International Journal of Sciences

Research Article Volume 11 – July 2022 (07)

# Aluminum Toxicity in the No-Tillage System: A Case Study

Felipe Franco de Oliveira[1], Camila da Silva Dourado[2]

[1]Graduando em Engenharia Agronômica, Centro Universitário Adventista de São Paulo, Campus Engenheiro Coelho. Estr. Mun. Pastor Walter Boger, S/N - Lagoa Bonita, Eng. Coelho - SP, CEP: 13448-900

[2]Professora no Centro Universitário Adventista de São Paulo, Campus Engenheiro Coelho. Estr. Mun. Pastor Walter Boger, S/N - Lagoa Bonita, Eng. Coelho - SP, CEP: 13448-900

**Abstract:** Acid soils cover about 40 to 50% of the world's agricultural area and are one of the main limiting factors to plant production. However, the natural process of soil acidification can be intensified by agricultural practices, mainly related to fertilization. In Brazil, soils are mostly naturally acidic and about 65% of the territory is covered by this type of soil, and as a consequence, there is greater availability of aluminum (Al). The toxicity caused by aluminum (Al) is one of the factors that has most limited crop productivity in acid soils of tropical and subtropical regions. The primary and most evident symptom of Al toxicity in plants is inhibition in root elongation and decreased nutrient absorption, which can be minimized with the No-Tillage System (NTS). In the NTS there are changes in the chemical, physical and biological characteristics of the soil, which can act in the reduction of Al toxicity in the composition of the soil. Therefore, this study aimed to perform a literature review about the toxicity of Al in a no-tillage system, seeking to present the damage to the growth and development of plants caused by Al toxicity, together with the mechanisms that help reduce the toxicity of this metal through the NTS.

**Keywords:** Agricultural Crops, Planting, Productivity, Acidic Soils

## Introduction

Acid soils cover about 40 to 50% of the world's agricultural area and are one of the main limiting factors to plant production. However, the natural process of soil acidification can be intensified by agricultural practices, mainly related to fertilization. In Brazil, about 65% of the territory is covered by this type of soil and the availability of aluminum (Al) in acidic soils is higher (RAHMAN et al., 2018; HE et al., 2019).

Al toxicity is one of the main limiting factors for food and biomass production. Studies show that inhibition of root growth is the first visible symptom of this toxicity in plants, which results in damage to the root system, hindering the absorption of nutrients and water, which can lead to mineral deficiency and water stress. The reduction in shoot growth occurs at a later time and appears to be a consequence of the damage that occurs to the roots (ECHART et al., 2001).

In the plant, the root apex is the primary site of induction of growth inhibition caused by Al, because this region accumulates the metal in greater quantity, suffering greater physical damage than mature tissues. Some authors consider that inhibition of root growth by Al is a consequence of inhibition of mitosis in apical meristem cells, while other authors believe that metal can be toxic before even penetrating the nucleus of root cells, because Al can bind to various components of the cell wall.

Thus, as reported by Chauhan et al. (2021), Al can alter the growth rate of cell expansion, influencing apparent hydraulic conduction, cell wall extensibility, water potential difference between cells and their surroundings, and turgid pressure. It can also affect membrane fluidity by altering the chemical environment of lipids, forming bonds between the polar regions of phospholipids, resulting in changes related to the function of membrane-bound enzymes and the ion transport system. In addition, it has antagonism with several minerals, such as phosphorus (P), calcium (Ca), magnesium (Mg), and molybdenum (Mo), and can inhibit several essential metabolic processes regulated by these elements. As a result, it is possible to observe damage in plant growth and development, with direct implications for agricultural production.

Several agricultural regions of Brazil face problems in production due to water erosions from the transport and leaching of sediments, due to inadequate soil management. The No-Tillage System (NTS) through crop rotation promotes the stabilization of aggregates in the soil profile due to the action of organic matter produced by the vegetable massif from the previous crop (CASTRO FILHO et al., 1998).

In addition, in the NT system, there are changes in the chemical, physical and biological characteristics of the soil, which can act in reducing al toxicity in the soil solution, through the increase of the ionic force of the solution, as well as the greater complexation of Al with organic ligands. However, to mitigate the negative effects of soil acidification on agricultural productivity, it is necessary to correct acidity through the practice of plowing, and in the NT system,


Published at: http://www.ijsciences.com/pub/issue/2022-07/
DOI: 10.18483/ijSci.2588; Online ISSN: 2305-3925; Print ISSN: 2410-4477

Felipe Franco de Oliveira (Correspondence)
+

limestone is applied on the surface and without incorporation (SALTON et al., 1998; PAVINATO & ROSOLEM, 2008; FERNANDES et al., 2019).

Therefore, the main goal of this study case was to present the damage to the growth and development of plants caused by Al toxicity, together with the mechanisms that help reduce the toxicity of this metal through the PD system.

**2. Toxicity of aluminum in plants grown in acidic soils**

Of the total land considered potentially arable in the world, approximately 40-50% consists of acid soils. Acid soils, which have pH $\leq$ 5.5, are globally distributed and comprise about 30% of the total area of the earth's surface (RAHMAN et al., 2018; HE et al., 2019), as shown in Figure 1. Tropical soils are generally acidic due to high precipitation, which leached considerable amounts of exchangeable soil bases, and also due to the absence of primary and secondary minerals, responsible for the replacement of these bases (CAMARGOS, 2005). In Brazil, most agricultural soils have medium to high acidity (QUAGGIO, 2000) exhibiting al and manganese (Mn) contents at toxic levels (SOUSA et al., 2007), in addition to ca, mg, p, and potassium (K) (VELOSO et al., 1992) deficiency, resulting in low fertility and low cation-exchange capacity (CTC) (MALAVOLTA, 1980).

