10. In the aboveground biomass, NST-20 resulted in a 700% increase in biomass compared to the control and a 180% increase compared to NST-5 (Figure 5D). The belowground biomass also showed a significant increase at NST-20 and was 150% higher than the control and significantly higher than NST-1.25 (Figure 5D).

3.4 | Nutrient Concentrations in Wheat Biomass

3.4.1 | Bio-Essential Elements

The nutrient concentration generally increased in the aboveground and belowground biomass with increasing NST application rates. Elements such as Ca, K, Mn, Fe, Mo, Zn, and Na exhibited no

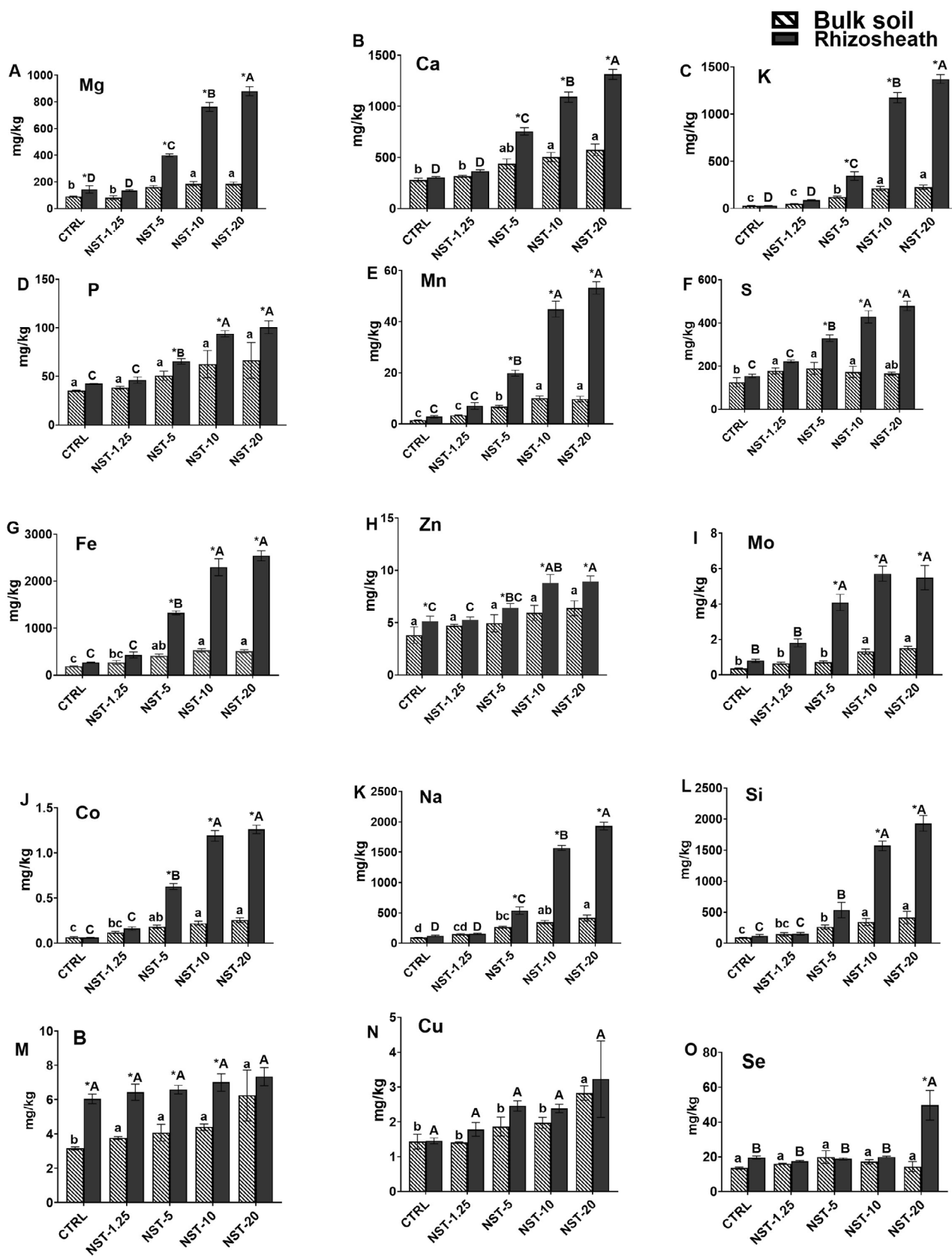


FIGURE 2 | Elemental composition of the NST amended soil and control. The values are the mean $\pm$ SE ($N=4$). Significant differences ($p < 0.05$) among application rates within the rhizosphere and bulk soil are indicated by different uppercase and lowercase letters. Significant differences between the rhizosphere and the corresponding bulk soil are indicated by the asterisks at the $p < 0.05$ level. CTRL = Control, NST-1.25 = 1.25 g/kg, NST-5 = 5 g/kg, NST-10 = 10 g/kg, and NST-20 = 20 g/kg of nepheline-syenite tailings.

