Soil Fertilization and Maize-Wheat Grain Production with Alternative Sources of Nutrients

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Abstract

This study evaluated regional sources of nutrients to improve the soil fertility status and yield of maize-wheat succession in Southern Brazil. The treatments were: T1: no fertilization; T2: liming with dolomitic marble; T3: alternative liming (AL) with limestone interbedded with shale; T4: AL + 50% P - with Arad natural phosphate (P-ANP) + 50% P – triple superphosphate (P-TSP); T5: AL + 100% P-ANP; T6: AL + 100% P-ANP + 100% K-rich monzogranite; T7: AL + 100% P-ANP + 100% N from tung pressed cake (N-TPC); T8: AL + 100% P-ANP + 100% K-rich monzogranite + 100% S; T9: AL + 100% NPK recommendation (urea, TSP and KCl). Immediate and residual effects were evaluated over 2.5 years (90, 360 and 900 d) on soil fertility and maize - wheat yield. The limestone interbedded with shale released Ca, Mg and corrected soil acidity similarly to dolomitic marble. The monzogranite increased the available K in soil, although improvements of the final product could enhance K release. The fertilization strategies used in T4, T7 and T8 presented a relative productivity index of 108, 111 and 108% when compared to T9 for maize plus wheat yield, while T3 (U$=1223) and T4 (U$=1284) resulted in higher profits (+4.2 and +9.4%, respectively) than T9 (U$=1174). The limestone interbedded with shale combined with 50% of P-ANP + 50% of P – TSP (T4) provided the best economical and technical results, highlighting the potential of selected rock powders for soil fertility correction and plant-nutrients supply.

Introduction

Soil fertility correction and proper plant nutrition are key factors for crop performance in modern agriculture. Intensive crop production in agroecosystems is strongly dependent on a limited list of highly concentrated nutrient sources, generally available in the form of soluble fertilizers, the exploration and manufacture of which is dominated by a few countries and companies. Brazil, according to ANDA (2021), imported about 85% of the total used fertilizers in 2021, where 88%, 64% and 95% refers to soluble sources of N (mainly urea and ammonium sulphate), P$_2$O$_5$ (mainly monoammonium phosphate) and K$_2$O (mainly potassium chloride) respectively, demonstrating the dependency of the Brazilian agriculture on foreign nutrient sources. To reduce the dependency on imports of soluble fertilizers, new strategies are required to provide alternatives to expensive conventional fertilizers, logistic concerns, foreign dependence, and restrictive access of small farmers to these products, in addition to the lower risks of nutrient losses and environment contamination (Ciceri et al. 2017; Fageria et al. 2010; Silva et al. 2012; Swoboda et al. 2022; van Straaten 2007).

Agrominerals, defined as rocks with the ability to restore soil fertility status and supply significant contents of plant-available nutrients, have been evaluated and used in a regional scale, in combination with organic sources to compose alternative fertilization strategies (van Straaten 2007). Several rock types are naturally enriched in nutrients present in the mineral structure. Therefore, the release rate, to meet the requirements of the crops in soils is challenging. In this way, the validation of regionally available raw materials that provide nutrients and organic compounds efficiently and safely, is fundamental for the sustainable development of countries like Brazil, whose agriculture plays a crucial role in the economy and food security.
Acidity is one of the main chemical limitations to crop productivity in tropical soils, and soil fertility is strongly dependent on pH correction. The corrective measure of liming affects food production across tropical soils in Asia, Africa and Latin America. In particular, grain crops are severely limited in uncorrected soils (Behera and Shukla 2015). Tropical soils are known for their high acidity and aluminum toxicity, as well as deficiency in essential macronutrients (Fageria and Nascente 2014). Therefore, acidity correction is the first step for the successful of farming in well-weathered soils.

The best way to overcome soil acidity is to lime the soil with calcium and/or magnesium carbonates (calcite and dolomite), whereby the minerals react with hydrogen released by the soil water as well as carbon dioxide and aluminum in the form of hydroxide, mitigating Al toxicity in plants (Goulding 2016). Liming also provide negative charges and increase the potassium and phosphorus availability to plants, although the magnitude of this depends on the limestone composition and soil nutrient stocks (Meriño-Gergichevich et al. 2010; Silva et al. 2015). Dolomitic marble is the main liming material used in Southern Brazil, extracted from metamorphic dolomitic rocks (Philipp et al. 2016), and its recommendation has been based on its effectiveness of pH correction (neutralization power) and its reactivity (particle size).

However, there is a growing demand for the use of regionally available liming materials like as by-products of the pyrobituminous shale exploration, a sedimentary rock from Irati Formation (Holanda et al. 2018), mainly the interbedded limestone layers. This material can provide secondary macronutrients (calcium, magnesium and sulfur) and micronutrients for plant nutrition, in addition to the capacity to neutralize soil acidity (Mangrich et al. 2001).

Apart from using conventional fertilizers, the correction of soil nutritional deficiencies can also be achieved with the application of finely ground rock types such as natural phosphates, gypsum, mafic and ultramafic rocks (Silva et al. 2012; Rafael et al. 2017). In recent years, the silicate rocks, mainly the fine residues from grinding process in quarries, has deserved more attention. With the advantage of being abundant and regionally available, these resources have been reused as sources for plant nutrients and reduce the external dependence, in particular K, Ca and Mg bearing rocks (Brazil, 2016; Swoboda et al. 2022). In addition, these resources can be used to increase the cation exchangeable capacity (Anda et al. 2015) and water holding capacity of sandy soils (Kahnt et al. 1986). The results of applying finely ground rocks on tropical soils largely depend on their chemical and mineralogical composition, on soil deficiencies, and specific crop requirements (van Straaten 2017).

Other nutrients present in rocks might be used to reduce soil deficiencies and match crop requirements. Silicate rocks containing K-bearing minerals and K-rich rocks such as phonolite and nepheline syenite (Nogueira et al. 2021; Soratto et al. 2021), glauconite bearing rocks (Safatle et al. 2020), biotite (Basak 2018, 2019; Pramanik et al. 2018, 2019) are available in a regional scale, and various studies have shown the successfully use of selected rocks in agriculture. Despite this, these nutrient sources cannot provide all plant needing’s, requiring the combination with other fonts. Common plant nutrient resources, such as P-bearing minerals (natural phosphates), and other agroindustry wastes (e.g., organic cakes) can be used in association with such agrominerals to develop a fertilization strategy for annual crops, as an alternative to
conventional fertilizers, while contributing for the circular economy and the sustainable recycling of wastes that are available in a regional scale.