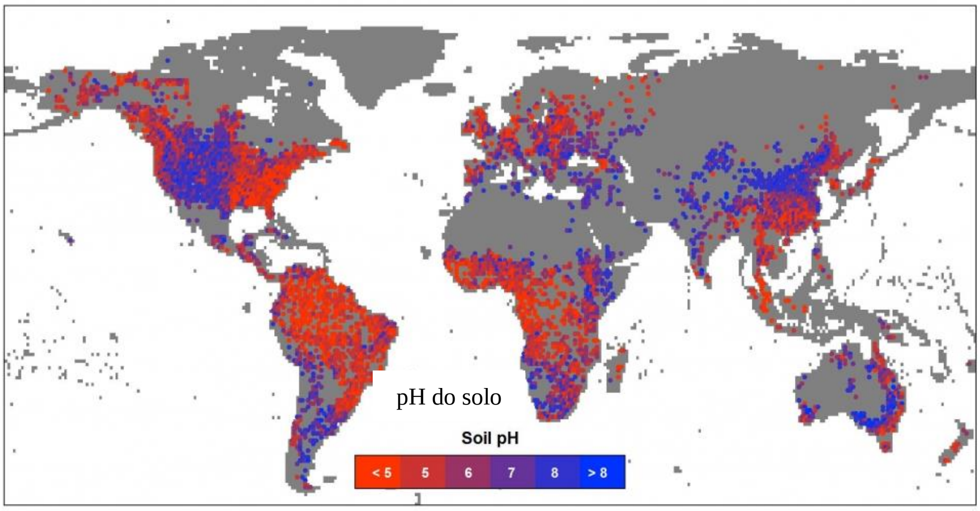


**Figura 1.** Distribution of acidic (red) soils in Brazil and worldwide. Adapted from Cohen et al. (2016).

If, on the one hand, soil acidification is a natural process that occurs mainly in tropical and subtropical regions, on the other hand, several natural and/or anthropogenic inputs are responsible for accelerating this acidification. Among the most important causes of soil acidification on agricultural land is the removal of exchangeable cations from the colloidal surface through rainwater, the entry of acidifying gases or particles such as sulfur dioxide ($SO_2$) and nitrate ($NO_3$), the application of elemental sulfur (S), the use of ammonium-based fertilizer ($NH^{4+}$), the mineralization of organic matter and the imbalance between anions and cations absorbed by the root system and continuous planting of legumes, which further accelerate the acidification process (NATALE et al., 2012; RAHMAN et al., 2018; HE et al., 2019). Thus, in a simplified way, soil acidification consists of the removal of basic cations, such as Ca, Mg, K, and sodium (Na) from the soil system, replacing them with acid iced cations (Al and H) (CAMARGOS, 2005).

As demonstrated in Figure 2, high acidity has an impact on nutrient availability in combination with an increase in Al concentrations in the soil. The ideal pH range for nutrient availability, as shown in this diagram, is between 5.8 and 6.8, and when the pH is less than 5.8, the concentration of Al increases. All other nutrients crucial to plants, except for iron (Fe), copper (Cu), Mn, and zinc (Zn), have their availability reduced at low pHs.

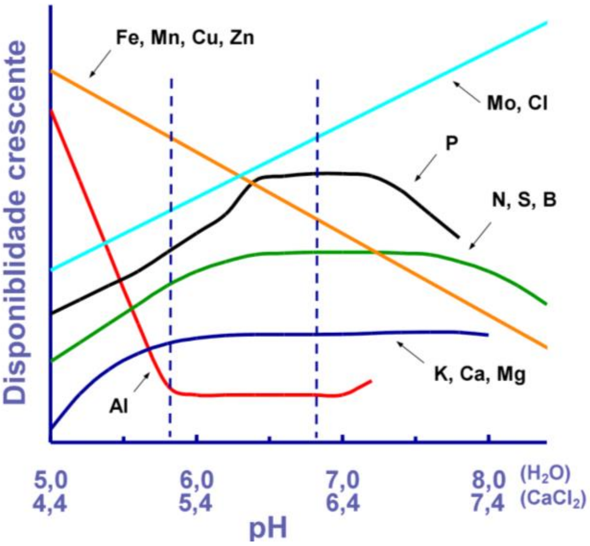


**Figura 2.** Availability of nutrients in different pH ranges. Adapted from Malavolta (1980).

Al is the most abundant metal on Earth and the third most abundant element in the earth's crust, comprising 7–8% of its mass, after oxygen ($O_2$) and silicon (Si). However, the specific biological function of Al is not yet known. In soil, Al is found mainly incorporated in the form of minerals such as aluminum oxides or aluminosilicates. However, the solubilization and speciation of Al depend on the chemical environment and pH of the soil solution, as shown in Figure 3. In acid soil with low pH, Al is solubilized in $[Al(H_2O)_6]^{3+}$, which is usually referred to as $Al^{3+}$. Although Al is observed in other ways, such as $Al(OH)^{2+}$, $Al(OH)^{2+}$, $Al(OH)^{3-}$, and $Al(OH)^{4-}$, $Al^{3+}$ is considered the most toxic form and has a great impact on plant growth and development (DELHAIZE & RYAN, 1995; SPARKS, 2003; HALISKI, 2018).

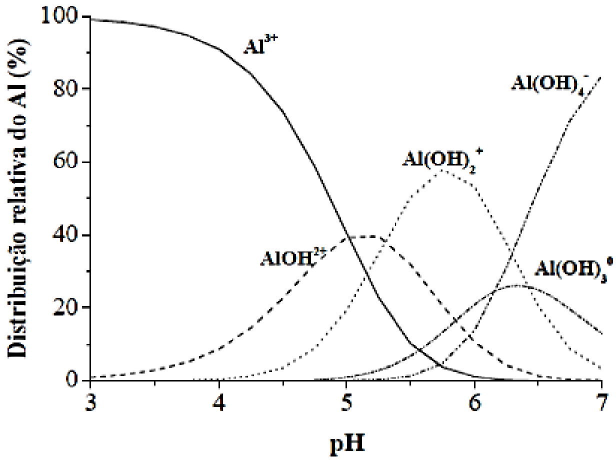


**Figura 3.** Relative distribution of Al species in soil solution. Adapted from Bertsch & Parker (1995).

One of the main consequences and the most obvious symptom of Al toxicity is inhibition of root growth in plants. Excess Al inhibits cell division, stretching, and hair formation in the roots and can also increase the development of swollen apexes in the roots. At the same time, toxic Al inhibits the absorption of water and nutrients by plants resulting in water stress and nutritional deficiency. In addition, a variety of effects, including the formation of barrel-shaped cells at the apex of the root are observed, together with changes in the enzymatic activities of metabolic pathways, in the synthesis of phytohormones, the increase of oxidative stress, and in variations in the assimilation rates of carbon dioxide ($CO_2$) (RAHMAN et al., 2018; HE et al., 2019; ZHOU et al., 2020; CHAUHAN et al., 2021).

