IMPACT OF NOVEL CROP SPECIES ON ACIDIC SOIL FERTILITY: AN AGROCHEMICAL ANALYSIS OF THE SOIL-PLANT SYSTEM

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Introduction

Soil acidity remains one of the principal constraints on agricultural productivity worldwide, affecting roughly a third of the planet's ice-free land and over half of its potentially arable soils (von Uexküll & Mutert, 1995; Csabai et al., 2022; Kosztyuné Krajnyák et al., 2023; Vágvölgyi & Kosztyuné Krajnyák, 2025). In acidic soils, declining pH increases the solubility of aluminum (Al^{3+}) and manganese (Mn^{2+}) while reducing the availability of phosphorus (P), calcium (Ca), magnesium (Mg), and molybdenum (Mo) (Fageria & Baligar, 2008; Weil & Brady, 2017). These conditions restrict root development and nutrient uptake, ultimately limiting crop growth and yield.

Acidification is frequently accelerated by intensive farming practices - repeated use of ammonium-based fertilizers, continuous nutrient removal through harvest, and leaching of basic cations under humid climates (Haynes & Naidu, 1998; Szabó et al., 2023). Beyond reducing fertility directly, progressive acidification alters microbial activity and organic matter turnover, with consequences for long-term soil functioning (Marschner, 2012). Liming is the most widely used strategy for reclaiming acid soils because it neutralizes exchangeable acidity, reduces aluminum toxicity, and replenishes exchangeable Ca and Mg (Fageria & Baligar, 2008). As H^+ and Al^{3+} on the exchange complex are progressively replaced by Ca^{2+} and Mg^{2+} from the amendment, base saturation rises and chemical fertility improves (Lindsay, 1979); the resulting increase in pH also reduces Al- and Fe-bound phosphate fixation, making more P available for plant uptake (Hinsinger, 2001). Crop responses to liming are, however, far from uniform. Species differ in their tolerance of acidity, root architecture, and nutrient-acquisition strategies (Marschner, 2012; Györgyiné Kovács et al., 2025). Cereals typically benefit from reduced Al toxicity through improved root elongation, whereas legumes show more complex responses, since biological nitrogen fixation is itself sensitive to soil reaction and Ca availability (Fageria & Baligar, 2008). Liming can likewise shift the availability of micronutrients such as Cu, Zn, Mn, and Fe, depending on the magnitude of the pH change and the soil's buffering capacity (Kabata-Pendias, 2011). Despite an extensive literature on liming, most existing studies focus either on yield responses or on a single crop species; comparative data integrating soil chemical fertility with macro- and micronutrient accumulation across several contrasting species under identical field conditions remain scarce. Closing this gap matters for developing species-specific liming and nutrient-management strategies on acid soils. The present study therefore evaluated the effects of a calcium oxide (CaO 95%) amendment on the chemical properties of an acidic Luvisol and on the macro- and micronutrient accumulation of ten agricultural crop species - including legumes, cereals, buckwheat, mustard, and sweet sorghum cultivated under identical experimental conditions. Particular attention was given to changes in acidity indicators, exchange-complex characteristics, nutrient availability, and plant nutritional status, in order to clarify the mechanisms through which liming improves soil fertility and crop nutrition.

Materials and Methods

The field experiment was conducted during the 2023–2025 agricultural year at the Agricultural Research and Development Station Livada (S.C.D.A. Livada), located in northwestern Romania (47°52'07.3"N 23°07'10.2" E). The soil is classified as an acidic Luvisol (Brown forest soil). The experiment was set up in large-scale single plots without field replicates to evaluate ten contrasting agricultural crop species (V1-V10), comprising cereals (wheat, triticale, sweet sorghum), legumes (clover, faba bean, chickpea, lupin, lentil), oilseeds (mustard), and pseudocereals (buckwheat). The ameliorative treatment consisted of applying a calcium oxide-based commercial calcareous amendment at a moderate correction dose of 1000 kg/ha prior to crop establishment. Soil incorporation was performed mechanically. Sowing of the crops was carried out in autumn for wheat, triticale, and clover, while the remaining crops were sown in spring, following the conventional agricultural technology established for the area: included herbicide application and specific fertilization rates consisting of 500 kg NPK (18-46-0) /ha of complex fertilizer for the autumn crops and 200 kg NPK (18-46-0) /ha of complex fertilizer for the spring crops. The results obtained at the beginning of the growing season are due to the liming application carried out in 2023 (1000 kg/ha calcium oxide), whereas the results at the end of the vegetative period accumulate the effects of both the 2023 and 2024 amendments.

Soil Sampling and Analysis

Initial physico-chemical characteristics of the soil were determined at the establishment of the experimental field. Soil samples were collected from the limed and unlimed experimental areas to evaluate the overall soil nutrient status independently of the individual crop species from 0-20 cm. Additional soil samples were collected after harvest from each of the ten limed and ten unlimed crop plots to evaluate treatment- and crop-specific changes in soil chemistry. Soil reaction (pH) was determined in a 1:2.5 (m/v) soil: water suspension. The following parameters were also determined: total nitrogen (N); humus (organic matter) content; available phosphorus (PAL) and available potassium (KAL, by ammonium acetate–lactate extraction at pH 3.75); the sum of basic cations (SB) and hydrolytic acidity (HA), used together to calculate base saturation according to Kappen; total exchangeable acidity (SH), by percolation to exhaustion with a potassium acetate solution buffered at pH 8.3; cation exchange capacity (CEC/T); base saturation degree (VAh, as % of CEC); exchangeable aluminum; mobile forms of micronutrients; and $CaCl_2$-extractable magnesium. Soil chemical fertility indicators were interpreted according to the Methodology of Agrochemical Soil Analysis (1981), and exchangeable aluminum content was classified according to Florea et al. (1987).

Plant Sampling and Chemical Analysis

To evaluate the nutritional response, the macro- and microelement contents were determined in the tested plants harvested from both the limed and unlimed plots. The plant tissue samples were chemically analyzed using the following methods: Total nitrogen was determined by the Kjeldahl method (sulfuric acid mineralization, sodium hydroxide distillation, sulfuric acid titration). Phosphorus was determined by UV-Vis spectrometry, potassium by flame photometry, and calcium and magnesium by atomic absorption spectrometry (AAS). Copper, zinc, manganese, and iron concentrations were measured by AAS.

Soil samples were collected separately from the limed and unlimed treatments to characterize the overall nutrient fertility. Each composite soil sample consisted of at least 15 randomly distributed soil cores collected within each treatment.

