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Original Article

Silicon Fluxes in Upland Corn Agroecosystems

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Abstract: Silicon (Si) is a beneficial element for plant growth, particularly in monocotyledons like corn (*Zea mays*). In upland agroecosystems, where soil weathering and erosion rates are high, the role of corn in the silicon cycle is crucial. This study evaluates the contribution of corn to silicon dynamics by analyzing Si concentrations in plant tissues and various soil Si fractions across 24 upland sites in Northern Vietnam. Our results indicate that corn leaves accumulate more Si ($\bar{x}$ = 10.9 g kg^{-1}) than stems ($\bar{x}$ = 4.28 g kg^{-1}), highlighting leaves as the primary sink of Si within the plant. In soils, amorphous NaOH-extractable Si was 6.35 g kg^{-1}, while exchangeable Si and water-soluble Si had low average content ($\bar{x}$ = 0.01 g kg^{-1}, $\bar{x}$ = 0.03 g kg^{-1}, respectively), reflecting varying degrees of bioavailability. Spearman correlation analyses revealed positive relationships between exchangeable Si fractions in soil and plant Si uptake, especially in leaves. These findings emphasize the role of corn in sustaining Si fluxes in upland agriculture and underline the need for soil management practices that maintain Si availability for long-term ecosystem stability.

Keywords: Corn; silicon cycle; mountainous agroecosystems; soil silicon; plant uptake.

1. Introduction

Silicon (Si), a ubiquitous element in the Earth's crust, has emerged as a significant factor influencing plant growth, development and stress tolerance [1]. While traditionally not considered an essential nutrient, Si has been shown to confer a range of beneficial effects on plants, including enhanced resistance to biotic and abiotic stresses, improved nutrient uptake, and increased plant biomass [2]. The uptake of Si by plants is a complex process that is

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influenced by various factors, including soil Si availability, plant genotype, and environmental conditions [3]. Once taken up, Si is transported to different plant tissues, where it can be deposited in various forms, such as amorphous silica and opal phytoliths. The deposition of Si in plant tissues can provide several benefits, such as increased mechanical strength, reduced water loss, and enhanced resistance to insect pests and diseases [4]. Soil is the primary source of Si for plants. The forms of Si in soil can vary widely, depending on factors such as soil mineralogy, organic matter content and pH [5]. The most common forms of Si in soil are primary minerals, such as quartz and feldspars, and secondary minerals, such as clay minerals [6]. Si can also be present in soil solution as silicic acid, which is the form that is readily available for plant uptake [7].

The relationship between Si in soil and plant tissues is complex and dynamic. Several studies have investigated the correlation between soil Si content and plant Si concentration, but the results have been inconsistent. Some studies have found a positive correlation between soil Si and plant Si [8], while others have found no significant relationship [9]. These inconsistencies may be due to a variety of factors, including differences in soil type, plant species and experimental design. To better understand the relationship between Si in soil and plant tissues, it is important to consider the various forms of Si in soil and their bioavailability to plants. Primary minerals, such as quartz and feldspars, are generally not readily available to plants [6]. However, these minerals can be weathered over time to release Si into the soil solution. Secondary minerals, such as clay minerals, can also release Si through weathering and dissolution processes [10]. The availability of Si from secondary minerals is often influenced by soil pH and organic matter content [11, 12].

In addition to soil Si availability, plant genotype can also influence Si uptake and accumulation [13]. Different plant species and cultivars have varying capacities to take up and utilize Si. Genetic factors can affect the expression of genes involved in Si uptake and transport, as well as the ability of plants to deposit Si in their tissues [1]. To further elucidate the relationship between soil Si and plant Si, it is essential to consider the role of microbial communities in Si cycling. Soil microorganisms can influence Si availability by altering soil pH, organic matter decomposition, and the formation of secondary minerals. Furthermore, some microorganisms can directly solubilize Si from minerals, making it more accessible to plants [4].

