Rock Powder Enhances Soil Nutrition and Coffee Quality in Agroforestry Systems

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Abstract: The use of rock powders is an agricultural practice that facilitates the agroecological transition and autonomy of many farmers. These inputs should be used in conjunction with management systems that enhance the weathering of the minerals contained in the rocks. This study aimed to assess the impact of incorporating gneiss powder on soil quality and coffee cultivation within agroecological and organic frameworks, encompassing agroforestry systems (AFSs) as well as areas fully exposed to sunlight (FS). Comprehensive analyses, including chemical, microbiological, and physical assessments, were carried out on the soil. The study involved evaluating various parameters such as electrical conductivity, grain density, total titratable acidity, and pH of the exudates to gauge the coffee quality. Following a 24-month application of rock powder, noteworthy observations included increased soil moisture in agroforestry systems (AFSs), presumably attributable to enhanced nutrient availability (potassium, calcium, magnesium, copper, and zinc) derived from the gneiss powder. In addition, a higher level of CO₂ was derived from microbial respiration than from soil production. Similarly, coffee beans presented lower electrical conductivity, higher density, and fewer defects in AFSs than fully exposed sun systems (FS). The total titratable acidity values remain consistent with the limits indicated in the literature for quality coffees; the pH values, however, were lower. The results suggest that the use of gneiss powder enhances soil microorganism activity and accelerates the biological weathering of minerals for coffee plantations in AFSs.

Keywords: gneiss; agroecological management; coffee; enhanced weathering; microbial respiration

1. Introduction

Soil quality is assessed using physical, chemical, and biological indicators, which indicate changes in ecological functions that result from use and management [1,2]. In tropical agroecosystems, soil quality often depends on the vegetation [3] that provides food for edaphic organisms and soil cover, especially where plant litter is found. Plant biomass also helps improve aggregation, water retention, and nutrient cycling [4,5]. Other agricultural practices, such as monoculture, fire, and the application of pesticides and soluble fertilizers, can cause the degradation of the biological quality of soil [6]. Conversely, agricultural systems based on agroecology with greater biodiversity, such as agroforestry systems (AFSs), increase or preserve soil quality.

Various advantages are associated with the adoption of AFSs, including enhancements in nutrient cycling [7]. Despite these benefits, the common practice of utilizing mineral fertilization to facilitate system development and sustain crop productivity raises
sustainability concerns. The use of soluble fertilizers poses challenges as they derive from non-renewable sources, coupled with the additional expenses incurred in their production, transportation, and distribution [8]. In Brazil, around 84% of these soluble fertilizers are imported [9,10] and are prohibited for use in organic agriculture [11] due to the adverse effects they cause, such as salinization of the soil, soil structure breakdown, groundwater contamination, and emission of pollutant gases, among others [12,13].

As a result, finding alternative sources of mineral nutrients is important. Silicate rock powders are one option, especially after Law nº 12.890, 10 December 2013 and Normative Instruction (IN) nº 05, 10 March 2016 [14,15] were put in place, which outline the concept of remineralizer and its determinants and guarantees of use. These sources slowly release macro- and micronutrients and result in a minimal saline effect compared to conventional sources. They are less susceptible to nutrient loss through leaching and have a greater residual effect on the soil, reducing the need for fertilizers and time spent on management and labor [16,17]. What’s more, due to their wide spatial distribution, their energy costs are lower [18]. In addition to increased soil fertility, product quality, and productivity [19], rock powders are known for their carbon capture capabilities. Instead of emitting greenhouse gases, they capture and store atmospheric carbon in the soil [20].

The nutrients present in silicate rock powders typically exhibit slow-release characteristics due to their inherent low solubility, a process influenced by factors like composition, particle size, mineral alteration levels, and edaphoclimatic conditions [21–23]. However, various mechanisms exist to enhance nutrient accessibility for plants. Implementing management systems that incorporate organic matter and foster increased biological activity in the soil, such as AFSs, can facilitate these processes [17,24]. Numerous research findings already attest to the efficacy of rock powders in enhancing soil fertility and promoting the productivity of coffee plants cultivated in fully exposed environments [25–27]. These studies highlight a notable increase in nutrient availability through remineralization in AFSs, positively impacting tree growth, including coffee plants.

For organic coffee production, agroecological farmers have tried to add value to their products [28]. Cortez [29] believes sensory analysis to be an important indicator (albeit subjective and subject to criticism) since its parameters are defined by the International Coffee Organization (ICO). Regarding physical and chemical parameters, density and electrical conductivity serve as valuable indicators for evaluating coffee quality, especially concerning the structural integrity of grain cell walls [30]. This approach ensures a more objective and quantifiable determination of coffee quality [31]. The primary objective of this study was to evaluate the impact of gneiss powder application on measurable parameters related to soil fertility and coffee quality. The availability of nutrients derived from gneiss rock in soil cultivated with coffee in agroforestry systems was of particular importance when comparing them to fully exposed sun cultivation and its effect on the physicochemical quality of coffee beans.