As a consequence, these changes are accompanied by a decrease in chlorophyll content, emergence of abnormal chloroplast structures, and a decrease in photosynthetic rates, which lead to plant dwarfism, yellowing, and leaf necrosis (RAHMAN et al., 2018; ZHOU et al., 2020; CHAUHAN et al., 2021). These effects will identify plant growth and reduce crop yields. Figure 4 shows the factors that affect soil acidification (a), the action of Al in soil (b), and impacts on roots (c) and shoots (d).

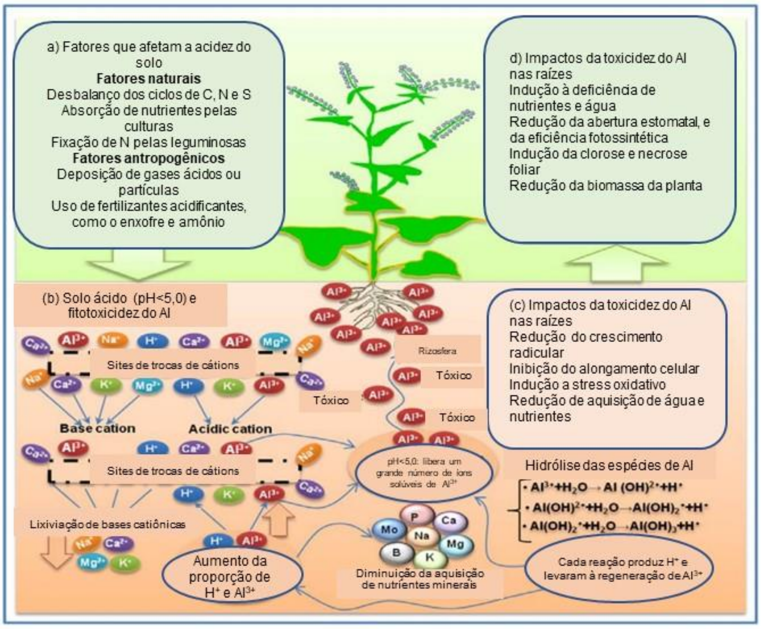


**Figura 4.** Overview of factors affecting soil acidification, subsequent Al toxicity, and plant impacts. (a) Natural and anthropogenic sources for the occurrence of soil acidification, (b) Impact of cation saturation ratio on soil that led to increased $Al^{3+}$ exchangeable and reduction of mineral nutrient acquisition, (c) Consequence of Al toxicity in roots, and (d) impact of Al toxicity on shoots. Adapted from Rahman et al. (2018).

On the other hand, the plants present several defense mechanisms to the presence of Al, as shown in Figure 5. Among the strategies used by plants to circumvent the toxic effects of Al is the synthesis of organic acids produced by the roots that complex Al in the rhizosphere. In other cases, there is an increase in pH in the root zone through the release of anions, insolubilizing Al, and impairing its absorption. In addition, the enzymatic and non-enzymatic antioxidant system takes action to protect cells from damage caused by excess reactive oxygen species (OUOs) produced in response to al entry through the cell membrane, together with metal compartmentalization (CHANDRA & KESHAVKANT, 2021), among other mechanisms involved.

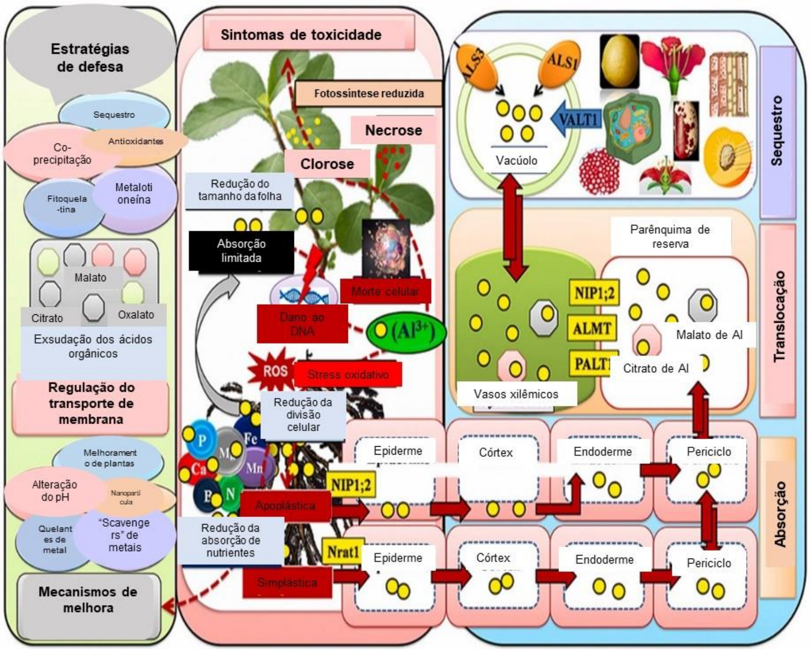


**Figura 5.** Mechanisms to protect al phytotoxicity and genotoxicity and plant defense strategies. Adapted from Chandra and Keshavkant (2021).

### 3. Relationship between PD system, soil acidity and aluminum toxicity

The NT system contributes to minimizing soil loss in the crop, ensuring the stability of its aggregates through minimal soil revolving and soil overlap with a plant layer (SALOMÃO et al., 2020). Furthermore, in this system, the accumulation of organic matter resulting from the plant material of previous crops together with the interactions between soluble organic compounds and soil minerals (SALES et al., 2016, SANTOS et al., 2017) generate conditions for the complexation of Al, leaving it in a less toxic form to plants (GARCÍA-RODEJA et al., 2004, ZAMBROSI et al., 2008).