This study aims to investigate the associations between multiple extractable forms of soil Si and the concentration of Si in corn leaves and stems across diverse soil conditions. We also explore how soil properties modify these relationships. The results provide insights into the selection of effective Si sources and soil management strategies to enhance Si availability and uptake by corn, contributing to more sustainable and stress-resilient crop production.

2. Methodologies

2.1. Study Sites and Sample Collection

The study areas are located in the northern mountainous region of Vietnam, encompassing the provinces of Lai Chau, Son La, and Dien Bien. This region is characterized by a complex geological landscape featuring high mountain ranges and limestone plateaus. The agricultural landscape is dominated by long-standing terraced fields, which have been developed since the 1990s to adapt to the steep terrain. The predominant soil types are Ferralsols (covering about 65% of the area) and yellow-red soils on mountains (classified by the FAO-UNESCO system), formed through intense weathering of parent rocks such as rhyolite, schist and limestone.

Kaolinite and illite are the most common clay minerals in the soil composition. The climate is tropical monsoon with clear seasonal differentiation according to altitude, featuring an average annual rainfall of 1,500 to 3,500 mm (the highest in the Hoang Lien Son area). Soil samples were collected from the 0-20 cm cultivation layer at 24 terraced fields and swidden sites in November 2023, during the harvest season for corn, before agricultural residues were returned to the soil. At each site, 3 soil cores were collected and combined into a representative composite sample. Corn plant samples were also collected at each site, following a similar composite sampling strategy. Aboveground biomass from three corn plants surrounding each soil sampling spot was cut at 5 cm above the ground surface. The biomass was then separated into leaves and stems to form composite leaf and stem samples, which were processed for further analysis. Leaf and stem samples were air-dried, oven-dried at 70 °C, and then finely chopped into ~1 mm segments prior to chemical analysis. Soil samples were air-dried and passed through a 1-mm sieve.

2.2. Analysis

Soil pH value was determined using 1 M KCl (w/v = 1:2.5). The organic carbon content was quantified using the Walkley-Black wet-oxidation method [14]. Soil texture was determined using the pipette method. The extractions of total silicon from corn leaves and stems were conducted as follows. Each 0.2 g of dried plant material was weighed into a centrifuge tube, 20 ml of 1 M NaOH was added, the mixture was shaken for 4 h, centrifuged and then run through a 0.45 µm membrane filter following protocols in [15]. Silicon in soil samples was extracted from different fractions as follows. Total Si was determined using XRF (DELTA-50, PREMIUM DP–6050). For other fractions, 0.2 g of dried soil material was weighed into a centrifuge tube. For easily plant-available Si, 20 ml of distilled water was added to the sample, shaken for 2 h. Exchangeable Si was extracted by adding 20 ml of 0.01 M $CaCl_2$, shaking for 2 h [16]. Amorphous Si, 20 ml 1 M NaOH was added, and the samples were incubated in a water bath at 80 – 90 °C for 4 h following a modified protocol based on [17]. All the extractants run through 0.45 µm membrane filters before being measured for Si concentrations by ICP-OES.

2.3. Statistical Analysis

All data were tested for normality and homogeneity of variance prior to statistical analyses. For each site, the mean and standard deviation were calculated based on three replicate samples. Spearman’s rank correlation analysis was conducted to explore relationships between Si fractions and soil physicochemical properties. In addition, linear regression models were used to assess the relationships between specific soil Si fractions and plant Si accumulation, with the coefficient of determination (R^2) and p-values reported. All statistical analyses were performed using Python-based statistical packages.