2. Material and Methods

2.1. Outline of Experiment Locations

This research was carried out on the agricultural holdings of two families located in the municipality of Divino (−20.615981 latitude, −42.156477 longitude) situated in the state of Minas Gerais. The climate in this region is categorized as Cwa (Cwa: C = Mild temperate, w = Dry winter, a = Hot summer), as per the Köppen-Geiger classification system. The average annual temperature stands at 19.9 °C, accompanied by an average annual precipitation of 1282 mm, given the altitude of 950 m. The farming properties are in the Taquaraçu community and are referred to as GA (Gilvânia and Anacleto) and LA (Luis and Aparecida). The coffee plantations have been operating for about 12 years, but they have been using organic cultivation for the last five (Figure 1).
Two areas of coffee plants (red and yellow Catuai variety—*Coffea arabica*) were selected from each property on which to conduct our research: one using an agroforestry system (AFSs) and the other using full exposure to the sun (FS). The soils were identified and categorized as Red-Yellow Argisol (RYA) and Yellow Latosol (YL). It is noteworthy that the property with RYA soil exhibits a more extensive diversity of arboreal, herbaceous, and shrub plants in comparison to the property with YL soil, as outlined in Table 1.

### Table 1. Arboreal and herbaceous species identified at the beginning of the study in agroforestry systems on properties in this study.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Arboreal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow Latosol (YL)</td>
<td><strong>Herbaceous</strong></td>
</tr>
<tr>
<td></td>
<td><em>Lablab purpureus</em>, <em>musa</em>, <em>Carica papaya</em>, <em>Saccharum officinarum</em>, <em>Xanthosoma sagittifolium</em>, <em>Ricinus communis</em>, <em>Ilex paraguariensis</em>, <em>Maytenus ilicifolia</em>, <em>Cucurbita</em>.</td>
</tr>
</tbody>
</table>

Soil characterization was conducted on both farming properties before applying the gneiss powder. Composite samples were collected from the agroforestry system (AFSs) and the full exposure to sun (FS) areas in the analyzed properties (Table 2). These samples were classified as sandy and clay loam soils.
Table 2. Chemical characteristics of soils cultivated with coffee in agroforestry (AFSs) and full exposure to sun (FS) systems on family-run agroecological farming properties (RYA and YL) at a depth of 0–20 cm, in the municipality of Divino, Minas Gerais.

<table>
<thead>
<tr>
<th></th>
<th>pH (H₂O)</th>
<th>P (mg dm⁻³)</th>
<th>K</th>
<th>Ca²⁺</th>
<th>Mg²⁺</th>
<th>Al³⁺</th>
<th>H⁺Al</th>
<th>SB A</th>
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<tr>
<td></td>
<td>(H₂O)</td>
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<tr>
<td>AFS RYA</td>
<td>5.35</td>
<td>2.8</td>
<td>112.0</td>
<td>2.97</td>
<td>0.77</td>
<td>0.0</td>
<td>4.3</td>
<td>4.00</td>
<td>4.03</td>
<td>8.33</td>
<td>57</td>
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<tr>
<td>FS RYA</td>
<td>5.40</td>
<td>1.2</td>
<td>50.0</td>
<td>2.18</td>
<td>0.84</td>
<td>0.0</td>
<td>3.7</td>
<td>3.15</td>
<td>3.15</td>
<td>6.85</td>
<td>46</td>
</tr>
<tr>
<td>AFS YL</td>
<td>5.71</td>
<td>10.1</td>
<td>87.0</td>
<td>2.61</td>
<td>0.74</td>
<td>0.0</td>
<td>2.7</td>
<td>3.57</td>
<td>3.57</td>
<td>6.27</td>
<td>48</td>
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<tr>
<td>FS YL</td>
<td>5.84</td>
<td>1.2</td>
<td>116.0</td>
<td>2.38</td>
<td>0.96</td>
<td>0.0</td>
<td>3.3</td>
<td>3.64</td>
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<td>6.94</td>
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<tr>
<td>AFS RYA</td>
<td>2.33</td>
<td>28.0</td>
<td>0.28</td>
<td>1.54</td>
<td>56.5</td>
<td>39.5</td>
<td>2.14</td>
<td>0.02</td>
<td>1.21</td>
<td>0.36</td>
<td>2.42</td>
</tr>
<tr>
<td>FS RYA</td>
<td>5.58</td>
<td>21.5</td>
<td>0.32</td>
<td>1.14</td>
<td>169.8</td>
<td>61.0</td>
<td>2.60</td>
<td>0.24</td>
<td>1.69</td>
<td>0.39</td>
<td>0.71</td>
</tr>
<tr>
<td>AFS YL</td>
<td>1.55</td>
<td>36.8</td>
<td>0.31</td>
<td>0.85</td>
<td>85.4</td>
<td>27.3</td>
<td>3.12</td>
<td>0.02</td>
<td>0.87</td>
<td>0.01</td>
<td>1.06</td>
</tr>
<tr>
<td>FS YL</td>
<td>2.71</td>
<td>25.3</td>
<td>0.32</td>
<td>1.51</td>
<td>34.8</td>
<td>48.1</td>
<td>1.85</td>
<td>nd</td>
<td>0.96</td>
<td>0.26</td>
<td>4.74</td>
</tr>
</tbody>
</table>

A: Total of basic cations (Ca²⁺, Mg²⁺, and K); B: Effective cation exchange capacity; C: Potential cation exchange capacity at pH 7.0; D: Base saturation index; E: Soil organic matter; F: Remaining Phosphorus; 7: Undetected.

