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Campus de Botucatu

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Botucatu

2025

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Doctoral dissertation presented to the São Paulo State University (Unesp) School of Agriculture (FCA), Botucatu, to obtain the degree: Doctor in Agronomy: Agriculture, in cotutelle with the University of Göttingen, Germany.

Advisors: Prof. Dr. Juliano Carlos Calonego and Prof. Dr. Susanne Neugart

Botucatu

2025

T649s

Toledo Marzullo, Yasmine Ohanna
SOIL FERTILITY AND NUTRITIONAL QUALITY OF SOYBEAN AND MAIZE IN PRODUCTION SYSTEMS WITH BASALT POWDER and Urochloa ruziziensis / Yasmine Ohanna Toledo Marzullo. -- Botucatu, 2025
110 p. : il., tabs.

Tese (doutorado) - Universidade Estadual Paulista (UNESP), Faculdade de Ciências Agronômicas, Botucatu
Orientador: Juliano Carlos Calonego

1. Agricultura. 2. Adubos e fertilizantes. 3. Sustentabilidade. 4. Farelo de milho. 5. Farelo de soja. 1. Título.

Sistema de geração automática de fichas catalográficas da Unesp. Dados fornecidos pelo autor(a).

CERTIFICADO DE APROVAÇÃO

TÍTULO DA TESE: SOIL FERTILITY AND NUTRITIONAL QUALITY OF SOYBEAN AND MAIZE IN PRODUCTION SYSTEMS WITH BASALT POWDER and Urochloa ruziziensis

AUTORA: YASMINE OHANNA TOLEDO MARZULLO
ORIENTADOR: JULIANO CARLOS CALONEGO

Aprovada como parte das exigências para obtenção do Título de Doutora em Agronomia (Agricultura), pela Comissão Examinadora:

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Data: 05/05/2025 11:00:05-0300
Verifique em https://validar.iti.gov.br

Botucatu, 29 de abril de 2025

ACKNOWLEDGMENTS

I would like to express my gratitude and appreciation:

To everyone who crossed my path and contributed to my growth during this challenging, yet successful and beautiful journey.

To both my supervisors, Prof. Dr. Juliano Calonego and Prof. Dr. Susanne Neugart, for their support, patience, dedication, trust and the given opportunities throughout my academic journey. Their professionalism and sensitivity in the supervision process was fundamental to my academic and personal learning and growth, and their inspiring qualities serve as a true model for others.

To all my friends and work colleagues, team and employees of the Department of Crop Sciense of the School of Agricultural Sciences in Botucatu, as well as the Department of Quality and Sensory Analysis of Plant Products in Göttingen.

To the Faculty of Agricultural Sciences – UNESP – Botucatu/SP for the support offered during my doctorate studies, and for the countless opportunities that education has granted me. And to the Graduate School of Forest and Agricultural Sciences of the University of Göttingen, which also welcomed me with open arms and became my second home throughout this journey.

To the CNPq – National Council for Scientific and Technological Development, for the scholarship granted.

And the deepest and eternal gratitude to my family, especially to my mother Willmichela Toledo, and my partner, Stefan Klein. I am forever grateful for the endless support and love I receive, which continually inspire and drive me to move forward.

ABSTRACT

Basalt powder is a soil remineralizer with potential for use in agriculture, which can provide improvements to root environment, in addition to being a source of nutrients and slow-release beneficial elements. The cultivation of forage grasses, such as *Urochloa Ruziziensis* (U.R) can accelerate the effects of remineralization due to the known effect of these plants on nutrient cycling. Thus, the aim of this study is to evaluate the residual effect of basalt powder on soil fertility, yield and grain nutritional quality, in a cropping system involving soybean in succession with maize, with or without the intercropping of U.R. The experiment was carried out in randomized blocks in a 4x2 factorial scheme. The evaluated factors consisted of four different fertilization sources (4) and maize intercropped or not with U.R (2) during the winter season. The fertilization sources were: i) Control; ii) Basalt Powder (BP); iii) MAP + KCl (monoammonium phosphate + potassium chloride); iv) BP + MAP + KCl. Soil fertility, yield, mass of 100 grains, nutritional and mineral composition were analyzed. Data were submitted to analysis of variance ($p<0.05$) and means were compared by Tukey's test ($p<0.05$). Multivariate analysis by PCA (principal component analysis) was performed for significant variables. BP demonstrated efficacy in improving soil fertility after two agricultural cycles. The use of BP increased contents of Ca, Mg, S.B, V%, m% and C.E.C. in the soil. In soybean, the application of BP increased levels of K, Mg and B, while in maize, Ca, Mg, P and K concentrations increased significantly after two agricultural cycles. In addition, BP influenced the content of carotenoids, phenolic compounds and antioxidant activity in maize. BP is an effective and sustainable soil amendment with considerable potential for soil remineralization and improvement of the nutritional quality of agricultural crops. However, further studies are needed to understand the medium to long-term effects and the optimal application methods to maximize its potential in agriculture.