Thus, the purpose of this study was to evaluate the effectiveness of organic and mineral sources of nutrients available in a regional scale on soil chemical quality and its effects on the grain production of the maize-wheat succession in the Southern Brazil.

**Materials And Methods**

**Study site**

The study was conducted at the Lowland Experimental Station (Embrapa Clima Temperado), Capão do Leão (52°26′35″W, 31°49′27″S), Rio Grande do Sul State, Brazil. According to the Köppen classification, the climate of the region is humid subtropical (Cfa) (Alvares et al. 2013), with an average annual temperature of 17°C and average annual rainfall of 1,400 mm. The soil of the site selected for this study was classified as an Albaqualf (IUSS 2014), and present a low fertility status in the arable layer (0.0–0.2 m): low clay content (< 200 g kg⁻¹), low organic matter content (< 25 g kg⁻¹), low water pH (< 5.0), low bases saturation (< 50%) and high aluminum saturation (> 20%), medium concentrations of available calcium (2.0–4.0 cmol_c dm⁻³) and magnesium (0.5–1.0 cmol_c dm⁻³), low extractable potassium (21–40 mg dm⁻³) and phosphorus (3.1–6.0 mg dm⁻³) content and high available sulfur (> 5 mg dm⁻³), zinc (> 0.5 mg dm⁻³), copper (> 0.4 mg dm⁻³) and boron (> 0.3 mg dm⁻³) contents. The data are presented in Table 1 and interpreted based on the Committee on Soil Chemistry and Fertility CQFS (2016) of Rio Grande Sul and Santa Catarina States, Brazil.

**Table 1**

Soil chemical attributes at 0.0 to 0.2 m of an Albaqualf before the implantation of the experiment (Embrapa Clima Temperado, Pelotas/RS)

| pH | Bases saturation | Al | Ca | Mg | K | P | S | Zn | Cu | B |
|----|------------------|----|----|----|---|---|---|----|----|----|---|
| 4.9| 40.3             | 20.3| 2.3| 0.7| 57| 11.4| 11.4| 0.6| 0.9| 0.3|

**Nutrient Sources**

Regionally available sources of nutrients were selected as resources for alternative fertilization strategies in comparison to the conventional use of NPK fertilizer. The agrominerals where selected to provide macronutrients to improve soil fertility status and to cultivate the maize-wheat succession for grain production. The mineralogy of the selected agrominerals is described in Table 2.
Table 2

Mineralogy description of the agrominerals used as nutrient alternative sources

<table>
<thead>
<tr>
<th>Rock powders</th>
<th>Mineralogy</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone interbedded with shale</td>
<td>quartz, plagioclase (albite), pyrite, illite, smectite, kaolinite, chlorite, calcite, dolomite and analcime</td>
<td>Ribas et al. (2017); Holanda et al. (2018)</td>
</tr>
<tr>
<td>Monzogranite</td>
<td>quartz, K-feldspar, plagioclase and mafic minerals (biotite, amphibole and hornblende)</td>
<td>Grecco et al. (2017)</td>
</tr>
<tr>
<td>Arad natural phosphate</td>
<td>francolite, calcite, calcareous microfossils foraminifera), clays (detrital kaolinite), chert, secondary gypsum, halite</td>
<td>Gill &amp; Shiloni (1994)</td>
</tr>
</tbody>
</table>

The monzogranite is geologically classified as a typical intrusive plutonic acid rock (< 66% total SiO$_2$) belonging to the Pelotas Batholith (Philipp et al. 2016). The minerals present in monzogranite with potential agronomic interest are mafic (biotite, hornblende and amphibole), plagioclase and altered K-feldspar (Table 2). After being mined in a quarry in Pelotas, RS State, Brazil, the monzogranite is crushed to produce gravel-size stones for civil construction purposes. During the crushing process, a ground material regarded as a residue of the grinding process was sampled, finely ground and sieved to obtain the desired particle size of 100% < 0.3 mm.

The limestone interbedded with shale (limestone shale) is a sequence of sedimentary rock layers belonging to the Irati formation, Parana Basin. The limestone occurs as interbedded layers between two main oil shale layers (Ribas et al. 2017). The oil shale layers are mechanically mined by Petrobras-SIX in São Mateus do Sul, Parana State, Brazil, and several layers of limestone shale are regarded either as a mining residue or stock piled as a co-product, mostly destined for regional road paving material in rural areas. Samples of limestone shale were manually selected from stock piles, finely ground and sieved to obtain the desired particle size of 100% < 0.3 mm.

The dolomitic marble is conventionally mined in open pit mines located in the Passo Feio Metamorphic Complex (Gomes et al. 2020) located in Caçapava do Sul, RS State, Brazil. The rock is explored for agricultural and civil construction purposes. The finely ground dolomitic marble is available in the local market as a typical liming material for soil acidity correction, available with the particle size of 95% < 0.3 mm. Due to the limited availability of P-bearing agrominerals in the South of Brazil, the Arad natural phosphate – ANP, a sedimentary reactive rock phosphate imported from Arad, Israel and regionally sold as natural phosphate product for agriculture was selected for this study.

All rocks were submitted to geochemical analysis (Acme Labs, Vancouver, Canada) after total digestion in aqua regia. Moreover, samples of the monzogranite were also submitted to Brazilian Geological Survey, CPRM-Porto Alegre for petrographic analysis. The elemental sulfur (powder) and the NPK fertilizer (granules), available as commercial fertilizers, were purchased on the local market. The tung pressed cake is a co-product from the tung oil agroindustry. Fruits of tung (Vernicia fordii) trees, harvested in Fagundes
Varela, RS State, Brazil were pressed by extrusion to extract the oil, remaining the tung pressed cake (crumbs), which is packed and sold as an organic fertilizer (N source) in the local market. The total concentrations of macronutrients of mineral and organic sources are presented in Table 3.

### Table 3
Total concentrations of N, P$_2$O$_5$, K$_2$O, CaO, MgO and S of mineral and organic sources

<table>
<thead>
<tr>
<th>Nutrient Sources</th>
<th>Total content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Dolomitic marble (PRNT = 60.8%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.9</td>
</tr>
<tr>
<td>Limestone shale (PRNT = 60%)</td>
<td>0.2</td>
</tr>
<tr>
<td>Monzogranite</td>
<td>0.1</td>
</tr>
<tr>
<td>Arad natural phosphate (ANP)</td>
<td>33.9</td>
</tr>
<tr>
<td>Tung pressed cake</td>
<td>2.7</td>
</tr>
<tr>
<td>NPK – conventional soluble fertilizer</td>
<td>5.0</td>
</tr>
<tr>
<td>Triple superphosphate (TSP)</td>
<td></td>
</tr>
<tr>
<td>Elemental sulfur</td>
<td></td>
</tr>
</tbody>
</table>

*Calculation of the application rate considered that 50% of the added K$_2$O can be available for the first two cropping cycles.