2.2. Characterization of Rock Powder

Gneisses are metamorphic rocks of varied composition, from medium to high grade, and result from pre-existing materials such as granites and/or argillaceous quartz sedimentary rocks. The material used for our research purposes was obtained from a mine in the municipality of São João do Manhuaçu (Minas Gerais), where it is sold as a construction material. According to Figueiredo [32], the gneiss is an enderbitic migmatite, a lithotype common to the Juiz de Fora complex, and is composed of orthopyroxene, plagioclase, clinopyroxene, hornblende, biotite, and quartz, in addition to zircon, apatite, epidote, and opaque minerals. The finely granulated material was previously air-dried and then filtered through a 0.074 mm sieve for subsequent X-ray diffraction analysis. Lithochemical characterization involved X-ray fluorescence for the macroelements. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was applied after a complete triacid opening for the remaining elements [33] (Table 3).

Table 3. Chemical characterization of gneiss powder.

<table>
<thead>
<tr>
<th>Macroelements (%)</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O</th>
<th>CaO</th>
<th>MgO</th>
<th>K₂O</th>
<th>P₂O₅</th>
<th>MnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.0</td>
<td>17.4</td>
<td>8.84</td>
<td>4.99</td>
<td>2.54</td>
<td>3.74</td>
<td>0.58</td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Microelements (mg kg⁻¹)</th>
<th>Li</th>
<th>Co</th>
<th>Cu</th>
<th>Zn</th>
<th>Ni</th>
<th>Cd</th>
<th>Cr</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0</td>
<td>13.0</td>
<td>15.0</td>
<td>85.0</td>
<td>&lt;3</td>
<td>&lt;3</td>
<td>1.0</td>
<td>9.0</td>
<td></td>
</tr>
</tbody>
</table>

Note: Parameters taken from IN 05 10 March 2016 [11].

2.3. Experimental Design

A nested statistical model (mixed nested factorial) of 2 × 4 was used for this study, with 4 repetitions. The two main predictive factors were two family-owned farming properties and four types of management (coffee plantations in AFSs or FS, with the symbols (+) or (−) to indicate addition or not, respectively, of rock powder), based on the following treatments: AFS RYA⁺, AFS RYA⁻, FS RYA⁺, FS RYA⁻ and AFS YL⁺, AFS YL⁻, FS YL⁺, FS YL⁻. Those plantations using rock powder received 2 kg plant⁻¹ of gneiss powder, applied in January 2019, for the coffee plants. This was equally distributed on both sides of the rows and was not introduced to the soil. No additional fertilization was utilized. Each plantation
had four homogeneous plots (7 × 9 m) containing 30 plants (3 rows, 10 plants in each). Only the six plants in the central row of each plot were sampled.

2.4. Analysis of Soil Quality

The soil analysis occurred two years after the application of the input. Twelve individual samples were collected from each plot (0–20 cm deep) using a Dutch auger. These samples were taken beside the coffee plant canopy, yielding a composite sample. After homogenization, the samples were divided into three parts: the first part was sieved (2 mm), air-dried, and then subjected to fertility analyses to assess F (phosphorus), K (potassium), Ca (calcium), Mg (magnesium), Mn (manganese), Fe (iron), Cu (copper), Zn (zinc), Ni (nickel), Cd (cadmium), Cr (chromium), and Pb (lead) available levels. These levels were determined after extraction in a KCl mil L\(^{-1}\) solution (for Ca\(^{2+}\) and Mg\(^{2+}\)), while the remaining nutrients were determined after extraction using the Mehlich-1 method [34]. The second portion was stored refrigerated in a hermetically sealed bag for microbiological analysis, and the third portion was weighed on a precision scale and dried for 48 h in an oven at 105 °C for moisture analysis.

Microbial respiration in the soil was determined following the methodology adapted from Mendonça et al. [35], utilizing the incubation method for 21 days. The total CO\(_2\) produced was calculated by summing the values obtained in each sampling. The CO\(_2\) calculation (mg C g\(^{-1}\) soil) employed the following formula: CO\(_2\) = (B - V) × M × (V\(_1\)/V\(_2\)), where B represents the volume (mL) utilized in the blank titration test, V signifies the volume (mL) of acid used in the titration of each sample, M denotes the molar concentration of the acid used in titration (set at 6), and V\(_1\)/V\(_2\) represents the ratio between the volume of NaOH used in CO\(_2\) capture and the volume used in titration (in this case, 1/6).