Keywords: Nutritional composition; Remineralization; Rock powder; Secondary metabolites; Soil Fertility.

RESUMO

O pó de basalto é um remineralizador de solo com potencial para uso na agricultura, podendo proporcionar melhorias no ambiente radicular, além de ser fonte de nutrientes e elementos benéficos de liberação lenta. O cultivo de gramíneas forrageiras em consórcio com culturas agrícolas favorece a remineralização do solo, melhorando a disponibilidade de minerais e otimizando a ciclagem de nutrientes através de seus sistemas radiculares profundos. Dentre as culturas agrícolas, a soja e o milho se destacam entre como commodities internacionais, utilizadas em uma grande variedade de alimentos para consumo humano e animal. Nesse sentido, o objetivo deste trabalho é avaliar o efeito residual do pó de basalto na fertilidade do solo e na qualidade nutricional dos grãos de soja e de milho, em sistema de cultivo envolvendo soja em sucessão de milho, este com ou sem o consórcio de *Urochloa ruziziensis* (U.R). O experimento foi conduzido em blocos casualizados, com 4 repetições, em esquema fatorial 4x2. Os fatores consistem em quatro diferentes manejos de adubação (4) presença ou não de U.R (2), em consórcio com milho na safra de outono-inverno. Os manejos de adubação consistem em: i) sem adubação (testemunha); ii) Pó de Basalto (BP); iii) MAP + KCl (fosfato monoamônico + cloreto de potássio); iv) BP + MAP + KCl. Foram realizadas análises de fertilidade de solo, produtividade e massa de 100 grãos, valor nutricional, composição mineral e metabólitos secundários. Os dados foram submetidos à análise de variância ($p<0,05$) e as médias comparadas pelo teste de Tukey ($p<0,05$). Análise multivariada por PCA (análise dos principais componentes) foi realizada para as variáveis significativas. BP demonstrou eficácia na melhoria da fertilidade do solo após dois ciclos agrícolas. O uso de BP aumentou o conteúdo de Ca, Mg, S.B, V%, m% e C.E.C. no solo. Na soja, a aplicação de BP elevou os níveis K, Mg e B, enquanto no milho, Ca, Mg, P e K aumentaram significativamente após dois ciclos agrícolas. BP influenciou o conteúdo de carotenoides, compostos fenólicos e atividade antioxidante na cultura do milho. BP é uma emenda de solo eficaz e sustentável, com considerável potencial para a remineralização do solo e melhoria da qualidade nutricional de culturas agrícolas. Entretanto, mais estudos são necessários para compreender os efeitos de médio a longo prazo e os métodos de aplicação ideais para maximizar o seu potencial na agricultura.

Palavras-chave: Composição nutricional; Fertilidade; Metabólitos secundários; Pó de rocha; Remineralização.