Plant chemical analyses were performed on composite samples prepared from a minimum of 10 plants collected per treatment. Data are presented as mean ± standard error (SE). Relative differences between limed and unlimed treatments were calculated to facilitate the comparison of soil chemical properties and plant nutrient concentrations. Mean values were compared using the Least Significant Difference (LSD) test at the 5% probability level *($p \leq 0.05$).* Different lowercase letters indicate statistically significant differences between treatments.

Thermal and Moisture Resources

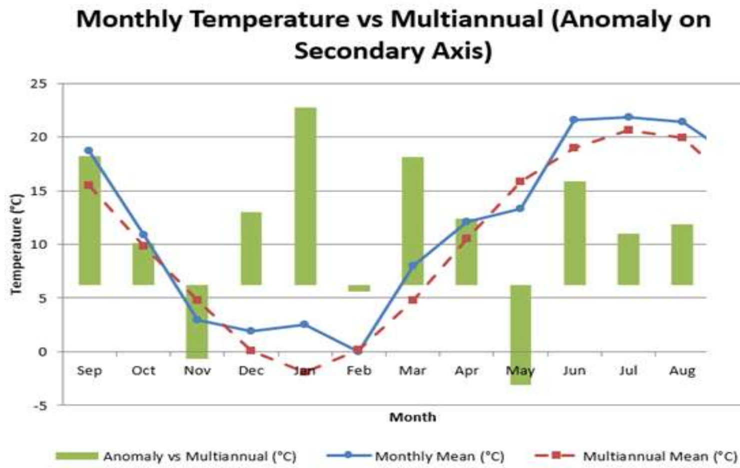

Fig. 1 Monthly Precipitation Trends and Anomalies
(2024-2025 vs Multiannual)

Over a 63-year period, the mean annual air temperature was 9.9°C. During the study period (September 2024 - September 2025), the mean annual temperature was 11.27°C. The mean annual temperature of 11.27°C indicates a warming trend, with an increase of 1.37°C compared to the multiannual average. The evolution of multiannual monthly mean temperatures and those recorded during the study year are presented in Fig.1. The warmest month of the year is July, with a multiannual mean temperature of 20.6°C, followed by August with 19.9°C and June with 19.0°C. In the agricultural year under study, monthly temperatures were generally higher than the multiannual averages, except for November, February, and May, when they were lower by 1.0-2.5°C.

Cold Season

The thermal characteristics of the cold season were analyzed through temperature limits that reflect the severity of winters (cold units and frost units). The cold units (the sum of negative temperatures during December, January, and February) totaled -25°C during the study year, and no frost units (the sum of temperatures below -15°C) were recorded. This indicates that the winter was mild, as typical cold unit values range between -100°C and -200°C.

Transition Period from Winter to Spring

This period is characterized by the spring onset index, represented by the sum of positive mean daily temperatures between February 1 and April 10. In the study year, this index reached 334.6°C. The historical extremes of this index were 162°C in 1976 (late spring onset) and 419°C in 1977 (early spring onset).

Vegetation Period

The thermal potential of the vegetation period is analyzed under two main aspects: Global temperatures - the sum of temperatures above 0°C between February 1 and November 30. Effective temperatures - the sum of biologically active temperatures above 10°C between April 10 and October 31. The thermal potential of the region, as indicated by the global temperature sum, is 3,800°C, with a minimum recorded value of 3,250°C in 1978 and a maximum of 3,950°C in 1966. The sum of biologically active temperatures was 1,558°C during the study year, compared to the historical maximum of 1,634°C recorded in 1963 and the minimum of 918°C recorded in 1980.

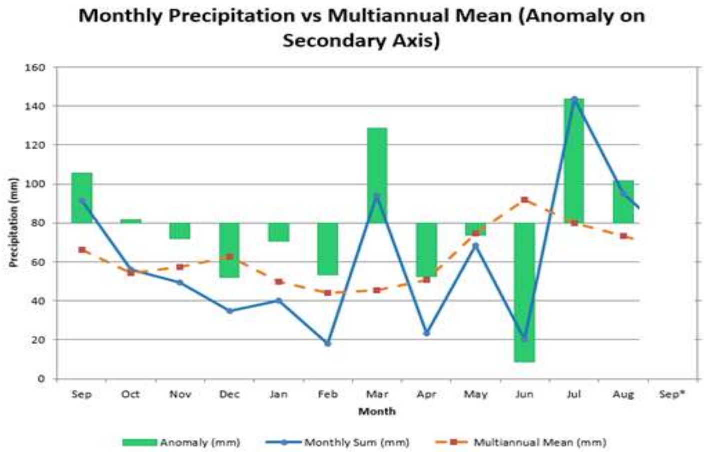

Fig. 2 Monthly Temperature Trends and Anomalies (2024-2025 vs Multiannual)

During the cold season (November-March), a total of 236 mm of precipitation was recorded, compared to the multiannual average of 259 mm. Precipitation during the autumn-winter period generally determines the agricultural character of the year: accumulated quantities of 280-340 mm indicate a wet year, while totals of 130-170 mm indicate a dry year. For the active vegetation period of autumn crops (April- July), the multiannual average precipitation is 297 mm. In 2025, the total precipitation for this period was 255.8 mm. During the vegetation period of spring-sown crops in 2025, precipitation totaled 91.7 mm, compared to the multiannual average of 125.5 mm. For the overall vegetation period of spring crops (April- October), the multiannual average precipitation is 490.9 mm, while in 2025, the total precipitation for this interval was 479.2 mm (Fig.2).

Results and Discussion

Effects of Liming on Soil Chemical Properties Before Sowing

Preliminary soil analyses conducted before crop establishment highlight the immediate efficiency of the Calcium oxide 95% amendment. As illustrated in Fig. 3, liming significantly reduced exchangeable aluminum (Al) from 1.19 to 0.49 /100 g while increasing the sum of basic cations (SB) from 5.15 to 6.92me/100 g. Concurrently, hydrolytic acidity (HA) decreased from 4.39 to 3.50me/100 g, and soil reaction (pH) shifted upward from 4.88 to 5.42 (Fig. 4). Base saturation (VAh) improved from 53.93% to 66.50%. An increase in cation exchange capacity (CEC) was observed from 9.55 to 10.42me/100 g (Fig. 5), confirming a substantial amelioration of the soil exchange complex.