However, to reduce the negative effects of soil acidification, it is necessary to practice the soil liming, and the acidity correctives most used in agriculture are ground limestone rocks, consisting of minerals such as calcite and dolomite, and which contain, in their composition, calcium carbonates ($CaCO_3$) and/or magnesium ($MgCO_3$), in addition to oxides, hydroxides, and silicates, which are also able to neutralize the acidity of the medium (HALISKI, 2018).

According to Embrapa, the impact of soil liming will be positive when the pH of the soil hits between 5.8 and 6. This is because high pH (basic) can reduce agricultural output by causing micronutrient deficiencies like zinc, manganese, and boron (B). It is critical to emphasize the importance of a soil analysis to determine the need for soil liming as well as soil nutritional parameters. The application of the NT system can be done by launching it on the soil surface without incorporating it (Figure 6). It's also worth noting that cover-applied limestone reacts more slowly (VERONESE et al., 2012), although it's still deemed effective for grain production (JORIS et al., 2016).

**Figura 6.** Application of limestone to toss, without incorporation. Adapted from blogaegro.com.br

Concomitantly with the action of the soil liming, the vegetation cover from the previous crop allows the occurrence of H and Al sorption on the surface of the plant material, complexation of Al by organic compounds, exchange of ligands between the oh-functional groups of Fe and Al oxyhydroxides and organic anions, in addition to the increase in the biological oxidation potential of organic anions (HALISKI, 2018), according to Figure 7.

In addition, the accumulation of organic matter allows its ligand agents to reduce the toxicity of Al due to the favoring of complexation due to the presence of cations and soluble organic carbon, in addition to acids such as fulvic, lactic, acetic, citric, malic and oxalic, which can be part of this metallic complex (OLIVEIRA et al., 2018).

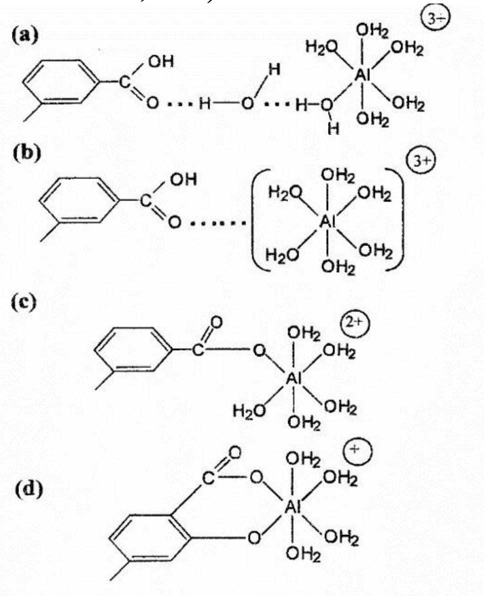


**Figura 7.** Forms of complexation of Al with soil organic matter: (a) hydrogen bridges; (b) electrostatic attraction; (c) exchange of binders with only one donor group; (d) and chelation. Adapted from Vance et al. (1995).

### 4. Case study

#### 4.1 Study of soil acidity at different levels of liming in no-tillage system

Al toxicity in soils can be read by surface liming. However, the calculation has a slow dynamic, especially in-depth concerning increased dissolution. Based on this fact, Ricardi et al. (2019) evaluated the residual effects of three levels of liming (dolomitic limestone) in an oxisol bruno: C1 0 (control); C2 5.67 t ha-1 equivalent to the need for liming (NC) to reach V=70% in the layer of 0.0-0.2 m depth; and C3 10.21 t $ha^{-1}$, equivalent to NC to reach V=100% in the 0.0-0.2 m layer. Then, soil samples stratified up to 0.80 m in geometry were analyzed for the attributes of soil characterization under the NT system.

The results obtained by Ricardi et al. (2019) show that in all layers the pH increased when comparing treatments with liming, as shown in Table 1. Up to the

0.60 m layer, the pH was higher according to the limestone dose. For potential acidity (H+Al), H+Al levels were higher in C1 compared to C2 and C3. Thus, the authors consider the effect of liming to be statistically significant in the correction of soil acidity up to 80 cm depth under consolidated PD. The alkalizing effect remains after 48 months of lime application and proportionally to the applied dose. However, according to Ricardi et al. (2019), this effect is of small magnitude and practical significance for plants below 0.20m.

**Tabela 1.** Chemical attributes of soil acidity at different depths.

| Prof. (cm) | pH ($CaCl_2$) | | | | H + Al ($cmol_c\ dm^{-3}$) | | | |
|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | CV% | C1 | C2 | C3 | CV% |
| 0-5 | 4,29 a | 4,46 b | 4,59 b | 4,11 | 10,14 b | 7,09 a | 6,10 a | 19,42 |
| 5-10 | 4,27 a | 4,51 b | 4,64 c | 3,30 | 10,58 c | 7,90 b | 6,74 a | 12,97 |
| 10-20 | 4,32 a | 4,54 b | 4,64 b | 3,11 | 9,42 b | 8,47 a | 8,11 a | 12,07 |
| 20-40 | 4,36 a | 4,54 b | 4,66 c | 2,66 | 8,81 b | 8,49 ab | 8,04 a | 9,95 |
| 40-60 | 4,40 a | 4,56 b | 4,65 c | 2,22 | 8,80 b | 8,15 a | 7,84 a | 5,30 |
| 60-80 | 4,45 a | 4,59 b | 4,64 b | 3,26 | 8,11 b | 7,73 a | 7,52 a | 3,69 |

Means followed by distinct letters in the line differ from each other by Tukey's test (1953), at the level of 5%. Adapted from Ricardi et al. (2019).

It is important to point out that the no-tillage system avoids the practice of turning the soil to incorporate limestone, as is done in conventional agriculture. Despite this, even if it is slow, it is possible to observe the dynamics of limestone in terms of soil depth, increasing pH and, consequently, a decrease in the concentration of $Al^{3+}$.

**4.2 Comparison between the response of bean cultivars to Al toxicity and yield in response to surface liming in the NT System.**

The common bean (*Phaseolus vulgaris* L.) is one of the most significant legumes for direct human consumption, particularly in developing countries like Central and South America and Southwest Africa. In Brazil, the common bean is grown all year in a wide range of environments, and roughly one-third of the bean-producing areas are in areas with sandy soil, low fertility, and high acidity and Al concentration, all of which have a detrimental impact on plant development and productivity.