Microbial biomass carbon (C\(_{mic}\)) was calculated according to Ferreira et al. [36] using the irradiation-extraction method, where the C\(_{mic}\) was calculated from the difference in the C levels in the irradiated and non-irradiated samples, using the following formula: C\(_{mic}\) = (C\(_I\) - C\(_NI\))/K\(_c\) = mg kg\(^{-1}\) of C in the soil, C\(_{mic}\) = microbial biomass carbon, C\(_I\) = Carbon in an irradiated sample, C\(_NI\) = Carbon in a non-irradiated sample, K\(_c\) = 0.33—the correction factor referring to the fraction of C extracted by K\(_2\)SO\(_4\).

2.5. Coffee Quality Assessments

The coffee quality was assessed through physicochemical analyses of the beans, after harvesting and stripping them with a propylene cloth. Harvesting began with an estimated percentage of green coffee beans of less than 10%. They were suspended and dried in the sun until the beans reached an 11% moisture level and were subsequently peeled.

To determine the physical-chemical quality indicators, we conducted analyses of the electrical conductivity, bulk density, pH, and total titratable acidity. Electrical conductivity was evaluated using raw bean extract in a portable conductivity meter as per the methodology described in Borém et al. [37]. Apparent density was measured by calculating the mass/volume ratio using a 1 L beaker. The beans were weighed on a precision scale [38]. The pH was measured in a pH meter at room temperature, using a water extract of roasted grains, as per Instituto Adolfo Lutz [39]. To determine the total titratable acidity, the same extract used in the pH analysis was titrated with NaOH 0.1 mol L\(^{-1}\) using a pH meter, up to a pH level of 8.2. This was done because the color made it impossible to visualize the turning point using an indicator [39,40].

2.6. Data Analysis

The collected data underwent a thorough analysis of variance, adhering to the statistical model pre-established by the sampling plan (Nested). The two farming locations were associated with fixed effects, while the four types of coffee plantation management were linked to random effects. To ensure the reliability of the analysis, normality, and homoscedasticity were assessed for errors through the Jarque-Bera and Bartlett tests. The means between different management practices were subsequently compared utilizing the
SNK test, with an error probability (α) set at 5%. All statistical analyses were performed using the SPEED Stat 2.4 software [41].

3. Results
3.1. Chemical Alterations in the Soil

The pH values varied within the range of 6.1 to 6.94. Al$^{3+}$ levels were absent in all treatments, and the H+Al level was identified as low, displaying no significant differences between the various treatments. Key soil attributes such as soil organic matter (SOM), the sum of bases (SB), and the cation exchange capacity (CEC) exhibited variations based on the management practices employed (Table 4). SB can be classified as good or very good in all treatments [42], but AFS$^+$ (RYA and YL) showed the highest values. Potential CEC was rated as good in all treatments, but the AFS$^+$ systems (RYA and YL) had the highest ($p < 0.05$) CEC [42].

Table 4. Soil chemical characteristics after 24 months of application (+) or non-application (−) of gneiss powder to coffee plantations under agroforestry management (AFSs) or full exposure to the sun (FS) for the two agroecological family-owned farming properties (RYA and YL).

<table>
<thead>
<tr>
<th>Prop.</th>
<th>System</th>
<th>pH (H$_2$O)</th>
<th>SB (cmol$_c$ dm$^{-3}$)</th>
<th>H+Al</th>
<th>CEC Potencial</th>
<th>SOM (dag kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RYA</td>
<td>AFS$^+$</td>
<td>6.82$^a$</td>
<td>10.31$^a$</td>
<td>1.33$^a$</td>
<td>11.63$^a$</td>
<td>6.55$^a$</td>
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<tr>
<td></td>
<td>AFS$^-$</td>
<td>6.31$^a$</td>
<td>7.10$^b$</td>
<td>2.00$^a$</td>
<td>9.10$^{ab}$</td>
<td>3.75$^b$</td>
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<td></td>
<td>FS$^+$</td>
<td>6.10$^a$</td>
<td>5.73$^b$</td>
<td>2.28$^a$</td>
<td>8.01$^b$</td>
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<tr>
<td></td>
<td>FS$^-$</td>
<td>6.78$^a$</td>
<td>7.40$^b$</td>
<td>1.58$^a$</td>
<td>8.98$^{ab}$</td>
<td>3.85$^b$</td>
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<td>YL</td>
<td>AFS$^+$</td>
<td>6.94$^a$</td>
<td>12.11$^a$</td>
<td>1.05$^a$</td>
<td>3.16$^a$</td>
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<td></td>
<td>AFS$^-$</td>
<td>6.67$^{ab}$</td>
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<td>9.83$^b$</td>
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<td>FS$^+$</td>
<td>6.62$^{ab}$</td>
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<td>1.95$^a$</td>
<td>8.89$^b$</td>
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<tr>
<td></td>
<td>FS$^-$</td>
<td>6.12$^b$</td>
<td>5.54$^b$</td>
<td>2.43$^a$</td>
<td>7.97$^b$</td>
<td>5.22$^a$</td>
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</table>

Means followed by different letters differ statistically from each other by the SNK test ($p < 0.05$).

