CHAPTER 18

GYPSUM IN AGRICULTURE

Acceptance date: 02/05/2024

Alceu Linares Pádua Junior
Universidade do Vale do Jequitinhonha and Mucuri, campus Unaí, Brazil

Hamilton César de Oliveira Charlo
Instituto Federal do Triângulo Mineiro, campus Uberaba, Brazil

Jose Luiz Rodrigues Torres
Instituto Federal do Triângulo Mineiro, campus Uberaba, Brazil

Ernane Miranda Lemes
Universidade Federal de Uberlândia, campus Uberlândia, Brazil

ABSTRACT: Gypsum (calcium sulfate) for agricultural uses is a source of essential nutrients for plants (calcium and sulfur) and a soil and root environment conditioner in surface and subsurface soil layers. Applying gypsum to the soil reduces physical, chemical, and biological losses. Gypsum is primarily available as mined (sedimentary rocks) or as a by-product of industrial processes (e.g., acid manufacturing), food protein production (lacto-gypsum), or pollution control systems (e.g., flue gas desulfurization gypsum). Many plant nutrients in the soil can be managed by applying gypsum alone or in combination with other components such as lime and organic amendments. Surface-applied gypsum improves nutrient distribution in the soil profile and reduces aluminum saturation in no-tillage cropping systems. There are multiple and simultaneous benefits of applying gypsum to the soil that may be responsible for increasing plant resistance to stresses (biotic and abiotic plant diseases) and increasing plant biomass, grain, fibers, and extract yields in traditional extensive agroenvironments or organic cultivation. However, the use of gypsum in agriculture depends on its availability and shipping costs compared to the expected soil and yield responses. When gypsum is economically viable, significant advances in yields and the overall efficiency of the production process can be achieved in various crops and soil conditions. The aim of this chapter is not to exhaustively cover all gypsum-related topics but to address concepts and studies that will (i) review the recent literature on the effects of gypsum application in the soil-plant-environment system; (ii) present the gypsum recommendation methodologies and considerations; (iii) discuss studies and cases of gypsum uses in different soils and environmental conditions; (iv) suggest ways of managing gypsum to efficient and sustainable agriculture, and (v) present themes to be studied and explored to advance the knowledge of this agricultural tool. The information presented in this chapter is intended for farmers, researchers, natural sciences students, agricultural management consultants, environmental regulators, and agricultural gypsum producers and traders.

KEYWORDS: calcium sulfate, calcium, sulfur, soil parameters, plant nutrition, crop management, efficient food production, eco-friendly agriculture

The sustainability of a growing human population depends on the sustainability of agriculture. Food, feed, fibers, and fuel from crop plants must consider preserving and improving healthy environments and their ecological services. Therefore, agriculture must be conducted according to adequate technical principles and precise farming management. The correct amount and time of fertilizer applications for crop production are essential for enhanced results and reduced environmental impacts.

Modern techniques for field fertilization include using highly efficient fertilizers and soil conditioners (products that affect soil physical, chemical, and biological attributes) to supply crop plants during their cycle. Agricultural gypsum is a fertilizer and a soil conditioner, and despite its underuse for farming, it is among the most important nutritional amendments used for crop production worldwide.

GYPSUM ORIGINS

Concentrated gypsum ($CaSO_4$, or calcium sulfate) contains about 23.3% calcium, 18.6% sulfur, and minor amounts of other elements; however, for agricultural purposes, hydrated gypsum ($CaSO_4 \times 2H_2O$, or gypsum) is more available to the farmers. The production of hydrated gypsum starts with gypsum natural rock (Deer et al., 1966), which is grounded and heated (190-200 ºC) to remove more than two-thirds of its water content. This less hydrated mined gypsum is a neutral salt containing approximately 79% calcium sulfate and 21% water, and it is a moderately soluble (2.5 g L^{-1}) and a relatively common mineral (Curi et al., 1993; Chen and Dick, 2011; Wang and Yang, 2018). Anhydrite (anhydrous gypsum) is another natural rock available as a gypsum source; however, the hardness and low reactiveness make it less economically attractive.

The world's top five mined gypsum producers are the USA (22 million tons), China, Iran, Turkey, and Thailand (Crangle Jr., 2021). Brazil produces about 3 million tons of mined gypsum (Crangle Jr., 2021), and 80 mines have been exploring this resource recently (IBRAM, 2020), mainly concentrated in the north, northwest, and central-west sides of the country (van Raij, 2008). Gypsum for agricultural uses is also available as (i) a by-product of phosphoric, hydrofluoric, and citric acid production, (ii) a by-product of the pollution-control processes (e.g., neutralization of sulfuric acid and flue-gas desulfurization), and minor (iii) from dairy whey side streams (Alcordo and Rechcigl, 1993; Zoca and Penn, 2017; Bondi et al., 2021).

The gypsum by-product of the manufacture of phosphoric acid from the sulfuric acid attack on rock phosphate is named phosphogypsum (van Raij, 2008; Vitti et al., 2008). This sort of gypsum is widely available and may have impurities such as small proportions of phosphorus, potassium, magnesium, sodium, boron, fluorine, silicon, iron, aluminum, heavy metals, and radionuclides depending on the gypsum rock composition and geological origins (Alcordo and Rechcigl, 1993), but the calcium and sulfur relative concentrations still very similar among the types of mined gypsum available (van Raij, 2008).

BENEFITS AND EFFECTS OF GYPSUM USE

The positive results of gypsum application to the soil-plant-environment system are long known (Mayer, 1768; Crocker, 1922; Brasil et al., 2020). The first studies to highlight the positive effects of gypsum on agriculture in Brazil were reported by Malavolta et al. (1979) - which indicated crop improvements and higher root development in high-sodium soils - and by Ritchey et al. (1980) - which stated that single superphosphate and gypsum application resulted in (i) increased soil calcium contents, (ii) lower subsoil aluminum saturation, and (iii) improved maize (*Zea mays*) root development.

Ritchey et al. (1980) also highlighted that the leaching of soil bases such as potassium and magnesium could occur as the gypsum rate increases and that the improvements generated by the gypsum application are not exclusively due to the calcium sulfate as a source of calcium and sulfur. Syed-Omar and Sumner (1991) observed that exchangeable magnesium was reduced throughout the first 0.525 m soil layer, while no reduction in exchangeable potassium was observed below the 0.225 m soil layer. Their study indicates magnesium is more susceptible to leaching loss than potassium after surface gypsum application (2, 5, or 10 Mg ha^{-1}). It was also suggested that surface-applied gypsum be used as a soil ameliorant along with proper management of magnesium and potassium fertilizers.

Gypsum dissociates into calcium cation (Ca^{2+}) and sulfate anion (SO_4^{2-}) in soil solution. The calcium added to the soil complex displaces other cations, such as magnesium (Mg^{2+}), potassium (K^+), and aluminum (Al^{3+}). These displaced cations react with the sulfate anion and originate less phytotoxic forms of aluminum and neutral ionic pairs (cation + SO_4^{2}), such as $MgSO_4$ and K_2SO_4, which are highly mobile ionic pairs in the soil profile (Carvalho and van Raij, 1997).

The magnesium leaching caused by gypsum application can be even more damaging to plant development if other soil nutrition strategies are not appropriately implemented. A plant magnesium deficiency in the Brazilian Cerrado was potentialized by gypsum application to a newly opened area (summer of 2023/2024) for grain cropping (Pádua Jr., A. L. – data not previously published). The affected area was treated with 3 Mg ha^{-1} of calcitic lime (45-55% CaO, 1-4.99% MgO) 90 days before maize sowing and 1 Mg ha^{-1} de gypsum 60 days before maize sowing. The soil magnesium content in the 0-0.2 m soil layer was also low (0.4 $\text{cmol}_c\ \text{dm}^{-3}$). However, the recommendation for magnesium-poor soils where gypsum is needed is the application of dolomitic lime (25-35% CaO, ≥ 5% MgO). Dolomitic lime (2 Mg ha^{-1}) was applied to only one section of the cropping area. The plants from where calcitic lime was applied presented leaf symptoms of magnesium deficiency (Figure 1).

Figure 1. Maize plants from where calcitic lime and gypsum were applied presented leaf yellowing due to magnesium deficiency (A). B. Initial maize leaf symptom of magnesium deficiency (interveinal chlorosis).

Source: Pádua Jr, A. L.

Such a condition of maize plants responding to low magnesium availability was caused by (i) the excess of calcium cations from lime and gypsum application, (ii) the increased cation leaching potential generated by gypsum application, and (iii) the low soil magnesium content. Thus, in this case, gypsum potentialized the abiotic stress caused by the soil magnesium shortage. Magnesium sulfate (9% magnesium) was applied via foliar to reduce damage to the crop yield. Still, a nutritional soil repositioning of magnesium must be done before the next crop season. The effects and recommendations on soil cation management and the joint application of gypsum and lime will be further discussed.

Moreover, gypsum application does not provide only calcium and sulfur; other nutrients are added with gypsum application (Alcordo and Rechcigl, 1993). According to van Raij (2008), some gypsums can add up to about 1 kg ha^{-1} of boron for each 2 Mg ha^{-1} of gypsum applied to the cropping system. Boron is essential for root system growth, cell wall formation, and root expansion in the soil volume.

The regular gypsum positive effects include calcium and sulfur source in superficial and deeper soil profiles but also have positive effects on soil physical, chemical, and biological conditioning; reclaimed soils; reduced damage caused by subsoil acidity (exchangeable aluminum) and pollutants on plant growth; increased the abundance of soil microorganisms; improved nutrient redistribution and its plant-use-efficiency in soil profile; enhanced seedling, shoot, and root development; lower nutrient losses in agricultural biological waste composting; increased rainfall absorption; lower soil particle dispersion; improve soil stability; lower surface crust formation, runoff, and soil erosion (Ritchey et al., 1980; Ritchey et al., 1995; Toma et al., 1999; Martins et al., 2002; Soratto and Crusciol, 2008; Chen and Dick, 2011; Cañadas et al., 2014; Batte and Forster, 2015; Qayyum et al., 2017; Zoca and Penn, 2017; Bossolani et al., 2018; Cuervo-Alzate and Osorio, 2020; Qu et al., 2020; Charlo et al., 2022; Goiba et al., 2023; Garbowski et al., 2023; Jin et al., 2023; Li et al., 2023; Niaz et al., 2023; Outbakat et al. 2023; Robinson et al., 2023; AbouRizk et al., 2024). Gypsum can also have other purposes and be carbonated with carbon dioxide (CO_2) to sequester it from the atmosphere; one megagram or one ton of hydrated gypsum can react with about 0.26 Mg of CO_2 and form lime (Wang et al., 2021).

About three decades ago, Wallace (1994) presented many reasons why gypsum is essential for agriculture maintenance on many soils. The main advantages of gypsum application to the soil include accumulating more soil organic matter and aggregate stability, improved water drainage into the soil, prevention, and correction of soil sodicity, and faster seed emergence. The author also highlighted that gypsum is an industrial waste product available at a relatively low cost in many locations.

Some agricultural areas may still be far from a gypsum source. The beneficial soil-plant-environment returns of gypsum must be considered before gypsum acquisition since shipping costs can be restrictive. The expenses of gypsum benefits naturally include purchasing the material, transporting it from industry to the crop area, and spreading it on the soil (Chen and Dick, 2011). Despite its many benefits, the commercial-scale use of gypsum still depends on its logistics and investment return compared to the yield responses achieved with its application, the cost/benefit ratio (Shainberg et al., 1989).

The review of Rashmi et al. (2018) resumed many of the impacts of gypsum application to crops, especially oilseed crops such as soybean (*Glycine max*) and mustard (*Brassica juncea*). The authors presented gypsum's fertilizer and soil conditioner roles and gypsum's impacts on plant biometrics, chemical composition, crop yield, and soil parameters. Although, as pointed out by Chen and Dick (2011), most farmers are unfamiliar with the field application of gypsum and consequently have not seen the gypsum benefits. Thus, there is a considerable lack of knowledge about the best management practices for using gypsum as an agricultural amendment.

Moreover, the soil chemical balancing for plants requires regular applications of minerals containing calcium, such as limestone (lime calcium carbonate, $CaCO_3$) and gypsum, to achieve cation balance on the soil exchange sites (Brock et al., 2020). The base cation saturation ratio of 13:2:1 (calcium, magnesium, and potassium contents, respectively) is usually indicated as a reference to support optimum crop development (Chaganti and

Culman, 2017). However, optimum crop development has been observed in commercial crop areas in Brazil for base cation saturation ratios of 8-10:3:1 (Pádua Jr., A. L. - personal information). Potassium luxury uptake by plants and reduced phosphorus deficiency are also observed in soils with chemically balanced cation saturation ratios (Kopittke and Menzies, 2007).

Gypsum can even be used as a phosphorus sorbing and retaining material in soils (Penn and Bryant, 2006; Bryant et al., 2012; McGrath et al., 2013; Endale et al., 2014; Penn and McGrath, 2014; Watts et al., 2021; Mao et al., 2022; Ekholm et al., 2024), reducing its losses up to about 66% (Murphy and Stevens, 2010; Kumaragamage et al., 2022). King et al. (2016) reported that the surface application of flue gas desulfurization gypsum (FGDG) (further discussed) considerably reduced dissolved reactive phosphorus and total phosphorus concentrations and loadings in drainage waters (runoff and tile solutions). Favaretto et al. (2012) also reported that gypsum application reduces water pollution by phosphorus but increases soil ammonium (NH_4^+) mobility. It is worth noting that the effects of gypsum application on soils and crops could take several years before demonstrable benefits (Farina and Channon, 1988; McKibben, 2012), but these effects can last for years (Toma et al., 1999).

The combination of gypsum with other materials frequently outcomes improved results. Tubail et al. (2008) reported that combining FGDG with organic waste (nitrogen-rich streams) results in a product with decreased nitrogen potential loss and reduced odors associated with ammonia volatilization during the composting process. Bossolani et al. (2020), after a long-term study, reported that the combined application of lime (13.04 Mg ha^{-1}) and gypsum (10 Mg ha^{-1}) increased soil fertility and biological nitrogen fixation to an extended level. These authors also reported (i) reduced soil nitrification and denitrification in maize rhizosphere intercropped with Ruzi grass (*Urochloa ruziziensis*), (ii) altered nitrogen cycle genes in the soil biota, (iii) reduced aluminum saturation, (iv) balanced micronutrient availability (especially manganese), (v) improved calcium and magnesium availability in soil, (vi) increased nitrogen acquisition and (vii) increased maize grain yield.