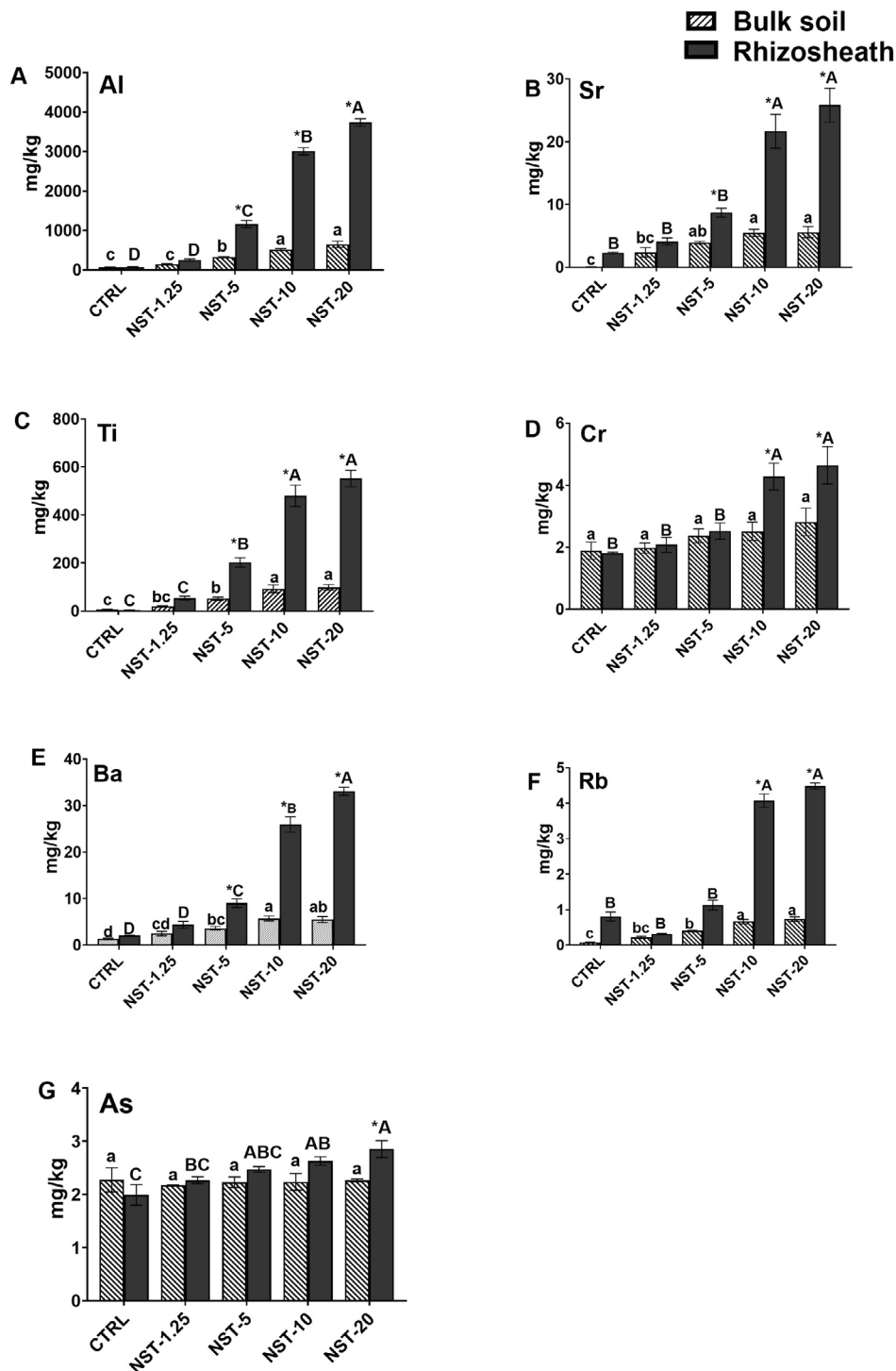


FIGURE 3 | PTE concentration of NST amended soils and control. The values are the mean $\pm$ SE ($N=4$). Significant differences ($p < 0.05$) between application rates within the rhizosphere and bulk soil are indicated by different uppercase and lowercase letters. Significant differences between the rhizosphere and the corresponding bulk soil are indicated by the asterisks at the $p < 0.05$ level. CTRL = Control, NST-1.25 = 1.25 g/kg, NST-5 = 5 g/kg, NST-10 = 10 g/kg, and NST-20 = 20 g/kg of nepheline syenite tailings.

significant differences between the NST-1.25, NST-5, and NST-10 treatments in the belowground biomass, or for Fe, Mo, and S in the aboveground biomass (Figure 6). In the aboveground and belowground biomass, Ca and K concentrations in NST-20 were approximately 100% higher than the control (Figure 6A,B). The Mg concentrations were 120% higher in NST-20 than in the control (Figure 6C). Concentrations of Fe in NST-20 were 200% higher than

in the control (Figure 6D). Concentrations of Mn, Zn, Co, B, and Cu in NST-20 exceeded the control by 60% to 100% (Figure 6E-I). Mo was approximately 200% higher in the NST-20 treatment compared to the control but did not differ significantly from NST-10 in either the aboveground or belowground biomass (Figure 6J). S increased by 50% in NST-20 compared to the control in the belowground biomass, but the aboveground biomass had no significant

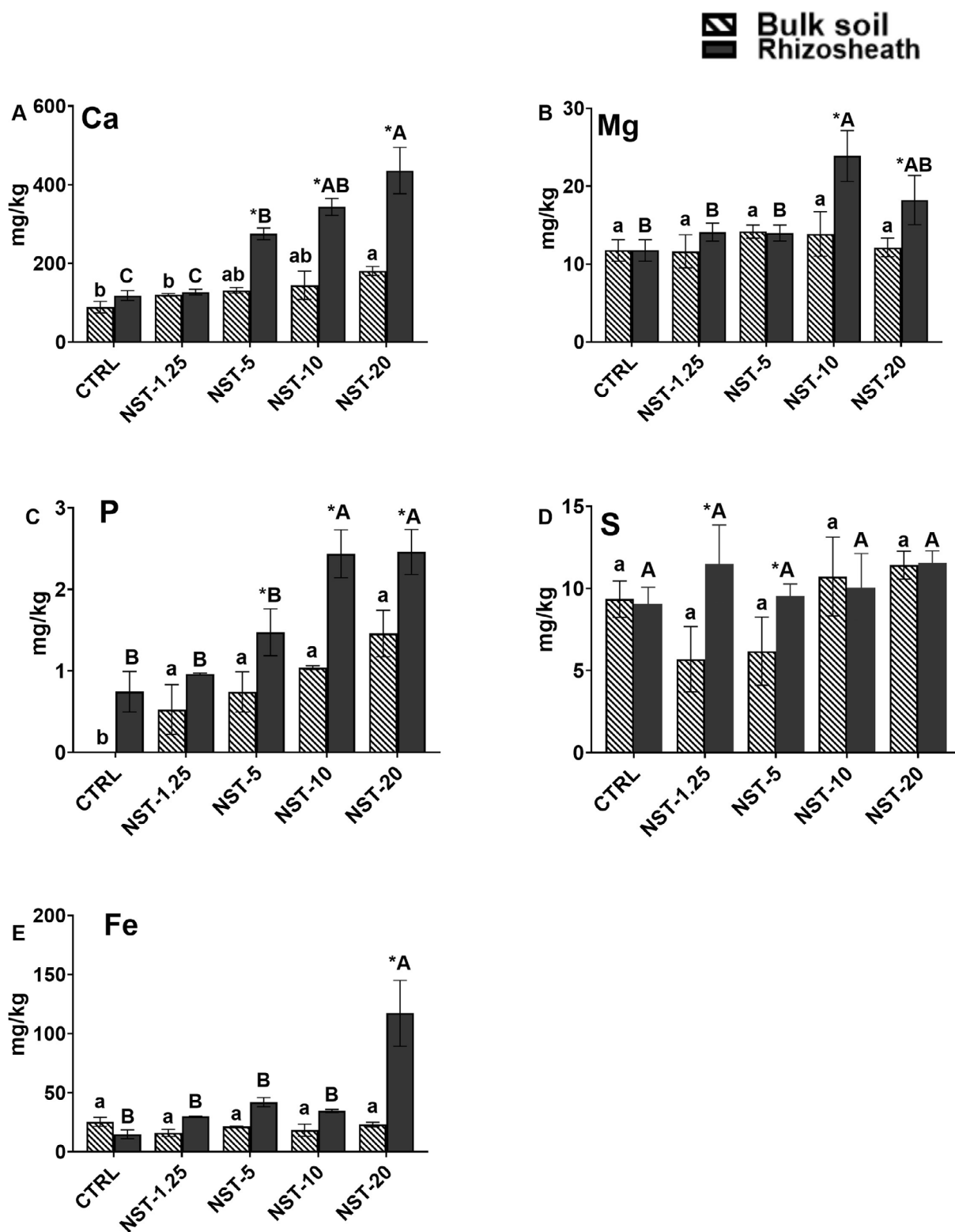


FIGURE 4 | Bioavailable elemental concentration in NST amended soil (Mehlich-3 extraction) and control. The values are the mean $\pm$ SE ($n=4$). Significant differences ($p<0.05$) among application rates within the rhizosheath and bulk soil were indicated by different uppercase and lowercase letters. Significant differences between the rhizosheath and the corresponding bulk soil are indicated by the asterisks at the $p<0.05$ level. CTRL = Control, NST-1.25 = 1.25 g/kg, NST-5 = 5 g/kg, NST-10 = 10 g/kg, and NST-20 = 20 g/kg of nepheline-syenite tailings.

differences across treatments (Figure 6K). P increased by 200% for NST-20 in the aboveground biomass compared to the control but decreased by 50% in the belowground biomass (Figure 6L). In the aboveground biomass, the Na concentration decreased

significantly for the higher NST application rates, with NST-20 being approximately 50% lower than the control (Figure 6M). Se and Si concentrations showed no significant differences across treatments (Figure 6N,O).