The addition of gneiss powder stimulated and altered macronutrient contents such as P (phosphorus) and K (potassium), especially in coffee plantation soils in AFSs. The P level increased by 110% (AFS$_{RYA}^+$) and 171% (AFS$_{YL}^+$) compared to AFSs with no rock powder (Figure 2A). The P levels in FS, with or without rock powder, increased by at least 199% (FS$_{RYA}^+$) and 30% (FS$_{YL}^+$). K levels increased by at least 40% (AFS$_{RYA}^+$) compared to the other treatments (Figure 2B). The Ca$^{2+}$ levels were 67.1% (AFS$_{RYA}^+$) and 89.3% (AFS$_{YL}^+$) higher (Figure 2C), and the Mg$^{2+}$ levels were 103.3% (AFS$_{RYA}^+$) and 59.4% (AFS$_{YL}^+$) higher (Figure 2D). The macronutrient levels in FS$^+$ and FS$^-$ did not differ.

In general, micronutrient availability was higher in AFSs$^+$ than in FS (Table 4). Cu levels were 74.4% (AFS$_{RYA}^+$) and 234.2% (AFS$_{YL}^+$), Zn levels were 34.8% (AFS$_{RYA}^+$) and 227.9% (AFS$_{YL}^+$), and Ni levels were 288.1% (AFS$_{RYA}^+$) and 147.6% (AFS$_{YL}^+$) (Table 5). The Mn levels were 74.4% (AFS$_{RYA}^+$), and Fe levels did not differ between both treatments. Potentially toxic elements (PTEs) such as Cd, Cr, and Pb were unchanged by applying gneiss powder. YL did present a difference between treatments ($p < 0.05$) (Table 5), but all contents were below the reference values for soil quality in Minas Gerais [43].

SNK test, with an error probability (α) set at 5%. All statistical analyses were performed using the SPEED Stat 2.4 software [41].
Table 5. Levels of micronutrients and heavy metals in soil after 24 months of application (+) or non-application (−) of gneiss powder in coffee plantations in agroforestry management (AFSs) or full exposure to sun (FS) for two agroecological family-owned farming properties (RYA and YL) located in Divino, Minas Gerais. Means followed by different letters differ statistically from each other by the SNK test (p < 0.05).

<table>
<thead>
<tr>
<th>Prop. System</th>
<th>Cu (mg kg⁻¹)</th>
<th>Mn (mg kg⁻¹)</th>
<th>Fe (mg kg⁻¹)</th>
<th>Zn (mg kg⁻¹)</th>
<th>Ni (mg kg⁻¹)</th>
<th>Cr (mg kg⁻¹)</th>
<th>Cd (mg kg⁻¹)</th>
<th>Pb (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RYA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFS⁺</td>
<td>2.19 a</td>
<td>71.23 a</td>
<td>25.3 a</td>
<td>23.78 a</td>
<td>1.26 a</td>
<td>0.05 a</td>
<td>0.16 a</td>
<td>0.4 a</td>
</tr>
<tr>
<td>AFS⁻</td>
<td>1.53 ab</td>
<td>72.75 a</td>
<td>20.95 a</td>
<td>12.78 a</td>
<td>0.40 b</td>
<td>0.02 a</td>
<td>0.23 a</td>
<td>0.02 a</td>
</tr>
<tr>
<td>FS⁺</td>
<td>1.25 b</td>
<td>64.05 a</td>
<td>17.35 a</td>
<td>9.55 a</td>
<td>0.04 b</td>
<td>0.00 a</td>
<td>0.19 a</td>
<td>0.22 a</td>
</tr>
<tr>
<td>FS⁻</td>
<td>0.89 b</td>
<td>43.25 a</td>
<td>23.35 a</td>
<td>4.44 b</td>
<td>0.03 b</td>
<td>0.00 a</td>
<td>0.18 a</td>
<td>0.6 a</td>
</tr>
<tr>
<td>YL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFS⁺</td>
<td>2.81 a</td>
<td>147.25 a</td>
<td>23.38 a</td>
<td>22.29 a</td>
<td>1.33 a</td>
<td>0.02 bc</td>
<td>0.00 a</td>
<td>0.52 a</td>
</tr>
<tr>
<td>AFS⁻</td>
<td>0.82 b</td>
<td>66.18 a</td>
<td>43.95 a</td>
<td>3.73 b</td>
<td>0.15 b</td>
<td>0.30 a</td>
<td>0.00 a</td>
<td>2.03 a</td>
</tr>
<tr>
<td>FS⁺</td>
<td>0.84 b</td>
<td>25.43 b</td>
<td>29.98 a</td>
<td>2.69 b</td>
<td>0.35 a</td>
<td>0.27 ab</td>
<td>0.02 a</td>
<td>1.44 a</td>
</tr>
<tr>
<td>FS⁻</td>
<td>1.20 b</td>
<td>68.35 b</td>
<td>34.88 a</td>
<td>2.56 b</td>
<td>0.50 b</td>
<td>0.03 c</td>
<td>0.02 a</td>
<td>1.84 a</td>
</tr>
</tbody>
</table>