### Multiannual field experiment

A field experiment was installed and conducted in a randomized complete block design using 36 plots of 50 m$^2$ (5 × 10 m), with nine treatments (fertilization strategies) and four replications. Three sampling times (90, 360 and 900 d after application of treatments) were performed to evaluate the effects of nutrient sources on soil chemical attributes over 2.5 years. Types and application rates of liming materials plus nutrient sources are presented in Table 4. The treatments were as follows: T1 - control (without liming nor fertilization); T2 - conventional liming material (marble); T3 - alternative liming material – AL (limestone interbedded with shale); T4 - AL + 50% of P recommendation through Arad natural phosphate (ANP, sedimentary) + 50% of P recommendation with soluble phosphate; T5 - AL + 100% of P via ANP; T6 - AL + 100% of P via ANP + 100% of K recommendation through monzogranite; T7 - AL + 100% of P via ANP + 100% of K recommendation through tung pressed cake (TPC, organic source); T8 - AL + 100% of P via ANP + 100% of K recommendation through monzogranite + 100% of N via TPC + 100% of S recommendation; T9 - AL + regional recommended rate of NPK fertilizer.
Table 4
Type and doses of mineral and organic sources of nutrients applied in each treatment

<table>
<thead>
<tr>
<th>Sources of nutrients</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
<th>T9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomitic marble</td>
<td>-</td>
<td>3.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Limestone shale</td>
<td>-</td>
<td>-</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Arad natural phosphate</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>-</td>
</tr>
<tr>
<td>Triple superphosphate</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Monzogranite</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.2</td>
<td>7.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tung pressed cake</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.4</td>
<td>3.4</td>
<td>-</td>
</tr>
<tr>
<td>Elemental sulfur</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.03</td>
</tr>
<tr>
<td>NPK conventional soluble fertilizer (05-20-20)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Recommendations of CQFS (2016), with reference to the soil chemical analysis (Table 1) guided the choice of application rates of nutrients. While the liming dose for all treatments was calculated to achieve the desired pH of 6.0, the dose of P (via Arad Natural Phosphate) and K (monzogranite) of T4 to T8 was calculated to correct soil levels (rise up from low to medium level) plus the recommended dose for maize crop maintenance, while for the NPK rate of T9 were calculated solely for maize crop maintenance. All nutrient sources were thoroughly distributed in the soil surface, then incorporated into the arable soil layer (0.0 to 0.20 m) before planting by a chisel plough pulled by a tractor, except T9 (NPK), which was applied in the planting row by a no-tillage seeder pulled by a tractor.

The grain productivity of two successive crops were used to evaluate the immediate (1st crop) and residual (2nd crop) effects on crop performance. The 1st cropping season was maize (cultivar Pioneer 30B39), implanted with a no-tillage seeder in early-December 2011, with a plant density of 60,000 plants ha$^{-1}$. The 2nd crop was wheat (cultivar Embrapa BRS 327), implanted in early June 2012 with a plant density of 300,000 plants ha$^{-1}$. After seedling and emergence, 170 kg ha$^{-1}$ of N (urea) was applied for all treatments, divided into two applications.

The relative productivity index (RPI) of each fertilization strategy (T1 to T9) in relation to T9 - alternative liming + NPK conventional fertilizer was obtained from the equation: RPI (%) = 100 x [(Y $T \bar{i}$)/(Y $T9$)] where: Y $T \bar{i}$= grain productivity by each fertilization strategy ($i$ = 1 to 9); Y $T9$= grain productivity of T9 - liming + NPK conventional fertilizer. The profit (P) of each fertilization strategy was calculated as: P = (grain productivity x price of the products) - (sum of the costs of all nutrient sources).

The effects of nutrient sources on the soil chemical parameters along the time were evaluated in a longer run, through 900 d (2.5 years). In this way, three soil samplings from the topsoil layer (0.0-0.2 m),
collected at the 90, 360 and 900 d after treatment application, respectively, were collected for chemical analyses. The following soil chemical attributes were evaluated according to the methodologies described in Tedesco et al. (1995): soil pH; available P and exchangeable K extracted with HCl 0.05 mol L\(^{-1}\) + H\(_2\)SO\(_4\) 0.0125 mol L\(^{-1}\) solution (Mehlich-1); exchangeable Ca, Mg, and Al extracted with KCl 1 mol L\(^{-1}\) solution; available S content (S-SO\(_4\)), evaluated through colorimetry after extraction with Ca(H\(_2\)PO\(_4\))\(_2\); available B extracted with hot water (55 ± 3°C); available Cu and Zn extracted with HCl 0.1 mol L\(^{-1}\) solution.

The original data were evaluated, including the presence of outliers, and subjected to statistical analysis of variance – ANOVA. The effects of treatments (fertilization strategies), sampling times (90, 360 and 900 d after application) and the interaction of both were analyzed. When the effects were significant (F test, p < 0.05), the means were compared by Tukey’s test (p < 0.05). All data and statistical analyses were performed using Winstat (2002) and Sigmaplot (2004) softwares.

**Results**

**Effect of fertilization strategies with regional sources of nutrients on soil chemical attributes**

The fertilization strategies significantly affected the main soil chemical attributes in the 0.0–0.2 m soil layer (Table 5). All soil macronutrients (P, K, Ca, Mg and S), pH, Al and bases saturation, Mn and Zn contents were influenced by at least one of the treatments that combine alternative nutrient sources. Considering fertilization, Cu and B contents were not affected, while for the soil sampling time, only Mn did not vary significantly over the three sampling dates. Meanwhile, for P and S contents, significant effects were observed for the interaction of fertilization x season (Fig. 2a, 2d).

| Source of experimental variation | pH     | Bases saturation (%) | Al\(^{3+}\) saturation (%) | P   | K   | Ca  | Mg  | S   | Mn  | Cu  | Zn  | B   |
|--------------------------------|--------|----------------------|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Fertilization                  | **     | **                   | **                          | **  | *   | **  | **  | **  | **  | NS  | **  | NS  |
| Season                         | **     | **                   | **                          | **  | **  | **  | **  | **  | **  | NS  | **  | **  |
| Fertilization x season         | NS     | NS                   | NS                          | *   | NS  | NS  | NS  | **  | NS  | NS  | NS  | NS  |