In a study carried out by Santos Netto et al. (2020), several bean genotypes were evaluated at different Al concentrations. According to these authors, from the length, volume, and dry mass of the roots, it was possible to determine that the bean cultivars IPQ Quero-Quero and BRS Esplendor (Table 2), KID 44, and WLine 5 (Table 3), can be cultivated under Al toxicity conditions, or used in breeding programs for the development of tolerant cultivars (SANTOS NETTO et al., 2020).

**Tabela 2.** Mesoamerican bean cultivars grown in nutrient solution with and without Al.

| Genótipos | Comprimento da raiz (cm) | | | Volume radicular ($cm^3$) | | | Peso da massa seca radicular (g) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 ppm | 4 ppm | RV (%) | 0 ppm | 4 ppm | RV (%) | 0 ppm | 4 ppm | RV (%) |
| Grupo Feijão Carioca | | | | | | | | | |
| BRS Estilo | 50,4 ab | 31,2 bb | 38 | 4,5 ab | 3,4 bd | 26 | 0,22 ac | 0,18 ac | 16 |
| IAC Alvorada | 54,6 aa | 30,3 bb | 44 | 5,8 aa | 4,9 bb | 15 | 0,28 ab | 0,26 aa | 5 |
| IPR Bem-Te-Vi | 45,1 ab | 33,4 ba | 26 | 5,4 aa | 4,7 ab | 13 | 0,32 aa | 0,27 aa | 15 |
| IPR Campos Gerais | 48,5 ab | 29,4 bb | 39 | 5,4 aa | 4,9 ab | 10 | 0,27 ab | 0,27 aa | 0 |
| IPR Quero-Quero | 60,4 aa | 39,8 ba | 34 | 6,4 aa | 6,0 aa | 6 | 0,30 aa | 0,31 aa | 0 |
| IPR Sabiá | 59,1 aa | 27,8 bb | 53 | 5,9 aa | 5,9 aa | 26 | 0,36 aa | 0,31 aa | 14 |
| IPR Tangará | 51,1 ab | 34,6 ba | 32 | 4,4 ab | 4,4 ab | 7 | 0,22 ac | 0,24 ab | 0 |
| CV(%) | | 16,49 | | | 14,14 | | | 18,56 | |
| Grupo Feijão Preto | | | | | | | | | |
| BRS Campeiro | 52,1 aa | 37,3 ba | 29 | 6,4 aa | 5,7 ab | 11 | 0,42 aa | 0,41 ab | 3 |
| BRS Esplendor | 52,4 aa | 38,1 ba | 27 | 5,6 ab | 6,2 aa | 0 | 0,44 aa | 0,46 aa | 0 |
| BRS Esteio | 49,9 aa | 38,5 ba | 23 | 5,2 ab | 5,9 ab | 0 | 0,34 ab | 0,44 ba | 0 |
| FT 110 | 49,6 aa | 30,4 bb | 39 | 6,4 aa | 6,2 aa | 3 | 0,46 aa | 0,52 ba | 0 |
| IAC Una | 55,7 aa | 36,0 ba | 35 | 5,7 ab | 6,7 ba | 0 | 0,43 aa | 0,46 aa | 0 |
| IPR Tuiuiu | 44,0 aa | 38,9 aa | 12 | 6,0 aa | 6,2 aa | 0 | 0,45 aa | 0,45 aa | 0 |
| IPR Uirapuru | 51,1 aa | 39,4 ba | 23 | 5,7 ab | 5,2 ab | 9 | 0,40 ab | 0,38 ab | 4 |
| CV(%) | | 13,81 | | | 12,52 | | | 13,30 | |

RV: rate of reduction of the variable (%) measured in plants cultivated in the presence of Al; means followed by the same letter did not differ from each other by the Scott-Knott test ($p \leq 0.05$).
Adapted from Santos Netto et al. (2020).

**Tabela 3.** Andean bean cultivars grown in nutrient solution with and without Al.

| Genótipos | Comprimento da raiz (cm) | | | Volume radicular (cm³) | | | Peso da massa seca radicular (g) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 ppm | 4 ppm | RV (%) | 0 ppm | 4 ppm | RV (%) | 0 ppm | 4 ppm | RV (%) |
| | | | | Grupo Feijão Vermelho | | | | | |
| BRS Embaixador | 34,7 aa | 27,6 ba | 38 | 4,7 ab | 4,0 ab | 15 | 0,28 aa | 0,25 aa | 11 |
| DRK15 | 26,8 ab | 28,1 ba | 25 | 5,1 aa | 3,8 bb | 26 | 0,25 aa | 0,23 aa | 9 |
| DRK18 | 27,1 ab | 28,4 ba | 25 | 5,7 aa | 5,0 aa | 12 | 0,26 aa | 0,25 aa | 4 |
| KID44 | 36,0 aa | 28,7 ba | 40 | 5,1 aa | 4,7 aa | 8 | 0,23 aa | 0,23 aa | 2 |
| RLine 1 | 28,8 ab | 22,5 ba | 22 | 4,0 ab | 4,6 aa | 0 | 0,24 aa | 0,20 aa | 13 |
| RLine 2 | 27,2 ab | 18,7 ba | 31 | 5,2 aa | 4,2 bb | 20 | 0,29 aa | 0,21 ba | 26 |
| RLine 3 | 30,9 ab | 28,6 ba | 33 | 4,5 ab | 4,3 bb | 6 | 0,25 aa | 0,22 aa | 13 |
| CV(%) | | 14,58 | | | 16,24 | | | 17,64 | |
| | | | | Grupo Feijão Branco | | | | | |
| BRS Artico | 43,4 ab | 29,5 bb | 32 | 6,6 aa | 6,0 ab | 9 | 0,38 aa | 0,38 aa | 1 |
| IPR Garça | 47,4 aa | 30,0 bb | 37 | 6,1 aa | 6,6 aa | 0 | 0,41 aa | 0,45 aa | 0 |
| WLine 1 | 49,0 aa | 24,6 bb | 50 | 6,1 aa | 5,6 ab | 8 | 0,43 aa | 0,36 aa | 16 |
| WLine 2 | 35,4 ac | 26,1 bb | 26 | 5,1 ab | 6,6 ba | 0 | 0,40 aa | 0,45 aa | 0 |
| WLine 3 | 36,6 ac | 30,5 bb | 17 | 5,0 ab | 6,5 ba | 0 | 0,36 aa | 0,42 aa | 0 |
| WLine 4 | 43,5 ab | 26,7 bb | 39 | 6,6 aa | 5,5 bb | 17 | 0,41 aa | 0,35 aa | 15 |
| WLine 5 | 51,7 aa | 39,3 ba | 24 | 6,1 aa | 6,8 ba | 0 | 0,35 aa | 0,41 aa | 0 |
| CV(%) | | 14,96 | | | | | | 21,83 | |