ZUSAMMENFASSUNG

Basaltpulver (BP) ist ein Bodenremineralisierungsmittel mit großem Potenzial für die Landwirtschaft, da es die Struktur des Wurzelumfelds verbessern und die mikrobiologische Aktivität des Bodens fördern kann. Es dient als Quelle wichtiger Nährstoffe und nützlicher Elemente und fördert eine schrittweise Freisetzung, die zur langfristigen Fruchtbarkeit und Nachhaltigkeit des landwirtschaftlichen Systems beiträgt. Der Anbau von Futtergräsern, wie *Urochloa Ruziziensis* (UR), im Verbund mit landwirtschaftlichen Nutzpflanzen fördert die Remineralisierung des Bodens, verbessert die Verfügbarkeit von Mineralien und optimiert den Nährstoffkreislauf durch das tiefe Wurzelsystem der Pflanzen. Unter den landwirtschaftlichen Nutzpflanzen sind Sojabohnen und Mais die wichtigsten internationalen Handelsgüter, die in einer breiten Palette von Nahrungsmitteln für den menschlichen und tierischen Verzehr verwendet werden. Das Ziel dieser Studie besteht darin, die Restwirkung von BP auf die Bodenfruchtbarkeit und die Nährstoffqualität in einem Anbausystem zu bewerten, in dem Sojabohnen und Mais nacheinander angebaut werden. Das Experiment wurde in einem randomisierten Blockdesign durchgeführt. Die Faktoren bestehen aus vier Düngemethoden (4) und Mischkultur aus UR + Mais oder Maismonokultur in Sojabohnenfolge (2). Das Düngemanagement besteht aus: i) Kontrolle ii) BP; iii) MAP + KCl (Monoammoniumphosphat + Kaliumchlorid); iv) BP + MAP + KCl. Es wurden Analysen zur Bodenfruchtbarkeit, Produktivität,Masse von 100 Körnern, Nährstoffzusammensetzung, Mineralstoffgehalt und zu sekundären Metaboliten durchgeführt. Für signifikante Variablen wurde eine multivariate Analyse mittels PCA (Hauptkomponentenanalyse) durchgeführt. BP zeigte nach zwei landwirtschaftlichen Zyklen eine deutliche Verbesserung der Bodenfruchtbarkeit. Durch die Verwendung von BP wurde der Gehalt an Ca, Mg, Basensättigung, Summe der Basen und Kationenaustauschkapazität. im Boden erhöht, und den prozentualen Anteil der Aluminiumsättigung reduziert. Bei Sojabohnen führte die BP-Anwendung zu einem Anstieg der K-, Mg- und B-Werte, während bei Mais die Ca-, Mg-, P- und K-Werte nach zwei landwirtschaftlichen Zyklen signifikant anstiegen. Im Vergleich zur Kontrollgruppe erhöhte BP nach zwei landwirtschaftlichen Zyklen den Gehalt an Lutein, β-Carotin, den Gesamtcarotinoidgehalt, die Ferulasäure, den Gesamtphenolgehalt und die antioxidative Aktivität in Maispflanzen. BP ist ein wirksamer und nachhaltiger Bodenverbesserer mit erheblichem Potenzial zur Remineralisierung des Bodens und zur Verbesserung der Nährstoffqualität landwirtschaftlicher Nutzpflanzen. Es sind jedoch weitere Studien erforderlich, um die mittel- bis langfristigen Auswirkungen und die idealen Anwendungsmethoden zu verstehen, um das Potenzial in der Landwirtschaft zu maximieren.

Schlüsselwörter: Fruchtbarkeit; Gesteinsstaub; Nährstoffzusammensetzung; Remineralisierung; Sekundärmetaboliten.

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General Introduction

Due to the increasing global demand for food, soybeans have become an important source of plant-based protein and stand out among the main national agricultural commodities. An essential component in animal feed production, and of growing importance in human nutrition, this oilseed crop has been the fastest-growing agricultural commodity in Brazil over the last three decades (Mores et al., 2022). Similarly, maize is characterized by a wide range of uses—from animal feed to high-tech industries—with the largest share of its consumption attributed to grain used for both animal and human food. It is also firmly established as one of Brazil's most significant agricultural export commodities The integration of grain-producing crops, such as maize, with forage species like *Urochloa ruziziensis*, is a widely used practice as an alternative for soil cover during the offseason and it is considered one of the best alternatives for the sustainability of tropical agricultural systems (Borghi et al., 2013). This is because the nutrient cycling that results from the decomposition of these crops residues, becomes an important factor of study to assist in fertilization management (Amado et al., 2002; Santos et al., 2008), which leads to the rationalization of input use with lower production costs for the farmer and reduced risk of losses and environmental imbalance.