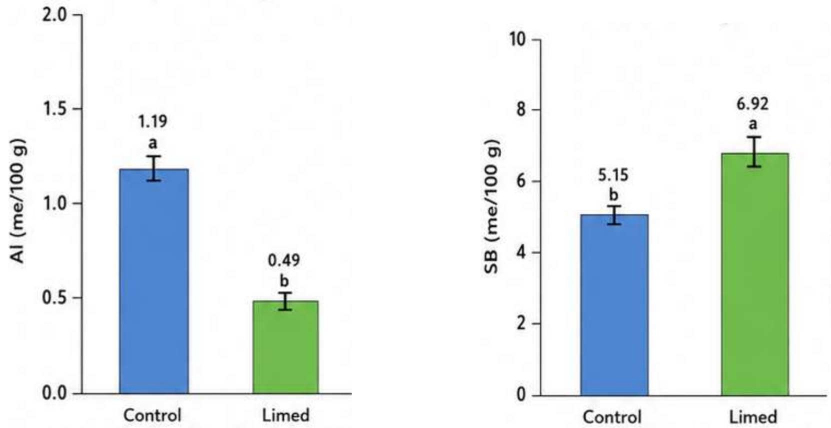

Fig. 3 Effect of liming on exchangeable aluminum (Al) and sum of basic cations (SB) in samples collected before sowing - Control (blue) vs. Limed (green)

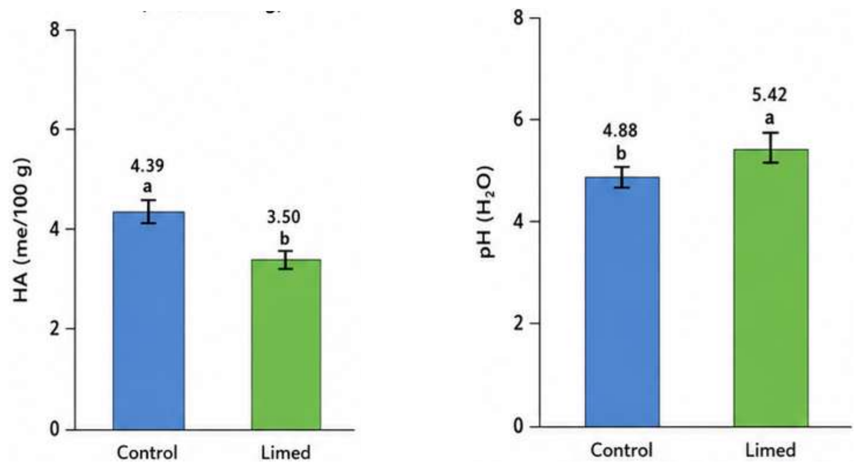

Fig. 4 Effect of liming on soil hydrolytic acidity (HA) and reaction (pH) in samples collected before sowing - Control (blue) vs. Limed (green)

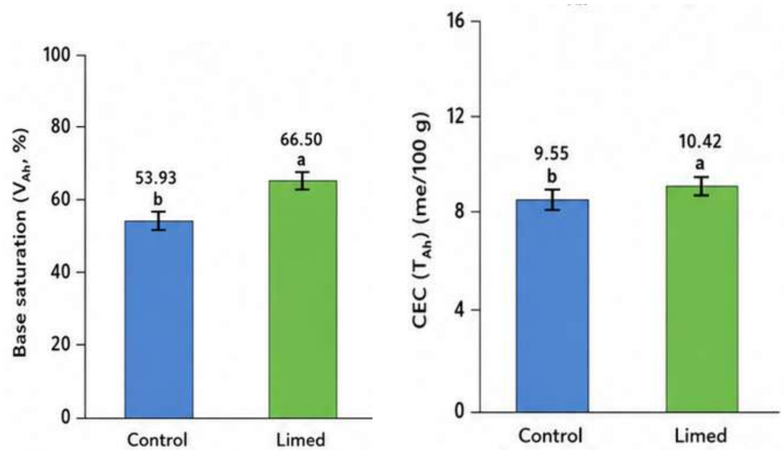

Fig. 5. Effect of liming on base saturation (VAh) and cation exchange capacity (CEC) in samples collected before sowing -Control (blue) vs. Limed (green)

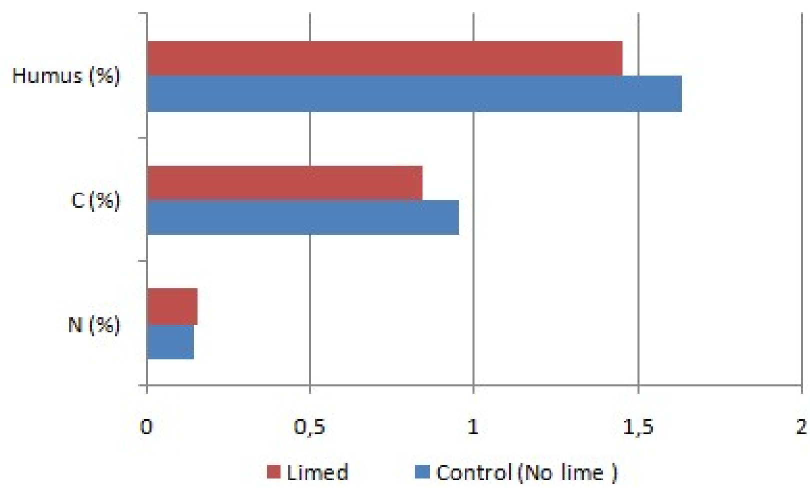

Fig. 5 Total Nitrogen Content (N_t), Organic Carbon Content (Corg), and Humus (%) . Control (blue) vs. Limed (red)

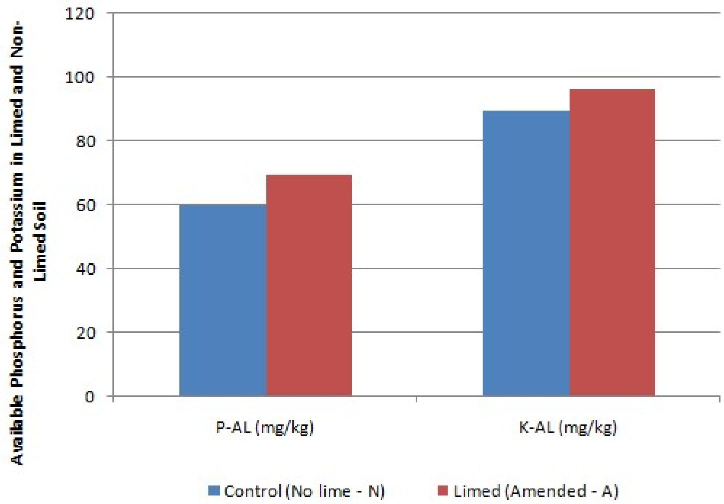

Fig. 6. Available Phosphorus and Potassium Content (PAL and KAL) in samples collected before sowing - Control (blue) vs. Limed (red)

In acidic soils (pH < 5.5), Al^{3+} becomes more soluble and mobile, increasing the concentration of exchangeable aluminum (Olego et al., 2021). Aluminum toxicity is considered a major limiting factor for plant development on acidic soils; however, the need to correct soil acidity through liming varies for each plant species. At soil pH values below 5.5, trivalent aluminum is preferentially adsorbed to the detriment of other cations, blocking the absorption and translocation of nutrient ions within the plant at the root system level (Methodology of Agrochemical Soil Analysis, 1981).