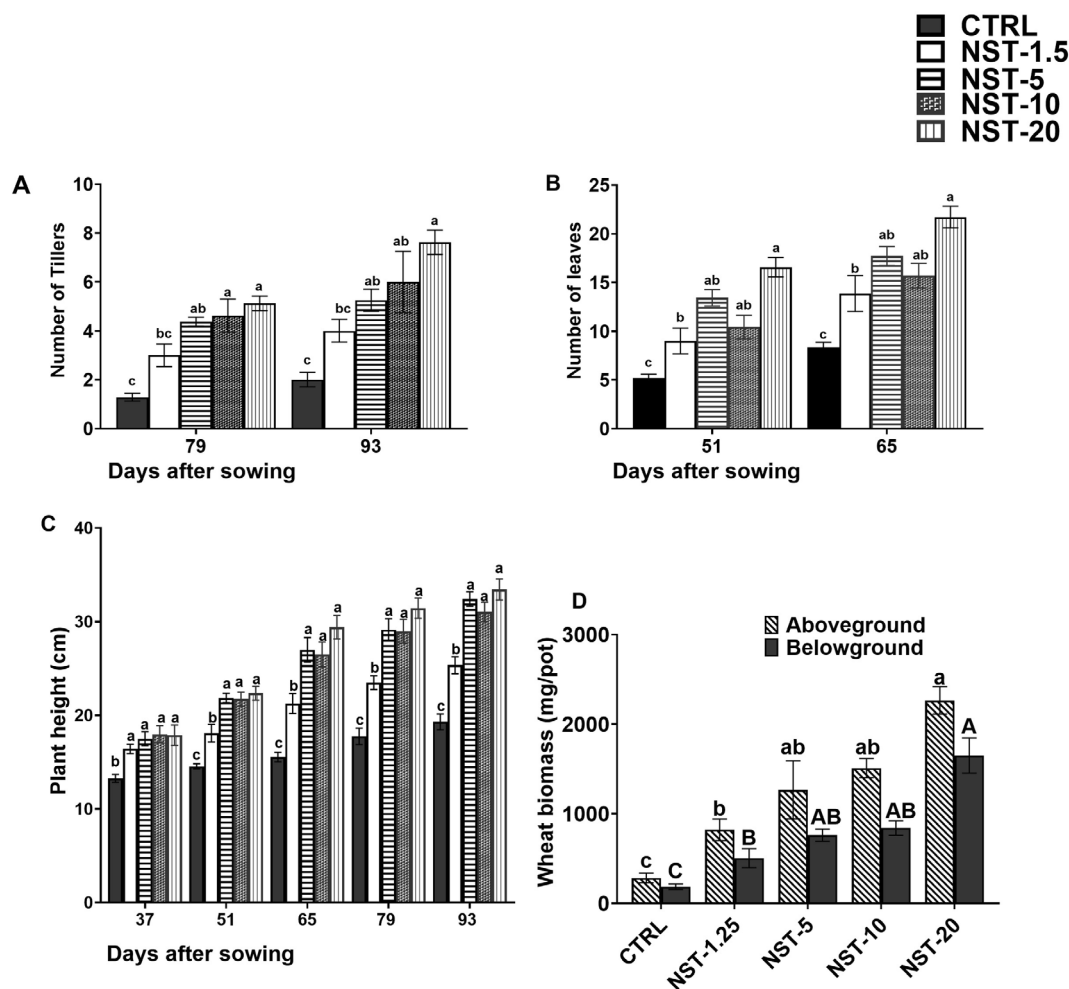


FIGURE 5 | Effect of NST application on wheat morphological characteristics (plant height, number of leaves, and number of tillers) and wheat biomass (aboveground and belowground biomass) after 100 DAS. The values are the mean $\pm$ SE ($N=8$). Uppercase and lowercase letters indicate significant differences ($p < 0.05$) among the NST application rates within the belowground and aboveground biomass. The same letters on the bars are not significantly different at $p \leq 0.05$. CTRL=Control, NST-1.25 = 1.25 g/kg, NST-5 = 5 g/kg, NST-10 = 10 g/kg, and NST-20 = 20 g/kg of nepheline-syenite tailings.

3.4.2 | Potentially Toxic Elements

The Ba concentration increased in the aboveground biomass with the application rate, ranging from 5.74 to 15.04 mg/kg, while in the belowground biomass, concentrations decreased from 19.27 to 8.47 mg/kg. However, no significant difference was found between the NST-5 and NST-10 treatments for either biomass type (Figure 7A). The Al and Sr concentrations in the aboveground biomass were approximately 150% and 200% higher, respectively, in NST-20 compared to the control in the aboveground biomass, with Sr showing a 100% increase in the belowground biomass (Figure 7B,C). Ti was 300% higher in the aboveground biomass in NST-20 compared to the control (Figure 7D). Rb in the belowground biomass was approximately 150% higher in NST-20 compared to the control (Figure 7E). The As concentration was highest in NST-1.25 in the aboveground biomass, decreasing at higher NST rates. The belowground biomass As concentration in NST-20 was similar to the control (Figure 7F). Cr concentrations in the aboveground biomass increased by about 100% in NST-20 compared to the control, with no significant changes in the belowground biomass (Figure 7G).

3.5 | Nutrient Uptake

3.5.1 | Bio-Essential Elements

In both aboveground and belowground biomass, the bio-essential element uptake increased with higher NST application rates, though there was no significant difference between the control, NST-1.25, and NST-5. While NST-20 had the highest uptake, the levels were only significantly different from NST-10 for Mn, Mo, and Zn (Figure 8). In both biomass types, Mg, Ca, and K uptake in the NST-20 treatment was 300%, 500%, and 350% higher, respectively than for 1.25 (Figure 8A–C). P, Mn, and S followed similar patterns, with NST-20 showing increases of approximately 2000%, 1500%, and 700%, respectively, compared to the control in both biomass types (Figure 8D–F). In both aboveground and belowground biomass, the Fe and Zn concentrations at NST-20 were 2000% and 1000% higher, respectively, than the control (Figure 8G,H). In both aboveground biomass, Mo increased by approximately 200%, Co by 300%, and Na by 300% compared to the control (Figure 8I–K). Si and B levels in NST-20 were approximately