However, the effectiveness of the benefits from gypsum application depends significantly on the physical and textural qualities of the gypsum reaching the field. Factors such as particle size, humidity, purity, and impurities play crucial roles in influencing the overall impact of gypsum effects on soil properties, plant growth, and yield responses. The moisture content of the gypsum to be applied must be low, and the gypsum material must be dry enough to be handled without clumping together due to high water content. Gypsum moisture content between 10 and 22% presents no significant physical limitations for field application [Paolinelli et al. (1986) in van Raij (2008) p. 34]. Occasionally, gypsum can arrive in the cropping area excessively wet (Figure 2), especially during high gypsum demands by crop management agendas.

Figure 2. Excessively wet phosphogypsum. Saturated load was dripping calcium sulfate solution (A) from a mass in the back of a truck (B) that was unloaded as a compacted material (C and D) physically inappropriate for field application.

Source: Guareschi, G.

Such a situation of excessive water content in gypsum constitutes two significant problems besides losing gypsum's overall agronomic efficiency: (i) wet gypsum cannot be homogeneously applied over the field using regular mechanical spreaders, and (ii) after wet gypsum dries, it becomes a hard solid material that needs to be grounded and sieved again before its application.

LESS EXPRESSIVE GYPSUM EFFECTS

Numerous reports of improvements in the soil system and crop yield increments are not always detected or consistent due to variations in soil type, crop species, and prevailing climate conditions. These observations challenge the identification of the precise improvements responsible for yield increases since many simultaneous physical and chemical interactions occur in soil (Zoca and Penn, 2017). Thus, it is more reasonable to understand crop yield improvements (when they occur) due to the synergic effects of the gypsum application to the soil-plant-environment system (Shainberg et al., 1989).

The improvements generated by the gypsum application are not always consistent and present mixed effects on soil, plant, and environmental parameters (Churka Blum et al., 2013; Tirado-Corbala et al., 2013; Buckley and Wolkowski, 2014; Bortolanza and Klein, 2016; Chaganti et al., 2019; Sun et al., 2019; Brignoli et al., 2021; Popp et al. 2021). For example, Adams et al. (2022) found that the surface runoff in grassland systems was reduced - regardless of management (grazing or hay) - by pasture aeration (spike aerator) following broiler litter application (5.6 Mg ha^{-1}), especially when compared to surface-broadcast traditional practices; however, the authors observed that gypsum application did not affect soil infiltration rates.

Kost et al. (2018) studied the effects of FGDG and mined gypsum application on soil, plant, and water parameters across ten sites distributed in the USA (Alabama, Arkansas, Indiana, New Mexico, North Dakota, Ohio, and Wisconsin states) via a data meta-analysis. The authors found relatively few significant effects of gypsum applications on the response variables. Some crop yield responses to gypsum were detected in some sites, but the overall results indicated no significant differences between the gypsum sources and the untreated control. Additionally, Charlo et al. (2020) reported that maize yield and plant biometric attributes were not influenced by gypsum or K_2O doses; they also reported that gypsum caused cation (potassium and magnesium) displacement to deeper soil layers (0.2-0.4 m), which was not enough to improve maize responses.

Gypsum application usually reduces the adverse effects of polluted soils on plants. However, Dubrovina et al. (2021) found no effect on alleviating metal phytotoxicity in the contaminated soil they studied [O horizon (forest litter) and A horizon (mineral soil)]. Instead, gypsum increased the concentrations of soluble metals in the soil solution and enhanced the metal plant uptake. The calcium cations from solubilized gypsum possibly displaced the metals in the exchangeable soil complex, making them more available to the plants and increasing the environmental hazard; thus, gypsum was ineffective and considered inappropriate as a soil remediation method to ameliorate soils polluted by metals. Argüello et al. (2022) also found limited effects of gypsum in cadmium-contaminated soils cultivated with cacao and, in some cases, even increased cadmium dissolution and plant-available by forming cadmium sulfate ($CdSO_4$) complexes.

GYPSUM AS BY-PRODUCT

Using industrial residues for soil amelioration and crop production can be a sustainable practice, and it has become of great interest in recent years. By-products from treated slags, such as yellow gypsum (Ali and Shahram, 2007; Ashrit et al., 2016; Ashrit et al., 2020; Prakash et al., 2020; Laxmanarayanan et al., 2022), and from pollution-control processes, such as the FGDG (Baligar et al., 2011; Watts and Dick, 2014; Wang and Yang, 2018) have demonstrated significant and positive results for the soil-plant-environment system. The yellow gypsum is produced from the Linz-Donawitz slag treated with concentrated sulfuric acid and neutralized with lime. The product (yellow gypsum) has about 87.98% of gypsum, plus other important nutrients such as iron (3.53%), silicon (1.79%), magnesium (0.78%), phosphorus (0.37%), titanium (0.15%), and other trace elements (Ashrit et al., 2015). The FGDG is primarily produced during the wet sulfur removal from fuel combustion gases in thermal power facilities, coal-fired power generation industries, smelters, and large-scale boilers (Koralegedara et al., 2019; Liu et al., 2021). Therefore, yellow gypsum and FGDG are mainly used in countries where their production is abundant, like China, the USA, India, and Germany.

The FGDG delivers similar benefits to the soil-plant-environment system as the gypsum from other origins (e.g., mined, by-product of acids production, dairy whey side streams). Reports of positive FGDG effects, even in long-term studies, are regular. Such effects include plant macro and micronutrients fertilization, reclaiming soil physicochemical attributes and polluted soils, stimulation of soil microbiota activity and ecological services, control of soil and nutrient erosions, improved plant development, and increased crop yield (Dick et al., 2006; Baligar et al., 2011; Watts and Dick, 2014; Marchis et al., 2016; Panday et al., 2018; Wang and Yang, 2018; Wang et al., 2021; USEPA, 2023). Zhao et al. (2019) studied the physical-chemical attributes and heavy metal contaminations after 17 years of FGDG application on sandy loam soil. After that period, the authors observed (i) an increased occurrence of soil macroaggregates (> 250 µm), (ii) no significant differences in the soil heavy metal contents (arsenic, cadmium, chromium, copper, mercury, nickel, lead, and zinc), and (iii) the soil reclamation effect caused by FGDG on sodic soils persisted and extended to deep soil layers.

FGDG can also be applied as an encapsulated or non-encapsulated soil amendment (Codling, 2017; Koralegedara et al., 2019). Additionally, FGDG typically presents a small and uniform size, with more than 95% of the particle sizing less than 150 microns, but it can be processed to form large-sized granules (Chen and Dick, 2011). However, gypsum produced from pollution-control processes may contain calcium carbonate, calcium sulfite, quartz (SiO_2), heavy metals, and other impurities that must be analyzed for safe environmental use before agricultural application (Chen and Dick, 2011; Wang and Yang, 2018; Koralegedara et al., 2019; Kong et al., 2023); therefore, for the environmentally responsible use of FGDG, it is necessary to accurately determine the contents of elements (plant nutrients or pollutants) in its composition (Chen and Dick, 2011; USEPA, 2023).

Chen et al. (2014) studied FGDG and mined gypsum application across many soils in the USA (Ohio, Indiana, Alabama, and Wisconsin states) to determine gypsum's ability to affect the concentration of trace elements (arsenic, barium, cobalt, chromium, copper, molybdenum, nickel, niobium, lead, antimony, selenium, strontium, vanadium, and zinc) in soils and earthworms. The authors found that (i) only mercury was slightly increased in some soils and earthworms when FGDG was applied; (ii) in some soils that received FGDG, selenium in earthworms was higher than in the untreated control but not higher than in mined gypsum treatment, and (iii) the bioaccumulation factor (ratio of element concentration in earthworm and element concentration in soil) where FGDG was applied were similar, or lower, to the untreated control and mined gypsum.

Additionally, Lee et al. (2007) indicated that the autumn surface application of FGDG in no-tillage systems managed before spring cropping would allow enough time for oxidation and dissolution reactions without causing significant negative effects on the soil biota. Thus, when properly managed and applied at the correct periods, FGDG represents a considerable input into agricultural systems.

GYPSUM ON SOIL ATTRIBUTES

The soil's physical characteristics are also essential for sustainable plant development. The soil infiltration rate (solution flux through a surface area per time) and water storage are usually improved by gypsum application (McIntyre et al., 1982; Truman et al., 2010; Muller et al., 2012; Zoca and Penn, 2017; Crusciol et al., 2019). The effects of gypsum on soil infiltration and water storage capacity originated from the flocculation and aggregation of subsoil components and improved root development. A developed root system also increases subsoil aggregation and reduces soil compaction; thus, gypsum, more precisely, calcium in gypsum, can minimize soil dispersion (Summer et al., 1990; Norton, 2008). As previously mentioned, gypsum can prevent soil surface crusting and reclaim calcareous non-sodic soils (Amezketa et al., 2005).

According to the Soil Science Society of America (1997), gypsum should be used as a calcium source in sodic soils, while the Brazilian legislation (Brasil, 2006) considers gypsum a soil sodicity corrector (sodium saturation reducer) and soil conditioner (soil attribute improver). These effects reduce soil erosion and improve water bodies' quality, particularly when applying gypsum with other management techniques. Soil aggregation induced by gypsum and polysaccharide (glucose) amendments can be enhanced (Walia et al., 2018). Such improved soil aggregation is usually attributed to the glucose gluing activity and the gypsum (calcium) binding-stabilizing activity.

Additionally, reports of positive effects of gypsum application on soil physics - soil structure (Tirado-Corbalá et al., 2019), water infiltration and drainage (Jayawardane and Blackwell, 1986; Tirado-Corbalá et al., 2013; Watts and Dick, 2014), bulk density (Buckley and Wolkowski, 2014), penetrometer resistance (Ellington, 1986) - are regular and important to the cropping system and raise the interest in the regular use of gypsum (Zoca and Penn, 2017; Rashmi et al., 2018). Gypsum is also used to reclaim sodic soils and to improve soil water infiltration decreased by low electrolyte concentration (Oster, 1982). However, the magnitude of soil and crop responses to gypsum application is affected by multiple variables such as soil characteristics, the history of the cropping area (previous agricultural practices), and crop variety (Shainberg et al., 1989). Despite many favorable reports in the literature, gypsum value is still poorly disseminated among farmers.

Gypsum is occasionally reported to change soil pH, especially soil water pH, either increasing or decreasing it (Farina and Channon, 1988; Shamshuddin and Ismail, 1995; Caires et al., 2006; Chen and Dick, 2011; Zoca and Penn, 2017; Tavakkoli et al., 2021). However, the range of soil pH changes caused by gypsum is modest and usually of a low extent (0.2-0.3 pH units). The soil pH response to the gypsum application is the product of the reactions between the gypsum and soil components. The replacement of hydrogen and aluminum in the cation exchange capacity (CEC) with calcium, the replacement of hydroxyl (OH^-) with sulfate (SO_4^{2-}), the precipitation of the solid soil phase, the ion-pair formation, and the self-liming effect are some of the gypsum reactions able to affect the soil pH significantly (Sumner, 1993). These reactions depend on the soil mineralogy and CEC ion composition, and the magnitude of each response dictates the influence of gypsum on soil pH (Zoca and Penn, 2017). However, when soil pH is high, presenting a soil pH of low acidity to alkaline conditions, the lime application is usually avoided. Thus, gypsum becomes an option for calcium and sulfur sources without significantly changing the soil pH in the soil profile.

Many areas worldwide present degraded soils or soil with severe chemical and physical limitations, raising concerns about food security (Kopittke et al., 2019; Agim et al., 2021; Kraamwinkel et al., 2021). Most of those degraded soils are highly weathered tropical soils, which need corrections to become highly crop-productive and sustainable. The soil acidity (low soil pH) is corrected with lime ($CaCO_3$ and $MgCO_3$). Still, the lime's beneficial effects are regularly limited to the soil layer of incorporation (usually up to 0.2 m deep) or the first centimeters if applied to the soil surface (usually up to 0.1 m deep). However, Fontoura et al. (2019) reported that the lime application to the soil surface of a moderately acidic Oxisol under no-tillage rapidly lowered the subsoil acidity up to 0.6 m deep in the soil profile. Other studies also reported the effects of lime and gypsum surface application in deep soil layers (Crusciol et al., 2019; Besen et al., 2021a).

The time needed for gypsum reaction in soil and significant effects arising from its application depends on regular factors but are not limited to soil type, gypsum granulometry, soil temperature, and gypsum way of application (on the soil surface, soil incorporated, and dissolved in irrigation). Table 1 presents a study done with gypsum application in an Oxisol (60% clay) cultivated with soil tillage and cropped with maize in 2013 (Pádua Jr., A. L. – data not previously published). Basic soil analysis was performed every 0.2 m up to 1 m depth before and after four months of gypsum (6 Mg ha^{-1}) application. The gypsum rate was applied on the soil surface 40 days before maize sowing.

Soil layer (m)	pH ($CaCl_2$)		SOM (dag dm^{-3})		Phosphorus (mg dm^{-3})		Calcium (cmol$_c$.dm^{-3})		Sulfur (mg dm^{-3})		CEC (cmol$_c$.dm^{-3})		V (%)		m (%)	
	t_0	4 m	t_0	4 m	t_0	4 m	t_0	4 m	t_0	4 m	t_0	4 m	t_0	4 m	t_0	4 m
0-0.2	4.4	5.4	3.2	3.3	2.2	1.8	2.2	4.5	2.5	6.4	8.1	8.7	49	75	5	2
0.2-0.4	4.0	4.8	2.3	2.1	0.7	1.2	1.1	2.9	1.2	34.4	7.9	8.5	30	52	32	4
0.4-0.6	3.9	4.7	1.5	1.7	0.5	0.7	0.6	2.3	0.7	18.1	6.9	7.5	22	45	50	11
0.6-0.8	4.0	4.5	1.1	1.4	1.0	0.7	0.6	1.4	1.0	10.7	6.3	6.6	20	32	50	19
0.8-1	4.0	4.4	1.1	1.0	0.2	0.6	0.5	1.4	1.4	5.3	6.2	6.7	18	31	57	32

SOM: soil organic matter; CEC: cation exchange capacity; V: soil base saturation; m: soil aluminum saturation. Source: Pádua Jr., A. L.

Table 1. Basic soil chemical analysis at different soil layers before (t_0) and four months (4 m) after gypsum (6 Mg ha^{-1}) application in a Haplorthox (Oxisol).

The gypsum application increased the contents of calcium, sulfur, and bases in the soil, reducing aluminum saturation in all the soil layers evaluated (Table 1). The maize grain yield observed raised from 6,600 kg ha^{-1} (control no gypsum) to 10,200 kg ha^{-1} (6 Mg ha^{-1}), indicating that applying gypsum about 40 days before sown is enough for the presented situation to cause significant increments to maize grain productivity. Interestingly, during the soil sampling in this soil tillage area, it was possible to demonstrate that only four months was enough for gypsum to run through the soil profile from the soil surface to depths up to 1 meter (Figure 3).