3. Result

3.1. Silicon in Corn Plants and Soil Fractions

This dataset provides critical insights into the role of corn plants in the Si cycle of mountainous agroecosystems by examining silicon dynamics in plant tissues and soil, alongside other key soil properties. The Si concentration in corn plants is represented by measurements in leaves and stems. In leaves, Si levels range from a minimum of 5.26 g kg^{-1} to a maximum of 18.23 g kg^{-1}, with an average content is 10.9 g kg^{-1}, indicating moderate variability among samples. Leaves exhibit higher silicon accumulation than stems, highlighting their role as a major silicon sink within the plant. Stem Si content averaged 4.28 ± 2.15 g kg^{-1} across all sites. The observed values ranged from 1.32 g kg^{-1} to 9.84 g kg^{-1}, indicating moderate variability, but a general narrower distribution compared to leaf Si concentration. In comparison, previously reported Si concentrations in other crops provide useful reference points. Rice (*Oryza sativa*), a known Si accumulator, typically contains 40 – 200 g kg^{-1} Si in leaves and stems [18]. Sugarcane

(*Saccharum officinarum*) also accumulates high Si levels, up to 50 – 70 g kg^{-1} in stems [19]. Meanwhile, vegetables like tomato (*Solanum lycopersicum*) and legumes such as chickpea (*Cicer arietinum*) usually have much lower Si concentrations, often below 5 g kg^{-1} dry weight [20]. These values suggest that corn is a moderate Si accumulator. This highlights the ecological significance of corn in the silicon cycle of agroecosystems, although its contribution is less pronounced than that of major silicon-accumulating species like rice.

The soil Si data comprises various fractions that represent different aspects of Si availability and mobility (Figure 1). Total Si was extremely high ($\bar{x}$ = 194.57 ± 93.8 g kg^{-1}), indicating a large but variable reservoir. Amorphous Si, extracted by NaOH, was markedly lower ($\bar{x}$ = 6.35 ± 3.1 g kg^{-1}). Fractions representing plant-available Si (water-soluble) and exchangeable forms ($CaCl_2$ extraction) were minimal (0.03 ± 0.01 and 0.02 ± 0.01 g kg^{-1}, respectively), suggesting limited immediate bioavailability despite abundant total Si reserves. The high variability in total Si suggests heterogeneous parent material or long-term accumulation processes across sites, while the modest variation in amorphous and available fraction may reflect short-term soil processes.

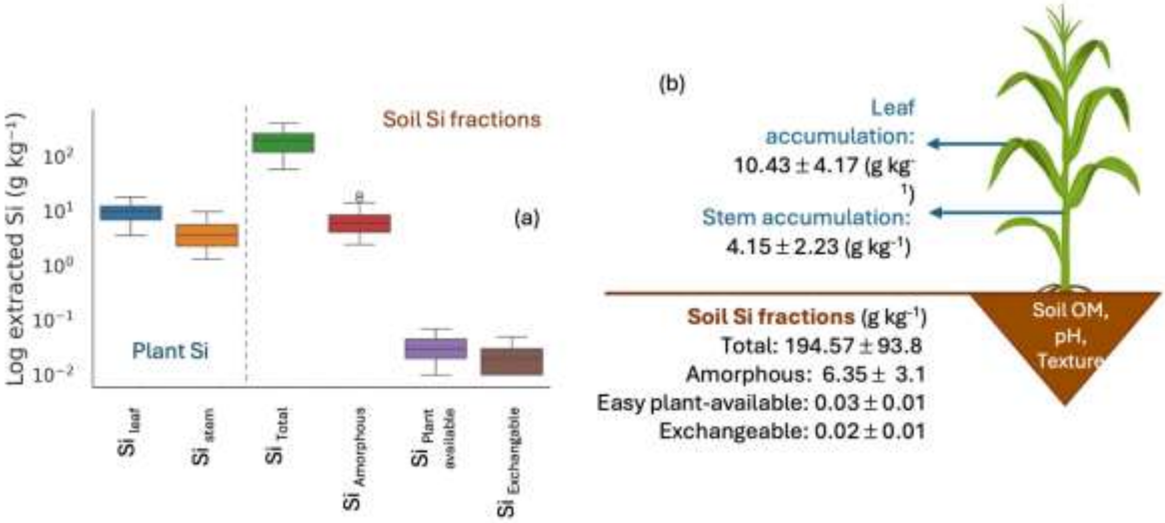

Figure 1. Comparison of plant and soil silicon fractions and their conceptual relationships.
a) Boxplots showing the logarithmic distribution of Si concentrations (g kg^{-1}) in plant tissues (leaf and stem) and in five operationally defined soil Si fractions. Boxes represent the interquartile range (IQR), horizontal lines denote the median, whiskers extend to 1.5×IQR, and points represent outliers.
b) Conceptual diagram illustrating the influence of soil Si fractions on Si accumulation in plant leaves and stems. Soil properties, including organic matter (OM), pH, and texture, modulate the availability and distribution of Si fractions, which in turn affect plant Si uptake.