Today, inputs such as fertilizers and agricultural pesticides play an active role in production costs. In general, the average share of fertilizers in operational costs for soybeans has shown an upward trend over the analyzed years (Monaco et al., 2024), due to factors such as the appreciation of the dollar and the verticalization of production. Brazil is the fourth-largest consumer of fertilizers in the world. In recent decades, the amount of imported NPK (nitrogen, phosphorus, potassium) fertilizers used in the country has increased from about 32% to 77% of total consumption (Farias et al., 2020). Given this scenario, there is a need to maximize the use of production factors to achieve higher productivity and profitability. Therefore, there has been a search for low-cost products aimed at ensuring efficient and sustainable nutrient supply and use for Brazilian agriculture, where the viability of industrial waste has been explored, with the use of remineralizers (RMs) standing out to supply nutrients and beneficial elements to plants, as well as to improve soil properties (De Silva, et al., 2023).

Soil remineralization with the use of rock powder is a technique that involves using finely ground rocks applied to the soil to restore its fertility through the minerals derived from them. Remineralizers, commonly known as rock powder or rock dust, are known to contain a wide range of minerals in considerable concentrations that can be made available to plants and soil microorganisms (Theodoro et al., 2012; Swoboda et al, 2022). They can be a viable alternative for agricultural use, both economically and ecologically, due to the low cost of the

beneficiation process, which consists of grinding the rocks that make up the product, releasing nutrients gradually, thus reducing losses due to leaching and favoring a long-term effect of the applied input (Hanisch et al., 2013). The remineralization technique has garnered interest from researchers seeking to positively alter soil fertility without affecting the environmental balance and to reduce medium- and long-term dependence on imported fertilizers, thus increasing the sustainability of production (Moretti et al., 2019). Additionally, to containing essential elements for plant development, remineralizers can provide important chemical elements for human nutrition. Improving the nutritional quality of agricultural crops, beyond improving soil fertility, has become an issue of extreme urgency and importance, as nutritional deficiencies constitute a serious public health problem, affecting more than half of the world's population, particularly in developing countries (WHO, 2018). Thus, improving the nutritional composition of plants used in food, particularly basic crops like soybeans and maize, is an urgent global need.

The adequate and balanced supply of nutrients to soybeans and maize with the use of mineral fertilizers, has the potential not only to increase productivity but also to improve the nutritional value of food crops. Therefore, the use of balanced fertilization could provide nutrients that are not present in sufficient quantities in the soil, promoting higher productivity and better organoleptic and nutritional quality of the grains, thus ensuring food security (Khambalkar et al., 2025). Improving the nutritional quality of grains may be key to more competitive supply chains. The goal is not to eliminate the use of soluble fertilizers for fast-growing grain crops, where the dependence on readily available nutrients is high, but the use of remineralizers and other sustainable soil management practices, such as the use of cover crops in the No-Tillage System, can create conditions to improve fertilization efficiency and nutrient uptake by plants. In this regard, forage species, like *Urochloa ruziziensis* can enhance the uptake of nutrients from low-solubility sources due to their greater hardiness, high ability to produce straw and roots, increased soil organic matter, and benefits to soil physical structure (Rodrigues et al., 2023), improving soil fertility, plant yield, and potentially the nutritional quality of the produced grains.

Few studies can be found in the literature regarding the interrelationship between fertilization, production systems, and the nutritional quality of grains. Research in this area is particularly justified during a time of international fertilizer shortages and the high global demand for maize and soybeans.

This study contributes to the growing body of work seeking alternatives to synthetic fertilizers by demonstrating that basalt powder, especially when paired with biologically diversified cropping systems, can sustain soil fertility and improve grain nutritional quality without compromising yield. The findings suggest that BP could be integrated into nutrient management plans not solely as a primary nutrient source, but as a long-term soil health amendment with co-benefits for food quality. Furthermore, the increase in bioactive compounds such as carotenoids and phenolics supports the use of BP in functional food production systems where nutritional enhancement is a key target. From an agroecological perspective, the study reinforces the value of intercropping as a means of enhancing soil function, optimizing resource use, and supporting resilience in cropping systems.