RV: rate of reduction of the variable (%) measured in plants cultivated in the presence of Al; means followed by the same letter did not differ from each other by the Scott-Knott test ($p \leq 0.05$).
Adapted from Santos Netto et al. (2020).

On the other hand, Silva et al. (2011) evaluated the effect of surface application of lime in a PD system on productivity and on the technological characteristics of grains of common bean cultivars. Applying dolomitic limestone at concentrations of 0, 1.8 t $ha^{-1}$, 3.6 t $ha^{-1}$, and 5.4 t $ha^{-1}$, the cultivars presented different productive performances depending on the applied lime rates. According to the authors, after six months of lime application, there was an improvement in the chemical attributes of the soil with an increase in pH, Ca and Mg contents, and base saturation, as well as a reduction in potential acidity and Al content. In addition, the cultivar Campeão 2 was more productive in the two years of experimentation and the cultivar IAPAR 81 responded linearly to the increase in lime rates in the second agricultural year, as shown in Table 4.

**Tabela 4.** Grain yield, cooking time (minutes) and crude protein content, as a function of bean cultivars and lime rates (t $ha^{-1}$) applied superficially in PD.

| Tratamento | Produtividade de grãos | | Teor de proteína bruta | | Tempo de cozimento | |
|---|---|---|---|---|---|---|
| | 2003 | 2004 | 2003 | 2004 | 2003 | 2004 |
| **Cultivares** | kg $ha^{-1}$ | | g $ha^{-1}$ | | min | |
| Carioca | 1.460 b | 2.333 b | 210 a | 220 a | 28 c | 30 b |
| IAC Carioca Eté | 960 d | 2.094 b | 230 a | 230 a | 27 c | 32 b |
| Pérola | 1.250 c | 2.367 b | 230 a | 220 a | 35 a | 40 a |
| IAPAR 81 | 1.340 bc | 2.291 b | 220 a | 220 a | 32 b | 37 a |
| Campeão 2 | 1.630 a | 2.709 a | 230 a | 230 a | 37 a | 30 b |
| CV (%) | 9,1 | 10,5 | 8,2 | 5,5 | 8,4 | 8,9 |
| Doses de calcário | | (¹) | | | | (²) |
| 0 | 1.390 | 2.180 | 230 | 220 | 31 | 31 |
| 1,8 | 1.280 | 2.390 | 220 | 220 | 32 | 33 |
| 3,6 | 1.340 | 2.400 | 220 | 220 | 32 | 34 |
| 5,4 | 1.250 | 2.460 | 230 | 220 | 32 | 38 |
| CV (%) | 11,8 | 10,9 | 6,8 | 5,7 | 6,4 | 6,3 |
| F Cultivares (C) | ** | ** | n.s. | n.s. | ** | ** |
| F Doses (D) | n.s. | ** | n.s. | n.s. | n.s. | ** |
| F Interação C x D | n.s. | * | n.s. | n.s. | ** | ** |
| R.L. | n.s. | * | n.s. | n.s. | n.s. | ** |
| R.Q. | n.s. | n.s. | n.s. | n.s. | n.s. | ** |

(¹) $Y = 45{,}33x + 2238{,}6$; $R^2 = 0{,}80$. (²) $Y = 1{,}2222x + 30{,}7$; $R^2 = 0{,}93$.
Médias seguidas de mesma letra, na coluna, dentro do fator cultivares, não diferem entre si a 5% pelo teste de Tukey. n.s.: Não significativo. * e **: Significativo a 5 e 1% de probabilidade pelo teste de F, respectivamente.
R.L. = regressão linear. R.Q. = Regressão quadrática.
Fonte: Adaptado de Silva et al. (2011).

Silva et al. (2011) also states that the increase in productivity may be related to the fact that in the second agricultural year of the crop succession (black oat/millet/beans) the availability of nutrients increased, with improvement in soil conditions, together with with the favorable climate and appropriate cultural practices.

Acidic soils can be found throughout the world, primarily in tropical and subtropical climates. This type of soil is the most common in Brazil, covering more than 65 percent of the country (Figure 1). The availability of different minerals in soil solutions with low pH is, however, the most serious issue with acidic soils. Essential elements such as K, Ca, Mg, P, S, B, nitrogen (N), molybdenum (Mo), and chlorine (Cl) are available in low concentrations under these conditions. Furthermore, at acidic pH levels lower than 5.5, $Al^{3+}$ ions, which are the most poisonous form and have a negative impact on plant growth and development, are abundant (Figure 2).

Thus, the need to raise the pH to values where the essential elements are available in higher concentration, that is, between 5.8 and 6.8, and, concomitantly, the available forms of Al that are not toxic to plants ( Figure 3), is extremely important. The most common management to raise the pH of the soil is the use of liming, which consists of the application of crushed limestone rocks. However, depending on the form of cultivation system used, the form of lime application is also important.

For NT systems, which aim at preserving and conserving the soil, minimizing its cultures turning over, and using plant cover from previous to protect the soil, maintain moisture, and deposition of organic matter, the application of limestone must be done by hauling and without incorporation. However, knowing that the dynamics of limestone in the soil are slow, the question arises as to how long it takes for the limestone to start to act, raising the pH of the soil in the different layers of depth.