Test F: *significant at p < 0.05; **significant at p < 0.01; NS not significant at p < 0.05 nor at p < 0.01.
Considering the effects of agrominerals on soil pH, as expected, liming the soil (T2-T9) significantly increased the pH compared to the control; (T1), specifically the treatments T3-T9 with limestone shale (sedimentary rock), similar to treatment T2 - dolomitic marble (metamorphic rock) (Fig. 1a). On other hand, it is important to note that at 90 d after liming, none of treatments achieved the desired pH of 6.0. The soil pH was increased and sustained until 360 d but reverted back significantly 900 d after application of treatments (Fig. 2b). A very similar behavior to soil pH was observed for bases saturation (Fig. 1c). Despite the significant effect of liming, the rates and nutrient sources applied in all treatments were insufficient to reach the desired pH of 6.0, although a quite satisfactory level of bases saturation (51–70%) was achieved, as recommended by SBCS/NEPAR (2017) for the maize-wheat succession. The combination of limestone shale with Arad natural phosphate, tung pressed cake and monzogranite (treatment T8) promoted the higher mean pH and bases saturation compared to other treatments (5.6 and 62%, respectively). The bases saturation was also affected by the time (Fig. 1d), showing lower mean values than recommended by SBCS/NEPAR 2017 at 900 d after application of treatments.

Importantly, low Al\(^{3+}\) saturation levels were observed in all treatments involving limestone shale (T3-T9) in relation to T1 (Fig. 1e), equal to observed with conventional liming (dolomitic marble). Again, similar to observed with pH and bases saturation, the behavior of Al\(^{3+}\) saturation values along the time (Fig. 1f) denote a limited persistence of liming effects at 2.5 years after application of treatments.

In general, the Al\(^{3+}\) saturation should be lower than 10% (CQFS 2016) to maximize agricultural effectiveness, as presented by treatments T2 to T9. As expected, the control soil lacking corrective addition (T1) showed an Al\(^{3+}\) saturation much higher than this critical limit since the beginning of the experiment. In this sense, lower Ca and Mg contents were observed in the control treatment during the evaluations, mainly at 900 d (supplementary data), when both nutrients fall below the critical content (Ca < 2.0 cmol\(_c\) dm\(^{-3}\) and Mg < 0.5 cmol\(_c\) dm\(^{-3}\)) for grain crops (CQFS 2016). Otherwise, the treatments with limestone shale (T3 to T9) as well as with dolomitic marble (T2), provided increases in Ca and Mg contents when compared to the initial characterization, remaining the Ca content (2–4 cmol\(_c\) dm\(^{-3}\)) classified in the medium availability range and the Mg content (> 1 cmol\(_c\) dm\(^{-3}\)) in the high availability range (CQFS 2016), even after maize-wheat succession (Fig. 3a). At 900 d, all treatments (T2 to T9) decreased their values for both nutrients, possibly due to the loss of nutrients from crop grain harvests and intense leaching of bases promoted by high cumulative rainfalls, helped by the limited capacity to retain cations, evidenced by the small clay content in the topsoil layer (160 g kg\(^{-1}\)).

Considering the soil’s K content, both fertilization strategies and time after application of treatments had significant influence on the soil’s K concentration (Table 5). The fertilization strategy T8 (limestone interbedded with shale + ANP + monzogranite + TPC) resulted in a higher value (0.09 cmol\(_c\) L\(^{-1}\)) than the control treatment T1 (0.07 cmol\(_c\) L\(^{-1}\)) (Fig. 2b). However, it should be noted that all values remained at low (0.08–0.15 cmol\(_c\) dm\(^{-3}\)) and very low (≤ 0.079 cmol\(_c\) dm\(^{-3}\)) availability ranges, independent of the period. This result shows that the monzogranite rock powder (310 kg ha\(^{-1}\) K\(_2\)O via 7 Mg ha\(^{-1}\)) provided at least part of the K crop demand. However, it was not effective enough to increase the readily available soil
content of K (extractable by Mehlich-1) above the sufficiency level (> 0.23 cmol\textsubscript{c} dm\textsuperscript{-3}) during the period of the experiment. It should be noted that the reference treatment with conventional NPK fertilizer (T9) also did not increased significantly this level.

The soil’s extractable phosphorus content (P Mehlich-1) showed significant differences for the treatments (T1-T9), for sampling time (90, 360 and 900 d after application) and for the interaction between treatments x sampling time (Table 5). Considering the fertilization strategies in the first sampling period, T6 (liming + ANP + monzogranite) differed from those treatments without P input (T1, T2 and T3), while the others with P through ANP (T4, T5, T7, T8) and soluble TSP (T9) remained equal to each other and to those without P input (T1, T2 and T3). For the 2nd sampling time (360 d), those treatments with ANP (T4 - with ½ part of P via TSP, T5, T6 and T8) showed higher P concentrations, remaining between 60 to 76 mg L\textsuperscript{-1} of P. The treatments without P sources (T1, T2 and T3) and with soluble TSP remained at the same P level (≤ 12.93 mg L\textsuperscript{-1} of P). For the 3rd sampling time (900 d), all treatments remained at the same level, ranging from 4.1 to 29.9 mg L\textsuperscript{-1} (Fig. 2a).

When ANP was combined with limestone shale (T5 and T6), and plus TSP (T4), the P content extracted by Mehlich-1 remained in the high to very high availability ranges from 90 to 360 d, but reduced to the medium range at 900 d. On other hand, when the ANP was combined with tung pressed cake, the extractable phosphorus level moved from the medium to the low availability range from 90 to 900 d in the T7 treatment, and from high to low availability from 90 to 900 d in T8. Finally, for the T9 treatment, where the limestone shale was associated with soluble TSP, the extractable P content in the soil remained low to very low throughout the experiment.