3.2. Correlation between Plant Si, Soil Si Fractions and Soil Properties

Figure 2 illustrates the relationships between Si concentrations in plant tissues (leaf and stem) and various operationally defined soil Si fractions. Figure 2a shows linear regressions, while Figure 2b presents a correlation heatmap with additional soil properties. Overall, plant Si concentrations, particularly in the leaves, showed moderate to weak associations with soil Si fractions, suggesting that not all soil Si pools are equally accessible or influential for Si uptake in plants. Among the soil Si fractions, exchangeable Si demonstrated the strongest positive correlation with leaf Si concentrations

($R^2 = 0.19$, $p = 0.034$) and stem Si ($R^2 = 0.09$, $p = 0.15$), followed by plant available Si ($R^2 = 0.03$, $p = 0.41$). In contrast, amorphous Si showed no significant relationship with either leaf ($R^2 = 0.012$, $p = 0.73$) or stem Si concentrations ($R^2 = 0.001$, $p = 0.78$). This lack of association suggests that biogenic Si, often composed of phytoliths or diatom frustules, may not be readily mobilized into plant-available forms in the short term [21, 22]. Interestingly, plant-available Si (extracted with H_2O) showed no correlation with plant Si content ($R^2 = 0.03$, $p = 0.41$ for leaf; $R^2 = 0.001$, $p = 0.96$ for stem), suggesting that even conventionally "available" forms may not reflect actual Si uptake under field conditions.