Broader Context and Future Research

To build upon this research and further advance our understanding, long-term field trials are recommended to assess the cumulative agronomic and environmental benefits and could provide a more comprehensive assessment of the cumulative impacts of BP, particularly considering its slow-release nature. Additionally, future studies could investigate the role of soil microbial communities, which likely play a key role in BP weathering and nutrient cycling, to deepen the mechanistic understanding of how intercropping enhances BP effectiveness. Additionally, conducting experiments across a range of locations and soil types would enhance the generalizability of the findings, providing valuable insights for optimizing BP application across different soil types and climatic zones. The incorporation of such alternative fertilization strategies holds the potential to reduce reliance on synthetic inputs, enhance food nutritional quality, and contribute to more sustainable and resilient agroecosystems.

Final Considerations

In conclusion, the use of basalt powder (BP) as a fertilization source in the successive cultivation of soybean and maize demonstrated notable benefits to soil fertility parameters (Chapter1 1). BP effectively improved cation exchange capacity (C.E.C.) after the first agricultural cycle. Furthermore, under intercropping system with *Urochloa ruziziensis*, it reduced soil acidity by lowering levels of m% (exchangeable aluminum) and Al^{3+}, increasing soil base saturation (SB) and V%, which are essential parameters long-term soil health. The combination of BP with the forage species *Urochloa ruziziensis* (U.R) in an intercropping system with maize proved to be particularly beneficial for enhancing soil fertility. This

synergistic effect not only optimized soil health but also promoted better nutrient availability and cycling, creating a more resilient soil environment and suggesting that BP is an effective soil remineralizer.

While these soil fertility improvements did not directly translate into yield increases, BP had a marked impact on the nutritional composition of soybean (Chapter 2). BP enhanced mineral levels of P, Ca and Mg after two crop cycles, highlighting the significance of proper crop fertilization and its impact on nutritional composition of food crops. These changes in nutritional content suggest that even in the absence of significant yield gains, BP can contribute to the overall quality of the crop, potentially offering benefits in terms of human nutrition. However, the intercropping with the forage species did not enhance BP effectiveness or performance. This indicates that while intercropping may provide other benefits, such as soil health or biodiversity, it did not significantly improve the nutritional outcomes observed in maize and soybean.

Furthermore, BP enhanced the secondary metabolite contents in maize with and without intercropping of *Urochloa ruziziensis* (Chapter 3), boosting levels of lutein, β-carotene, total carotenoid content, ferulic acid, total phenolic content and antioxidant activity in maize after two crop cycles, to similar levels as the chemical fertilization sources, suggesting potential health benefits and resilience improvements in the plants. However, when comparing the two-cultivation system, the presence of intercropping exhibited the highest performance for these variables, suggesting a positive correlation between the intercrop of the forage species and the use of BP to increase phenolic content in maize, having the ability to present comparable content to that of traditional/chemical fertilization sources.

Furthermore, the residual effects of BP over time demonstrate its potential as a sustainable approach to improving maize quality without compromising agricultural systems. These results open avenues for further research into the mechanisms underlying BP's impact on plant secondary metabolism and its applications in agriculture for bioactive compound enrichment in crops. These findings underscore the importance and efficiency of BP in promoting soil health and improving the nutritional quality of crops, while its role in boosting yield may require further exploration under different environmental conditions or additional factors. The positive effects on soil fertility and plant metabolism position BP as a promising sustainable input for improving fertility and quality, particularly in cultivation system, highlighting its potential as a natural soil amendment with benefits extending beyond immediate yield outcomes.