The available S content in soil was significantly affected by fertilization (T1-T9), by the sampling times (90 x 360 x 900 d) and by the interaction fertilization x sampling time. The S soil content was classified in the high availability class (10–20 mg L\textsuperscript{-1}) before starting the experiment. After 90 d, treatment T8 presented the highest S level (22.1 mg L\textsuperscript{-1}), followed by treatment T4 and T9, all these contrasting with the lower levels of S observed for treatments T1, T2, T3 and T7. The addition of 0.03 Mg ha\textsuperscript{-1} of elemental sulfur in treatment T8 was the most probable reason of the increase in available S contents in this treatment T8, although this effect was quite temporary, because for the 2nd and 3rd sampling time, no significant differences between treatments were observed. Considering the effect of the sampling time, the treatments of T4, T8 and T9 significantly reduced the S content from the 1st to 2nd and 3rd soil samplings, back to similar levels observed in T1 and before the start of the experiment.

For the evaluated micronutrients, all of them were initially classified in the high availability range before the start of the experiment (Table 1). During the experiment, while Mn and Zn contents were significantly affected by treatments (Table 5), Cu and B were not. For instance, the sampling time affected the levels of Cu, Zn and B. Higher Mn mean value was observed in treatment T1 compared to treatments T2 and T8 (Fig. 3e). Conversely, no effect of sampling time was observed for Mn, and mean values of all treatments remained within a short interval, between 12.88 to 13.84 mg L\textsuperscript{-1} (Fig. 3f).

**Effect of fertilization strategies on crop productivity**
Different fertilization strategies significantly affected the crop productivity of both maize/corn and wheat grains (Table 6). The maize yield was significantly higher in treatments T7 (4,884 kg ha$^{-1}$), T8 (4,877 kg ha$^{-1}$), and T4 (4,835 kg ha$^{-1}$) in relation to T5 (3,171 kg ha$^{-1}$), T2 (3,021 kg ha$^{-1}$), T1 (2,932 kg ha$^{-1}$), and T6 (2,881 kg ha$^{-1}$). Important to note is that the maize yield in T7, T8 and T4 treatments was close to the regional average (4,807 Mg ha$^{-1}$) observed in 2012.
Mean yield and standard errors of maize (main effect) and wheat (residual effect) grown in Albaqualf under different mineral and organic sources, differences in relation to mean yield of crops in Rio Grande do Sul State, Brazil (Δref), the relative productivity index (RPI) and the profit (P) of the fertilization strategies

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Maize yield</th>
<th>Δref</th>
<th>RPI</th>
<th>Wheat yield</th>
<th>Δref</th>
<th>RPI</th>
<th>Maize + Wheat yield</th>
<th>Δref</th>
<th>RPI</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha⁻¹</td>
<td>%</td>
<td></td>
<td>kg ha⁻¹</td>
<td>%</td>
<td></td>
<td>kg ha⁻¹</td>
<td>%</td>
<td></td>
<td>U$</td>
</tr>
<tr>
<td>T1</td>
<td>2,932 ± 443 b</td>
<td>-39</td>
<td>70</td>
<td>1,303 ± 212 b</td>
<td>-33</td>
<td>66</td>
<td>4,235 ± 412 c</td>
<td>-37</td>
<td>69</td>
<td>1001</td>
</tr>
<tr>
<td>T2</td>
<td>3,021 ± 935 b</td>
<td>-37</td>
<td>72</td>
<td>1,543 ± 126 ab</td>
<td>-21</td>
<td>78</td>
<td>4,564 ± 904 bc</td>
<td>-32</td>
<td>74</td>
<td>968</td>
</tr>
<tr>
<td>T3</td>
<td>3,871 ± 717 ab</td>
<td>-19</td>
<td>92</td>
<td>1,629 ± 76 ab</td>
<td>-16</td>
<td>83</td>
<td>5,500 ± 711 abc</td>
<td>-19</td>
<td>89</td>
<td>1223</td>
</tr>
<tr>
<td>T4</td>
<td>4,835 ± 599 a</td>
<td>1</td>
<td>115</td>
<td>1,817 ± 108 a</td>
<td>-6</td>
<td>92</td>
<td>6,651 ± 648 a</td>
<td>-1</td>
<td>108</td>
<td>1284</td>
</tr>
<tr>
<td>T5</td>
<td>3,171 ± 603 b</td>
<td>-34</td>
<td>75</td>
<td>1,613 ± 228 ab</td>
<td>-17</td>
<td>82</td>
<td>4,784 ± 669 bc</td>
<td>-29</td>
<td>78</td>
<td>631</td>
</tr>
<tr>
<td>T6</td>
<td>2,881 ± 319 b</td>
<td>-40</td>
<td>69</td>
<td>1,803 ± 200 a</td>
<td>-7</td>
<td>92</td>
<td>4,684 ± 406 bc</td>
<td>-31</td>
<td>76</td>
<td>327</td>
</tr>
<tr>
<td>T7</td>
<td>4,884 ± 1,110a</td>
<td>2</td>
<td>116</td>
<td>1,954 ± 262 a</td>
<td>1</td>
<td>99</td>
<td>6,837 ± 1,293a</td>
<td>1</td>
<td>111</td>
<td>798</td>
</tr>
<tr>
<td>T8</td>
<td>4,877 ± 748 a</td>
<td>1</td>
<td>116</td>
<td>1,810 ± 161 a</td>
<td>-7</td>
<td>92</td>
<td>6,687 ± 878 a</td>
<td>-1</td>
<td>108</td>
<td>478</td>
</tr>
<tr>
<td>T9</td>
<td>4,205 ± 581 ab</td>
<td>-13</td>
<td>100</td>
<td>1,966 ± 283 a</td>
<td>1</td>
<td>100</td>
<td>6,171 ± 654 ab</td>
<td>-9</td>
<td>100</td>
<td>1174</td>
</tr>
<tr>
<td>Regional yield</td>
<td>4,807*</td>
<td>1</td>
<td>100</td>
<td>1,942</td>
<td>1</td>
<td>100</td>
<td>6,749</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

T1 - control; T2 - conventional liming; T3 - alternative liming; T4 - alternative liming + 50% P natural phosphate + 50% P soluble triple phosphate; T5 - alternative liming + 100% P natural phosphate; T6 - alternative liming + 100% P natural phosphate + 100% K monzogranite; T7 - alternative liming + 100% P natural phosphate + 100% N organic source; T8 - alternative liming + 100% P natural phosphate + 100% K monzogranite + 100% N organic source + 100% S; T9 - alternative liming + NPK at base fertilization (recommended dose for crop maintenance). Values followed by the same letter in the column are not significantly different by the Tukey test (p < 0.05).

*of corn and wheat in Rio Grande do Sul State, Brazil (CONAB, 2018).