3.2. Microbiological Changes in Soil

The release of CO₂ because of microbial respiration was higher in soils in AFSs than in FS, with or without the application of gneiss powder (Table 6). In RYA, Cmic was higher in soils in AFSs, while in YL there was no difference between treatments (Table 6).
Table 6. Release of CO$_2$ because of microbial respiration in soils under agroforestry management (AFSs) or full exposure to the sun (FS) after 24 months of application (+) or non-application (−) of gneiss powder in two agroecological family-owned farming properties (RYA and YL). Means followed by different letters differ statistically from each other by the SNK test ($p < 0.05$).

<table>
<thead>
<tr>
<th>Prop.</th>
<th>System</th>
<th>Microbial Respiration (mg kg$^{-1}$ of Soil)</th>
<th>Cmic (mg kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RYA</td>
<td>AFS$^+$</td>
<td>8.27 $^a$</td>
<td>8.48 $^{ab}$</td>
</tr>
<tr>
<td></td>
<td>AFS$^-$</td>
<td>8.11 $^a$</td>
<td>9.05 $^a$</td>
</tr>
<tr>
<td></td>
<td>FS$^+$</td>
<td>4.49 $^b$</td>
<td>6.55 $^b$</td>
</tr>
<tr>
<td></td>
<td>FS$^-$</td>
<td>4.77 $^b$</td>
<td>8.20 $^b$</td>
</tr>
<tr>
<td>YL</td>
<td>AFS$^+$</td>
<td>7.68 $^a$</td>
<td>8.93 $^a$</td>
</tr>
<tr>
<td></td>
<td>AFS$^-$</td>
<td>7.85 $^a$</td>
<td>9.11 $^a$</td>
</tr>
<tr>
<td></td>
<td>FS$^+$</td>
<td>5.18 $^b$</td>
<td>9.98 $^a$</td>
</tr>
<tr>
<td></td>
<td>FS$^-$</td>
<td>5.52 $^b$</td>
<td>9.27 $^a$</td>
</tr>
<tr>
<td>C.V (%)</td>
<td></td>
<td>10.01</td>
<td>41.39</td>
</tr>
</tbody>
</table>

3.3. Physical Changes to Soil

Soil moisture differed between treatments as it was higher in AFSs soils than FS soils, with or without rock powder. In YL, the moisture in AFS$^+$ was higher than in AFS$^-$. In RYA, the moisture in FS$^+$ was higher than in FS$^-$. This demonstrates the effect rock powder has on maintaining moisture in the system (Figure 3).

Figure 3. Average moisture (g g$^{-1}$) on a wet basis of soil samples after 24 months of application (+) or non-application (−) of gneiss powder in coffee plantations in agroforestry management (AFS) or full exposure to the sun (FS) for two agroecological family-owned farming properties (RYA and YL) located in Minas Gerais. Means followed by different letters differ statistically from each other by the SNK test ($p < 0.05$).

3.4. Assessment of Coffee Bean Attributes

Coffee beans grown on FS presented higher electrical conductivity (Figure 4A) than on AFSs (RYA: 50.3% and YL: 51.1%), demonstrating the effect that agroforestry systems have on coffee quality regardless of whether rock powder is used or not. Bean density...
differed between treatments (Figure 4B). Coffee beans grown under AFSs had a higher density (38.2% for RYA and 19.4% for YL) when compared to FS+ (Figure 4B).

![Figure 4](https://via.placeholder.com/150)

**Figure 4.** Electrical conductivity (A) of coffee exudates and bean density (B) after 24 months of application (+) or non-application (−) of gneiss powder in coffee plantations in agroforestry management (AFSs) or full exposure to the sun (FS) for two agroecological family-owned farming properties (RYA and YL) located in Divino, Minas Gerais. Means followed by different letters differ statistically from each other by the SNK test (*p* < 0.05).

The titratable acidity of coffee exudates was lower in AFS	extsubscript{RYA}− and higher in AFS	extsubscript{YL}− but did not differ between the other treatments (Figure 5A). The pH level differed only in FS	extsubscript{RYA}− (average of 2.3% lower than in other treatments (Figure 5B)).

![Figure 5](https://via.placeholder.com/150)

**Figure 5.** Total titratable acidity (ATT ml\(^{-1}\)) (A) and pH (B) of coffee exudates after 24 months of application (+) or non-application (−) of gneiss powder in coffee plantations in agroforestry management (AFSs) or full exposure to the sun (FS) for two agroecological family-owned farming properties (RYA and YL). Means followed by different letters differ statistically from each other by the SNK test (*p* < 0.05).