As observed in the graphical representations (Fig. 3), the values of extractable aluminum content are significantly reduced in the limed plots compared to the values obtained from the control plots. In determining the dose of calcareous amendments necessary to neutralize acidity, it is useful to determine the hydrolytic acidity (HA), which indicates the soil's acidity reserve and which, together with the sum of basic cations (SB), serves to calculate the degree of base saturation according to Kappen. Another aspect associated with low soil pH values is the determination of total exchangeable acidity (SH), achieved by percolation to exhaustion with a potassium acetate solution buffered at pH=8.3. Base saturation, which expresses the proportion of basic cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) fixed on the colloidal complex relative to the cation exchange capacity, allows the classification of soils in terms of trophicity, representing an essential indicator of the soil's nutritional richness.

According to the Methodology of Agrochemical Soil Analysis (1981) and considering both VAh and V8.3, the soil is classified as oligo-mesobasic, registering values between 46-75% for VAh and 31-55% for V8.3. Liming constitutes an effective practice for mitigating the constraints caused by soil acidity, yielding positive results in achieving optimal crop yields due to the improved bioavailability of phosphorus, calcium, and magnesium. Correcting the pH reduces aluminum and hydrogen toxicity, stimulating microbial activity and the activity of enzymes responsible for decomposing organic matter, which ultimately leads to a faster release of nitrogen (Mkhonza et al., 2020). The nitrogen contents in the soil samples collected from the limed and unlimed areas indicate that the calcareous amendment stimulated nitrogen mineralization and mobilization. This process led to a slight decrease in the total nitrogen measured in the soil but likely resulted in an increase in plant-available nitrogen (NH_4^{+}, NO_3^{-}) (Fig. 5).

Conversely, the organic carbon and humus contents indicate that liming had a positive effect on humus accumulation and stabilization. The stabilization of organic matter mediated by Ca^{2+} thereby enhances the soil's long-term fertility. Consequently, the humus content ranges from

1.36% to 1.59% in the control samples, whereas the values are higher in the limed plots, falling within the range of 1.58% to 1.74% (Fig. 5).

Specific Modification of the Soil Exchange Complex

Table 1. Effect of liming on the soil exchange complex: Absolute variation (Δ) of base saturation, base addition, and acidity reduction across experimental plots (V1-V10).

Plant Species	Δ VAh (%) (Saturation increase)	Δ SB (me/100g) (Base addition)	Δ Ah (me/100g) (Acidity reduction)	|Δ SB| + |Δ Ah| (me/100g)
V1	38,70	6,91	-3,53	10,44
V2	33,90	3,80	-3,02	6,82
V3	23,90	2,92	-2,34	5,26
V4	9,20	2,24	-0,68	2,92
V5	16,60	0,29	-2,95	3,24
V6	15,30	0,97	-1,85	2,82
V7	29,80	4,47	-2,13	6,60
V8	28,90	4,38	-2,34	6,72
V9	13,70	1,56	-1,93	3,49
V10	19,50	3,01	-1,62	4,63

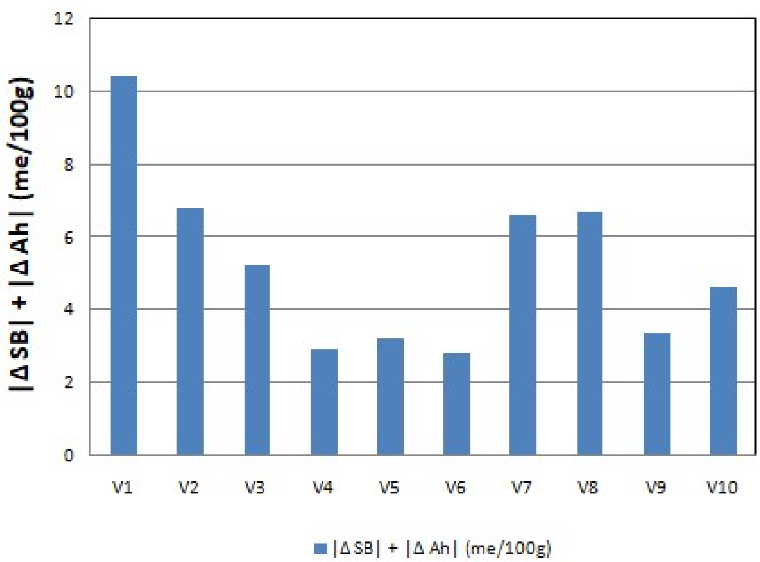

Fig. 7. Total modification of the soil exchange complex (ΔSB + ΔAh) across experimental variants

To evaluate how strongly each crop's presence modulated the neutralization reactions, the absolute variation in base saturation (ΔVAh), base addition (ΔSB) and acidity reduction (ΔAh) was calculated for each of the ten experimental variants, together with a synthetic turnover index (|ΔSB| + |ΔAh|) summarizing the total change in the exchange complex (Table 1).

Base saturation increased in every variant (ΔVAh between 9.20% and 38.70%), and hydrolytic acidity decreased consistently (ΔAh exclusively negative, reaching up to –3.53 me/100g). The synthetic turnover index was highest in the wheat (V1, 10.44 me/100g) and triticale (V2, 6.82

me/100g) plots, closely followed by lentil (V8, 6.72) and lupin (V7, 6.60), and lowest in clover (V4, 2.92) and chickpea (V6, 2.82). This pattern suggests that the intensity of the neutralization reactions depends not only on the applied amendment dose but also on species-specific root traits - root exudates and differential Ca and Mg extraction rates - interacting with local pedological micro-conditions during the growing season (Fig. 7).