References

Amado, T. J. C., Mielniczuk, J., Aita, C. (2002). Recomendação de adubação nitrogenada para o milho no RS e SC adaptada ao uso de culturas de cobertura do solo, sob sistema plantio direto. *Revista Brasileira de Ciência do Solo*, *26*(1), 241–248. https://doi.org/10.1590/S0100-06832002000100025

Begam, A., Pramanick, M., Dutta, S., Paramanik, B., Dutta, G., Patra, P. S., Kundu, A., & Biswas, A. (2024). Inter-cropping patterns and nutrient management effects on maize growth, yield and quality. *Field Crops Research*, *310*, 109363. https://doi.org/10.1016/j.fcr.2024.109363

Bojtor, C., Mousavi, S. M. N., Illés, Á., Golzardi, F., Széles, A., Szabó, A., Nagy, J., & Marton, C. L. (2022). Nutrient Composition Analysis of Maize Hybrids Affected by Different Nitrogen Fertilisation Systems. *Plants*, *11*(12), 1593. https://doi.org/10.3390/plants11121593

Borghi, E., Crusciol, C. A. C., Mateus, G. P., Nascente, A. S., & Martins, P. O. (2013) Intercropping time of corn and palisadegrass or guineagrass affecting grain yield and forage production. *Crop Science*, 53, 629-636. https://doi.org/10.2135/cropsci2012.08.0469

Bottega, E. L., Queiroz, D. M. D., Pinto, F. D. A. D. C., & Souza, C. M. A. D. (2013). Variabilidade espacial de atributos do solo em sistema de semeadura direta com rotação de culturas no cerrado brasileiro. *Revista Ciência Agronômica*, *44*(1), 1–9. https://doi.org/10.1590/S1806-66902013000100001

Brandan, C. P, Chavarría D., Huidobro, J., Meriles, J. M., Brandan, C., P., Gil, S. V. (2017) Influence of a tropical grass (Brachiaria brizantha cv. Mulato) as cover crop on soil biochemical properties in a degraded agricultural soil. *European Journal of Soil Biology*, 83,84-90. https://doi.org/10.1016/j.ejsobi.2017.10.009.

Ministério da Agricultura, Pecuária e Abastecimento (MAPA). (2022). *Plano Nacional de Fertilizantes – PNF: Estratégias para redução da dependência de importação de fertilizantes e estímulo à produção nacional*. Retrieved 30 Jun, 2022, from: https://www.gov.br/agricultura/pt-br

Cavalieri, K. M. V., Tormena, C. A., Vidigal Filho, P. S., Gonçalves, A. C. A., & Costa, A. C. S. D. (2006). Efeitos de sistemas de preparo nas propriedades físicas de um Latossolo Vermelho distrófico. *Revista Brasileira de Ciência do Solo*, *30*(1), 137–147. https://doi.org/10.1590/S0100-06832006000100014

De Silva, S., Carson, P., Indrapala, D. V., Warwick, B., & Reichman, S. M. (2023). Land application of industrial wastes: impacts on soil quality, biota, and human health.

Environmental Science and Pollution Research, 30(26), 67974-67996. https://doi.org/10.1007/s11356-023-26893-7

Embrapa. (2020). Esclarecimentos sobre uso de agrominerais silicáticos (remineralizadores) na agricultura - Esclarecimentos Oficiais. 2020. Retrieved 27 July, 2021, from: <https://www.embrapa.br/esclarecimentos-oficiais/-/asset_publisher/TMQZKu1jxu5K/content/esclarecimentos-sobre-uso-de-agrominerais-silicaticos-remineralizadores-na-agricultura?inheritRedirect=false.>.

Eppes, M. C., Magi, B., Scheff, J., Warren, K., Ching, S., & Feng, T. (2020). Warmer, Wetter Climates Accelerate Mechanical Weathering in Field Data, Independent of Stress-Loading. *Geophysical Research Letters*, *47*(24), 2020GL089062. https://doi.org/10.1029/2020GL089062

Farias, P. I. V., Freire, E., Cunha, A. L. C. d., Grumbach, R. J. d. S., & Antunes, A. M. d. S. (2020). The Fertilizer Industry in Brazil and the Assurance of Inputs for Biofuels Production: Prospective Scenarios after COVID-19. *Sustainability*, *12*(21), 8889. https://doi.org/10.3390/su12218889

Ferreira, E. R. N. C., Almeida, J. A., Mafra, A. L. (2009). Pó de basalto, desenvolvimento e nutrição do feijão comum (*Phaseolus vulgaris*) e propriedades químicas de um Cambissolo Húmico. *Revista de Ciências Agroveterinárias*, 8 (2), 111-121.