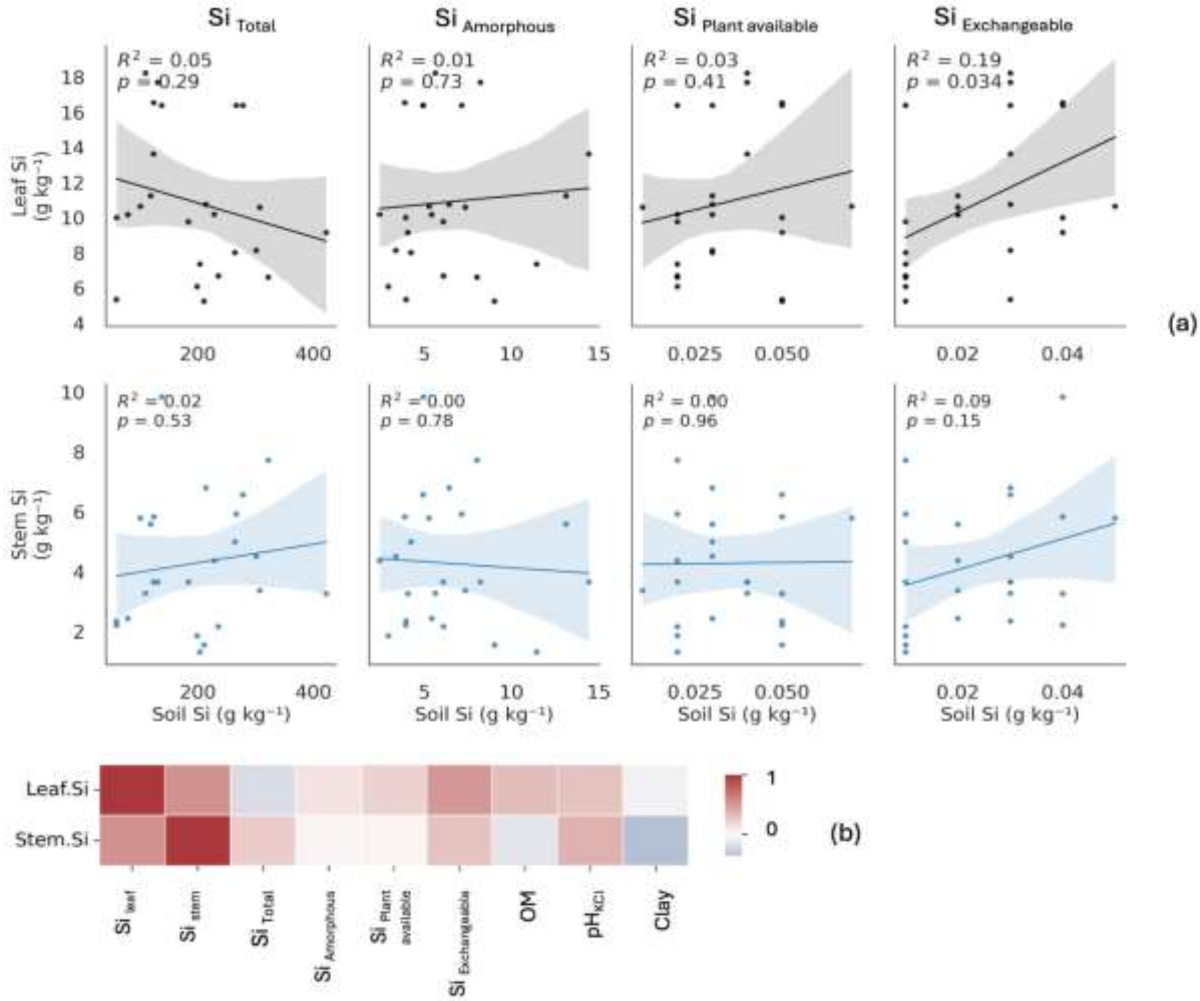

Figure 2. Relationships between different soil silicon fractions and plant silicon content.
a) Scatter plots show the relationships between soil Si fractions and silicon concentrations in leaves (top row, black points) and stems (bottom row, blue points). Lines represent linear regression fits with 95% confidence intervals (shaded areas). Coefficient of determination (R^2) and p-values are shown for each regression. Note: Trend lines are included for visual reference only. Among the eight relationships, only the correlation between leaf Si and exchangeable soil Si was statistically significant ($p = 0.034$), while others were not ($p > 0.05$).
b) Heatmap showing Spearman correlation coefficients between Si content in plant tissues and selected soil properties, including soil Si fractions and soil physicochemical parameters (organic matter, pH and clay). Red indicates stronger positive correlations, while gray indicates negative correlations.

Leaf Si content appeared more strongly associated with amorphous and exchangeable Si pools than did stem Si. This could reflect tissue-specific Si allocation or differing physiological functions of Si within the plant, where leaves often act as primary sinks for silicification [9]. The difference in regression strength between leaf and stem Si also highlights the importance of considering tissue-specific dynamics when assessing bioavailable Si.

The heatmap (Figure 2b) further illustrates that leaf and stem Si both exhibit a positive correlation with exchangeable soil Si, while showing minimal to negative correlation with total and amorphous Si fractions. Notably, clay content was negatively associated with Si in both tissues, suggesting that finer textures may bind Si in forms less accessible to plants under upland conditions. Organic matter (OM) and pH (measured in KCl) displayed weak positive correlations with plant Si, particularly in the stem, potentially supporting the role of OM in Si mobilization through organic complexation [23]. Conversely, coarser soil components (e.g., sand) showed weak or negative correlations with plant Si, potentially due to their lower capacity to retain soluble Si species. These relationships may also reflect broader edaphic controls on Si cycling, including the interplay of desorption–sorption equilibria and Si weathering inputs [24]. In summary, the results suggest that exchangeable Si is a better predictor of plant Si uptake than total or amorphous Si pools. Moreover, the low R^2 values highlight the complexity of Si bioavailability, influenced by both soil chemical properties and plant-specific factors. This supports the notion that operational soil Si fractions must be interpreted with caution when used as proxies for plant-available Si under field conditions.