Figure 3. Deposit of solubilized gypsum in the 0.8-1 m soil layer four months after its application to a soil tillage area. Soil sample extracted with the aid of a Dutch auger.

Source: Pádua Jr., A. L.

Even in no-tillage cropping systems, the benefits of recent gypsum applications could be observed in soybean crops, especially in tropical soils. The gypsum application (3 Mg ha^{-1}) 60 days before soybean sowing improved nutrient distribution in the soil profile, raised grain yield, and increased residual effect of lime and gypsum for the succeeding crop seasons in Oxisol (Pádua Jr., A. L. – data not previously published). The gypsum application increased soybean grain yield by about 240 to 720 kg ha^{-1}.

Another soybean study in Oxisol presented the positive effects of gypsum (2 Mg ha^{1}) - applied 40 days after lime application (2 Mg ha^{-1}) and 20 days before soybean sowing - on some soil cations contents in deep soil layers (Pádua Jr., A. L. – data not previously published). Calcium and magnesium soil contents and aluminum saturation are compared between the year of gypsum application (2015) and two years after (Figure 4).

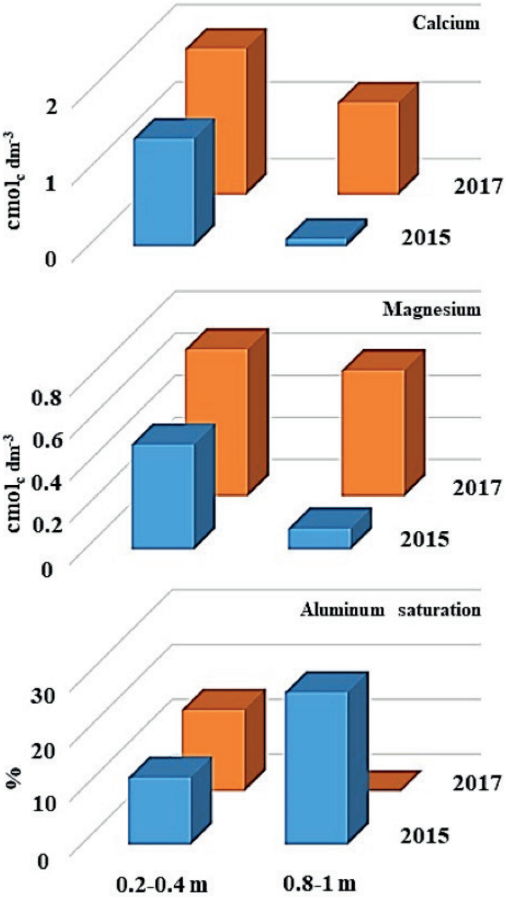

Figure 4. Soil calcium, magnesium, and aluminum contents in deep soil layers of an Oxisol in the year of gypsum application (2 Mg ha^{-1}) and two years after.

Source: Pádua Jr., A. L.

The increased soil aluminum saturation at the 0.2-0.4 m soil layer in 2017 is probably due to a boosted soybean root system cropped in the area. The gypsum application improved soil attributes in deeper soil layers and enhanced deeper root development conditions. This robust soybean root system would naturally absorb more soil cations and compensate for such extra absorption by exudating more hydrogen ions (H^+) in the soil solution. The increased H^+ availability reduced soil pH and increased aluminum availability and its saturation in soil. In the 0.8-1 m soil layer, the drop in the soil aluminum saturation was very expressive. It reflected the consequences of the arrival of solubilized soil cations from the gypsum applied above. In this soil depth (0.8-1 m), the influence of the soybean root system is lower than the effect of soil cation arrival from gypsum application, thus reducing the soil aluminum saturation.

Additionally, the greater volume of roots produced in the soil profile due to gypsum application increases soil phosphorus contents and cation exchange capacity over time after root decomposition.

GYPSUM AND LIME

The low lime solubility (about 172 times lower than gypsum) and the lack of soil disturbance in areas under no-tillage cropping systems reduce the effectiveness of the lime benefits to the soil profile when applied to the soil surface. In the Brazilian tropical soils, gypsum application frequently occurs from July to October, usually 40-60 days after lime and before routine fertilization and sowing. Still, no defined criteria for joint gypsum and lime application or the exact time for application is considered. This circumstance raises the need for studies including lime and gypsum (more soluble) in the soil surface to improve subsoil conditions for root systems development.

The interaction of gypsum and lime on soil attributes and crop yields is reported in the literature, especially but not exclusively for no-tillage cropping systems where the amendments must be applied to the soil surface (Caires et al., 2011a; Pauletti et al., 2014; Crusciol et al., 2016; Costa and Crusciol, 2016; Dalla Nora et al., 2017; Zoca and Penn, 2017; Fontoura et al., 2019; Anderson et al., 2021a). However, the results of the gypsum and lime interaction are occasionally contrasting.

In a no-tillage cropping system, the subsoil acidity is of significant concern since lime application to the soil surface could not solve this problem in deep soil layers. Due to the higher solubility and movement (deeper penetration) in the soil profile of the calcium-sulfate pair, the gypsum application can potentially reduce the subsoil acidity (aluminum saturation) (Ritchey et al., 1980; McBride, 1994; Zoca and Penn, 2017). The increment in exchangeable calcium (cation concentration effect) and sulfate [aluminum precipitation - $Al_2(SO_4)_3$] reduces the toxic aluminum effects in subsoil layers (Shainberg et al., 1989; Zambrosi et al., 2007).

According to Vitti and Mazza (2002), gypsum application to sugarcane (*Saccharum officinarum*) cropping areas must occur immediately after lime application, and the positive results are more expressive in Oxisols and quartz sand soils. However, according to Demattê (2005), the best efficiency of the gypsum reactions and effects in the soil is achieved three to six months after lime application. The author also exposed that such a procedure (gypsum three to six months after lime application) is counterproductive (timely) and suggested that good results are still observed when lime is applied before gypsum (two operations) and then incorporated.

Crusciol et al. (2019) evaluated the effects of lime (2.7 Mg ha^{-1}) and gypsum (2.1 Mg ha^{-1}) on (i) soil (sandy clay loam) attributes, (ii) plant nutrition, (iii) forage dry matter and crop yield, (iv) estimated cattle meat production, and (v) economic issues, and concluded that the surface application of lime plus gypsum is essential for food production in acid soils under no-tillage in tropical agriculture. The authors reported that (i) lime increased soil pH, reduced the exchangeable acidity ($H^+ + Al^{3+}$) and the relative concentration of aluminum up to 0.6 m soil depth; (ii) gypsum increased calcium contents through the soil profile; (iii) lime (with or without gypsum) improved the nutrient acquisition by the crops cultivated in rotation; (iv) lime and gypsum raised the forage dry matter yield and crude protein concentration of palisade grass (*Urochloa brizantha*); (v) estimated meat production of the joint application (lime + gypsum) was 26% higher than lime alone and 225% higher than the untreated control, and (vi) increased the economic performance during four cropping seasons. The authors also emphasized that lime and gypsum applied one day apart can generate positive agronomic and economic results; however, the usual recommendation is to apply lime first to the soil, then gypsum application later or in the next crop season.

Field empirical experience has shown that crop responses to gypsum application in tropical soils occur more expressively when applied in alternated years with lime application –gypsum application in the first year, lime application the next year, and follows successively alternating fertilizers (Pádua Jr., A. L. - personal information). Moreover, Besen et al. (2024) reported that applying lime and gypsum to the soil surface is preferable in no-till cropping areas for improved soybean and wheat performance.

The combined application of lime and gypsum can also be an adequate alternative to supply calcium and magnesium in deep soil layers of stabilized no-tillage systems (> 10 years without significant soil tillage), especially in drylands. However, in irrigated areas, the conditions are different. In general, artificial watering over time improves the subsoil's chemical and physical properties and helps build the attributes along the soil profile. Thus, crops in areas artificially irrigated can be less responsive to gypsum applications.

Additionally, gypsum is more effective than lime for sodic soil reclamation as it increases the concentration of electrolytes in the soil solution and displaces sodium with calcium within the structure of the clay components (Oster, 1982; Raine and Loch, 2003). Many agricultural amendments [e.g., rice (*Oryza sativa*) straw, press mud (residue from sugarcane juice filtration), cow manure, combined organic residues, biochar, beneficial microorganisms, and phytohormones] have also been applied with gypsum to improve sodium removing, salt-leaching efficiency, soil biological properties, reclaim degraded lands, and crop yield (Kilpatrick, 2012; Schultz et al., 2017; Yamika et al., 2018; Ahmed et al., 2020; Basak et al., 2021; Bello et al., 2021; Rezapour et al., 2021; Yahya et al., 2022; Xu et al., 2023).

Zhao et al. (2019) studied buried layers of maize straw (6, 12, and 18 Mg ha^{-1}) and soil incorporated (0-0.2 m) FGDG (0.75 Mg ha^{-1}) on soil attributes and sunflower grain yield. Generally, the combined application (buried straw and incorporated gypsum) reduced soil pH and exchangeable absorption percentage. It increased the soil's electrical conductivity and grain yield (17.4% in the first year, 20.4% in the second year). The authors also concluded combining organic residue and FGDG reduces soil salinity and sodicity. Moreover, gypsum application with *Atriplex halimus* (sea orache, Mediterranean saltbush, and a phytomedicine) can reclaim highly saline-sodic clay loam soils (Gharaibeh et al., 2011). The application of gypsum with compost (mix of plant and animal residues) and nanoparticles of manganese and selenium also improved some chemical and physical soil properties, water productivity, and yield of fava beans *(Vicia faba)* in salt-affected soil (Amer et al., 2023). The joint utilization of gypsum with lignin sludge as an organomineral fertilizer has also been a viable way to sustainably place gypsum, improve forest cultivation, and reclamation of disturbed lands, slopes of highways, and landfills of solid municipal waste (Matveeva et al., 2022).

CROP RESPONSES TO GYPSUM

Calcium is a low-mobility nutrient in plants and can not be mobilized from older tissues and redistributed in the plant via the phloem (Hanger, 1979; White and Broadley, 2003). Once calcium is associated with a compound within the plant structures, its relocation is slow, if at all, from one part of the plant to another. Fruits, for example, are at the end of the xylem transport system and are prone to receiving less calcium than other plant organs (Tonetto de Freitas and Mitcham, 2012; Song et al., 2018). Therefore, calcium must constantly be available to the roots (Chen and Dick, 2011); consequently, the crop responses, especially the yield responses, are prone to be sensitive to gypsum, a calcium source.

However, such yield responses are related to improved soil calcium and sulfur content increases and/or reductions in the subsoil layers' toxic aluminum (Al^{3+}) saturation. Additionally, the yield responses are frequently observed after enough time (months) of gypsum application to allow dissolved gypsum to be leached down into the subsoil layers (Sumner, 1993). However, Caires et al. (2011b) found a positive maize yield response to gypsum application in Oxisol right in the first year of application but no yield response to the soybean subsequently cropped.

In their chapter, Zoca and Penn (2017) concluded that all gypsum sources could generate positive crop yield responses and reduce the negative effects of stressful conditions. However, the authors highlighted that the impacts of gypsum application (positive or negative) must be evaluated for each specific objective, region (soil type and rainfall regime), crop species, and cultivation system. Rashmi et al. (2018) also concluded that gypsum could positively and negatively impact the soil-plant-environment system and that oilseed crops do not have a suitable recommendation for different soil types, climates, crop species, and cropping systems.

Despite some contrasting results, the positive effects also present a variety of ranges, going from substantial increases to a slight decrease in grain yield. In this sense, Pias et al. (2020) performed a meta-analysis comprising 129 harvests of six different crop species, including barley, maize, rice, wheat (*Triticum sativum*), soybean, and white oat (*Avena sativa*), to identify the conditions under which grain yield responds to gypsum application in no-tillage areas (Figure 5).

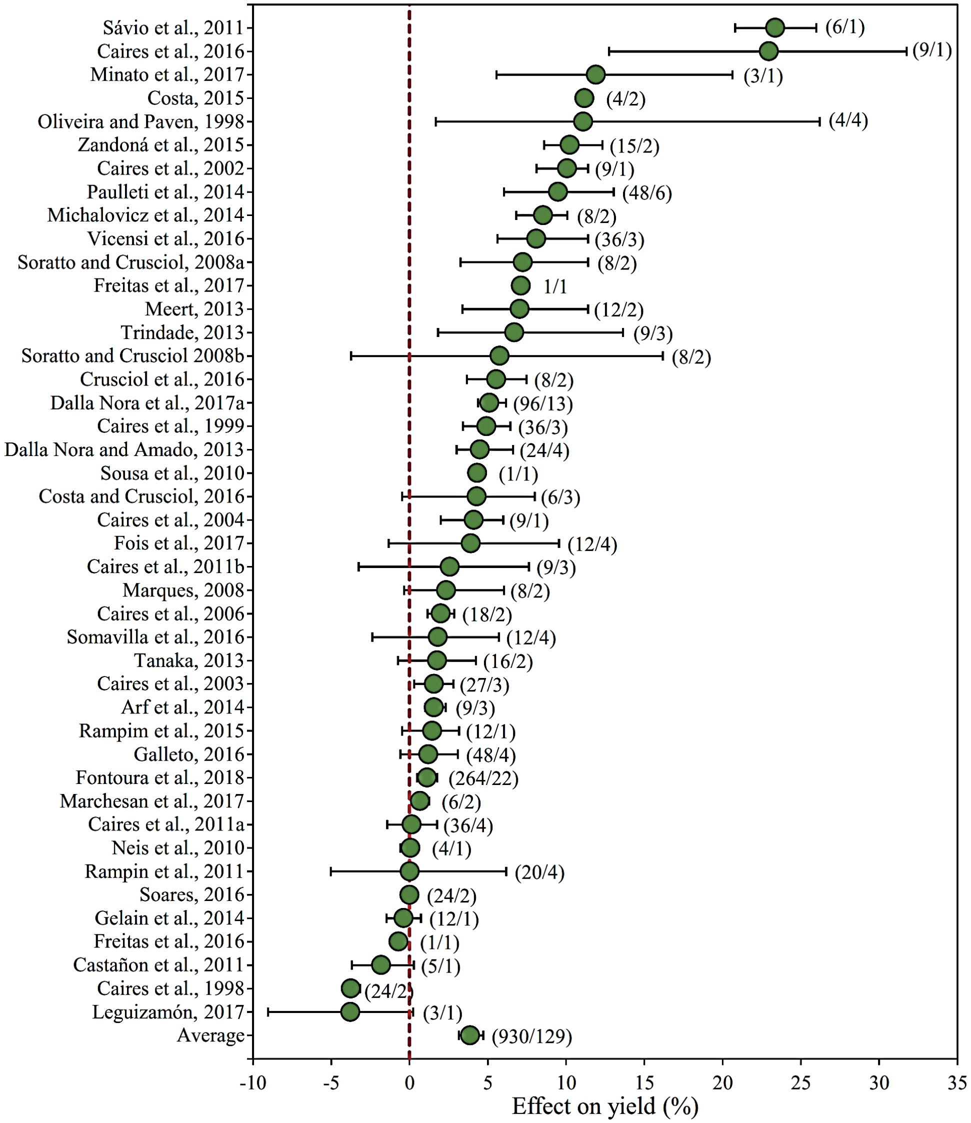

Figure 5. Mean effects (%) of gypsum application on crop grain yield in no-till soils in each primary study included in the meta-analysis. Error bars represent 95% confidence intervals of the means. The number of observation pairs and the total number of crop harvests (environment × year) included in each category are shown in parentheses.