Food and Agriculture Organization of the United Nations (FAO). (2021). FAOSTAT Statistical Database: Crop production and trade statistics. Retrieved Oct 30, 2021, from: https://www.fao.org/faostat/en/#data/QCL

Garcia, R.A., Crusciol, C.A.C., Calonego, J.C, Rosolem, C.A. (2008). Potassium cycling in a corn-brachiaria cropping system. *European Journal of Agronomy,* 28(4), 579-585. https://doi.org/10.1016/j.eja.2008.01.002

Guareschi, R. F. G., Boddey, R. M., Alves, B. J. R., Sarkis, L. F., Martins, M. R., Jantalia, C. P., Peña Cabriales, J. J., Vera Núñez, J. A., & Urquiaga, S. (2019). Nitrogen, phosphorus and potassium balance in agriculture of Latin America and the Caribbean. *Revista Terra Latinoamericana*, 37(2), 105–119. https://doi.org/10.28940/terra.v37i2.423

Hanisch, A. L. (2013). Efeito de pó de basalto no solo e em culturas anuais durante quatro safras, em sistema de plantio direto. *Revista Brasileira de Agropecuária Sustentável*, 3, 100-107. https://doi.org/10.21206/rbas.v3i2.224

Hasanuzzaman, M., Bhuyan, M., Nahar, K., Hossain, Md., Mahmud, J., Hossen, Md., Masud, A., Moumita, & Fujita, M. (2018). Potassium: A Vital Regulator of Plant Responses and Tolerance to Abiotic Stresses. *Agronomy*, *8*(3), 31. https://doi.org/10.3390/agronomy8030031

Izsáki, Z. (2006). Effect of nitrogen supplies on protein content and amino acid composition in maize (*Zea Mays* L.) kernels. *Cereal Research Communications*, *34*(1), 497–500. https://doi.org/10.1556/CRC.34.2006.1.124

Khambalkar, P.A., Agrawal, S., Dhaliwal, S. S., Yadav, S. S., Sadawarti, M. J., Singh, A., Yadav, I. R., Yadav, K., Shivansh, Prasad, D., Singh, A., & Afreen, N. (2025) Sustainable Nutrient Management Balancing Soil Health and Food Security for Future Generations. *Applied Food Research*, 101087. https://doi.org/10.1016/j.afres.2025.101087

Klein, H. S., & Luna, F. V. (2018). *Feeding the world: Brazil's transformation into a modern agricultural economy*. Cambridge University Press. https://doi.org/10.1017/9781108569101

Lehmann, J., & Joseph, S. (Eds.). (2015). Biochar for Environmental Management: Science, Technology and Implementation (2nd ed.). Routledge. https://doi.org/10.4324/9780203762264

Manzeke-Kangara, M. G., Joy, E. J. M., Lark, R. M., Redfern, S., Eilander, A., & Broadley, M. R. (2023). Do agronomic approaches aligned to regenerative agriculture improve the micronutrient concentrations of edible portions of crops? A scoping review of evidence. *Frontiers in Nutrition*, *10*, 1078667. https://doi.org/10.3389/fnut.2023.1078667

Masetto, T. E., Ribeiro, D. M., & Rezende, R. K. S. (2013). Germinação de sementes de Urochloa ruziziensis em função da disponibilidade hídrica do substrato e teor de água das sementes. *Pesquisa Agropecuária Tropical*, *43*(4), 385–391. https://doi.org/10.1590/S1983-40632013000400010

Matsumoto, H. (2000). Cell biology of aluminum toxicity and tolerance in higher plants. International *Reviews of Cytology*, 200, 1-46. https://doi.org/10.1016/s0074-7696(00)00001-2

Monaco, H., Colussi, J., Schnitkey, G, & Paulson, N. (2024) Shifting Dynamics in Soybean Farm Funding in Brazil. *farmdoc daily* (14):186, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign. Retrieved on 31 Oct, 2024, from: https://farmdocdaily.illinois.edu/2024/10/shifting-dynamics-in-soybean-farm-funding-inbrazil.html