In relation to wheat productivity, treatments T9 (1,966 Mg ha⁻¹), T7 (1,954 Mg ha⁻¹), T4 (1,817 Mg ha⁻¹), T8 (1,810 Mg ha⁻¹) and T6 (1,803 Mg ha⁻¹) were similar to the regional average yield (1,942 Mg ha⁻¹) while treatments T2, T3 and T5 were up to 20% lower (Table 6).
The cumulative yield and the relative productivity index (RPI), which was calculated for all treatments in relation to T9, demonstrate the performance of alternative fertilization strategies on maize, wheat and maize + wheat yields, compared to conventional fertilization commonly used in Southern Brazil, also confirming the benefits in a longer run (Table 6).

**Discussion**

**Improvements on soil fertility**

The application of mineral and organic sources of nutrients improved the soil fertility status. As expected, macronutrient levels in the soil were improved by alternative and conventional liming, thus affecting soil acidity-related variables like as pH, Al and bases saturation.

The first stage of soil acidity neutralization occurs when carbonates are applied to acid soils, the dissolution in water produces bicarbonate, which is much more reactive with the exchangeable and residual soil acidity (Fageria and Nascente 2014; Brady and Weill 2016). Consequently, Ca and Mg react with $H^+$, replacing it on the clay and organic matter exchange sites (Meriño-Gergichevich et al. 2010; Fageria and Nascente 2014).

In this way, the pH and the bases saturation rules soil fertility status and their dynamic was driven by the dolomite and calcite carbonate dissolution, present in marbles and in the limestone shale (Ribas et al. 2017; Saif et al. 2017). Carbonates undergo congruent dissolution, being converted over time. The rainfall amount is of primary importance for the speed of the liming reaction. From the time of lime application until the 1st soil sampling the rainfall was 348 mm (90 d), while the 2nd soil sampling took place when the cumulative rainfall was 1,174 mm (360 d), reinforcing the effect of climatic factors on carbonate dissolution.

Besides the effects of precipitation, the particle-size distribution of rock powders plays a fundamental role in the dissolution rate. Rock powder containing carbonates and having liming effects are sold commercially with 95% of particles < 0.3 mm, and therefore considered reactive within 90 d after incorporation in the arable soil layer. It is expected that the soil with limestone shale might have an equal or even higher carbonate dissolution rate than the dolomitic marble, probably due to the rock nature formation and/or texture. The limestone shale is a sedimentary rock, with less crystallized minerals, composed of microgranular grains of dolomite and calcite minerals, with rhombohedral structures and relatively equidimensional grains (Saif et al. 2017). Therefore, in addition to the neutralization power and granulometry, petrographic analyses, characterization of the mineral composition, texture, particle-size distribution, and a description of the fine-grained structure of rocks can influence the corrective's choice.

Considering the liming sources, the limestone interbedded with shale, used individually or in association with other agrominerals containing CaO and MgO, is similar in increasing soil pH and decreasing the $Al^{3+}$ saturation in relation to dolomitic marble (Fig. 1e). Other studies have shown the positive effects of
limestone shale, corroborating the effectiveness of carbonates from the Irati Formation (Rodrigues et al. 2021a, b).

The decrease of mean values of pH (Fig. 1b), bases saturation (1d), Ca and Mg (Fig. 3b, 3d), and the increase in Al\(^{3+}\) saturation (Fig. 1f), have shown that soil acidity and related problems returned faster than expected, probably because the limited liming effects. Thus, an acceleration of acidification in the soil system might also contribute, typically when N input sources react in the soil (urea and TPC). Soil acidification by synthetic fertilizers and organic matter decomposition (Fageria and Nascente 2014) mostly occurs due to the release of H during the nitrification process (Brady and Weil 2016). In Brazil, studies about the application of tung pressed cake, used as a substrate for vegetable's production, showed a tendency to reduce the pH with increasing application rates (Watthier et al. 2017), possibly by H dissociation from carboxylic groups, by nitrate leaching or N releases in the soil profile (Burle et al. 1997). In tropical climate, the high weathered soils become naturally acidified due to high rates of precipitation, the main H\(^{+}\) introducer in the soil system (Brady and Weill 2016), as well as a result of leaching of bases (Fageria and Nascente 2014). Therefore, soils with low natural fertility like the one of this study should be frequently monitored (e.g., every 2 years) to assure suitable pH conditions for grain crops.

Considering the use of agrominerals to supply K for soil correction and plant requirements, the finely ground monzogranite, formed by K-feldspar, plagioclase, biotite, amphibole and quartz (Vieira et al. 2016; Ciceri et al. 2017) can be considered an alternative source of K. Usually, the more relevant part of the K supplied to plants might be supplied by the available K fraction of soil, while the remaining can be extracted from organic matter or other less available forms of mineral phases. According to Britzke et al. (2011), exchangeable and non-exchangeable K fractions might supply part of the K required for crop development in lowlands. Furthermore, several monocots such as elephant grass and corn have a stronger K extraction capacity because of the ability to release low molecular weight acids to brake chemical bonds of silicates. Therefore, as proposed by Ciceri et al. (2017), the crop performance in response to the application of an agromineral with K-feldspar should consider, in addition to the K\(_2\)O content, petrographic characteristics that reveal the K-mineral's texture and degree of mineral alteration in the rock. In this sense, weatherable minerals such as biotite and secondary clay minerals (celadonite, smectite, vermiculite) might be important K sources for plants.

The particle-size of the monzogranite used in this study (100% of particles < 0.3 mm) are fine and comparable to calcareous rocks but might still be not fine enough to release most of K through mineral dissolution within one crop season. Thus, a significant part from the evaluated monzogranite are well-crystallized minerals, formed under slow cooling and producing ordered, medium to coarse and subhedral to euhedral crystals, the most common characteristic of the monzogranite found in the region (Vieira et al. 2016). On other hand, local conditions might change significantly the type and degree of alteration of minerals. Granite derived rocks can be classified as S- or I-type, and this governs the weathering intensity of minerals. The I-type of granites favors mineral weathering in a way that the higher the proportion of mafic minerals, the higher the clay content and soil fertility as well (Silva et al., 2016). Since monzogranite belong to the granite group of rocks, with a relative abundance of able minerals like biotite and hornblende
(Table 2), a significant release of K, Ca and Mg could have positively affected the results of soil attributes and plants.