Source: Pias et al. (2020)

Pias et al. (2020) found that (i) increased grain yield is very plausible (77-97%) when gypsum was applied to soils with aluminum saturation exceeding 5% in the 0.2-0.4 m soil layer - the decreased subsoil aluminum toxicity caused by the gypsum application allowed improved grain yields - (ii) the average increments in grain yield were 14 and 7% for cereal crops grown under water deficiency or not, respectively, and (iii) gypsum application should be avoided if aluminum saturation is below the critical thresholds since gypsum can cause excessive magnesium leaching across the soil profile. The authors also observed that soybeans positively responded to gypsum, even in areas with water deficit and aluminum saturation greater than 10%. The probability of a positive response was 88%, and the average yield increase was 12%. Such meta-analysis indicated that gypsum increased grain yield, decreased it, or presented no appreciable effect in 57, 5, and 38% of the evaluated studies, respectively.

Therefore, plant responses to gypsum application can be highly variable. For example, annual crops such as maize, wheat, and soybean, in general, present improved but extensively variable grain yield results (Dalla Nora et al., 2017; Soratto & Crusciol, 2008). Other studies do not reveal any positive gypsum effect on grain yield, maintaining similar results to the control (no-gypsum) (Marchesan et al., 2017; Fontoura et al., 2019), and there are studies even reporting minor drops in grain yield (Somavilla et al., 2016).

The variations in many reported results could be justified, in most cases, by the influence of other variables such as plant species and varieties, the time after gypsum application, gypsum application rates, soil chemical, physical, and biological properties, and climate (e.g., rainfall rates, average temperature) affecting the reports. Zoca and Penn (2017) also presented an excellent survey on agronomic gypsum studies varying from gypsum significantly improving soil attributes, crop performance, and yield results to no positive results.

The improvements in crop yield due to gypsum application are difficult to define, and delineating the exact positive effects besides a nutrient source due to many physical and chemical changes co-occurring in the soil is challenging. However, the impact of gypsum on soil characteristics and crop responses is primarily positive. It results from the synergic, accumulative, and additive effects of each potential change to the soil-plant-environment system caused by gypsum application.

GYPSUM TO GRAINS CROPS

In a long-term study (58 months), Caires et al. (2006) observed that (i) gypsum improved the subsoil chemical conditions, (ii) raised soil pH (0.01 mol L^{-1} $CaCl_2$), calcium, and sulfur contents, but also (iii) caused magnesium leaching in the soil profile. However, the authors could not identify a gypsum effect on soybean grain yield, but gypsum improved soybean grain quality, presenting higher protein, sulfur, phosphorus, potassium, and calcium contents. The authors concluded that applying gypsum to no-tillage soybean crops is important to produce high-quality seeds.

The residual effects of lime and gypsum application (3.71 or 7.42 Mg ha^{-1}) on clayey soil and the grain yield of soybean and wheat in southern Brazil were studied by Besen et al. (2021a). The studied area has been cultivated under no-tillage since 1975. The authors found after 48 months of gypsum application that (i) aluminum contents decreased until 0.6 m soil depth if lime was incorporated (0.2 m) and until 0.3 m soil depth if lime was applied to the soil surface; (ii) lime incorporation reduced soil organic matter content in the surface soil layer; (iii) superficial lime application increased the magnesium contents in the 0.4-0.6 m soil layer; (iv) 7.42 Mg ha^{-1} had a pronounced residual effect in subsoil layers but increased the vertical displacement of magnesium and potassium contents, and (v) soybean and wheat yields were not affected by the soil base saturation variations. Therefore, the authors concluded that the standard gypsum rate (3.71 Mg ha^{-1}) provided the best results and highlighted that the benefits of superficial gypsum application extend beyond surface soil layers in clayey soil from subtropical environments. Applying gypsum to the soil surface is also preferable to preserve the benefits of a continuous no-tillage cropping system.

Da Costa et al. (2016) reported different soil organic matter and soybean yield results. They found that (i) lime (2 Mg ha^{-1}) application, with or without gypsum (2.1 Mg ha^{1}), can increase soil organic matter accumulation in the long term, and (ii) application of lime associated with gypsum to soil surface increased soybean and sorghum (*Sorghum bicolor*) calcium absorption and their respective grain yields. The authors also found that the subsoil's sulfur residual effects were observed after five years of gypsum application. In another study on sorghum, Charlo et al. (2022) reported that gypsum effectively increases soil calcium content by 60.5% in the 0-0.2 m soil layer and 34% in the 0.2-0.4 m soil layer. The authors also observed that (i) the highest gypsum dose studied (4,000 kg ha^{-1}) increased the soil availability of phosphorus and sulfur by 32.5 and 681%, respectively, and (ii) the nutrients increments would improve the crop's resistance to drought stress. Such improved nutrient availabilities mainly result from (i) the ions added to the soil with the gypsum application and (ii) the ion displacements in the soil complex caused by the added ions.

A noteworthy study was published by Fontoura et al. (2019), where they evaluated the surface gypsum and liming application on the chemical properties of four soil layers (0-0.1, 0.1-0.2, 0.2-0.4, and 0.4-0.6 m) in two periods 10 years apart (1 and 11 years after lime and gypsum application). Between the first and eleventh year of the experiment, 26 crops were cultivated [10 soybean crops, four white oats, three maize, three wheat, three barley (*Hordeum vulgare*), and three forage radish (*Raphanus sativus*)] under a no-tillage cropping system. The authors found (i) no synergic effect of gypsum and lime on soil chemical properties, crop yield, and most leaf-tissue macronutrients; (ii) yield increments were minor for cereals (4%) than for soybean (14%) and were limited to just 25% of cereal crop seasons, and 40% for soybean; (iii) in the short term, gypsum raised more the exchangeable calcium content to 0.6 m soil depth than lime, but the latter presented more reductions in the soil acidity and extended residual effect (improved soil conditions for extended period), and (iv) the lime application to the soil surface under no-tillage lowered the subsoil acidity up to 0.6 m in the first year after its application, and improved soybean grain yield.

Fleuridor et al. (2021) indicated no yield improvements for maize, alfalfa (*Medicago sativa*), or alfalfa-mixed grasses after two years of gypsum application. However, gypsum consistently increased sulfur concentrations in soil and crop tissues as soon as five months after each gypsum application. In the short term, the authors also observed that gypsum did not affect mineralizable soil carbon, penetrometer resistance, or unsaturated hydraulic conductivity. However, the second gypsum application reduced the soil protein and magnesium contents; the authors also reported magnesium leaching. Magnesium and potassium leaching to subsoil layers is regularly reported in the literature on gypsum and soil attributes. Therefore, planning magnesium and potassium fertilization before gypsum application must be considered as a way to improve soil fertility deeper in the soil profile.

In the long-term observations, Caires et al. (2011a) observed a residual effect on the subsoil sulfur content of an oxidic soil. After eight years of gypsum application, the sulfate concentrations in the subsoil were still high. After 7-10 years of surface-applied gypsum (no-tillage), maize grain yield improved, but soybean grain yield did not. The authors also reported that using gypsum in no-till systems is interesting when maize is frequently grown in crop rotations.

Additionally, it is essential to state that the residual effect of gypsum in the soil-plant-environment is unseparated from the soil attributes. Different soil characteristics (chemical, physical, and microbiological aspects) affect the extension of gypsum residual. Other significant factors that influence the gypsum residual include (i) the physical and chemical characteristics of the soil B horizon, (ii) the occurrence of impediments in lower soil layers, (iii) soil organic matter content, and (iv) the predominant soil structure.

De Moura et al. (2018) studied maize crop response in an Argisol (soil classified as Argisol in the Brazilian soil classification system) after five years of gypsum application and combinations with the residues of leguminous plant species [*Gliricidia sepium* (gliricidia) and *Acacia mangium* (acacia)]. They found that the mixed application of leguminous residues, urea, and gypsum (6 or 12 Mg ha^{-1}) reduced soil penetration strength and increased soil calcium content, soil organic matter, maize leaf area index, plant nitrogen amounts, and the maize grain yield. The authors concluded that managing gypsum and leguminous residues in humid tropic agrosystems is an appropriate strategy to improve maize productivity and crop sustainability.

Regarding the soil incorporation of such soil amendments, Besen et al. (2021b) evaluated lime incorporation approaches (incorporated or superficial) and the effect of reapplied lime and gypsum on soil chemical properties and grain yield of wheat and maize in southern Brazil. Similar to other studies, the authors reported that (i) incorporating lime reduces soil acidity (increasing soil pH and reducing available aluminum), increases calcium and magnesium contents, and decreases the organic matter content in the revolved soil surface; (ii) gypsum increases sulfur and calcium availability in deeper soil layers; (iii) high gypsum rates (> 7.42 Mg ha^{-1}) reduce the magnesium content in the surface layer; (iv) lime associated with gypsum and applied to the soil surface resulted in the highest wheat and maize yields indicating that the benefits of the continuous no-tillage system could be maintained. Besen et al. (2021b) also indicated the increasing sulfur content as the main factor for increased crop yields. Additionally, reductions in aluminum saturation in deeper soil layers were a common effect of the gypsum application to wheat, soybean, and maize (Rampim et al., 2011; Nora et al., 2014)

Also, on wheat, Rawat et al. (2020) studied the plant development (plant emergence, tillers per square meter, biometrics, yield) after applying nano-sized gypsum in silty clay loam soil and found positive results. The treatments that reduced the regular mineral fertilization (75%) plus nano-sized gypsum presented similar or superior plant development to the complete regular mineral fertilization (100%). Such treatments generated up to 25% economy compared to the recommended rates of mineral fertilizer with no grain yield penalty. Abbas et al. (2023) observed no noticeable impact of gypsum rate on the straw yield; however, the authors also observed that 3 Mg ha^{-1} of gypsum improved soil moisture conservation, nutrient uptake, and wheat grain yield with less input cost.

GYPSUM TO SUGARCANE CROP

Gypsum and lime ratios and application methods (incorporated, superficial, or applied in-furrow) in sugarcane were studied by Morelli et al. (1987) after 6 and 18 months of the application of the treatments. They concluded that (i) lime effectiveness was limited to the soil layer near the soil surface, regardless of incorporation method; (ii) gypsum improved base saturation and reduced aluminum saturation up to 0.75 m deep in the soil profile; (iii) calcium and magnesium saturation reduced in the second evaluation (18 months), and (iv) gypsum alone or with lime resulted in greater sugarcane yields than lime alone. A similar conclusion was pointed out by Lorenzetti et al. (1992).

Morelli et al. (1992) reported increased soil calcium contents and base saturation in deep soil depths after 18 months of gypsum application in another sugarcane study. The same was not observed when only lime was applied. The authors also reported that (i) the best calcium and magnesium distribution in the soil profile and the most prominent base saturation were observed when gypsum and lime were combined; (ii) the application of gypsum alone (without lime) caused magnesium leaching to deep soil layers; (iii) the combined application of gypsum and lime resulted in greater sugarcane yields than each one alone, and (iv) the highest sugarcane root biomass and yield - after four sugarcane harvests - were observed when 4 Mg ha^{-1} of lime were applied with 2 Mg ha^{-1} of gypsum.

Crusciol et al. (2017) studied the surface application of gypsum with silicate, or lime, on sugarcane yield and the amendment of subsoil acidity in a 12-month study. The subsurface soil layer (0.2-0.4 m) presented reduced aluminum saturation and increased calcium, magnesium, potassium contents (base saturation), and sulfur contents with the surface gypsum application. The association of gypsum with silicate, or lime, increased sugarcane stalk, bagasse, trash yield, and energy yield; however, applying gypsum in association with silicate leads to the most superior profitability.

The dolomitic lime and gypsum surface application in green sugarcane ratoon was studied by Rossato et al. (2017) after 12 months of the treatment's application. They concluded that gypsum acted as a subsurface conditioner and contributed to the liming benefits of surface lime application to reach deeper soil layers. This deepening of the soil improvements caused by the gypsum and lime application allowed the development of the sugarcane root system to greater depths. It generated increments in sugarcane stalk, bagasse, trash yield, and sugar yield. However, the authors also indicated that gypsum might lead to the leaching of magnesium and potassium into deep soil layers.

Araújo et al. (2019) studied the influence of gypsum (5 Mg ha^{-1}) on soil carbon up to 2 m depth of an Oxisol. The carbon accumulation, its relationships with the soil's chemical properties, and the development of the sugarcane root system were evaluated next to the seventh sugarcane cut (87 months after gypsum application). The authors reported (i) increased calcium and sulfur contents and reduced aluminum saturation in the soil profile, which were responsible for the improved sugarcane root system development, and (ii) increased carbon sequestration in the deeper soil layers (1-2 m), where the leading supplier of soil acidity were the sugarcane roots.

GYPSUM TO OTHER CROPS

All living plants need calcium, sulfur (macronutrients found in gypsum), and other essential nutrients to complete their cycle. Crop plants of high productivity continuously need those nutrients and other beneficial nutrients in balanced proportions to develop and produce fully. Thus, several other crops present significant responses to the gypsum application. Most observed results are positive, highlighting the benefits of regular gypsum use and management for crop production and improved yield.

In coffee (*Coffea arabica*), the contents of soil calcium, magnesium, and potassium and their sulfate (SO_4^{2-}) ionic pair along the soil profile (0-2.4 m deep) were evaluated by Ramos et al. (2013). The authors studied an Oxisol 16 months after gypsum application and reported that (i) 96% of ionic potassium (K^+) in soil solution was at 0.35 to 0.45 m in its free form; (ii) the predominant leached chemical species occurred in the free forms (Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}), and (iii) the content of the chemical species of calcium and magnesium sulfate was higher than the potassium sulfate chemical specie.