4. Discussion

4.1. Chemical Changes to the Soil

The improvement in soil quality observed in its chemical, physical, and biological attributes, mainly under cultivation in AFSs+, demonstrates the potential of gneiss powder, especially for processes that foster the life of the soil. In AFSs, the greater diversification of strata and the contribution of organic matter encourage greater activity of microorgan-
isms in the soil, which can have several benefits, such as greater nutrient cycling and increased solubility of minerals in rocks. In general, trees with deep roots prefer arbuscular mycorrhizal fungi (AMF) and greater cycling and availability of nutrients [44,45].

As shown in Table 4, the application of rock powders in AFSs+ raises the soil pH, which is in line with the results from Soares [27], Carvalho [46], and Gillman et al. [47]. Some of the released nutrients (Figure 2) also make up the soil exchange complex, displacing Al^{3+}, which precipitates and stops participating in the acid hydrolysis that releases H^+ and reduces the pH [48].

Farmers can control the spontaneous vegetation by pruning and trimming it. The AFSs have a continual input of organic matter [49] that comes from the pruning and trimming, the leaves that fall from the aerial part, and the decomposition of roots. Hydrolysis, one of the main chemical reactions that occur during the dissolution of silicate minerals, uses free H^+ from the soil and facilitates an increase in pH, an indicator of rock reactivity. Basic (Figure 2) and metallic cations are released during hydrolysis, as well as silicate anions (H_nSiO_4^-) [50].

The large amount of organic matter because of the decomposition of leaves and branches, combined with the action of soil microorganisms [51], may have enhanced the release (weathering) of nutrients (F (phosphorus), K (potassium), Ca (calcium), and Mg (magnesium)) in the gneiss powder in the AFS+ areas.

Due to the mineralogy of the rock, the greater availability of nutrients is likely derived from the andesine, amphiboles, and biotite minerals. These minerals are more susceptible to weathering, followed by orthoclase (feldspar-K), which is one of the main gneiss minerals [52,53]. The weathering of apatite, an accessory mineral of gneiss [54], may have contributed to the availability of P.

When P interacts with Si in the soil, it can increase the availability of P [55] due to its desorption in clay minerals [56]. Together with soil microbiota [57], this is one of the main mechanisms of P availability in weathered soils [58].

As a result, P levels in AFSs may be higher than in full exposure to sun areas [45,59]. Furthermore, according to Beenhouwer et al. [44], coffee plantations in AFSs have a greater number of mycorrhizal fungi roots and spores compared to coffee plantations in full exposure to the sun, which itself favors P cycling, yet does not favor microbial activity in less complex and deep root systems.

The higher K levels in AFS (Figure 2B) are favorable for building coffee plantations as they are especially demanding in terms of K. The loss of K^+ from leaching is reduced in these AFS systems as they have better structuring and higher levels of organic matter in the soil [60]. In our research, we were able to verify that the biological conditions of the AFSs (Table 6) facilitate the availability of K derived from minerals (especially micas) in the gneiss.

The greater biological activity of the AFSs may also have contributed to the greater release of Cu, Zn, and Ni levels (Table 5) in some minerals such as tourmaline, which is rich in Zn, apatite, and P, but can lead to increased levels of Zn. The dissolution of hydroxyapatites can lead to increased levels of Zn, which can replace Ca^{2+} in the phosphate structure [61,62].

According to Carvalho [46], the greater diversity of plants in complex systems such as the AFSs (Table 1), or together with spontaneous plants, beans, and green manure, tends to add to the availability of Zn from the minerals that constitute gneiss (Table 5). The Cu levels in RYA and YL, before and after the experiment, were higher than expected due to a pH above 6.0 and adequate levels of organic matter in the soil. However, the Cu levels (including Zn, Ni, Cd, Cr, and Pb) are below the limits established by the soil quality reference values for Minas Gerais [43].

The pH above 6 and the average values of organic matter contributed to the low levels of Cd in the soils (Table 5). The factors that are most important for controlling the mobility of Cd ions in the soil are pH and oxidation potential (in acidic pH conditions, Cd has high
mobility). Fe, Al, and Mn oxides, clay minerals, and organic matter are the main adsorbents of Cd in soil [63].

According to Linhares et al. [64], Pb has a similar dynamic to Cd in immobilization and availability in the soil, where the main ligands of Cd are also ligands of Pb. In tropical soils, Fe and Al oxides are usually retained through chemisorption [64], which is highly specific and high-energy adsorption of Pb, resulting in the formation of inner-sphere complexes [65]. These connections make Pb less mobile in soils because they are less reversible than ion exchange connections [66].

Lastly, gneiss powders, despite their demonstrated potential, are not considered remineralizers by IN 5/2016 due to their free silica content (in the form of quartz) being greater than 25%. However, the results obtained in our research indicate that its use should be encouraged. Any material that does not qualify as a remineralizer but presents positive agronomic results can be classified as a new product, according to the norms set forth by the Brazilian Ministry of Agriculture. Using these materials can contribute to the autonomy of family-owned farming and the general sustainability of agroecosystems.