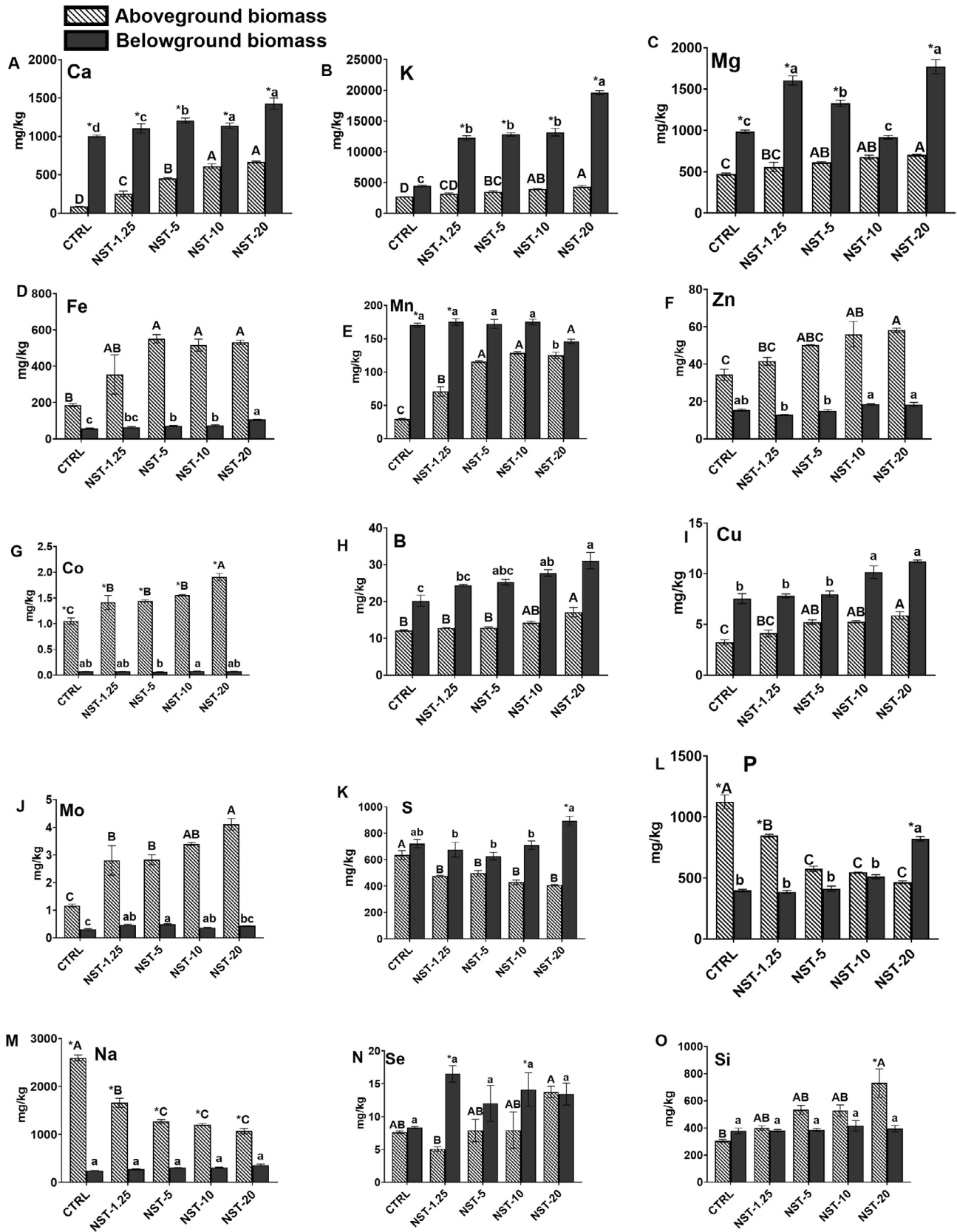


FIGURE 6 | Effect of NST application on wheat nutrient concentration. Values are the mean $\pm$ SE ($N=3$). Significant differences ($p < 0.05$) within the aboveground and belowground biomass are indicated by different uppercase and lowercase letters. Significant differences between the nutrient constituents of the aboveground and belowground biomass are indicated by asterisks ($p < 0.05$). CTRL = Control, NST-1.25 = 1.25 g/kg, NST-5 = 5 g/kg, NST-10 = 10 g/kg, and NST-20 = 20 g/kg of nepheline syenite tailings.

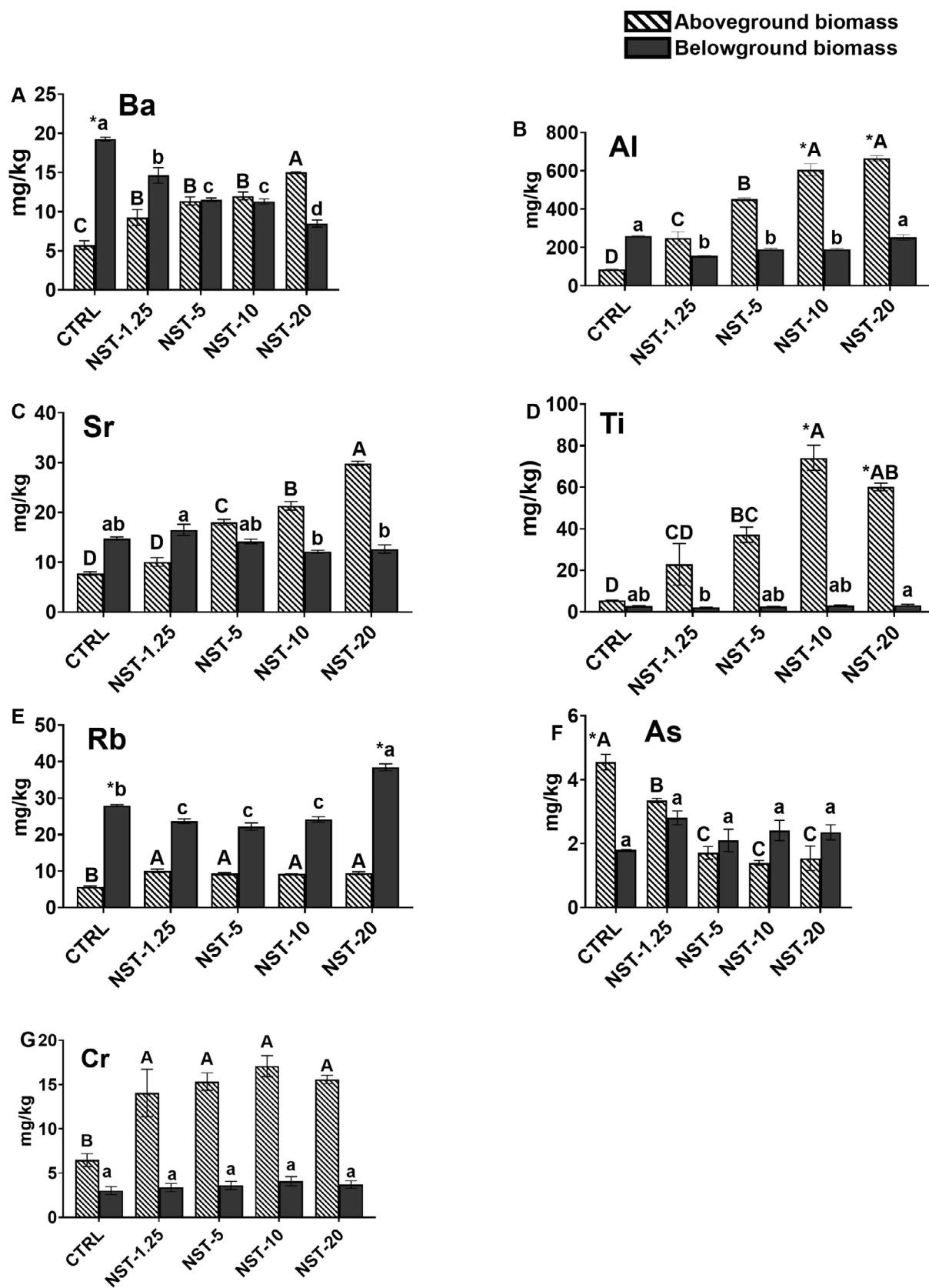


FIGURE 7 | Effect of NST application on potentially toxic element constituents of wheat biomass. The values are the mean $\pm$ SE ($N=3$). Significant differences ($p < 0.05$) between the NST rates within the aboveground and belowground biomass are indicated by different uppercase and lowercase letters. Significant differences ($p < 0.05$) between the nutrient constituents of the aboveground and belowground biomass are indicated by asterisks. CTRL = Control, NST-1.25 = 1.25 g/kg, NST-5 = 5 g/kg, NST-10 = 10 g/kg, and NST-20 = 20 g/kg of nepheline-syenite tailings.