Anikwe et al. (2016) found that the combined application of lime (5 Mg ha^{-1}) and gypsum (2.5 Mg ha^{-1}) to an Ultisol improved soil physicochemical properties and cassava (*Manihot esculenta*) yield. The authors argued that the calcium applied via lime and gypsum flocculated the soil particles, enhancing the soil's physical attributes and pH, soil infiltration and aeration, soil phosphorus availability, and plant nutrient uptake for improved cassava growth. Corroborating the results observed by Anikwe et al. (2016), the effects of lime on soil physics are already known and usually affect soil flocculation, density, aggregates, and porous structure (Auler et al., 2019; Conradi et al., 2020).

Magnesium sources such as kieserite (standard magnesium source for agriculture - $MgSO_4.H_2O$), ground magnesium limestone [$CaMg(CO_3)_2$], and magnesium-rich synthetic gypsum (an industrial by-product that has > 70% of gypsum, 17.1% of magnesium hydroxide, 4.3% of calcium hydroxide, 2.3% of calcium carbonate, and pH 8.8) were evaluated in oil palm (*Elaeis guineensis*) by Ayanda et al. (2020). The authors concluded that the magnesium-rich synthetic gypsum is a viable soil conditioner for fertilizing and liming the soil. This source satisfied oil palm plants' calcium and magnesium requirements like other sources. Such a magnesium-improved gypsum would minimize the magnesium-induced deficiency caused by the magnesium-leaching potential when conventional gypsum sources are applied.

In eucalyptus (*Eucalyptus* sp.) seedlings, Gabriel et al. (2018) reported that lime decreased soil acidity and improved plant development; however, the authors also noted that the gypsum effect on the variables evaluated was insignificant and highlighted that gypsum could reduce seedling growth if excessive rates are applied. Ferreira et al. (2020) assessed the eucalyptus development for 36 months after applying up to 9.6 Mg ha^{-1} of gypsum and reported no benefits to the dendrometric growth. The authors discussed the lack of plant response to gypsum benefits (source of calcium, sulfur, and a soil conditioner). They indicated a combination of factors responsible for the results' non-significance, such as soil type, eucalyptus tolerance to soil acidity, agronomic management, and climatic conditions.

Other perennial crops, such as turfgrasses, need corrections and supplementations in deep soil layers to achieve full development. Such improvements in deep soil layers can not be reached only with lime, especially when tilling is not an option (e.g., gardens and golf courses). Schlossberg et al. (2006) reported amelioration of the subsoil attributes up to 0.6 m deep after two years of soil surface gypsum application (10.6 or 20 Mg ha^{-1}). Thus, gypsum was a necessary soil amendment to manage macronutrients and potential soil acidity. The authors also reported that the turfgrass beneficial growth responses to the gypsum application vary among species.

Many horticultural crops, for example, presented improved yield, quality, shelf life, and profitability when gypsum is applied (Korcak, 1993; Brown, 2018; Lantzke, 2018; Santos et al., 2020; Charlo et al., 2021; Watts et al., 2021). Even crop production in soilless growth media can benefit from gypsum. Media containing FGDG and organic composts have provided excellent plant production with no harmful environmental results (Chen and Dick, 2011). Bardhan et al. (2005) studied tomato (*Lycopersicum esculentum*) and wheat development in a low-cost, high-quality growth media for nursery, greenhouse, and landscape industries. The authors reported (i) improved plant growth (35 days after planting) for the tested media growth containing gypsum compared to the commercial media brand, and (ii) no toxic elements were detected in excess in the media solution leachates or the plant tissue evaluated.

Plants that exhibit rapid growth rates and are multipurpose, such as hemp (*Cannabis sativa*) and hops (*Humulus lupulus*) – both from the Cannabaceae botanical family – will positively respond to adequate fertilization and soil management (Brooks et al., 1961; Duke, 1983; Cannoy, 2015; Anderson et al., 2021b; Rehman et al., 2021). Industrial by-products applied as crop fertilizers and soil conditioners have also been tested for hemp production. Zielonka et al. (2017) studied the effects of sewage sludge (with and without gypsum) on hemp photosynthetic performance. The authors reported increased chlorophyll content in the leaves; however, this effect varied among hemp varieties. In hops, the gypsum benefits are long known (Mayer, 1768); however, no specific recommendation for calcium or sulfur rates has been reported yet (Gingrich et al., 2000; HĀPI, 2019). In these cases, where there is a lack of information regarding gypsum rate, the use of soil parameters - as indicated by other researchers for gypsum recommendations (Ernani et al., 1992; Sousa et al., 1992; van Raij et al., 1997; Sousa and Lobato, 2004; Sousa et al., 2007; Guimaraes et al., 2015; Pauletti and Motta, 2017; Tiecher et al., 2018) - is the most appropriated approach of determining a gypsum rate to be applied.

PLANT DISEASE RESPONSES TO GYPSUM

As highlighted here, gypsum is primarily a source of calcium and sulfur, especially in subsoil layers, which can provide adequate nutrition to improve the plant root system, absorption of nutrients, and natural disease control. Some reports of gypsum success management in controlling plant diseases have been published in the literature. The plant protection enhanced by gypsum application is probably related to improved calcium and sulfur plant nutrition, besides the soil improvements already mentioned.

Calcium is an essential factor for cell wall and membrane stability (structural functions) but also a secondary messenger in many physiological processes (signaling functions) that include the plant's responses to stresses via calcium-dependent proteins (Lecourieux et al.; 2006; Zheng et al., 2013; Thor, 2019). Sulfur plays an essential role in plant development by being a structural constituent of critical macro-biomolecules (amino acids, proteins, and oils) that regulate many processes regarding plant tolerance to environmental stresses (Zenda et al., 2021). Additionally, sulfur positively interacts with soil nitrogen, phosphorus, and microorganisms, improving soil health.

Walker and Csinos (1980) evaluated the effects of gypsum application on peanut (*Arachis hypogaea*) yield, kernel grade, and pod rot (*Pythium myriotylum* and/or *Rhizoctoniu solani*) damage in five peanut varieties in a sandy loam soil for three consecutive years. The authors detected reductions in pod rot severity, increments in kernel calcium content, and peanut yield for all cultivars as the gypsum rate increased. In watermelon (*Citrullus lanatus*), the rising rates of calcium applied as gypsum also reduced the incidence of blossom-end rot. This abiotic disease is caused by calcium deficiency, and the symptom is characterized by increasing dark rotten spots at the end of the watermelon fruit (Scott et al., 1993).

Narasimhan et al. (1994) studied the foliar applications of calcium sulfate, magnesium sulfate, ammonium molybdate, soil gypsum applications (500 kg ha^{-1}), and fungicide (carbendazim) application to manage sheath rot (*Sarocladium oryzae*) in rice. The sheath rot incidence was assessed 20 days after the treatment's application and was counted as the percentage of tillers affected by the disease. The gypsum application to the soil or the foliar fungicide application presented similar results regarding the management of sheath rot and grain yield increase. The authors also observed that all gypsum treatments reduced the incidence of sheath rot in rice, but this did not always translate into yield gains. However, Zahra and Sarwar (2015) found positive effects of gypsum and potassium silicate on rice yield parameters (plant height, productive tillers, straw, grain yield, and total biomass). The same authors also highlighted that the role of gypsum was more prominent than that of potassium silicate in improving the rice yield.

Messenger et al. (2000) reported that the application of gypsum reduced root rot (*Phytophthora cinnamomi*) in avocado (*Persea americana*) seedlings regardless of good or poor soil drainage. The authors highlighted that (i) the gypsum reduced the negative effect of root rot on the entire avocado seedling and root weight; (ii) seedlings grown in gypsum-amended soil were more resistant to root rot; (iii) reductions in root rot infection were not caused by avocado growth, improved root resistance, or reduced cell-membrane permeability in the roots, and (iv) the root rot infection was not profoundly affected by poor soil drainage when high gypsum rates were applied.

According to Fernando et al. (2021), gypsum is an important soil amendment to enhance plant growth, protection, and onion (*Allium cepa*) production. The authors reported that the best results for anthracnose (*Colletotrichum* spp.) control (non-occurrence of tip-burning or bulb rot) and onion bulb yield were observed when gypsum application was split in two (50 kg ha^{-1} at planting and 50 kg ha^{-1} two weeks after). This result indicates that a more constant nutrient availability by splitting the fertilizer rate is an adequate strategy to improve plant performance and sanity.

Applying gypsum (8 Mg ha^{-1}) on Mombaça grass (*Panicum maximum* cv. Mombaça) also generated significant improvements, increasing plant fresh-biomass, seed production, and root system volume in an Oxisol. Additionally, the sulfur in gypsum reduced leaf spot occurrence and severity (*Bipolaris maydis*) (Figure 6).

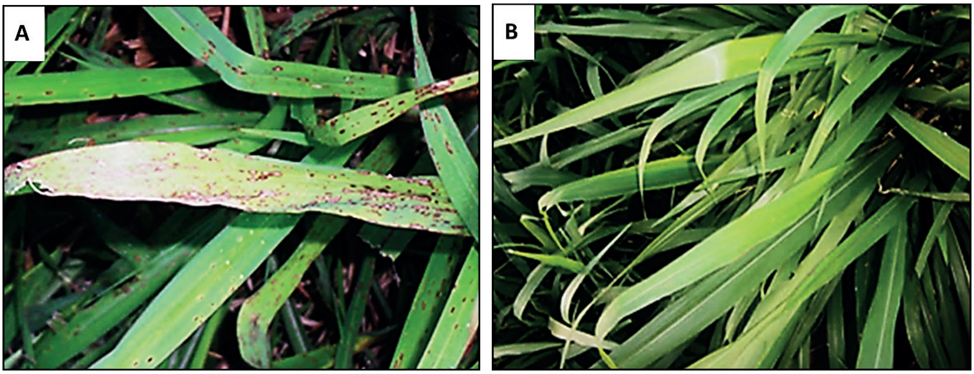

Figure 6. Incidence of leaf spot (*Bipolaris maydis*) on Mombaça grass (*Panicum maximum*). A: control treatment (no gypsum applied). B: gypsum treatment (8 Mg ha^{-1}).

Source: Pádua Jr., A. L.

GYPSUM AGRICULTURAL RATE RECOMMENDATIONS

Many of the gypsum interactions with the soil are known, and the results expected from its application are relatively well described, at least for the short-term experience with gypsum; however, the method of gypsum recommendation varies for different purposes and circumstances (van Raij, 2010). The positive effects of gypsum application in soil and plants are usually expected to occur when (i) root penetration is limited by available aluminum or low calcium contents in subsurface soil layers and when (ii) soil compaction can be alleviated by reducing the dispersion of clays in the soil. Ritchey et al. (1995) also indicated that (i) soils under periodic drought (water stress) or (ii) excessive rainfall (increased nitrogen leaching) and (iii) areas where the application of calcium can decrease the subsoil acidity are areas prone to present improved plant results from the gypsum application. Soils of dystrophic, dystrophic alic, aluminic, and acric characteristics are also prone to respond positively to gypsum application (Santos et al., 2018).

Gypsum application is standard for soil and crop management in many tropical soils, such as Brazil. Different methods of gypsum recommendations for crop production and soil conditioning are presented, and all of them are adequate for defined scenarios. However, a unique method for determining suitable gypsum application rates for all soils and cropping systems is unavailable. Many gypsum recommendations are based on empirical experiences and ranges of rate responses to gypsum. For example, Koske et al. (2005) reported for many Louisiana (USA) soils that if soil analysis indicates low calcium contents and soil pH of low acidity to alkaline, then 2,441 to 3,906 kg of gypsum should be added per hectare and incorporated by soil tillage before tomato planting in greenhouse areas.

Other imprecise recommendations include soil and medium ameliorations in greenhouses, nurseries, landscapes, and sports fields. These recommendations are usually based on the same soil attributes considered for field crops; however, the rates applied to those specific places are generally higher to reduce the frequency of gypsum application (Chen and Dick, 2011). In most tropical soils, the regular gypsum rate recommendations for no-tillage (no soil disturbance) cropping systems are established on the subsoil contents of calcium, aluminum, sulfur, and phosphorus, the clay content, and the CEC. Those regular gypsum rate recommendations were naturally developed for conventional tillage cropping systems. However, Guimaraes et al. (2015) found a strong correlation between grain yield increase in no-tillage cropping areas and calcium saturation (78-84%) at 0-0.1 m soil depth. The authors used a machine learning technique and concluded that calcium saturation in the effective CEC, instead of aluminum saturation, is essential to estimate gypsum requirements in no-tillage cropping areas.

However, when the exchangeable calcium content is 0.5 $\mathrm{cmol_c\ dm^{-3}}$ or lower and/or subsoil aluminum saturation is 20% or greater, significant positive responses to the soil and crop plants are expected, according to Sousa and Lobato (2004), Sousa et al. (2007), and Pauletti and Motta (2017). Other recommendations are based on different variables. Demattê (1986) presented a gypsum recommendation for sugarcane crops based on the average soil CEC and soil base saturation (Table 2) in the 0-0.4 m layer of dystrophic sandy soil. The author also observed the (i) rise of soil base saturation in deep soil layers and (ii) 14 $\mathrm{Mg\ ha^{-1}}$ more sugarcane produced (three cuts average) when 2 $\mathrm{Mg\ ha^{-1}}$ of gypsum was applied to ratoon sugarcane.

CEC ($\mathrm{mmol\ dm^{-3}}$)	V (%)	Gypsum rate ($\mathrm{Mg\ ha^{-1}}$)
< 30	< 10	2
	10 - 20	1.5
	20 - 35	1
30 - 60	< 10	3
	10 - 20	2
	20 - 35	1.5
60 - 100	< 10	3.5
	10 - 20	3
	20 - 35	2.5

Table 2. Approximated gypsum rate according to the cation exchange capacity (CEC) and soil base saturation (V).

Source: Demattê (1986).

Oliveira et al. (2007) recommended gypsum application to sugarcane crops when the soil calcium contents are below 0.4 $\mathrm{cmol_c\ dm^{-3}}$ and the aluminum saturation is bigger than 20% in the 0.2-0.4 m soil layer. The authors recommended gypsum based on a fraction of the recommended lime rate for sugarcane multiplied by a correction factor according to the soil layer: $G = (LR \times 0.3) \times (SL/0.2)$, where G is the rate of gypsum to be applied (Mg ha^{-1}), LR is the lime recommendation (Mg ha^{-1}) for the respective area, and SL is the soil layer depth interval that will be conditioned (m).

Vitti et al. (2005) also studied the application of gypsum to the sugarcane crop. The authors presented that if the calcium content is lower than 0.5 cmol$_c$ dm^{-3}, or the aluminum content is higher than 0.5 cmol$_c$ dm^{-3}, or the aluminum saturation is higher than 30%, or the base saturation is lower than 30% in the subsoil layer (0.2-0.4 m), then, significant effects of gypsum applications are expected to happen to the sugarcane crops. The gypsum recommendation proposed by Vitti et al. (2005) depends on the soil base saturation and CEC: $G = ((V_2 - V_1) \times CEC)/50$, where G is the rate of gypsum to be applied (Mg ha^{-1}), V_2 and V_1 are the desired and the actual soil base saturation (%), respectively, and CEC is the cation exchange capacity (cmol$_c$ dm^{-3}).