Mores, G. V., Dewes, H., Talamini, E., Vieira-Filho, J. E. R., Casagranda, Y. G., Malafaia, G. C., Costa, C., Spanhol-Finocchio, C. P., & Zhang, D. (2022). A Longitudinal Study of Brazilian Food Production Dynamics. *Agriculture*, 12(11), 1811. https://doi.org/10.3390/agriculture12111811

Moretti, L. G., Bossolani, J. W., Crusciol, C. A. C., Moreira, A., Micheri, P. H., Rossi, R., & Imaizumi, C. (2019). Dunite in agriculture: physiological changes, nutritional status and soybean yield. *Communications in Soil Science Plant Analysis*, 50, 1775-1784. https://doi.org/10.1080/00103624.2019.1635143

Rodrigues, P. R., Paciullo, D. S. C., Soares, N. A., Gomide, C. A. de M., Morenz, M. J. F., Lopes, F. C. F., Souza Sobrinho, F. de, & Lana, A. M. Q. (2023). Productive traits and nutritional value of *Urochloa ruziziensis* submitted to different planting densities and defoliation intensities. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia,* 75(5), 1005-1015. https://doi.org/10.1590/1678-4162-12976

Santos, F. C. D., Neves, J. C. L., Novais, R. F., Alvarez V., V. H., & Sediyama, C. S. (2008). Modelagem da recomendação de corretivos e fertilizantes para a cultura da soja. *Revista*

Brasileira de Ciência do Solo, *32*(4), 1661–1674. https://doi.org/10.1590/S0100-06832008000400031

Serafim, M. E., Barbosa, S. M., Zeviani, W. M., Severiano, E. D. C., Costa, K. A. D. P., Romano, L. R., & Silva, B. M. (2025). Biopores, soil decompacting potential, and biomass of Brachiaria cultivars. *Revista Brasileira de Ciência Do Solo*, *49*, e0240079. https://doi.org/10.36783/18069657rbcs20240079

Silva, M. L. S., Ramos, C. G., & Oliveira, L. F. (2023). Potential soil remineralizers from silicate rock powders in the Amazon region. *Minerals, 13*(10), 1255. https://doi.org/10.3390/min13101255

Schiebelbein, B. E. (2022). *Plantas de cobertura e as inter-relações com a saúde do solo* (Tese de doutorado, Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz). https://doi.org/10.11606/9786587391335.

Schmoeller, G. R., Santos, E. R., Almeida, K. O., Ribeiro, F. L. A., Silva, A. M., Martins, Z. L., & Oliveira, J. M. d. (2024). *Influence of sowing depth in the emergence of Urochloa and Panicum*. Journal of Agricultural Science, 11(7), 231. https://doi.org/10.5539/jas.v11n7p231

Swoboda, P., Döring, T. F., & Hamer, M. (2022). Remineralizing soils? The agricultural usage of silicate rock powders: A review. *Science of The Total Environment*, *807*, 150976. https://doi.org/10.1016/j.scitotenv.2021.150976

Theodoro, S. H., Leonardos, O. H., Rocha, E. L. & Rego, K. G. (2006). Experiências de uso de rochas silicáticas como fonte de nutrientes. *Revista Espaço e Geografia*, 9(2), 263-292. https://doi.org/10.26512/2236-56562006e39794

Theodoro, S. H.; Tchouankoue, J. P.; Gonçalves, A.O.; Leonardos, O.; Harper, J. (2012). A Importância de uma Rede Tecnológica de Rochagem para a Sustentabilidade em Países Tropicais. R*evista Brasileira de Geografia Física*, 5(6), 1390-1407. http://dx.doi.org/10.26848/rbgf.v5i6.232929.

Van Straaten, P. (2006). Farming with rocks and minerals: challenges and opportunities. *Anais da Academia Brasileira de Ciências*, 78, 731-747. https://doi.org/10.1590/S0001-37652006000400009.

World Health Organization (WHO). (2018). World Health Statistics 2018: monitoring health for the SDGs, sustainable development goals. Geneva: WHO, 2018. Retrieved July 20, 2024, from https://www.who.int/publications/i/item/9789241565585.