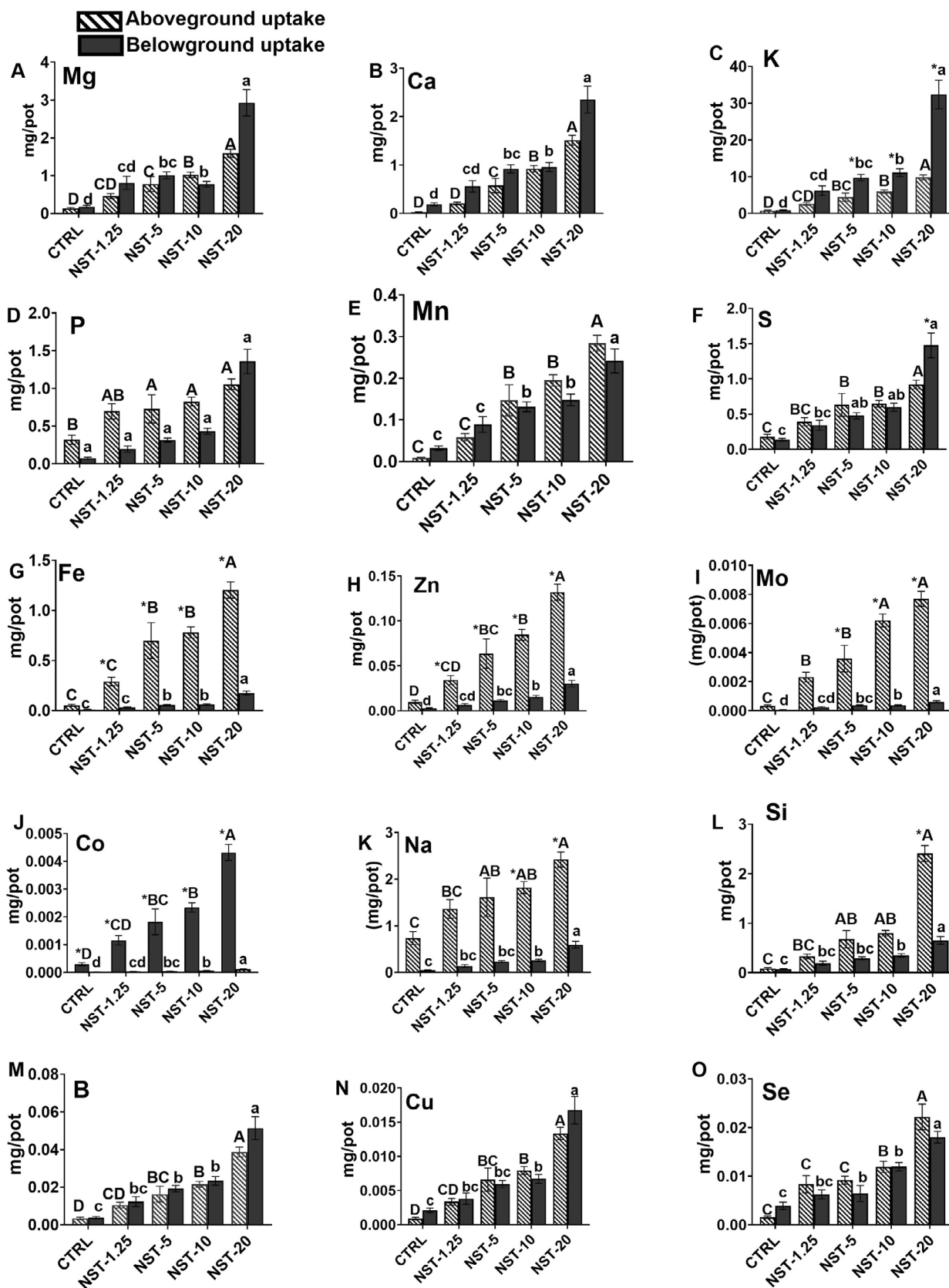


FIGURE 8 | Effect of NST application on wheat nutrient uptake (mg/pot). The values are the mean $\pm$ SE ($N=4$). Significant differences ($p < 0.05$) among the NST rates within the aboveground and belowground biomass are indicated by different uppercase and lowercase letters. Significant differences ($p < 0.05$) between the nutrient constituents of the aboveground and belowground biomass are indicated by an asterisk. CTRL = CTRL, NST-1.25 = 1.25 g/kg, NST-5 = 5 g/kg, NST-10 = 10 g/kg, and NST-20 = 20 g/kg of nepheline syenite tailings.

2700% and 1000% higher in aboveground biomass, and 800% and 1000% higher in belowground biomass, compared to the control (Figure 8L,M). Similarly, Cu and Se levels increased by approximately 1000% and 400% in aboveground biomass, and 700% and 1000% in belowground biomass, respectively, at NST-20 compared to the control (Figure 8N,O).

3.5.2 | Potentially Toxic Elements

The PTE uptake increased with increasing NST application (Figure 9). No significant differences were observed between NST-1.25 and NST-5. However, at NST-20, Ba uptake was 400% higher in the aboveground biomass compared to the control, although Ba uptake remained below 0.04 mg/pot across treatments (Figure 9A). The Al levels in the aboveground biomass were approximately 6000% higher for NST-20 compared to the control. In the belowground biomass there was an increase of 800% for Al at NST-20 compared to the control (Figure 9B). At NST-20 Sr. was approximately 3000% higher than the control in the aboveground biomass and 600% higher in the belowground biomass (Figure 9C). The Ti levels in the aboveground biomass were approximately 70% higher for NST-20 compared to the control. In the belowground biomass there was a decrease of 90% for Ti at NST-20 compared to the control (Figure 9D). Rb was approximately 1000% higher in both biomass types at NST-20 compared to the control (Figure 9E). The As concentration showed an increase of 200% in the aboveground biomass and 1000% in the belowground biomass at NST-20 compared to the control, with minimal variation across other treatments (Figure 9F). The Cr levels in the aboveground biomass were approximately 2000% higher for NST-20 compared to the control. In the belowground biomass, there was a 1000% increase in Cr in the NST-20 compared to the control (Figure 9G).

3.6 | Nutrient Use Efficiency

Increasing NST application rates led to a decrease in both the K and O REP, AE, PE, and PFP for aboveground and belowground biomass, with no significant differences observed between NST-1.25, NST-10, and NST-20 (Figure 10). REP-P (Figure 10A) and REP-K (Figure 10B) for NST-20 were approximately 50% lower than for NST-1.25. AE-P (Figure 10C) and AE-K (Figure 10D) for NST-20 were approximately 80% lower than for NST-1.5. PE-P decreased by 70% from NST-1.25 to NST-20 (Figure 10E), while PEP-K decreased by approximately 50% (Figure 10F). PFP-P (Figure 10G) and PFP-K (Figure 10H) for NST-20 were approximately 90% lower than for NST-1.25.

3.6.1 | Pearson Correlation Analysis

A Pearson correlation analysis indicated a strong positive relationship between the concentrations for most bio-essential elements and total plant biomass, with 10 bio-elements (Ca, Mn, Fe, Mg, Si, Na, P Co, S, K) showing strong correlations ($r > 0.8$, $p < 0.0001$), indicating that the increased availability of nutrients are critical drivers for increased wheat growth

(Figure 2S). In contrast, Se concentration exhibited a moderate negative correlation with biomass ($r = -0.546$, $p < 0.05$), indicating that lower Se accumulation was linked to increased growth. This pattern does not suggest Se toxicity, but rather a dilution effect whereby greater biomass reduces the relative concentration. Se uptake (absolute amount per plant) showed a strong positive correlation with biomass, indicating greater growth results in greater Se accumulation, only concentration per unit biomass decreased (Figure 3S). P has been shown to influence Se uptake and distribution (Liu et al. 2004), suggesting that nutrient interactions could have modulated Se dynamics in our study, as reflected by the strong positive correlation between P concentration and biomass. The total uptake of all the bio-essential elements, including Se, Ca, Mn, Fe, Mg, Si, Na, P Co, S, and K, also showed strong positive correlations with plant biomass ($r > 0.8$, $p < 0.0001$) (Figure 2S).

4 | Discussion

4.1 | Soil pH

During silicate mineral weathering, the consumption of protons by silicate anions (SiO_4^{-4}) to form monosilicic acid (H_4SiO_4) in solution results in the soil pH increasing and drives the dissociation of water to release protons (McBride 1994). Many SRD studies have reported soil pH increases; for instance, in basalt-amended soil the pH increased from 4.5 to 4.82 (Anda et al. 2013), dunite-amended soil from 5.2 to 5.6 (Crusciol et al. 2019), and olivine-amended soil from 5.12 to 5.75 (Cunha et al. 2022). With increasing SRD dose, the pH correspondingly increases. For example, after dolerite (a basaltic rock) applications at 2, 5, and 20 t/ha, the soil pH increased to 4.74, 4.76, and 4.82, respectively (Cunha et al. 2022). A soil pH increase of 3.8 to 4.9 over 4 months in field trials with dolerite was attributed to the hydrolysis reaction of SiO_4^{-4} released during the weathering of olivine and pyroxene (Panhwar et al. 2016). In the current study, pH increased in both the rhizosphere and bulk soil following the application of NST, and this can be attributed to the consumption of protons and release of cations during the weathering of the silicate minerals in the NST, such as plagioclase (albite), clinopyroxene, hornblende, K-feldspar, and muscovite. The variation between the SRD studies is driven by a combination of initial soil pH, SRD application rate, the mineralogical composition of the silicates applied (since different minerals weather at substantially different rates), and environmental factors such as soil water saturation.