The harmful subsoil conditions of low calcium content and acidity generate poor root system penetration, especially when exchangeable aluminum is highly available. These can be considered the most detrimental conditions for plant development and yield. Gypsum can help solve those limitations to improve plant development. According to Lorenzi et al. (1997), soils presenting less than 0.4 cmol$_c$ dm^{-3} of calcium and/or aluminum saturation greater than 40% are significantly responsive to gypsum application. The gypsum recommendation in these soils was also based on the soil clay content: $G = 6 \times clay$, where G is the rate of gypsum to be applied (kg ha^{-1}), and $clay$ is its amount (g kg^{-1}) in the subsoil layer (0.2-0.4 m).

Alvarez et al. (1999) indicated that if the calcium content is lower than 0.4 cmol$_c$ dm^{-3}, or the aluminum content is higher than 0.5 cmol$_c$ dm^{-3}, or the aluminum saturation is higher than 30% in the subsoil layer (0.2-0.4 or 0.3-0.6 m), then the positive effects of gypsum applications are expected to happen to the crops and soils. The gypsum recommendation is based on soil texture and varies from 0-400 kg ha^{-1} (0-15% clay) to 1200-1600 kg ha^{-1} (60-100% clay).

According to Sousa et al. (2001), the gypsum rate for soils cultivated with pasture can be recommended based on the soil clay content and soil texture when gypsum is intended as a soil conditioner and based on the sulfur content when gypsum is designed as a sulfur source. The gypsum rate estimated from the soil clay content is calculated as $G = 50 \times clay$, where G is the rate of gypsum to be applied (kg ha^{-1}), and $clay$ is its amount (% or dag kg^{1}) in the subsoil layer (0.4-0.6 m). According to soil texture, the gypsum recommendation varies from 700 kg ha^{-1} (sandy soils) to 3,200 kg ha^{-1} (clayey soils). The residual effects of gypsum, recommended according to soil clay content or texture, can last at least five years.

The gypsum recommendation to supply sulfur to the plants is based on the average soil sulfur contents in the 0-0.4 m soil layer (Sousa et al., 2001). To soils with low sulfur contents ($\leq$ 4 mg dm^{-3}), the gypsum rate is $G = 10 \times clay$, where G is the rate of gypsum to be applied (kg ha^{-1}), and $clay$ is its amount (% or dag kg^{-1}) in the soil. To soils with medium sulfur contents (5-9 mg dm^{-3}), the gypsum rate is $G = 5 \times clay$. The residual effects of gypsum, recommended according to soil clay content or texture, can last at least two years. When the soil sulfur content is high (≥ 10 mg dm^{-3}), no gypsum application is needed unless the area is intended for pasture establishment or recovery and the soil sulfur content is lower than 4 mg dm^{-3} in the first 0.2 m of the soil profile.

Pias et al. (2019) also argued that (i) the no-tillage cropping system altered the soil sulfur dynamics, (ii) the emergence of high-yield crop varieties, (iii) the application of low-concentration sulfur fertilizers, and (iv) the reduction in atmospheric sulfur depositions makes the recommendation for sulfur fertilizers a priority since positive responses are expected, especially when the soil analysis (0-0.2 m depth) is below 7.5 mg dm^{-3}.

Sousa and Lobato (2004) also indicated that if the calcium content is 0.5 $cmol_c$ dm^{-3} or lower and/or subsoil aluminum saturation is 20% or greater, and the gypsum rate is for an annual crop, then it can be estimated as $G = 50 \times clay$, where G is the rate of gypsum to be applied (kg ha^{-1}), and $clay$ is its amount (% or dag kg^{-1}) in the subsoil layer (0.2-0.4 m); if the gypsum rate is for a perennial crop, then it can be estimated as $G = 75 \times clay$, where G is the rate of gypsum to be applied (kg ha^{-1}), and $clay$ is its amount (% or dag kg^{-1}) in the subsoil layer (0.2-0.4 m)

According to Sousa et al. (1992), the study of subsoils in Cerrado (Savanna-like biome presenting weathered acid soils) indicated that significant responses to gypsum application might occur when subsoil exchangeable calcium contents below 0.1 $cmol_c$ kg^{-1}, regardless of subsoil aluminum content. The authors also showed that when soil calcium contents exceed the plant's needs, the aluminum content dictates the occurrence of significant gypsum effects. In these conditions, significant soil and plant responses are expected to happen when aluminum saturation contents are above 65% and lower responses when aluminum saturation is below 35%. Sousa et al. (1992) presented a formula to determine gypsum recommendation also based on the soil clay content: $G = 17 + 6.508 \times clay$, where G is the rate of gypsum to be applied (kg ha^{-1}), and $clay$ is its amount in the subsoil layer (g kg^{-1}). Moreover, acid soils with low CEC were reported to be similarly responsive to gypsum application (Demattê, 1992), including Oxisols, oxidic Ultisols, and low-CEC acid Inceptisols and Entisols. Sousa et al. (1992) also suggested using remaining phosphorus to indicate the gypsum rate; the extreme rate values varied from about 0.453 to 0 Mg ha^{-1} for 30 to 60 mg dm^{-3} of phosphorus and from 1.680 to 0.720 Mg ha^{-1} for 0 to 19 mg dm^{-3} of phosphorus.

Despite the many options, some inconsistencies regarding the gypsum recommendations and rates have been pointed out. Pivetta et al. (2019) evaluate cotton root development in an Oxisol related to aluminum and calcium activity and speciation in the soil solution as affected by gypsum rates based on soil clay content. The authors found that (i) the cotton root growth was more related to soil properties such as calcium content, aluminum saturation, base saturation, ratio calcium-effective cation exchange capacity, and ratio aluminum-calcium than to soil solution attributes, and (ii) that the current gypsum recommendations based on soil clay content are underestimating the gypsum rates needed by the cotton crop.

Lately, Caires and Guimarães (2018) suggested a method for estimating gypsum rates based on the increase in calcium saturation to 60% in the effective CEC (eCEC = soil base sum + aluminum) at the subsoil layer (0.2-0.4 m). Over 10 years, the authors studied the effects of gypsum application on maize, soybean, wheat, and barley and, through an algorithm approach to regressions, proposed $G = (0.6 \times eCEC - Ca) \times 6.4$, where G is the rate of gypsum to be applied (Mg ha^{-1}), $eCEC$ is the effective cation exchange capacity (cmol$_c$ dm^{-3}), and Ca is the exchangeable soil calcium (cmol$_c$ dm^{-3}). The gypsum rates recommended by this method were closer to those associated with maximum economic yield than those indicated by other methods based on subsoil clay content, which is currently used in Brazil. Thus, the proposed method can be efficiently utilized when subsoil acidity is an important growth-limiting factor.

Therefore, among many gypsum rate recommendations for most agricultural situations, the selection of an appropriate rate usually depends on the contents of exchangeable ions (e.g., calcium, aluminum, sulfur, phosphorus), soil type, clay content, soil CEC and eCEC, base saturation, cropping system, rainfall regime, and the purpose of gypsum application (Sousa et al., 2001; Chen and Dick, 2011; Kost et al., 2014). The soil morphology is another variable that could be considered in the definition of adequate gypsum management, especially the rate of gypsum application and the moment of its reapplication. As reported by Cooper & Vidal-Torrado (2005), there are soil horizons, for example, characterized by extended development of structural pores (macropores), which favor water conduction processes (higher hydraulic conductivity), and less development of textural pores (micropores), reducing water retention in the horizon. Such conditions would affect the dynamic of gypsum results in soil and the time of its residual effect on plants.

In subtropical regions, gypsum application is still not a common practice. The knowledge of its effect on the soil-plant-environment system is less detailed, with no well-established parameter to decide for gypsum application. However, Tiecher et al. (2018) found significant and positive results with gypsum application when aluminum saturation was above 10% and calcium content was below 3 cmol$_c$ dm^{-3} in subtropical subsoil layer (0.2-0.4 m) under no-tillage cropping system. Under these subsoil conditions (aluminum saturation > 10%, calcium < 3 cmol$_c$ dm^{-3}), maize and winter cereals grain yield increased by about 16 and 19%, whether the soil was water-deficient or not. Soybean grain yield only increased (27%) when gypsum was applied to soils of high subsurface acidity and water deficiency. The authors also highlighted that high gypsum rates (6-15 Mg ha^{-1}) are applied to soils with low aluminum saturation and high calcium contents that may cause reductions in grain yield due to induced potassium and magnesium deficiency.

Additionally, Ernani et al. (1992) studied the application of gypsum to clayey soils with high CEC in temperate regions of regular rain distribution. The calcium contents in the studied soils were high, well above the level where calcium deficiencies would be expected.

Consequently, the authors observed low to no positive responses from the gypsum application, indicating the importance of identifying the subsoil characteristics that would positively respond to the gypsum application.

GYPSUM DOSAGE ERRORS

The under and overestimation of the gypsum rates can occur when soils present specific conditions with thick A or A-E horizons (over 0.4 m thick) – arenic and thick arenic soils – and soils with B horizons with high contents of available aluminum and clay. Therefore, the traditional methodologies for gypsum recommendation presented here might not reflect the adequate gypsum rate to deliver the expected soil-plant-environment benefits. In Oxisol and Nitosol soils (weathered soils with different B horizon attributes) of similar texture, the gypsum recommendation based on soil clay content might not meet the plant's requirements for its full development or the expected soil improvements.

In Nitosols, the water flow through soil layers is reduced by the occurrence of clay films and soil structure of subangular to prismatic blocks (B nitic) (Cooper and Vidal Torrado, 2005; Grego et al., 2011). The lower drainage of these soils increases the gypsum residual effects compared to the Oxisols (weak subangular blocky structure, with or without the granular structure, and no or faint clay film), thus affecting gypsum effects due to similar gypsum recommendations for soils of similar clay contents. Figure 7 exemplifies the differences observed between distinct soils cropped with soybeans.

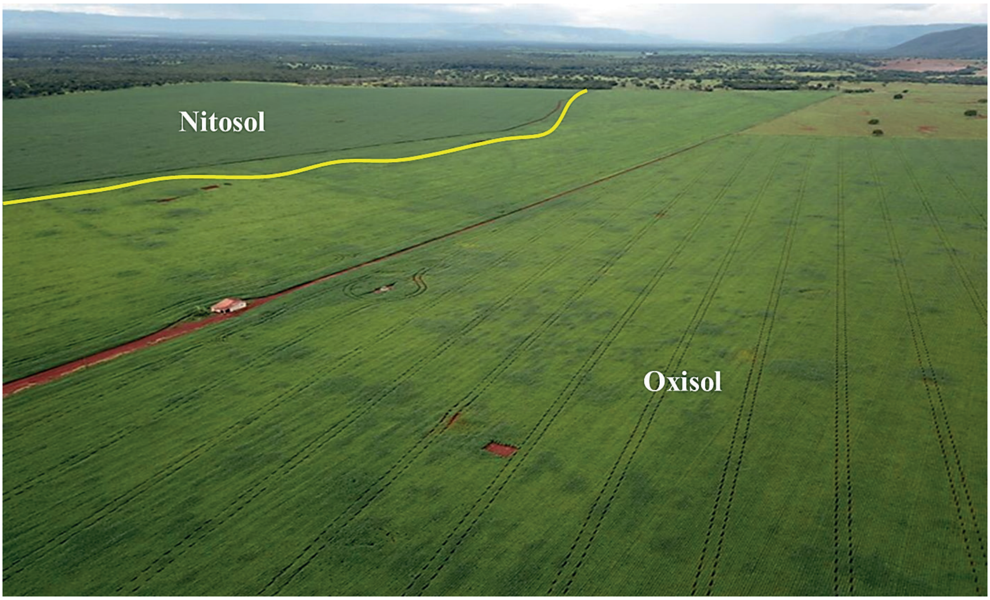

Figure 7. The residual effect of gypsum fertilization (4 Mg ha^{-1} applied 4 years before the picture register in the summer of 2022) in a Nitosol and Oxisol.

Source: Fachinetto, G. K.

The suggestion for situations where soil parameters affect the reaction of gypsum is to evaluate soil in more profound depths. Predicting adequate gypsum rates thus requires information about soil attributes that can reach 1 meter or deeper. Soil information from deep soil layers helps to understand the limitations and improvements needed for high gypsum efficiency and crop performance.

GYPSUM HANDLING AND APPLICATION

Gypsum (mined or FGDG) is not combustible or explosive and is not expected to produce any hazards under regular everyday use. No specific individual protection equipment is usually required for gypsum handling under ordinary conditions; still, always consult the current regulatory guidelines and policies before taking and storing any substance. However, a valid recommendation is to avoid, as much as possible, breathing gypsum dust, which may irritate in contact with the eyes, respiratory tract, throat, and skin. Gypsum is usually stored in the open at a strategic point that facilitates its future distribution in the cropping areas; however, when gypsum is stored in a closed-covered structure, enough ventilation must be provided to control airborne dust when generated.

Summarized gypsum rate recommendations, time of application, and method of application are presented by Chen and Dick (2011). The authors also recommended (i) annual gypsum application when gypsum is intended to be a nutritional source of calcium and sulfur and (ii) split gypsum application if high rates are required. In this latter situation, the initial gypsum rate should be higher to remediate the restrictive soil situation, and the subsequent rates should be for maintenance and annually applied. The gypsum application can be made any time of the year; however, its application during autumn and winter is usually the most common practice. The gypsum application in those seasons permits (i) the application after crops are harvested, (ii) soil drying, which implies lower damage caused by the drive of heavy spreading equipment across the field, and (iii) allows enough time for gypsum-soil reactions to provide the gypsum benefits to the next crop season.

As indicated here, there are many gypsum recommendation methods. At the same time, there is a lack of a reliable way of defining gypsum rates and frequency of application for many situations. This lack presents a potential difficulty for farmers, researchers, and consultants when determining adequate gypsum management. For those without a gypsum recommendation for a specific situation, we suggest consistent literature research (e.g., scientific papers, book chapters, bulletins, regional technical circulars, and advertisements) for particular soil conditions, climate, and crops intended to be cultivated. Then, identify the closest and most successful reports as references for a gypsum management strategy.