4.1.1. Microbiological Changes in the Soil

The greater diversity of plants (Table 1) in the AFSs was a possible factor in the greater microbiological activity of the soils (Table 5) since microorganisms are responsible for nutrient cycling in addition to contributing to plant nutrition. Where there is a greater diversity of plants, there is a greater production of root exudates, leaf residues, etc., for organisms [51,67].

According to Carvalho [46], the bioavailability of nutrients derived from rocks affects the activity of arbuscular mycorrhizal fungi (AMF) and, as a result, plant growth. This is particularly true in AFSs due to the greater amount of organic matter, which favors the biological activity of the soil [68,69]. The release of organic acids and CO₂ during microbial respiration increases the degradation of silicates, which leads to the release of nutrients [70]. Soil microorganisms also play a vital role in phosphorus mineralization and immobilization [71]. P availability was greater in the AFSs, especially when gneiss powder was added. This reaffirms the action of microorganisms in bioweathering with these inputs [72].

The FS areas in monoculture (less diversity of plants) showed less microorganism activity (Table 5), even though they currently have good yields and adequate levels of organic matter [73].

4.1.2. Physical Changes to the Soil

Rock powders can improve plant development in the short term and contribute to improving the physical quality of the soil, such as through better aggregation and greater soil porosity. Consequently, they can improve water infiltration into the soil [74], as occurred in AFS+RYA. Theodoro et al. [17] also observed greater water retention capacity in soils cultivated in agroforestry systems that were fertilized with remineralizers.

In addition, the conditions of permanent soil cover in AFSs and the microclimate were both factors in maintaining the humidity in these areas (Figure 3). Compare this to FS areas, which either have lower runoff or loss due to evaporation, as observed by Franco et al. [75]. The extensive coverage of the tree canopy diminishes direct solar radiation and minimizes the emission of indirect radiation from the air that reaches the ground [76]. It also increases water infiltration, reduces water stress in the AFSs [77,78], and helps maintain the water supply for soil organisms, including during the dry period [75].

4.2. Electrical Conductivity, pH, Total Titratable Acidity, and Coffee Quality

Shaded coffee plantations in AFSs not only provide greater sustainability in cultivation but are also capable of generating a higher-quality beverage when compared to areas of conventional cultivation in full exposure to the sun [79,80]. Our research confirmed this
capacity through the electrical conductivity of coffee exudates grown in AFSs and through coffee bean density.

According to Romero et al. [81], coffees grown in AFSs produce a lower percentage of bean defects, which results in lower electrical conductivity values and higher beverage quality. Beans can be damaged by organisms such as the coffee borer beetle, one of the main causes of defects in coffee beans, which leads to further loss of quality [82].

Electrical conductivity also affects coffee density [56]. Our results show that lower electrical conductivity produces denser coffee beans, especially when fertilized with gneiss powder, like in AFS+ (RYA). This finding corresponds with results from DaMatta [82], (Figure 4). Denser fruits produce better quality beverages as they have a lower percentage of defects, and the beans contain greater physical integrity [56], possibly due to better plant nutrition from the minerals in gneiss. The presence of K in the soil is essential for producing a higher-quality coffee, especially when N (nitrogen) is present for the formation and physical integrity of the beans, chemical composition, and final quality of the beverage [83].

The levels of titratable acidity (Figure 5A) were within the acidity limit values (from 10.95 to 40.04 mL NaOH 100 g−1) discovered by authors of Arabica coffees in conventional cultivation systems [83,84], however, no titratable acidity data were found for quality coffees grown in AFSs. In general, low levels of total titratable acidity indicate quality loss due to the fermentation process that occurs during the drying and harvesting of beans before they have matured [37,84,85]. Even so, there are few studies that relate the management system to the titratable acidity levels of coffee [37,86].

The lower pH of the coffee exudate obtained in FSR+ (varying between 3.9 and 4.5) indicates that the management of AFS and the addition of gneiss powder led to increased pH levels in the exudates (Figure 5B), even though they remained below 5. According to Sivetz and Desrosier [87], for coffee beans to produce quality beverages, their pH values must be between 5.31 and 5.61. Other variables could affect the pH values here, such as the efficiency and roasting point of the beans [35]. However, some researchers suggest that total acidity, not pH, is the factor that best determines coffee acidity [88].

5. Conclusions

The use of rock powder tends to contribute to more sustainable agriculture, and this material is widely available in Brazil. For it to be more efficient, it should be used with ecological management that enhances the activity of soil microorganisms and accelerates the bioweathering of minerals.

The application of gneiss powder improved the quality of soil cultivated with coffee, mainly in AFSs, and favored greater biodiversity and higher microbial activity, which made it possible to increase the availability of macro- and micronutrients for plants. The increase in soil quality indicators was reflected in coffee plants, which produced beans with better attributes, especially those produced in AFSs, verified by electrical conductivity, density, and titratable acidity.

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