4. Discussion

While the results demonstrate significant Si reserves in soils, the low availability to plants raises critical questions regarding the factors that regulate Si mobilization and plant assimilation, which are examined in the ensuing discussion. The contrasting patterns observed between soil and plant silicon pools suggest a decoupling between total soil Si content and plant Si uptake. Although soils exhibited relatively high levels of amorphous and biogenic Si, the extremely low concentrations of plant-available Si forms imply a bottleneck in Si bioavailability. This limitation likely constrains Si acquisition by plants, necessitating active root-mediated mobilization mechanisms or reliance on transiently available Si pools. It is also important to note that the timing of sample collection may have contributed to the low concentration of plant-available Si observed in soil. Since both soil and plant samples were collected at the end of the growing season, the extractable Si pool may have been depleted due to continuous uptake by corn throughout the earlier development stage. Previous studies have shown that Si accumulation in corn increases significantly from vegetative to reproductive stages, particularly under field or stress conditions [25]. Furthermore, available Si in soil solution mainly in the form of monosilicic acid is rapidly absorbed and may not be replenished during the season without active mineral weathering or organic matter decomposition [26].The strong accumulation of Si in leaves relative to stems further supports the hypothesis of selective allocation toward organs where Si confers greater ecological or physiological advantages, such as stress mitigation.

These findings emphasize the critical role of corn in mobilizing and redistributing various forms of Si within the Si cycle of mountainous agroecosystems [27]. In soil, Si exists in multiple forms, including soluble Si, Si adsorbed onto mineral surfaces such as clay and metal oxides, amorphous Si, and crystalline Si forms such as quartz, feldspar, and silicate minerals [28]. Among these, soluble Si is the only form readily absorbed by plants and exhibits the most dynamic behavior in terrestrial ecosystems [27].

Soil management practices such as increasing organic matter content and maintaining a near-neutral pH have been shown to enhance both the retention and dissolution of Si, thereby improving the availability of soluble Si for plant uptake [29]. This is supported by strong correlations between soil organic matter, pH, and bioavailable Si fractions (e.g., soluble Si, exchangeable Si, and amorphous Si) [27, 30]. Furthermore, the application of Si fertilizers or organic amendments can accelerate the transformation of amorphous Si pools (e.g., phytoliths and biogenic silica) into soluble forms, thus enhancing the Si uptake efficiency of corn.

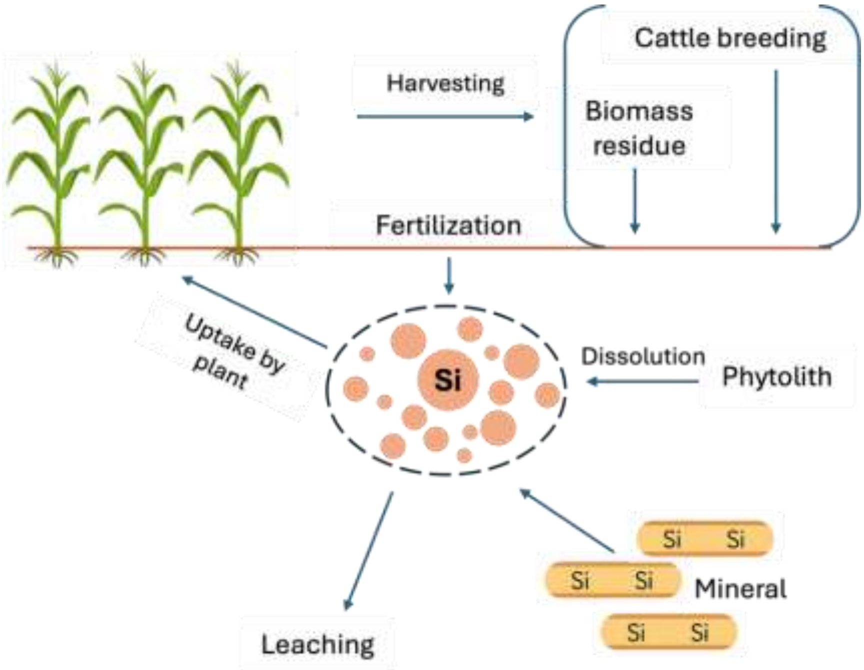

Figure 3. Schematic illustration of Si fluxes and pools in a soil-corn system.