Several technologies might be employed to boost K-release in K-bearing agrominerals. These include ultrafine grinding that increase the proportion of particles < 0.074 mm, which increased the K-release of a phonolite from Minas Gerais, Brazil (Nogueira et al. 2021), hydrothermal treatment with sulfuric acid (Safatle et al. 2020), incubation of waste mica with organic acids and K-solubilizing microorganisms (Basak 2019), co-composting (Basak 2018), among others (Pramanik et al. 2019, 2020). It is important to use materials that promote agronomic efficiency and keep the transport distances short, these technologies have potentials as local solutions for the use of K-rich agrominerals to cultivate annual crops.

The use of 3.4 Mg ha$^{-1}$ of tung pressed cake (Table 4) added around 122 Kg ha$^{-1}$ K$_2$O (Table 3) in treatments T7 and T8, while 60 kg ha$^{-1}$ of K$_2$O was added in treatment T9 via soluble form through KCl, but these treatments did not promote significant increase of extractable K (Mehlich-1) in the soil compared to T6 (monzogranite as a solely source of K$_2$O). In fact, for treatment T9 the amount of K$_2$O (60 kg ha$^{-1}$) applied as KCl was not previously designed to increase the K-level in the soil. It was applied only for crop maintenance, like as for T7 with the organic source (tung pressed cake) and T8 (tung pressed cake + monzogranite). Nevertheless, the K-release was not sufficient to change the K level above 0.23 cmol$_c$ dm$^{-3}$ in the soil. The K release from tung pressed cake still remains to be studied. Also, the monzogranite, although significant effect was observed for available K in soil (T8), the release rates from the various K bearing minerals, K feldspar, biotite, need to be studied.

It is important to note that K is commonly considered as highly susceptible to leaching in sandy soils (Rosolem et al. 2010). The soil of the study has only 160 g kg$^{-1}$ clay, thus, if large rates of soluble K$_2$O are applied, this element can be easily leached out from the topsoil after heavy rainfalls. High K$_2$O rates can also induce a reduction in Ca, Mg and S uptake, like observed in upland rice by Filho et al. (2017). Therefore, this characteristic limit the application of high rates of highly soluble K sources close to root systems, highlighting the importance to find and develop lower soluble and alternative K sources.

Considering the P content, the treatments without natural or reactive phosphorus sources (treatments T1, T2 and T3) remained in the low to very low range of soil P availability (CQFS 2016), independent of the period. Considering that the P content in the initial soil characterization was classified in the low availability class (Table 1), these results were expected for these treatments. Even with the increase of soil pH in the T2 and T3 treatments, and for treatment T9, there was no increase in soil P availability, mostly because the dose considered only the crop maintenance, to the detriment of P level correction in the soil. In addition, the sandy property of the soil (160 g kg$^{-1}$) deserve low P stocks, and the nutrient extraction by the crop probably explain the negligible change in the P levels. Considering the geochemistry characterization presented in Table 3, the ANP provided up to 475 kg ha$^{-1}$ of P$_2$O$_5$ to the soil (total content), explaining the most part of soil P content changes over time. It is very important to note that
Mehlich-1 extraction overestimates soil P available contents after natural phosphate application (Bortolon et al. 2009), and usually plants do not access all this P content. In this way, although the effects of the application of natural phosphate (ANP) on available P in the soil are remarkable (Fig. 2a), its effects on crop performance is less evident, as presented by the grain productivity data obtained in this study (Table 6).

The Zn content was especially favored by the T6, T8, T4 and T5 treatments in relation to T2. These results show that the combination of limestone interbedded with shale, ANP and monzogranite played an important role in to supply the available Zn content, despite that Zn is already naturally present in the soil (Zn values in the T1 treatment were at the same level as all other treatments). Considering the sampling times, the Zn contents reduced significantly from 1st (0.99 mg L$^{-1}$ at 90 d) to 2nd (0.68 mg L$^{-1}$ at 360 d) sampling, demonstrating the impact of plant extraction and soil losses/fixation of Zn after two cropping seasons. Therefore, special attention should be paid for this element after two cropping seasons (see supplementary material). In relation to Cu and B, the treatments did not differ significantly during the evaluated period, but both were affected by the sampling time: Cu mean contents reduced from 0.79 mg L$^{-1}$ to 0.43 mg L$^{-1}$ while for B it increased from 0.23 mg L$^{-1}$ to 0.42 mg L$^{-1}$ from the 1st to 3rd sampling time, respectively (Fig. 4d; Fig. 4f). These patterns might be highly affected by soil pH because the availability of such micronutrients is usually controlled by this soil chemical property.

The results of chemical properties clearly show the technical effectiveness of selected nutrients sources, with special emphasis on finely ground rock powders, in improving the available contents of major nutrients in the soil exchangeable complex. The limestone interbedded with shale was comparable to conventional liming to increase the soil pH, as well as to increase Ca and Mg contents in the soil. The Arad natural phosphate, despite that not being produced in the region, confirmed the already well-known capacity to increase P in the soil. The monzogranite resulted in higher extractable K in soil, although this effect had lesser effects than the effects of other agrominerals. In this context, considering agronomic and environmental aspects, the combination of the selected regional sources can be used as an alternative fertilization strategy, keeping the available soil nutrients within affordable levels.

**Improvements on crop productivity**

The results of maize grain productivity (1st crop cycle) presented by fertilization strategies in comparison to conventional NPK fertilizer demonstrate the technical viability of using regional sources as an alternative way to provide nutrients for annual cropping systems. The low maize yield observed in T1 was expected because the low natural soil nutrient levels, without receiving any acidity corrective nor NPK as base fertilization. The maize yield in the T2 treatment remained around to 37% lower than the regional mean, even with the addition of dolomitic marble. The concomitant application of limestone interbedded with shale and ANP (T5) and monzogranite (T6) highlight the negative effect verified in yield when applying liming materials and rock phosphate powders together right before seedling, which resulted in limited availability of P and yield reductions of 34% and 40% for T5 and T6 (Table 6). ANP dissolution is limited in soils with high Ca concentrations and high pH (> 5.5). At these pH levels, immobilization of soluble P by Ca occurs, forming calcium phosphates. On the other hand, this negative result can be
compensated by applying at least a part of the recommended phosphate through soluble P forms, like as used in treatment T4.

In the case of treatments T5 and T6, the P release pattern of ANP strongly influenced maize yield. The high P content observed in treatments with ANP at 90 d (Fig. 2a) is partially explained by the Mehlich-1 extraction method, which uses an acidic extractive solution, dissolving the calcium phosphate particles that had not yet completely dissolved in the soil, thus overestimating the P availability for plants. On the other hand, the phosphate ions are released concomitantly with calcium from liming. This causes precipitation as dicalcium phosphate and, consequently, transformed into more stable, unavailable forms of P to plants, such as octo-calcium phosphate and hydroxyapatite, yielding a drastic reduction of P in soil solution. Similar results were observed by Shen et al. (2011) in a calcareous soil.