The additional pH increases in the rhizosphere compared to the bulk soil are likely related to root exudates. Organic acids released by the roots, such as citric, malic, and oxalic acids, can accelerate mineral weathering mainly through the complexation of base cations. Although these acids are capable of lowering pH, under our initial acidic conditions, their dissociation and cation-binding effects likely contribute to enhanced SRD weathering, pH buffering, and a net increase in pH (Ruiz et al. 2022). Additionally, exudates such as sugars (e.g., glucose, fructose, and sucrose) and amino acids (e.g., glutamate, aspartate, and alanine) are critical energy sources for rhizosphere microorganisms. Microbial activity has been

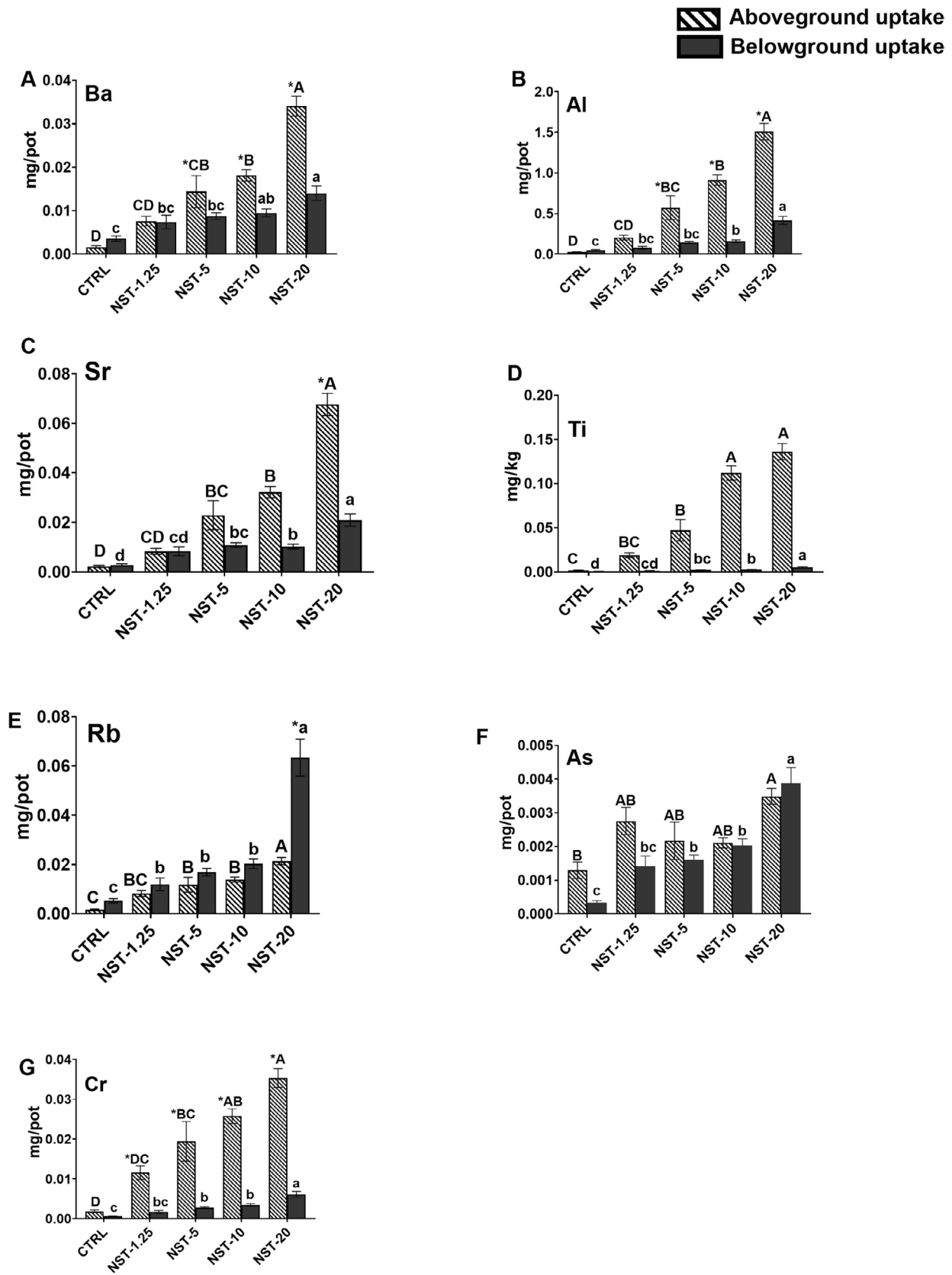


FIGURE 9 | Effect of NST application on potentially toxic element uptake of wheat biomass. The values are the mean $\pm$ SE ($N=4$). Significant differences ($p < 0.05$) among the NST rates within the aboveground and belowground biomass are indicated by different uppercase and lowercase letters. Significant differences between the nutrient constituents of the aboveground and belowground biomass are indicated by the asterisk at the $p < 0.05$ level. CTRL= control, NST-1.25= 1.25 g/kg, NST-5= 5 g/kg, NST-10= 10 g/kg, and NST-20= 20 g/kg of nepheline-syenite tailings.

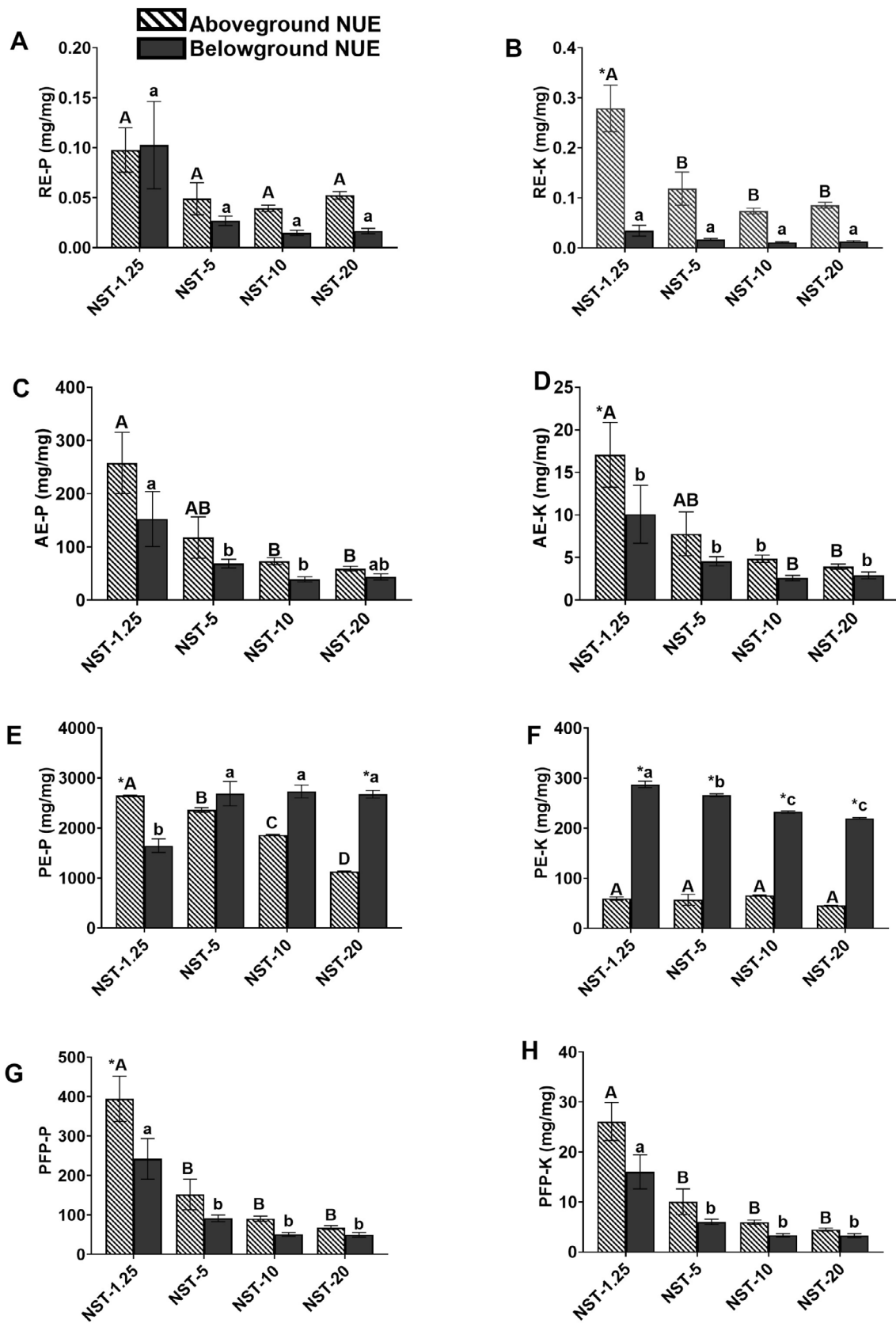


FIGURE 10 | NUE of wheat biomass in response to NST treatments. The values are the mean $\pm$ SE ($N=4$). Significant differences ($p < 0.05$) between application rates and aboveground and belowground biomass are indicated by uppercase and lowercase letters. Significant differences in the aboveground and belowground NUE are indicated by the asterisks at the $p < 0.05$ level. CTRL=CTRL, NST-1.25=1.25 g/kg, NST-5=5 g/kg, NST-10=10 g/kg, and NST-20=20 g/kg of nepheline-syenite tailings. NUE, Nutrient use efficiency, PFP, Partial factor productivity, AE, Agronomic efficiency, RE, Recovery efficiency, and PE, Physiological efficiency.

hypothesised to enhance the weathering of SRD (Macias-Benitez et al. 2020).