Although the vegetation cover acts to raise the pH through Al complexation (OLIVEIRA et al., 2018), liming is still an essential tool for reducing soil acidity. In studies carried out by Ricardi et al. (2019), it is possible to verify the action of limestone at the different depths analyzed, as shown in Table 1. It is clear to observe the increase in pH and the decrease in the concentration of $Al^{+3}$.

It is also interesting to observe that plants have Al tolerance mechanisms, as shown in Figure 5. The exudation of organic acids is currently considered the first response of the roots to the presence of Al, preventing its entry into the plant. However, several other mechanisms, such as the antioxidant response system, and compartmentalization, among others, act to ensure the survival of plants to this toxicity. In this sense, studies carried out by Santos Netto et al. (2020) show that bean cultivars such as IPQ Quero-Quero, BRS Esplendor, KID 44, and WLine 5 have Al tolerance and can be used both in classical genetic improvement or as material for studying the physiological, biochemical, genetic and structural. On the other hand, while Al-tolerant genotypes with high productivity are still being studied, the use of surface liming for bean planting is still fundamental, as shown by the studies by Silva et al. (2011), confirming that the growth, development, and consequently increase of bean productivity in acidic soils is dependent on a set of techniques and management, such as crop rotation, improvement of soil conditions, favorable climate and appropriate cultural practices.

## Conclusão

Soil acidity and, consequently, the high concentration of $Al^{3+}$, considered extremely toxic to plants, since it affects the roots, impairing the absorption of water and nutrients, resulting in damage to the growth and development of plants, need to be corrected. In addition to the use of liming to raise the pH of the soil, in the no-till system, Al complexation is available through organic matter deriving from plant deposition from previous crops. The use of less invasive techniques, such as liming by hauling, together with the conservationist system of the NT, is fundamental for agriculture, aiming at productivity together with sustainability.

## References


1. BERTSCH, P. M.; PARKER, D. R. *Aqueous polynuclear aluminum species*. In: The environmental chemistry of aluminum. Ed: SPOSITO, G. 2nd Ed, 1996, 480p. Disponível em: https://www.taylorfrancis.com/chapters/edit/10.1201/9780138736781-4/aqueous-polynuclear-aluminum-species-paul-bertsch-david-parker.
2. CAMARGOS, S. L. *Acidez do solo e calagem (reação do solo)*. Apostila da Disciplina Solos II da Faculdade de Agronomia e Medicina Veterinária da Universidade Federal de Mato Grosso, 2005, 26p. Disponível em: https://www.ufjf.br/baccan/files/2019/04/Apostila_Capitulo_2_Acidez_Calagem.pdf.
3. CASTRO FILHO, C. D.; MUZILLI, O.; PODANOSCHI, A. L. Estabilidade dos agregados e sua relação com o teor de carbono orgânico num Latossolo Roxo distrófico, em função de sistemas de plantio, rotações de culturas e métodos de preparo das amostras. *Revista Brasileira de Ciência do Solo*, v. 22, n. 3, p. 527-538, 1998. Disponível em: https://www.scielo.br/j/rbcs/a/dXTDkRQqTBB3ZP5q8QnKXJS/?format=pdf&lang=pt.
4. CHAUHAN, D. K.; YADAV, V.; VACULÍK, M.; GASSMANN, W.; PIKE, S.; ARIF, N.; SINGH, V.P.; DESHMUKH, R.; TRIPATHI, D. K. Aluminum toxicity and aluminum stress-induced physiological tolerance responses in higher plants. *Critical Reviews in Biotechnology*, v. 41, n. 5, p. 715–730, 2021.
5. CHANDRA, J.; KESHAVKANT, S. Mechanisms underlying the phytotoxicity and genotoxicity of aluminum and their alleviation strategies: A review. *Chemosphere*, 278, 130384, 2021.
6. COHEN, J.; SLESSAREV, E. *Soil pH fertility: The Current*; University of California: Santa Barbara, CA, USA, 2016;