After the definition of gypsum management (rates and frequency of application), the method to use gypsum will depend on its granulometry (finer granulometry means faster reaction in soil), gypsum source, and the urgency for its benefits. Crushed or powdered gypsum provides the same benefits as pelletized gypsum (granular form). However, pelletized gypsum offers important benefits such as (i) improved handling (pellets are easier to handle, store, transport, and apply; also, powdered gypsum has a great potential to clump together, clogging equipment and increasing maintenance requirements); (ii) better distribution (powdered gypsum is dusty and often becomes windblown reducing the precision of its application; also, pellets move quickly through standard spreading equipment), and, (iii) reduced product loss (powdered gypsum result in a significant amount of product losses due to its dusty origin which makes it easy to fly away from the targeted area). Conversely, pelletized gypsum might need extended time for its complete solubilization reaction in soil due to its low solubility. When deciding on powdered gypsum, avoiding its application during intense windy days is recommended to reduce material losses.

Gypsum is usually spread over the soil's surface in no-tillage cropping areas, or gypsum is incorporated downward into the subsoil. Gypsum incorporation is less frequent in tropical areas (hot, rainy areas). Gypsum incorporation is also an alternative to avoid and decrease gypsum erosion by wind and water; however, soil turning to incorporate gypsum, or any crop input is a pricy activity. Additionally, this soil management reduces the soil's water-holding capacity due to de-structuring during the soil incorporation process, which lowers the plant's resistance to occasional drought stress. Still, when soil turning is needed, many doubts arise regarding the frequency and cost-benefits of such activity together (or not) with gypsum management.

Nevertheless, dry-material spinners or drop spreaders regularly apply gypsum to the soil surface. Gypsum can also be dissolved in irrigation water if it is a fine powder (0.074 mm in size or smaller) for fast gypsum results in soil and uniform gypsum application (Chen and Dick, 2011). However, avoid foliar applications with gypsum and other agrochemicals, as they tend to form precipitates when the foliar spray solution dries on the plant's surfaces. This dried spray solution covers the plants with a thin film of gypsum, potentially blocking a fraction of sunlight and reducing the photosynthesis efficiency.

GYPSUM KNOWLEDGE GAPS AND FUTURES RESEARCH

Considering the points discussed here and the fact that the application of agricultural gypsum is still not a regular practice in many regions worldwide, we understand that to improve its usage, we must primarily stimulate and support public policies about the benefits of adequate gypsum management. These policies must reach the crop production system with technical criteria and initial professional support, especially to the smaller farmers who generally are the least benefited from technologies that seek sustainability in agriculture.

Even with all the research on the effects and benefits of gypsum application to the agricultural complex - including soil dynamics, plant physiology, environmental safety, and economic thresholds - many critical issues are still not fully understood (Watts and Dick, 2014; Dalla Nora et al., 2017; Pias et al., 2020). Some aspects of the gypsum's long-term effects on (i) soil organic matter; (ii) nitrogen, magnesium, and phosphorus dynamics in soil; (iii) lime joint application and management; (iv) doses and frequency of regular fertilizer application; (v) the time needed to achieve significant results from the gypsum application; (vi) the economic value of gypsum crop management on yield (cost-benefits), and (vii) the environmental services are not well comprehended and need to be elucidated.

Additionally, other agricultural technologies are being developed and implemented to improve crop productivity (yield per area) and the sustainability of the agricultural activity, and indeed, they will affect the soil and plant responses and the agronomic recommendations for gypsum management. Such improved technologies include (i) smart fertilizers (e.g., slow and controlled release fertilizers, bioformulated fertilizers, nanofertilizers, beneficial nutrients) developed to enhance nutrient use efficiency and crop yield with low impacts on the natural environment (Raimondi et al., 2021; Karthik and Maheswari, 2021; Tayade et al., 2022; Verma et al., 2022; Abiola et al., 2023; Areche et al., 2023; Chakraborty et al., 2023); genetic engineering and genome editing techniques of crop plants to improve their resistance to stresses and use-efficiency of agricultural amendments (Jan and Shrivastava, 2017; Mackelprang and Lemaux, 2020; Clouse and Wagner, 2021; Lebedev et al., 2021; Raza et al., 2022); large-scale application of artificial lights (light supplementation) to field crops (Lemes et al., 2021), and digitalization-integration-robotization plus AI (artificial intelligence), DL (deep learning) and blockchain of agriculture (Krithika, 2022; Srivastava, et al., 2022; Adamides and Edan, 2023; Ali et al., 2023; Mahibha and Balasubramanian, 2023; Cheng et al., 2023; Mesías-Ruiz et al., 2023; Okolie et al., 2023; Wakchaure et al., 2023; Zeng et al., 2023) are emerging and represent some of the most recent advances for modern sustainable and productive agriculture.

Overall, we can assure you that gypsum is very important to maintain and improve soil health and its functionality for high crop nutrition and yield performance. Gypsum and other technologies can also lower production costs, reduce the negative impacts of agriculture on the natural and social environment, and increase world food safety.

ACKNOWLEDGMENTS

To *Universidade do Vale do Jequitinhonha and Mucuri*, to *Instituto Federal do Triângulo Mineiro*, and to *Universidade Federal de Uberlândia* for personnel and structural support.

To all previous researchers, cited or not here, who used their expertise and time to understand and improve gypsum agricultural management. Many thanks!

REFERENCES

Abbas, F.; Siddique, T.; Fan, R.; Azeem, M. 2023. Role of gypsum in conserving soil moisture macronutrients uptake and improving wheat yield in the rainfed area. Water, 15: 1011. https://doi.org/10.3390/w15061011

Abiola, W. A.; Diogo, R. V. C.; Tovihoudji, P. G.; Mien, A. K.; Schalla, A. 2023. Research trends on biochar-based smart fertilizers as an option for the sustainable agricultural land management: bibliometric analysis and review. Frontiers in Soil Science, 3: 1136327. https://doi.org/10.3389/fsoil.2023.1136327

AbouRizk, J. S.; Dhar, A.; Naeth, M. 2024. Sandy soil with phosphogypsum improves hydraulic conductivity and leachate chemical properties for reclamation. Environmental Sustainability. https://doi.org/10.1007/s42398-024-00302-2

Adamides, G; Edan, Y. 2023. Human-robot collaboration systems in agricultural tasks: A review and roadmap. Computers and Electronics in Agriculture, 204, 107541. https://doi.org/10.1016/j.compag.2022.107541

Adams, T. C.; Ashworth, A. J.; Owens, P. R.; Popp, M.; Moore, P.A.; Pennington, J. 2022. Pasture conservation management effects on soil surface infiltration in hay and grazed systems. Journal of Soil and Water Conservation, 77(1): 59-66. https://doi.org/10.2489/jswc.2022.00182

Agim, L. C.; Ahukaemere, M. C.; Uzoh, I., Onwudike, S. U.; Osisi, A. F.; Ihem, E. E.; Nkwopara, U. 2021. Soil degradation and the human condition, including the pandemic, interactions, causes, impacts, control measures and likely future prospects. In: Aide, M. T.; Braden, I. (Eds.), Soil Science - Emerging Technologies, Global Perspectives and Applications. IntechOpen. https://doi.org/10.5772/intechopen.101153

Ahmed, K.; Qadir, G.; Nawaz, M. Q.; Riaz, M. A.; Nawaz, M.; Ullah, M. M. 2020. Combined effect of growth hormones and gypsum induces salinity tolerance in wheat under saline-sodic soil. Pakistan Journal of Agricultural Sciences, 58(6): 1749-1757. https://doi.org/10.36899/japs.2021.1.0200

Alcordo, I. S.; Rechcigl, J. E. 1993. Phosphogypsum in agriculture: A review. In: Spark DL (Ed) Advances in Agronomy, 49: 55-118. https://doi.org/10.1016/S0065-2113(08)60793-2

Ali, A.; Hussain, T.; Tantashutikun, N.; Hussain, N.; Cocetta, G. 2023. Application of smart techniques, internet of things and data mining for resource use efficient and sustainable crop production. Agriculture, 13, 397. https://doi.org/10.3390/agriculture13020397

Ali, M. T.; Shahram, S. H. 2007. Converter slag as a liming agent in the amelioration of acidic soils. International Journal of Agriculture and Biology, 9(5): 715-720. Available at: https://www.fspublishers.org/Issue.php?no_download=published_papers/81882_..pdf&issue_id=1313

Alvarez V. V. H.; Dias, L. E.; Ribeiro, A. C.; Souza, R. B. 1999. Uso de gesso agrícola. In: Ribeiro, A. C. Guimarães, P. T. G.; Alvarez V. V. H. (Ed.). Recomendação para o uso de corretivos e fertilizantes em Minas Gerais: 5ª aproximação. Viçosa, MG: Comissão de Fertilidade do Solo do Estado de Minas Gerais. p.67-78.

Amer, M. M.; Aboelsoud, H. M.; Sakher, E. M.; Hashem, A. A. 2023. Effect of gypsum, compost, and foliar application of some nanoparticles in improving some chemical and physical properties of soil and the yield and water productivity of faba beans in salt-affected soils. Agronomy, 13(4): 1052. https://doi.org/10.3390/agronomy13041052

Amezketa, E.; Aragüés, R.; Gazol, R. 2005. Efficiency of sulfuric acid, mined gypsum, and two gypsum by-products in soil crusting prevention and sodic soil reclamation. Agronomy Journal, 97: 983-989. https://doi.org/10.2134/agronj2004.0236

Anderson, G. C.; Pathan, S.; Hall, D. J. M.; Sharma, R.; Easton, J. 2021a. Short- and long-term effects of lime and gypsum applications on acid soils in a water-limited environment: 3. Soil solution chemistry. Agronomy, 11: 826. https://doi.org/10.3390/agronomy11050826

Anderson, S. L. II; Pearson, B.; Kjelgren, R.; Brym, Z. 2021b. Response of essential oil hemp (*Cannabis sativa* L.) growth, biomass, and cannabinoid profiles to varying fertigation rates. PLoS ONE 16(7): e0252985. https://doi.org/10.1371/journal.pone.0252985

Anikwe, M.; Eze, J.; Ibudialo, A. 2016. Influence of lime and gypsum application on soil properties and yield of cassava (*Manihot esculenta* Crantz.) in a degraded Ultisol in Agbani, Enugu Southeastern Nigeria. Soil Tillage Research, 158: 32-38. http://dx.doi.org/10.1016/j.still.2015.10.011

Araújo, L. C.; Souza, D. M. G.; Figueiredo, C. C.; Rein, T. A.; Nunes, R. S.; Santos Jr, J. D. G.; Malaquias, J. V. 2019. How does gypsum increase the organic carbon stock of an Oxisol profile under sugarcane? Geoderma, 343: 196-204. https://doi.org/10.1016/j.geoderma.2019.02.029

Areche, F. O.; Aguilar, S. V.; More López, J. M.; Castañeda Chirre, E. T.; Sumarriva-Bustinza, L. A.; Pacovilca-Alejo, O. V.; Camposano Córdova, Y. F.; Montesinos, C. C. Z.; Quincho Astete, J. A.; Quispe-Vidalon, D.; Brito Mallqui, C. H.; Camayo-Lapa, B. F.; Malpartida Yapias, R. J.; Corilla Flores, D. D.; Salas-Contreras, W. H. 2023. Recent and historical developments in chelated fertilizers as plant nutritional sources, their usage efficiency, and application methods. Brazilian Journal of Biology, 24(83): e271055. https://doi.org/10.1590/1519-6984.271055

Argüello, D.; Dekeyrel, J.; Chavez, E.; Smolders, E. 2022. Gypsum application lowers cadmium uptake in cacao in soils with high cation exchange capacity only: A soil chemical analysis. European Journal of Soil Science, 73(2): e13230. https://doi.org/10.1111/ejss.13230

Ashrit, S.; Banerjee, P. K.; Chatti, R. V.; Rayasam, V.; Nair, U. G. 2015. Synthesis and characterization of yellow gypsum from LD slag fines generated in a steel plant. Current Science, 109(4): 727-732. Available at: https://www.currentscience.ac.in/Volumes/109/04/0727.pdf

Ashrit, S.; Chatti, R. V.; Sarkar, S., Venugopal, R.; Udayabhanu, G. 2020. Potential application of yellow gypsum from LD slag as a soil conditioner. Current Science, 118(1). https://doi.org/10.18520/cs/v118/i1/114-118

Ashrit, S.; Chatti, R.V.; Udpa, K. N.; Venugopal, R.; Nair, U. G. 2016. Process optimization of yellow gypsum synthesized from LD Slag fines-an opportunity for value addition of LD Slag. Metallurgical Research and Technology, 113(6): article 605. https://doi.org/10.1051/metal/2016037

Auler, A. C.; Caires, E. F.; Pires, L. F.; Galetto, S. L.; Romaniw, J.; Charnobay, A. C. 2019. Lime effects in a no-tillage system on Inceptisols in Southern Brazil. Geoderma Regional, 15, e00206. https://doi.org/10.1016/j.geodrs.2019.e00206

Ayanda, A. F.; Jusop, S.; Ishak, C. F. 2020. Othman, R. Utilization of magnesium-rich synthetic gypsum as magnesium fertilizer for oil palm grown on acidic soil. PLoS ONE, 15: e0234045. https://doi.org/10.1371/journal.pone.0234045

Baligar, V. C.; Clark, R. B.; Korcak, R. F.; Wright, R. J. 2011. Flue gas desulfurization product use on agricultural land. Advances in Agronomy, 111: 51-86. https://doi.org/10.1016/B978-0-12-387689-8.00005-9

Bardhan, S.; Chen, L.; Dick, W. A. 2005. Soilless media created from coal combustion products and organic composts: environmental and chemical properties. In: Agronomy Abstracts. American Society of Agronomy, Madison, Wis. Available at: https://scisoc.confex.com/a-c-s/2005am/techprogram/P5391.HTM

Basak, N.; Sheoran, P.; Sharma, R.; Yadav, R. K.; Singh, R. K.; Kumar, S.; Krishnamurthy, T.; Sharma, P. C. 2021. Gypsum and pressmud amelioration improve soil organic carbon storage and stability in sodic agroecosystems. Land Degradation & Development 32(15): 4430-4444. https://doi.org/10.1002/ldr.4047

Batte, M. T.; Forster, D. L. 2015. Old is new again: the economics of agricultural gypsum use. Journal of the American Society of Farm Managers and Rural Appraisers, 56-74. Available at: https://www.usagypsum.com/wp-content/uploads/2016/04/economics-of-agricultural-gypsum-use.pdf

Bello, S. K.; Alayafi, A. H.; AL-Solaimani, S. G.; Abo-Elyousr, K. A. M. 2021. Mitigating soil salinity stress with gypsum and bio-organic amendments: a review. Agronomy, 11, 1735. https://doi.org/10.3390/agronomy11091735