Soil Chemical Properties After Harvest, by Crop

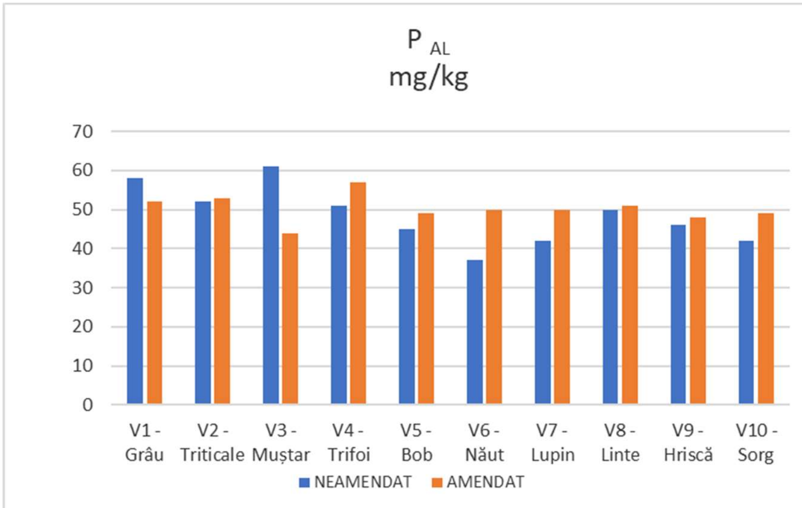

Fig. 8 Effect of liming on available phosphorus (PAL) content in samples collected after harvesting for V1-V10 plots (V1-Wheat, V2-Triticale, V3-Mustard, V4-Clover, V5-Faba bean, V6-Chickpea, V7-Lupin, V8-Lentil, V9-Buckwheat, V10-Sorghum) - Unlimed (blue) vs. Limed (orange)

Following harvest, available phosphorus tended to decrease in the limed variants relative to the control across most crops (Figure 8), a common short-term effect of liming on soil mobile P, which nonetheless tends to increase P bioavailability for the growing crop (Liao et al., 2020).

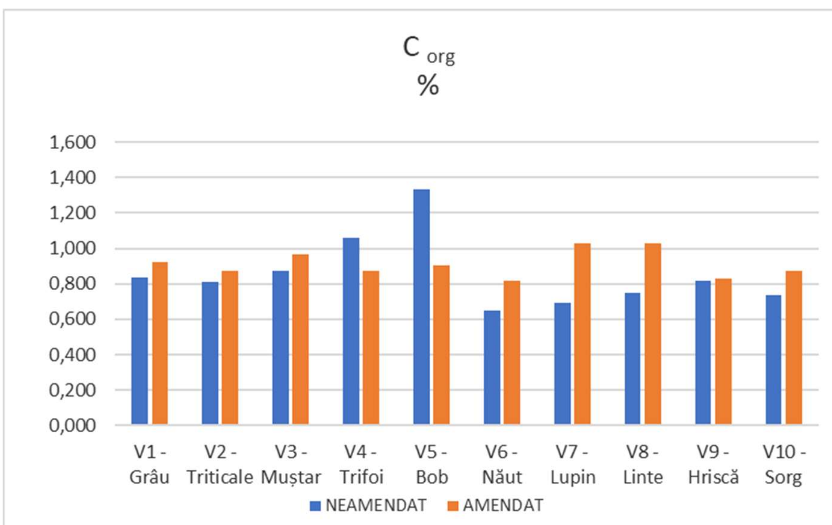

Fig. 9. Effect of liming on organic carbon (Corg) content in samples collected after harvesting for V1-V10 plots (V1-Wheat, V2-Triticale, V3-Mustard, V4-Clover, V5-Faba bean, V6-

Chickpea, V7-Lupin, V8-Lentil, V9-Buckwheat, V10-SorghumSorghum) Unlimed vs. Limed (orange)

Higher nitrogen content values were obtained from leguminous crops, such as clover, faba bean, chickpea, lupin, and lentil, particularly in the limed variants. This is attributed to a greater input of organic nitrogen into the soil, primarily through root residues and nitrogen-fixing nodules. For grasses, which are considered to have a deep root system, such as wheat, triticale, and sorghum, nitrogen mobilization and recycling are expected, albeit with somewhat more modest effects on the total N increase compared to legumes (Ejigu et al., 2023). The values obtained for the tested grasses ranged between 0.124% and 0.138%, which are lower than the contents found in the variants cultivated with clover and faba bean. The total nitrogen supply status places the soil of the experimental field in the low-content category (between 0.100% and 0.140%). This is also explained by the pH values, which did not fall within the optimal range of 5.5–7.5 required for mineralization processes. At pH values below 5.0, the proportion of mineralizable nitrogen can decrease to approximately 0.4% of the total nitrogen (Methodology of Agrochemical Soil Analysis, 1981). As observed in Figure 4, for most of the tested crops, soil organic carbon contents increase in the limed variants, with values falling into the medium supply category. Liming raises the soil pH, which stimulates microbial and enzymatic activity. Consequently, organic matter (plant residues, roots, etc.) decomposes more rapidly, meaning that the carbon contained within the soil organic matter is consumed faster in limed soils, especially the more labile fractions. Therefore, after harvest, if the organic matter input does not compensate for this mineralization, the organic carbon content may decrease (Sağlıker et al., 2018; Tedone et al., 2023).

Regarding the results obtained for the clover and faba bean crops, if the calcareous amendment stimulates the degradation of plant residues, the net soil organic carbon content post-harvest might be lower than in the control variants. In unlimed soils, degradation is slower, allowing organic carbon to accumulate more efficiently from crop residues (Fig. 9).