4.2 | Soil Element Concentration

NST increased the total and available soil K in the rhizosphere and bulk soil, with the most likely sources in the NST being nepheline and K-feldspar (orthoclase; Bakken et al. 1997). Although nepheline has a lower K content than orthoclase, it has a faster weathering rate and was a significant source of K in similar experiments (Mohammed et al. 2014). The 361% K increase observed at a 5 g/kg NST application rate over 3.2 months (Table S1) is substantially higher than the 200% increase reported for andesite over 4 months (Celimar Dalmora et al. 2020) or the 115% increase for tephrite over 4 months (Cunha et al. 2022), both of which have very different mineralogical compositions and experimental durations. Even at the lowest application rate (1.25 g/kg), NST exhibited an 85% K increase exceeding the 2.5 g/kg of tephrite (Cunha et al. 2022), 5 g/kg siltstone (Cunha et al. 2022), and 10 g/kg of basalt over 4 months (Panhwar et al. 2014). The comparisons indicate NST is better at supplying K than andesite, tephrite, siltstone, and basalt, even at lower application rates. This is due to the high content of rapidly weathering nepheline in NST. Its silica-undersaturated (in geological terms) composition also means that quartz, which strongly resists weathering, is absent; granitic rocks, in comparison, typically contain ~20–60 vol% quartz (Gonzalez-Esvertit et al. 2025), which dilutes the proportion of nutrient-bearing minerals and reduces their effectiveness as K sources. This absence of quartz makes NST a more effective K source.

The high efficiency of NST at lower application rates reduces the mass required, cutting transportation and application costs. For example, NST exhibited a 194% K increase at 1.25 g/kg, exceeding basalt, tephrite, and siltstone, which require higher application rates to deliver comparable results. While experimental duration can influence the magnitude of nutrient release, the difference between 3.2 (14 weeks) and 4-month studies is relatively small compared with the timescales typically required for silicate mineral weathering, suggesting that mineralogy and application rate are the dominant factors explaining the observed differences.

Although significant, the increases for Ca and Mg were lower than previously seen for other SRDs, even at the highest application rate of 20 g/kg (Table S1). For instance, Anda et al. (2013) reported a 323% increase in Ca and a 1033% increase in Mg with 2.5 g/kg of basalt, while Panhwar et al. (2016) observed a 223% increase in Ca and a 202% increase in Mg with 2 g/kg of basalt on acid sulphate soil (Table S1), attributing this to the weathering of albite and augite. The variation indicates SRD composition will change the elements and quantities released, and that applications could be tailored based on crop needs or soil deficiencies. NST does not contain Ca-rich plagioclase or pyroxene, which are the sources of Ca and Mg reported in studies of basaltic rocks.

A wide range of studies have shown increased soil macro and micronutrient (P, Fe, Zn, Na, Mn, Cu, and Si) after SRD amendments (Table S1). Other bio-essential elements such as B, Co, S, and Mo also increased in the NST amended soil (Melo et al. 2012;

Rodrigues et al. 2024). In our study, NST increased the available Si concentration by 187% at 5 g/kg, more than double the increase observed with basalt, while the Na increased by 59% at 5 g/kg, lower than the 241% increase observed with basalt (Anda et al. 2013). The Cu levels in NST treatments were enhanced by 36% at 5 g/kg, which is lower than the 105% increase seen with basalt, while the Mn increased by 150% at 1.25 g/kg, exceeding the 61% observed with basalt (Panhwar et al. 2016). The P content in the NST increased by 89% at 20 g/kg, exceeding the 50% increase with andesite observed by Dalmora et al. (2020). Surprisingly, the Fe levels increased by 45% at 1.25 g/kg, contrasting with the 58% decrease in Fe with basalt reported by Panhwar et al. (2016). These findings suggest that NST is particularly effective at releasing Si, Mn, Fe, and P compared with basalt and andesite. In contrast, basalt was more effective at releasing nutrients such as Na and Cu. While NST showed a significant increase in Si, Mn, Fe, and P compared to values reported for other SRDs (e.g., basalt and andesite), drawing definitive conclusions remains challenging. Differences in experimental designs, soil types, application rates, SRD particle sizes, crop types, and climatic conditions all influence nutrient release and uptake, complicating direct comparisons across studies.

Even the lowest NST dose (1.25 g/kg) increased the soil nutrients, with a further significant increase observed when the dose increased from 1.25 g/kg to 20 g/kg. Interestingly, for most nutrients, there was no significant difference between the 10 g/kg and 20 g/kg doses. Rodrigues et al. (2024) suggested that while higher doses of SRD application led to enhancements in soil nutrient levels, there is a threshold beyond which additional increases will not result in further short-term benefits. In the rhizosphere, the nutrient concentrations and others were significantly higher than in the bulk soil for many elements (e.g., P, Ca, Mg, K, S) (Figure 2) as a result of enhanced mineral weathering in the rhizosphere (April and Keller 1990; Kodama et al. 1994). The rhizosphere is a microenvironment that typically exhibits higher acidity than the bulk soil, due to greater organic matter content and higher microbial activity, both of which contribute to accelerated weathering (Séguin et al. 2005). For instance, the weathering of biotite in the rhizosphere resulted in greater vermiculite formation compared to the bulk soil (Adamo et al. 1998). Similarly, the application and weathering of phlogopite resulted in higher Mg, K, and vermiculite in the rhizosphere of rape (*Brassica napus*) and ryegrass (*Lolium multiflorum* Lam.) (Hinsinger et al. 1993). April and Keller (1990) and Courchesne and Gobran (1997) reported that easily weathered minerals such as amphiboles and expandable phyllosilicates were depleted in the rhizosphere compared to the bulk soil, implying higher and faster weathering rates within proximity to plant roots.

Among the PTEs, Ba naturally occurs through the substitution for K in the feldspar and nepheline crystal lattice; however, the Ba concentration across all NST application rates was far below the world soil average of 362 mg/kg (Kabata-Pendias 2000). For example, at the highest application rate (NST-20, rhizosphere soil), Ba was 33.1 mg/kg compared with the world soil average of 362 mg/kg. Other PTEs, such as Al, As, Sr, and Rb, increased following the application of the NST. Rubidium substitutes for K in minerals such as micas and K-feldspar due to its similar ionic radius (Butterman and Reese 2003). As a result, rubidium is released alongside potassium during the weathering of the NST

(Négre et al. 2018). Nonetheless, the concentrations of PTEs in the NST-amended soils remained well below the world soil average. At the highest application rate (NST-20, rhizosphere soil), Al, As, Sr, Cr, and Ba were 3738.8, 2.85, 25.8, 4.64, and 33.1 mg/kg, respectively, compared with their corresponding world soil averages of 20,000, 4.70, 250, 59.9, and 362 mg/kg (Kabata-Pendias 2000). Although the concentrations of PTEs remained well below world soil averages, application of NST led to detectable increases above baseline levels in the artificial soil system, indicating that in natural soils, NST could incrementally raise PTE concentrations above background levels, depending on existing soil conditions and cumulative applications.