In relation to wheat productivity, the results show the importance of the residual effect of alternative fertilization strategy. Liming plus ANP and TPC (T7) and soluble S (T8), or liming plus ANP, where ANP was partially substituted by highly soluble forms of phosphorus (T4) could sustain a 2nd crop cycle in a similar way than NPK.

For the monzogranite (treatments T6 and T8), the most possibly process of K release is by the incongruent dissolution of silicates over time (Garcia et al. 2020; Silva et al. 2021). The weathering of K-bearing silicate minerals from monzogranite (biotite, K-feldspar) can also result in other benefits for sandy soils, by generating negative permanent charges which may increase the cation exchange (Santos et al. 2021), and increasing water holding capacity (Mastella et al. 2022; Mazahar and Umar 2022). Rhizosphere processes and biological activity, which may further enhance mineral dissolution through H-ions release and complexing of organic compounds that react with mineral surfaces (Shen et al. 2011), as well as isomorphic substitution, are the main ways to generate negative charges by agrominerals in agricultural soils.

For the cumulative yield, the limestone interbedded with shale was at least equal to or even more efficient than the dolomitic marble for reducing soil acidity, releasing Ca and Mg and improving crop productivity. On other hand, the combination of liming through limestone shale and P - ANP (treatment T5 and T6) restricted the crop productivity, therefore, their concomitant application must be avoided. This can be achieved by using a part of P application through conventional TSP, as to observed in treatment T4. The relative productivity index of T4 was 111% when compared to T9 for maize plus wheat yield, and resulted in higher profit (+9.4%) than T9 (U$=1174). Evidently, the profit of annual crops largely depends on the sum of costs of all nutrient sources, sources, thus, there is essential provide for the farmers new, efficient and low-cost nutrient sources, in a regional scale. In this sense, the limestone interbedded with shale, alone (T3) or combined with 50% of P-ANP + 50% of P – TSP (T4) provided the best economical and technical results, highlighting the potential of selected regionally available resources (rock powders) to perform soil fertilization strategies as an alternative or complement to conventional fertilization.

**Conclusions**
This study evaluated the effects of organic and mineral sources of nutrients on soil chemical properties over a period of 2.5 years after soil incorporation, using maize and wheat yields and the resulted profit as indicators of each fertilization strategy. The treatments for soil fertilization considered regional agrominerals (limestone shale and monzogranite) in combination with natural phosphate, tung pressed cake - organic source of nitrogen, as alternative to conventional fertilizers. The limestone shale was agronomically effective by releasing Ca and Mg, and correcting soil acidity similarly to dolomitic marble, with marked improvement on maize and wheat yields. Additionally, the best profit was reached when limestone shale was combined with 50%P-natural phosphate plus 50% P-triple superphosphate. Nevertheless, special care should be taken with the simultaneous application of limestone shale with natural phosphates that strongly limited the crop productivity, as a result of P immobilization.

The monzogranite increased the available K of soil in treatment T8 and sustained the crop productivity during two cropping seasons (maize + wheat), although the level of exchangeable K remained in the medium class in the soil, and the additional costs provided by its inclusion resulted in lower profits than other fertilization strategies. Therefore, improvements in the final product (e.g. selection/concentration of mafic minerals, increase the particle surface area through ultrafine grinding, pre-treatment by heating or with acids) should be tested to increase the K release.

The agronomic efficiency of maize and wheat promoted by alternative liming material + 50% of P via Arad natural phosphate + 50% of P via triple superphosphate (treatment T4), alternative liming material + 50% of P via ANP + 100% of N via tung pressed cake (treatment T7), and alternative liming material + 100% of P via ANP + 100% of K through monzogranite + 100% of N via TPC + 100% of S via elemental sulfur (treatment T8) was comparable to NPK fertilization (treatment T9), highlighting the technical viability of low grade and less soluble agrominerals as nutrient alternative sources. On other hand, when considered the resulted profit, only T3 and T4 surpassed the use of conventional fertilizers.

Finally, the results of the present study highlight the strategy of using lower grade and less soluble agrominerals, considering the locally available resources as alternative nutrient sources. This new strategy should be accompanied by a shift of recommending fertilization sources and rates, from a single crop to a production system-driven solution. The amount of nutrients and inputs should therefore not focus only on the immediate effects but center on the recovery and maintenance of fertility in the medium to long run, with the advantage of encourage the recycling of wastes/co-products, being a more sustainability-orientated approach to agricultural production.

**Declarations**

**Acknowledgements**

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Declaration of Interest Statement

The authors declare no potential conflict of interest.

References


**Supplementary Materials**

The Supplementary Data and Materials are not available with this version.

**Figures**
Figure 1

Effect of fertilization through local sources of nutrients on soil pH, bases saturation and aluminum saturation of the arable soil (0.0-0.2 m) at 90, 360 and 900 d after application of treatments

Boxes with the same low case letter are not significantly different by the Tukey test (p < 0.05). ns: not significant. Vertical bars represent the standard deviation of each treatment mean n = 12 and days after
Figure 2

Extractable phosphorus and potassium (Mehlich-1), and available sulfur of the arable soil (0.0-0.2 m) at 90, 360 and 900 d after fertilization through local sources of nutrients.
For P and S, treatments with the same low case letters are not significantly different by the Tukey test ($p < 0.05$). Within each fertilization strategy (T1-T9), means with the same upper-case letters do not differ significantly by the Tukey test ($p < 0.05$). The vertical bars represent the standard deviation. For P and S: each treatment mean $n = 4$. For K: each treatment mean $n = 12$, for days after application $n = 36$. 

**Figure 3**
Available calcium, magnesium and manganese of the arable soil (0.0-0.2 m) at 90, 360 and 900 d after application of treatments

Boxes with the same low case letter are not significantly different by the Tukey test (p < 0.05). ns: not significant. Vertical bars represent the standard deviation of each treatment mean n = 12 and days after application n = 36.

Figure 4
Influence of fertilization through local sources of nutrients on available zinc, copper and boron of the topsoil (0.0-0.2 m) at 90, 360 and 900 d after application of treatments

Boxes with the same low case letter are not significantly different by the Tukey test (p < 0.05). ns: not significant. Vertical bars represent the standard deviation of each treatment mean n = 12 and days after application n = 36.