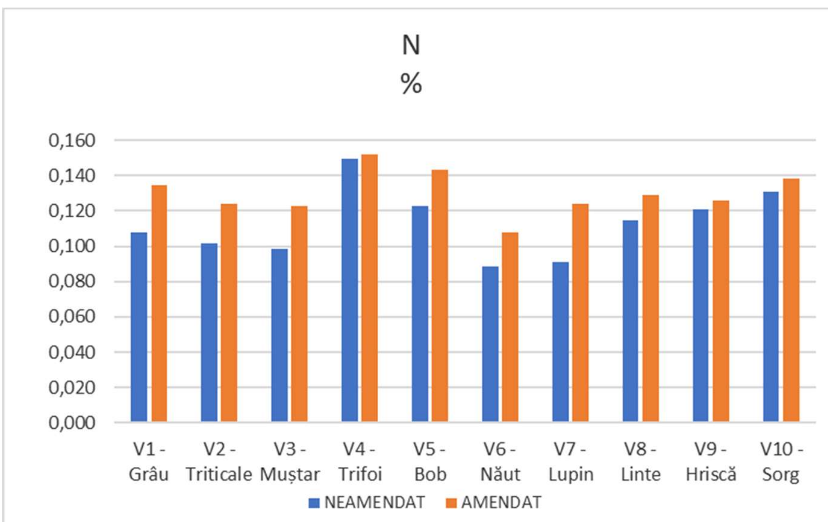

Fig. 10 Effect of liming on total nitrogen (N_t) content in samples collected after harvesting for V1-V10 plots (V1-Wheat, V2-Triticale, V3-Mustard, V4-Clover, V5-Faba bean, V6-Chickpea, V7-Lupin, V8-Lentil, V9-Buckwheat, V10-Sorghum) – Unlimed (blue) vs. Limed (orange)

Conversely, the higher values recorded in the soil cultivated with clover are primarily due to the biological nitrogen fixation process performed by symbiotic bacteria (Rhizobium). This process releases protons into the rhizosphere, which leads to an increase in soil acidity (Zahran, 1999; Haynes, 1983). Additionally, the mineralization of nitrogen-rich plant residues can further contribute to soil acidification (Hinsinger et al., 2003) (Fig. 10).

Available potassium after harvest fell into the medium-supply category for field crops (Fig. 11). Liming tended to slightly reduce mobile K, likely reflecting Ca^{2+}-K^{+} competition and K fixation on clay minerals, though this effect is generally considered acceptable given liming's longer-term benefit of reducing K losses through leaching (Kebede & Dereje, 2017). The potassium response was otherwise species-dependent: mustard and clover showed reduced K content after liming, while wheat and sorghum showed higher K availability and plant uptake under the calcareous amendment; more broadly, long-term fertilizer and organic-amendment history is known to influence potassium uptake by sorghum and the forms of K present in soil (Venugopal et al., 2018).

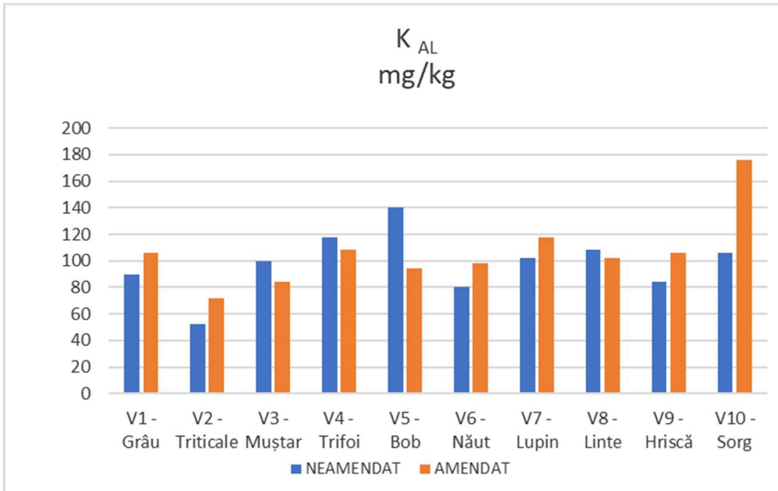

Fig. 11 Effect of liming on available potassium (KAL) content in samples collected after harvesting for V1-V10 plots (V1-Wheat, V2-Triticale, V3-Mustard, V4-Clover, V5-Faba bean, V6-Chickpea, V7-Lupin, V8-Lentil, V9-Buckwheat, V10-Sorghum) - Unlimed (blue) vs. Limed (orange)

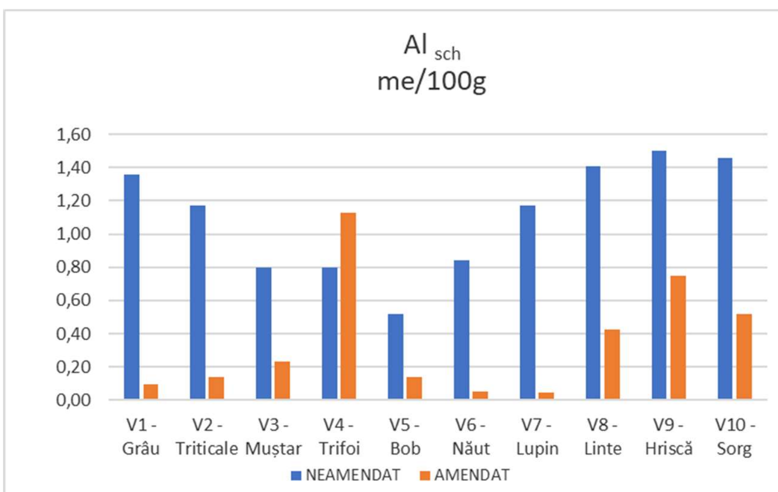

Fig. 12 Dynamics of Exchangeable Aluminum (Al_{sch}) for V1-V10 plots (V1-Wheat, V2-Triticale, V3-Mustard, V4-Clover, V5-Faba bean, V6-Chickpea, V7-Lupin, V8-Lentil, V9-Buckwheat, V10-Sorghum) Unlimed (blue) vs. Limed (orange)

Exchangeable aluminum after harvest was generally higher in the unlimed variant, as expected (Fig. 12), though clover was again an exception: its exchangeable Al did not show the same clear reduction, plausibly because organic-acid exudation from clover roots can temporarily alter rhizosphere chemistry and re-mobilize Al independently of the liming effect (Ma et al., 2022) - a crop-specific nuance rather than evidence that the amendment itself was ineffective.