Comparatively, soluble Si in the form of monosilicic acid serves as the immediate source for plant nutrition, whereas adsorbed and amorphous forms act as dynamic reservoirs that can be mobilized when equilibrium conditions shift. In contrast, crystalline Si forms (e.g., quartz, feldspar, and silicate clays), although representing the largest proportion of soil Si, dissolve very slowly and act primarily as long-term reserves. As such, total soil Si content does not accurately reflect plant-available Si; instead, soluble and exchangeable Si fractions are more reliable indicators of soil Si fertility [31]. Notably, studies have shown that corn leaves accumulate significantly more Si ($\overline{x}$ = 10.9 g kg^{-1}) than stems ($\overline{x}$ = 4.28 g kg^{-1}), indicating that foliage plays a crucial role in the biological Si cycle of mountainous farming systems. This accumulation not only enhances the plant's tolerance to biotic and abiotic stressors but also contributes to Si recycling through leaf litter and plant residue decomposition, effectively sustaining a biogenic Si loop within the ecosystem. However, a trade-off exists between the pool of bioavailable Si in the soil and the plant's ability to absorb it. This is illustrated by a negative correlation between NaOH-extractable Si (mainly representing amorphous Si) and Si concentrations in corn tissues. Such findings underscore the need to balance the release of Si from soil reservoirs and the plant uptake process to maintain a sustainable Si dynamic in the agroecosystem. Similar observations have been reported by Tubana et al., (2016) and Schaller et al., (2021), who also highlighted the significance of soluble and amorphous Si fractions in supporting crop productivity and key ecosystem services, including nutrient cycling and soil health. Soil and crop management strategies should prioritize the maintenance and enhancement of bioavailable Si fractions (soluble, exchangeable, and amorphous Si), rather than focusing solely on total Si content [30, 32]. This approach is essential for optimizing the Si cycle and improving the sustainability of mountainous agricultural systems.

5. Conclusion

This study elucidates the critical role of corn plants in the Si cycle within mountainous agroecosystems by examining Si dynamics in plant tissues and corresponding soil fractions. Key findings reveal significantly greater Si accumulation in leaves ($\overline{x}$ = 10.9 g kg^{-1}) compared to stems ($\overline{x}$ = 4.28 g kg^{-1}), indicating foliar tissues serve as a major Si sink within the plant system. Among soil Si fractions, total Si showed the highest concentration ($\overline{x}$ = 194.57 g kg^{-1}), followed by amorphous Si ($\overline{x}$ = 6.35 g kg^{-1}), while exchangeable Si had the lowest ($\overline{x}$ = 0.02 g kg^{-1}), reflecting differences in abundance and bioavailability. Correlation analyses indicated positive relationships between plant Si content particularly in leaves and soil-available Si, particularly exchangeable Si. Furthermore, Spearman correlation results emphasized the influence of key soil properties, notably organic matter and pH on the mobilization and retention of plant-available Si. These results highlight the importance of maintaining silicon availability in soils through soil management practices and promoting a balance between soil properties, Si availability, and plant absorption. These insights are critical for enhancing crop productivity, resilience, and overall sustainability in mountainous agroecosystems. Future research should explore the temporal dynamics of soil Si availability throughout crop growth stages, investigate the interactive effects of climate variables and land-use practices on Si mobilization, and evaluate the long-term agronomic and environmental impacts of Si amendments under field conditions.

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