Available online: http://www.news.ucsb.edu/2016/017434/soil-fertility. Acessed: 30 October 2021.
7. DELHAIZE, E.; RYAN, P.R. Aluminum toxicity and tolerance in plants. *Plant Physiology*, v.107, p.315-321, 1995.
8. ECHART, C.L.; CAVALLI-MOLINA, S. Fitotoxicidade do alumínio: efeitos, mecanismo de tolerância e seu controle genético. *Ciência Rural*, v. 31, p. 531-541, 2001.
9. EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. Disponível em: https://www.agencia.cnptia.embrapa.br/Repositorio/CONTAG01_87_1311200215104.html. Acesso em 14 abr. 2022.
10. FERNANDES, C. H. S.; TEJO, D. P.; ARRUDA, K. M. A. Desenvolvimento do sistema de plantio direto no Brasil: histórico, implantação e culturas utilizadas. *Uniciências*, v. 23, n. 2, p. 83-89, 2019.
11. GARCÍA-RODEJA, E.; NÓVOA, J.C.; PONTEVEDRA, X.; MARTÍNEZ-CORTIZAS, A. & BUURMAN, P. Aluminium fraccionation of European volcanic soils by selective dissolution techniques. *Catena*, v. 56, p. 155-183, 2004.
12. HALISKI, A. *Acidez do solo e toxicidade do alumínio em sistema de plantio direto de longa duração*. Tese. Doutorado em Agronomia, Universidade Estadual de Ponta Grossa, 144 p.
13. HE, H.; LI, Y.; HE, L. F. Aluminum toxicity and tolerance in Solanaceae plants. *South African Journal of Botany*, v. 123, p. 23-29, 2019.
14. JORIS, H.A.W; CAIRES, E.F.; SCHARR, D.A.; BINI, A.R.; HALISKI, A. Liming in the conversion from degraded pastureland to a no-till cropping system in Southern Brazil. *Soil & Tillage Research*, v. 162, p. 68-77, 2016.
15. MALAVOLTA, E. *Elementos de Nutrição Mineral de Plantas*. São Paulo: Editora agronômica Ceres Ltda. 1980. 251 p.
16. NATALE, W.; ROZANE, D. E.; PARENT, L.E.; PARENT, S. E. Acidez do solo e calagem em pomares de frutíferas tropicais. *Revista Brasileira de Fruticultura*, v. 34, n. 4, p. 1294-1306, 2012.
17. OLIVEIRA, A. S. *A matéria orgânica na redução do efeito tóxico do alumínio*. Monografia. Curso de Agronomia, Universidade Tecnológica Federal do Paraná, 39f., 2018.
18. PAVINATO, P. S.; ROSOLEM, C. A. Disponibilidade de nutrientes no solo: decomposição e liberação de compostos orgânicos de resíduos vegetais. *Revista Brasileira de Ciência do Solo*, v. 32, p. 911-920, 2008.
19. QUAGGIO, J. A. *Acidez e calagem em solos tropicais*. Campinas. Instituto Agronômico, 2000. 111p.
**20.** RAHMAN, M.; LEE, S. H.; JI, H. C.; KABIR, A. H.; JONES, C. S.; LEE, K. W. Importance of mineral nutrition for mitigating aluminum toxicity in plants on acidic soils: current status and opportunities. *International Journal of Molecular Sciences*, v. 19, n. 10, p. 3073, 2018.
21. RICARDI, A. C.; KOSZALKA, V.; LOPES, C.; EURICH, K.; MULLER, M. M. L. *Acidez do solo em função de níveis de calagem em sistema plantio direto*. Anais eletrônicos da VI Reunião Paranaense de Ciência do Solo – RPCS: o desafio da produção agropecuária com baixo impacto ambiental de 28 a 31 de maio de 2019 [Publicação eletrônica] / Eduardo Augusto Agnellos Barbosa et al. (Org.). Ponta Grossa: UEPG/PROEX, 2019. 994p.; E-book PDF ISBN: 978-85-63023-46-9.
22. SALES, R.P.; PORTUGAL, A.F.; MOREIRA, J.A.A.; KONDO, M.K.; PEGORARO, R.F. Physical quality of a latosol under no-tillage and conventional tillage in the semi-arid region. *Revista Ciência Agronômica*, v. 47, p. 429-438, 2016.
23. SALOMÃO, E. A.; KRIEBEL, W.; SANTOS, A. A.; MARTINS, A. C. E.A importância do sistema de plantio direto na palha para reestruturação do solo e restauração da matéria orgânica. *Research, Society and Development*, v. 9, n. 1, e154911870, 2020.
24. SALTON, J. C.; HERNANI, L. C.; ZANONI, C. *Sistema Plantio Direto*. Coleção 500 Perguntas, 500 Respostas. Editora Embrapa Informação Tecnológica, 5ª Impressão (2012), 248 p., 1998.
25. SANTOS, O.F.; SOUZA, H.M.; OLIVEIRA, M.P.; CALDAS M.B.; ROQUE C.G. Propriedades químicas de um Latossolo sob diferentes sistemas de manejo. *Revista de Agricultura Neotropical*, v. 4, p. 36-42, 2017.
26. SANTOS NETO, J. dos; DELFINI, J.; SILVA, T.W.; HIROSE, A.A.; NOVAIS, J.M.; GONÇALVES, L.S.A.; MODA-CIRINO, V. Response of Common Bean Cultivars and Lines to Aluminum Toxicity. Agronomy, v. 10, n. 2, p. 296, 2020.
27. SILVA, T. R. B.; LEMOS, L. B.; CRUSCIOL, C. A. Produtividade e características tecnológicas de cultivares de feijão em resposta à calagem superficial em plantio direto. *Bragantia*, v. 70, n. 1, p. 196-205, 2011.
28. SILVA, C. O.; BRITO, D. S.; SILVA, A. A. da; ROSA, V. do R.; SANTOS, M. F. S.; SOUZA, G. A. de; AZEVEDO, A.A.; DAL-BIANCO, M.; OLIVEIRA, J.A.; RIBEIRO, C. Differential accumulation of aluminum in root tips of soybean seedlings. *Brazilian Journal of Botany*, v. 43, n. 1, p. 99–107, 2020.
29. SOUSA, D. M. G.; MIRANDA, L.N.; OLIVEIRA, S.A. *Acidez do solo e sua correção*. In: NOVAIS, R.F.; ALVAREZ, V.H.; BARROS, N.F.; FONTES, R.L.; CANTARUTTI, R.B.; NEVES, J.C.L. Fertilidade do solo. Viçosa, MG; Sociedade de Ciência do Solo, p. 205-275, 2007.
30. SPARKS, D.L. *Environmental Soil Chemistry*. 2.ed. EUA: University of Delaware, 2003. 345p.
31. VANCE, G. F.; STEVENSON, F. J.; SIKORA, F. J. *Environmental chemistry of aluminum-organic complexes*. In: SPOSITO G (ed). Environmental chemistry of aluminum. p. 169-220, 1995.
32. VELOSO, C. A. C.; BORGES, A. L.; MUNIZ, A. S.; VEIGAS, J. A. J. M. Efeito de diferentes materiais no pH do solo. *Scientia Agricola*, v. 49, n. 1, p. 123-128, 1992.
33. VERONESE, M.; FRANCISCO, E.A.B.; ZANCANARO, L.; ROSOLEM, C.A. Plantas de cobertura e calagem na implantação do sistema plantio direto. *Pesquisa Agropecuária Brasileira*, v. 47, p. 1158-1165, 2012.
34. ZHAO, W.-R.; LI, J.-Y.; JIANG, J.; LU, H.-L.; HONG, Z.-N.; QIAN, W.; XU, R.-K.; DENG, K.-Y.; GUAN, P. The mechanisms underlying the reduction in aluminum toxicity and improvements in the yield of sweet potato (*Ipomoea batatas* L.) after organic and inorganic amendment of an acidic ultisol. *Agriculture, Ecosystems & Environment*, v. 288, p. 106716, 2020.
35. ZHOU, J.; LI, Z.; ZHOU, T.; XIN, Z.; WU, L.; LUO, Y.; CHRISTIE, P. Aluminum toxicity decreases the phytoextraction capability by cadmium/zinc hyperaccumulator Sedum plumbizincicola in acid soils. *Science of the Total Environment*, v. 711, p. 134591, 2020.