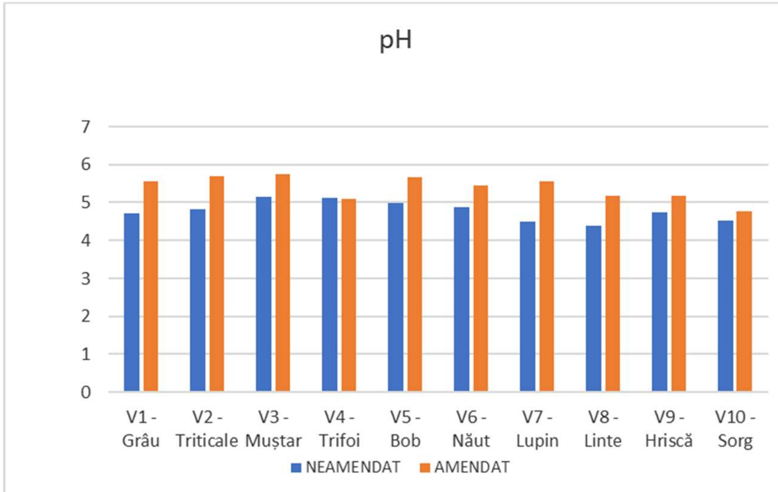

Fig. 13 Dynamics of Soil Reaction (pH) for V1-V10 plots (V1-Wheat, V2-Triticale, V3-Mustard, V4-Clover, V5-Faba bean, V6-Chickpea, V7-Lupin, V8-Lentil, V9-Buckwheat, V10-Sorghum) - Unlimed (blue) vs. Limed (orange)

The determination of actual soil acidity, conducted after the conclusion of the specific vegetation periods for each crop using the 1:2.5 (m/v) aqueous soil/solution suspension method, revealed clear differences between the experimental variants. Consequently, in the unlimed plots, the soil reaction was classified as strongly acidic for wheat, triticale, faba bean, chickpea, lupin, lentil, buckwheat, and sorghum, and as moderately acidic for mustard and clover. The application of calcium oxide 95% at a dose of 1 t/ha, serving as a maintenance or moderate correction treatment, partially neutralized the acidity, leading to an increase in pH values by more than 0.5 units in most of the limed variants.

This shifted the soil classification from strongly acidic to moderately acidic, with the exception of the sorghum plots, which remained in the strongly acidic category (Fig. 13). The application of calcium oxide contributes to the increase of soil pH, which can reduce the solubility and mobility of aluminum ions, particularly in acidic soils. This process mitigates Al-induced phytotoxicity, thereby protecting plant roots and enhancing their overall development (Gillespie et al., 2021). According to the classification framework for exchangeable Al content (Florea et al., 1987), the unlimed variants exhibited very low to low contents, whereas the limed variants recorded extremely low levels.

Plant Nutrient Accumulation

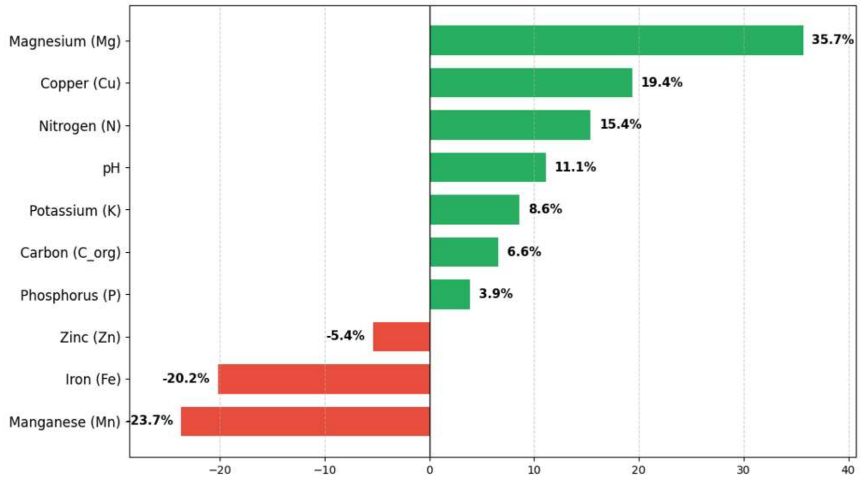

Fig. 14 Relative variation (%) of soil agrochemical parameters - Limed (green) vs. Unlimed (red)

The relative variation in soil agrochemical parameters between limed and unlimed plots (Fig. 14) also showed a modest increase in extractable copper, plausibly reflecting the soil's transition out of the strongly acidic range together with the complexing action of humic and fulvic acids from crop residues. By the interpretation limits for ammonium acetate-EDTA (pH 7.0) extractable micronutrients, the soil's supply status was low for zinc and high for copper and manganese. $CaCl_2$-extractable magnesium increased following amendment, likely reflecting several combined mechanisms: reduced Al^{3+} blockage of the adsorptive complex releasing Mg^{2+} (Lindsay, 1979); a possible dolomitic component of the amendment providing a direct Mg source (Fageria et al., 2010); recycling of Mg through decomposition of legume and deep-rooted crop residues (Marschner, 2012); and desorption of Mg^{2+} driven by the higher Ca^{2+} concentration on the exchange complex (Kabata-Pendias, 2011).

Because the pH increase achieved by this liming rate did not reach the 6-7 range generally considered optimal for nitrogen mineralization and plant nitrogen uptake (Ylivainio et al., 2024), exceptionally large gains in plant macronutrient content were not expected, and this was broadly confirmed by the plant-tissue data (Figure 13). In wheat, liming increased tissue concentrations of phosphorus, potassium, calcium, magnesium, copper and zinc. In mustard and clover, by contrast, nitrogen, phosphorus and potassium concentrations decreased after liming - a pattern attributable to a combination of factors: the pH increase itself reducing the bioavailability of certain nutrient forms, reduced nitrogen-fixing activity in the legumes, a dilution effect from greater vegetative biomass, and secondary interactions with micronutrients (Chambliss & Kidder, 2003).

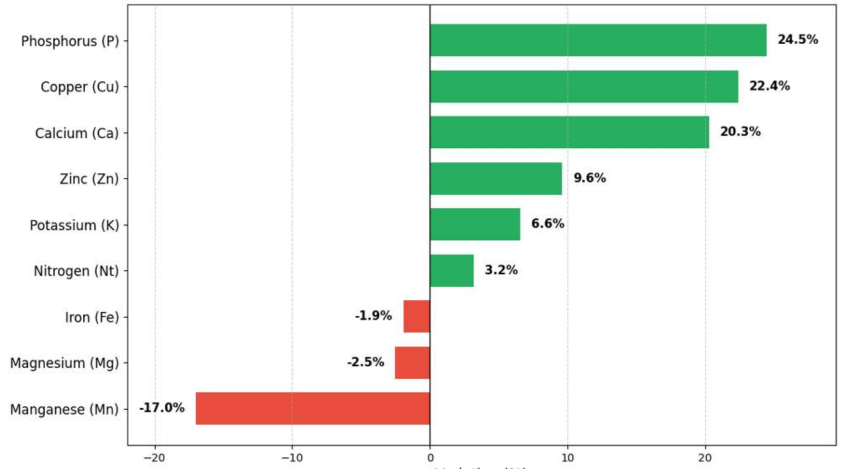

Fig. 15 Relative variation (%) of macro- and micronutrient assimilation in plant tissue - Limed (green) vs. Unlimed (red)