4.3 | Wheat Morphology and Biomass

We attributed the increase in tiller numbers, number of leaves, and plant height to NST increasing the soil concentration of bio-essential nutrients (e.g., Mg, Ca, S, P, K, Co, Mn, Fe) and pH. The improved nutrient availability likely facilitated nutrient uptake and growth, which may be explained by enhanced cell division and elongation, enzymatic functions, and metabolic processes within the plant (Van Straaten 2007). Similar to our results, Boniao et al. (2002) reported the height of maize increased by 0.35%–3% in silicate amended soil. The belowground and aboveground biomass increased in response to NST, similar to results from Cunha et al. (2022), who observed biomass increases of 296% and 342% relative to the control when olivine melilitite (an ultramafic rock dominated by olivine, melilite and pyroxene) was applied on soybean fields at a rate of 5 and 10 t/ha, respectively. Similarly, a significant increase in wheat biomass has been reported in granite-amended soil, attributed to the increase in release of K and other macronutrients from the granite (Hinsinger et al. 1995). However, like many previous studies, the micronutrients were not measured or considered (Hinsinger et al. 1995).

4.4 | Nutrient Uptake

In both the aboveground and belowground biomass, the Ca and Mg uptake increased with increasing NST due to the increased availability of Ca and Mg from the weathering of the NST. The increased K uptake observed in the NST amended soil aligned with previous findings (Von Wilpert and Lukes 2003; Badr 2006; Ciceri et al. 2017; Skov et al. 2024). An average increase of 25% in K uptake was observed in three barley harvests following the application of Lurgi (NST) (Bakken et al. 1997). In field experiments, K increased by 44.5% in upper crown spruce needles four years after phonolite rock dust was applied on an acidified glacial loam (Von Wilpert and Lukes 2003). Also, Badr (2006) reported an 11.3% increase in total K uptake (tomato fruits + shoots) compared to the control with a feldspar rock application rate of 120 kg K/ha. When the application rate was increased to 240 and 340 kg K/ha, the K uptake increased by 16% and 19%, respectively, attributed to the K in the feldspar. The increase in K uptake may be influenced by the soil pH and the potassium release from mica minerals (e.g., muscovite and biotite), which weather to form illite.

The increased uptake of P in the aboveground and belowground biomass in the NST amended soil is due to P release from the

NST. The released P increased the available P and enhanced the wheat plants' P uptake. Cunha et al. (2022) reported an increase in the P concentration in cocoa leaves of 18%, 33%, and 48% following the application of 2.5, 5, and 10 t/ha tephrite rock dust, respectively. Similarly, Panhwar et al. (2016) reported a 27% increase in rice grain P after a 4 t/ha application of basalt compared to the control. Essential elements such as Mo, Cu, Co, Se, Fe, Zn, Mn, S, and Na increased in the biomass of plants grown in NST amended soil. Fe, Mn, and Zn concentrations increased by 5%, 14%, and 20% in cocoa leaves from plants grown in soils treated with glauconite siltstone compared to the control (Dias et al. 2018).

Even at the highest NST dose, Ba was 0.0024% of wheat biomass and significantly lower than the 1% toxicity threshold for barley (Chaudhry et al. 1977). The results suggest that despite NST increasing, the Ba accumulation was below the levels necessary to negatively impact wheat yield. The low uptake of Ba is likely due to the slower weathering of feldspar compared with nepheline, with feldspar releasing Ba in forms that are not immediately available for plant uptake (Kabata-Pendias 2000) as well as the inherently low Ba content in the soil. In the aboveground biomass (closest to grain), the uptakes of Cr and As, known carcinogens at high intake levels, were far below the Food and Agriculture Organization (FAO) wheat grain limits of 1 mg/kg for Cr and 0.5 mg/kg for As across all NST treatments, indicating no immediate risk to food safety (Åkesson et al. 2015).

It should be noted that pooling biomass was necessary due to low weights, which restricts a full determination of variations in biomass nutrient accumulation between treatments. High heterogeneity and low statistical power mean that Type I errors cannot be discounted. Readers are therefore encouraged to interpret effect sizes and confidence intervals with appropriate circumspection.

4.5 | P and K Use Efficiency

Nutrient use efficiency (NUE) is used to evaluate fertilizer use and is influenced by soil conditions and plant-water interactions (Fixen et al. 2015). Various indices, including agronomic efficiency (AE), recovery efficiency (RE), physiological efficiency (PE), and partial factor productivity (PFP), are also commonly used primarily to measure NUE for nitrogen, phosphorus, and potassium (Puentes-Páramo et al. 2014; Turner and Lambert 2015).

For conventional fertilizers, studies have consistently shown that P and K use efficiency decreases as the application rate of highly soluble fertilizers increases, largely due to runoff and leaching losses (Hong and Guanghuo 2004; Zhou et al. 2008; Jin 2012). In this study, the NUE indices decreased as the SRD application increased. However, the SRD applied in this study is of low solubility, and our results suggest that excess P and K were retained in the soil. This retention has the potential to support nutrient availability in subsequent growing seasons and reduce re-fertilization needs. However, a direct assessment of NST weathering rates would be required to confirm this mechanism.

As NST application increased, P and K use efficiency declined, a pattern that is consistent with responses reported for conventional fertilizers (Zhou et al. 2008; Jin 2012). However, unlike soluble fertilizers where excess nutrients are typically lost from the soil system, NST additions are of low solubility and the nutrients remain in the soil, potentially available for subsequent crops. This suggests that conventional NUE indices, which assume applied nutrients are either uptaken or lost from the system within a single growing season, may underestimate the longer-term benefits of slow-release silicate amendments where unused nutrients are retained. Alternative approaches are needed to more accurately capture the agronomic value of SRD, particularly their capacity to enhance nutrient availability over multiple cropping cycles.

5 | Conclusions

The application of nepheline syenite tailings (NST) resulted in increases in both aboveground and belowground wheat biomass (50% to 200%) at all NST doses compared to the control, attributed to improved soil nutrient availability (Mg, Ca, S, P, K) and elevated soil pH. These findings demonstrate the ability of NST to enhance soil fertility and support plant growth. However, a saturation point appears evident, as no further biomass increase was observed at NST application rates greater than 10 g/kg.

As the NST application increased, phosphorus (P) and potassium (K) use efficiency declined. This suggests that conventional nutrient use efficiency (NUE) indices may not be appropriate for evaluating slow-release soil amendments, where nutrient release is time-dependent, and the low soluble forms will be retained in the soil for subsequent growing seasons. Slow-release silicate minerals likely require alternative methods of evaluation to account for cumulative benefits across multiple growing seasons.

From the results of this study, the use of NST and rocks with similar mineralogical composition can promote healthier plant growth and increased biomass over time, offering farmers a potential strategy to sustain productivity with fewer inputs. This is particularly valuable in regions with macro- and micronutrient-deficient soils or where conventional fertilisers are economically inaccessible. Integrating silicate rock dusts (SRDs) such as NST into agricultural systems could help reduce reliance on chemical fertilisers, mitigate environmental impacts, and promote sustainable use of mined materials.

This study was conducted using artificial soil to control for background variability in soil mineralogical composition and to ensure that NST was the sole source of nutrients. This approach reflects the behaviour of the treatment independent of the soil. The experimental framework will be extended in future work, allowing direct, mechanistic comparisons between different silicate rock dust types and variations in response between crop species. Future field-based studies are needed to assess long-term weathering rates, cumulative nutrient release, and crop responses under realistic agricultural conditions.

Author Contributions

S. O. Apori: conceptualization, investigation, methodology, visualization, writing – original draft, writing – review and editing, software, formal analysis, data curation, project administration. **S. Flynn:** conceptualization, investigation, methodology, resources, supervision, visualization, writing – review and editing, funding acquisition. **D. A. C. Manning:** conceptualization, investigation, methodology, writing – review and editing, project administration, supervision, resources, validation. **G. Stewart:** software, data curation, validation, writing – review and editing, supervision. **M. E. Wakefield:** supervision, resources, project administration, funding acquisition, writing – review and editing. **M. Edwards:** conceptualization, methodology, funding acquisition, resources, supervision, project administration, visualization, writing – review and editing. **L. Collins:** writing – review and editing, project administration, formal analysis, resources, supervision, conceptualization, methodology. **K. J. McInnes:** conceptualization, methodology, funding acquisition, writing – review and editing, project administration, supervision, resources.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.