Phosphorus content increased in most limed plants, with values between 0.14% and 0.29% - concentrations around 0.2% that suggest phosphorus fertilization could still increase yield in several of the tested crops. Calcium content increased with liming in most crops; wheat and triticale grain in particular showed improved Ca content, with associated benefits for grain quality (Chambliss & Kidder, 2003). Magnesium followed a broadly similar pattern in wheat and triticale, increasing alongside pH amelioration, although excess Ca can in principle compete with Mg at the root uptake level. Across all samples, Mg concentrations in the unlimed soil ranged from 0.05% (wheat) to 0.41% (buckwheat), and in the limed variants from 0.09% (wheat, the lowest value recorded) to 0.33% (faba bean, the highest); most values fell within the 0.20-0.50% range generally considered typical, with deficiency expected below 0.10-0.15%.

For micronutrients, the relevant literature indicates that Cu, Mn, Fe, and Zn availability is highest between pH 5.5 and 6.5, and declines above pH 6.5 (Plaster, 2013). Since pH remained at or below 6.5 in every variant of every crop, the liming treatment is not expected to have compromised micronutrient nutrition, and the tissue data support this: copper concentrations were higher in the limed variants for most crops, consistent with the increase observed in soil-extractable Cu. Iron concentrations mostly fell within the 50–300 mg/kg range considered normal, though wheat and triticale showed values outside this range in places - worth monitoring for early deficiency symptoms, with micro-fertilizer correction (Zn, Cu, Mn, Fe) available if needed. Manganese values (typical range 20–1,500 mg/kg, most commonly 50–200 mg/kg) fell within the normal range for all crops and treatments. Zinc, which typically varies between 6 and 600 mg/kg depending on plant organ, variety, and growth stage, showed normal values (6–57 mg/kg) for most crops, without a consistent trend of the amendment altering tissue Zn content.

Conclusion

Application of the calcium oxide (CaO 95%) amendment increased soil pH by an average of 0.54 units, corresponding to an approximate 71.2% reduction in exchangeable acidity, and correspondingly reduced exchangeable aluminum from the "very low to low" to the "extremely low" category (Florea et al., 1987) - addressing what had been a major constraint on root development in the unlimed soil. Base saturation increased consistently across all ten crop variants (by up to 38.70%), and hydrolytic acidity decreased in parallel, indicating a clear improvement in soil trophicity and overall chemical fertility.

The amendment was also associated with higher humus content in the limed plots, suggesting a net positive effect on organic matter stabilization despite some evidence of accelerated residue mineralization. Because the pH increase achieved at this liming rate remained below the 6-7 range generally considered optimal for nitrogen mineralization, its effect on plant-available nitrogen should be regarded as a plausible but not directly confirmed mechanism: the modest decline in total soil nitrogen observed in the limed plots is consistent with, but does not by itself prove, increased mineralization to NH_4^+/NO_3^- forms. Phosphorus, calcium and magnesium bioavailability, by contrast, showed clearer and more consistent gains under liming. Nutrient assimilation was markedly species-dependent. Deep-rooted cereals - wheat and triticale in particular - showed the most consistent gains in macronutrient uptake and also drove the largest changes in the soil exchange complex. Legume responses were more variable and were shaped by root exudation and by the activity of symbiotic nitrogen-fixing bacteria, which can locally acidify the rhizosphere even as the bulk soil is being limed; mustard and clover, notably, showed reduced N, P and K content after liming rather than the gains seen in the cereals.

Sorghum stands out as a further species-specific exception: despite receiving the same amendment, its soil remained strongly acidic after harvest, unlike every other tested crop, indicating that the applied rate was insufficient to fully correct acidity under this crop's specific plot conditions. Although rising soil pH generally tends to reduce micronutrient mobility, copper, zinc, manganese, and iron concentrations in plant tissue remained within the ranges considered normal for plant nutrition across essentially all crops and treatments, supporting the conclusion that the applied amendment rate did not induce micronutrient deficiencies.

Overall, these results support liming as an effective, low-risk practice for improving the chemical fertility of this acidic Luvisol, while underlining that a single fixed application rate does not correct acidity uniformly across contrasting crop species - as illustrated by the sorghum exception - and that legume responses in particular require closer attention. As this study covers a single agricultural year, a single amendment rate, and, based on the sampling design as reported, limited field replication, these conclusions should be confirmed through multi-year trials testing a range of liming rates and a fully replicated field design; such work would also allow the plant-available nitrogen response to be verified directly through NH_4^+/NO_3^- measurements rather than inferred from total-N changes alone.

Fig. 16 Aerial view of experimental field

Abstract

Soil acidity is one of the major constraints limiting crop productivity by reducing nutrient availability and increasing exchangeable aluminum toxicity. Liming is widely recognized as an effective strategy for improving the chemical fertility of acidic soils; however, crop-specific responses remain insufficiently documented under diversified cropping systems. This study evaluated the effects of calcium oxide (CaO 95%) amendment on soil chemical properties and the uptake of macro- and micronutrients by ten crop species, including legumes, cereals, buckwheat, mustard and sweet sorghum, cultivated on an acidic Luvisol. Soil analyses included pH, organic matter, available phosphorus and potassium, exchangeable bases, hydrolytic acidity, cation exchange characteristics, exchangeable aluminum and mobile micronutrients. Plant tissues were analyzed for nitrogen, phosphorus, potassium, calcium, magnesium, copper, zinc, manganese and iron concentrations. Liming substantially improved soil chemical quality by increasing soil pH and base saturation while reducing hydrolytic acidity and exchangeable aluminum. Available phosphorus and potassium generally increased following amendment application, whereas changes in soil organic matter indicators were comparatively small. Plant nutrient acquisition exhibited marked species-specific responses. Wheat and triticale showed enhanced accumulation of several macroelements, particularly phosphorus, potassium, calcium, and magnesium, whereas legumes displayed more variable responses, reflecting differences in rhizosphere processes and biological nitrogen fixation. Despite the increase in soil pH, micronutrient concentrations in plant tissues generally remained within the ranges considered adequate for plant nutrition, indicating that the applied liming rate did not induce nutritional imbalances.

Keywords: acidic soil; liming; calcium oxide; exchangeable aluminum; base saturation; nutrient uptake;

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