Besen, M. R.; Coneglian, C. F.; Cassim, B. M. A. R.; Kachinski, W. D.; Inoue, T. T.; Batista, M. A. 2021a Forms of lime application and use of phosphogypsum in low acid soil in southern Brazil: soybean-wheat yield and soil chemical properties. Revista Brasileira de Ciência do Solo, 45: e0210001. https://doi.org/10.36783/18069657rbcs2021000x

Besen, M. R.; Ribeiro, R. H.; Esper Neto, M.; Minato, E. A.; Coneglian, C. F.; Kachinski, W. D.; Tormena, C. A.; Inoue, T. T.; Batista, M. A. 2021b. Lime and phosphogypsum application management: changes in soil acidity, sulfur availability and crop yield. Revista Brasileira de Ciência do Solo, 45: e0200135. https://doi.org/10.36783/18069657rbcs20200135

Besen, M. R.; Santos, G. L. A. A.; Cordioli, V. R.; Coneglian, C. F.; Inoue T. T.; Batista, M. A. 2024. Effects of applying lime and phosphogypsum in soybean and wheat nutrition. Journal of Plant Nutrition. https://doi.org/10.1080/01904167.2024.2308195

Bondi, G.; Fenton. O.; Sawdekar, P.; Keane, H.; Wall, D. P. 2021. Potential of lacto-gypsum as an amendment to build soil quality. Frontiers in Sustainability, 1:625727. https://doi.org/10.3389/frsus.2020.625727

Bortolanza, D. R.; Klein, V. A. 2016. Soil chemical and physical properties on an inceptisol after liming (surface and incorporated) associated with gypsum application. Revista Brasileira de Ciência do Solo, 40: e0150377. https://doi.org/10.1590/18069657rbcs20150377

Bossolani, J. W.; Crusciol, C. A. C.; Merloti, L. F.; Moretti, L. G.; Costa, N. R.; Tsai, S. M.; Kuramae, E. E. 2020. Long-term lime and gypsum amendment increase nitrogen fixation and decrease nitrification and denitrification gene abundances in the rhizosphere and soil in a tropical no-till intercropping system. Geoderma, 375: 114476. https://doi.org/10.1016/j.geoderma.2020.114476

Bossolani, J. W.; Lazarini, E.; Santos, F. L.; Sanches, I. R.; Meneghette, H. H. A.; Parra, L. F.; Souza, L. M. 2018. Surface reapplication of lime and gypsum on maize cultivated sole and intercropped with *Urochloa*. Communications in Soil Science and Plant Analysis, 49(15): 1855-68. https://doi.org/10.1080/00103624.2018.1475565

Brasil, E. C.; Lima. E. V.; Cravo, M. S. 2020. Uso de gesso na agricultura. In: Recomendações de calagem e adubação para o estado do Pará. 2. ed. – Brasília, DF: Embrapa, p. 133-145. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1127247

Brasil. Ministério da Agricultura, Pecuária e Abastecimento. Instrução Normativa SDA nº 35, 04-jul-2006. Normas sobre especificações e garantias, tolerâncias, registro, embalagem e rotulagem dos corretivos de acidez, de alcalinidade, de sodicidade e dos condicionadores de solo, destinados à agricultura. Diário Oficial da União, 12-jul-2006. Seção 1. Available at: https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/in-35-de-4-7-2006-corretivos.pdf

Brignoli, F. M.; Gatiboni, L. C.; Mumbach, G. L.; Grando, D. L.; Souza Junior, A. A.; Iochims, D. A. 2021. Soybean agronomic performance does not change with gypsum application in a Cambisol submitted to water restriction in Southern Brazil. Open Journal of Agricultural Research, 1(1): 30-44. https://doi.org/10.31586/ojar.2021.010106

Brock, C.; Jackson-Smith, D.; Kumarappan, S.; Brown, C. 2020. Farmer and practitioner conceptions and experiences with soil balancing. The Ohio State University. 45 p.

Brooks, S. N.; Horner, C. E.; Likens, S. T.; United States - Agricultural Research Service. 1961. Hop production. Agriculture Information Bulletin, n° 240. Agricultural Research Service, U.S. Department of Agriculture. 46 p. Available at: https://handle.nal.usda.gov/10113/CAT30947736

Brown, B. W. 2018. Horticultural uses for flue gas desulfurization gypsum. PhD Dissertation. Horticulture, Auburn University. 98 p. Available at: http://hdl.handle.net/10415/6221

Bryant, R. B.; Buda, A. R.; Kleinman, P. J.; Church, C.; Saporito, L. S.; Folmar, G. J.; Bose, S.; Allen, A. L. 2012. Using flue gas desulfurization gypsum to remove dissolved phosphorus from agricultural drainage waters. Journal of Environmental Quality, 41(3): 664-671. https://doi.org/10.2134/jeq2011.0294

Buckley, M. E.; Wolkowski, R. P. 2014. In-season effect of flue gas desulfurization gypsum on soil physical properties. Journal of Environment Quality, 43(1): 322-327. https://doi.org/10.2134/jeq2012.0354

Caires, E. F.; Churka, S.; Garbuio, F. J.; Ferrari, R. A.; Morgano, M. A. 2006. Soybean yield and quality a function of lime and gypsum applications. Scientia Agricola, 63(4): 370-379. https://doi.org/10.1590/S0103-90162006000400008

Caires, E. F.; Guimarães, A. M. 2018. A novel phosphogypsum application recommendation method under continuous no-till management in Brazil. Agronomy Journal, 110(5): 1987-1995. https://doi.org/10.2134/agronj2017.11.0642

Caires, E. F.; Joris, H. A. W.; Churka, S. 2011a. Long-term effects of lime and gypsum additions on no-till corn and soybean yield and soil chemical properties in southern Brazil. Soil Use Management, 27: 45-53. https://doi.org/10.1111/j.1475-2743.2010.00310.x

Caires, E. F.; Maschietto, E. H.G.; Garbuio, F. J.; Churka, S.; Joris, H. A. W. 2011b. Surface application of gypsum in low acidic Oxisol under no-till cropping system. Scientia Agricola, 68(2): 209-216. https://doi.org/10.1590/S0103-90162011000200011

Cañadas, E. M.; Ballesteros, M.; Valle, F.; Lorite, J. 2014. Does gypsum influence seed germination? Turkish Journal of Botany 38: 141-147. https://doi.org/10.3906/bot-1305-19

Cannoy, D. C. 2015. Green gold - a *Cannabis sativa* L. Lucis suitability analysis for West Virginia. Theses. Marshall University. Available at: https://mds.marshall.edu/etd/964/

Carvalho, M. C. S.; van Raij, B. 1997. Calcium sulphate, phosphogypsum and calcium carbonate in the amelioration of acid subsoils for root growth. Plant and Soil, 192 (1): 37-48. https://doi.org/10.1023/A:1004285113189.

Chaganti, V. N.; Culman, S. W. 2017. Historical perspective of soil balancing theory and identifying knowledge gaps: A review. Crop, Forage & Turfgrass Management, 3(1): 4220-4230. https://doi.org/10.2134/cftm2016.10.0072

Chaganti, V. N.; Culman, S. W.; Dick, W. A.; Kost, D. 2019. Effects of gypsum application rate and frequency on corn response to nitrogen. Agronomy Journal, 111: 1109-1117. https://doi.org/10.2134/agronj2018.10.0683

Chakraborty, R.; Mukhopadhyay, A.; Paul, S.; Sarkar, S.; Mukhopadhyay, R. 2023. Nanocomposite-based smart fertilizers: a boon to agricultural and environmental sustainability. Science of the Total Environment, 10(863): 160859. https://doi.org/10.1016/j.scitotenv.2022.160859

Charlo, H. C. O.; Almeida, J. S. M.; Castoldi, R.; Moreira, E. F. A.; Torres, J. L. R.; Lemes, E. M. 2022. Soil attributes and productivity of sorghum as a function of gypsum and potassium doses. Communications in Soil Science and Plant Analysis, 53(13): 1630-1643. https://doi.org/10.1080/00103624.2022.2063311

Charlo, H. C. O.; Almeida, J. S. M.; Lana, R. M. Q.; Castoldi, R.; Moreira, É. F. A.; Franco Jr, M. R.; Santos, W. B. 2020. Changes in chemical soil and corn yield after application of gypsum and potassium doses. Bioscience Journal, 36(3): 810-826. https://doi.org/10.14393/BJ-v36n3a2020-42443

Charlo, H. C. O.; Almeida, J. S. M.; Moreira, E. F. A.; Castoldi, R.; Luz, J. M. Q.; Lemes, E. M. 2021. Gypsum and potassium doses on cauliflower nutritional status and production. Revista Caatinga, 34(2), 370. https://doi.org/10.1590/1983-21252021v34n213rc

Chen, L.; Dick, W. A. 2011. Gypsum as an agricultural amendment: general use guidelines. The Ohio State University Extension. Available at: https://fabe.osu.edu/sites/fabe/files/imce/files/Soybean/Gypsum%20Bulletin.pdf

Chen, L.; Kost, D.; Tian, Y.; Guo, X.; Watts, D.; Norton, D.; Wolkowski, R. P.; Dick, W. A. 2014. Effects of gypsum on trace metals in soils and earthworms. Journal of Environmental Quality, 43(1): 263-272. https://doi.org/10.2134/jeq2012.0096

Cheng, C.; Fu, J.; Su, H.; Ren, L. 2023. Recent advancements in agriculture robots: benefits and challenges. Machines, 11(1): 48. https://doi.org/10.3390/machines11010048

Churka Blum, S. C.; Caires, E. F; Alleoni, L. R. F. 2013. Lime and phosphogypsum application and sulfate retention in subtropical soils under no-till system. Journal of Soil Science and Plant Nutrition, 13(2): 279-300. https://dx.doi.org/10.4067/S0718-95162013005000024

Clouse, K. M.; Wagner, M. R. 2021. Plant genetics as a tool for manipulating crop microbiomes: opportunities and challenges. Front Bioengineering and Biotechnology, 9: 567548. https://doi.org/10.3389/fbioe.2021.567548

Codling, E. E. 2017. Effects of ammonium nitrate encapsulated with coal combustion byproducts on nutrient accumulation by corn and rye. Journal of Plant Nutrition, 40(12): 1702-1709. https://doi.org/10.1080/01904167.2017.1310891

Conradi, E. Jr.; Gonçalves, A. C. Jr.; Seidel, E. P.; Ziemer, G. L.; Zimmermann, J.; Dias de Oliveira, V. H.; Schwantes, D.; Carlos, D. Z. 2020. Effects of liming on soil physical attributes: a review. Journal of Agricultural Science, 10: 278-286. https://doi.org/10.5539/jas.v12n10p278

Cooper, M.; Vidal-Torrado, P. 2005. Caracterização morfológica, micromorfológica e físico-hídrica de solos com horizonte B nítico. Revista Brasileira de Ciência do Solo, 29: 581-595. https://doi.org/10.1590/S0100-06832005000400011

Costa, C. H. M.; Crusciol, C. A. C. 2016. Long-term effects of lime and phosphogypsum application on tropical no-till soybean–oat–sorghum rotation and soil chemical properties. European Journal of Agronomy, 74: 119-132. https://doi.org/10.1016/j.eja.2015.12.001

Crangle Jr, R. D. 2021. Gypsum. In: Mineral Commodity Summaries. U.S. Geological Survey. pp. 74-75. https://doi.org/10.3133/mcs2021

Crocker, W. 1922. History of the use of agricultural gypsum. Gypsum Industries Association, Chicago, IL.

Crusciol, C. A. C.; Artigiani, A. C. C. A.; Arf, O.; Carmeis Filho, A. C. A.; Soratto, R. P.; Nascente, A. S.; Alvarez, R. C. F. 2016. Soil fertility, plant nutrition, and grain yield of upland rice affected by surface application of lime, silicate, and phosphogypsum in a tropical no-till system. Catena 137: 87-99. https://doi.org/10.1016/j.catena.2015.09.009

Crusciol, C. A. C.; Marques, R. R.; Filho, C. A. C. A.; Soratto, R. P.; Costa, C. H. M.; Neto, F. J.; Castro, G. S. A.; Pariz, C. M.; Castilhos, A. M.; Franzluebbers, A. J. 2019. Lime and gypsum combination improves crop and forage yields and estimated meat production and revenue in a variable charge tropical soil. Nutrient Cycling in Agroecosystems, 115, 347-372. https://doi.org/10.1007/s10705-019-10017-0

Crusciol, C. A. C.; Rossato, O. B.; Foltran, R.; Martello, J. M.; Nascimento, C. A. C. 2017. Soil fertility, sugarcane yield affected by limestone, silicate, and gypsum application. Communications in Soil Science and Plant Analysis, 48(19): 2314-2323. https://doi.org/10.1080/00103624.2017.1411507

Cuervo-Alzate, J. E.; Osorio, N. W. 2020. Gypsum incubation tests to evaluate its potential effects on acidic soils of Colombia. Revista Facultad Nacional de Agronomía Medellín, 73(3): 9349-9359. https://doi.org/10.15446/rfnam.v73n3.85259

Curi, N; Larach, J. O. I.; Kampf, N.; Moniz, A. C.; Fontes, L. E. F. 1993. Vocabulário de ciência do solo. Sociedade Brasileira de Ciências do Solo, Campinas (Brasil). 89 p.

Da Costa, C. H. M.; Crusciol, C. A. C. 2016. Long-term effects of lime and phosphogypsum application on tropical no-till soybean-oat-sorghum rotation and soil chemical properties. European Journal of Agronomy, 74: 119-132. http://dx.doi.org/10.1016/j.eja.2015.12.001

Dalla Nora, D.; Amado, T. J. C.; Nicoloso, R. S.; Gruhn, E. M. 2017. Modern high-yielding maize, wheat and soybean cultivars in response to gypsum and lime application on no-till Oxisol. Revista Brasileira de Ciência Solo, 41: 1-21. https://doi.org/10.1590/18069657rbcs20160504

De Moura, E. G.; Portela, S. B.; Macedo, V. R. A.; Sena, V. G. L.; Sousa, C. C. M.; Aguiar, A. D. C. F. 2018. Gypsum and legume residue as a strategy to improve soil conditions in sustainability of agrosystems of the humid tropics. Sustainability, 10: 1006. https://doi.org/10.3390/su10041006

Deer, W. A. Howie, R. A.; Zussman, J. 1966. An introduction to the rock-forming minerals. New York: John Wiley, 582 p.

Demattê, J. L. I. 1986. Solos arenosos de baixa fertilidade: estratégia de manejo. In: 5° Seminário Agroindustrial e 29° Semana “Luiz De Queiroz”, Piracicaba. Anais... Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz.

Demattê, J. L. I. 1992. Aptidão agrícola de solos e o uso do gesso. II Seminário Sobre o Uso do Gesso na Agricultura. Anais... IBRAFOS, Uberaba, Brazil, pp. 307-324.

Demattê, J. L. I. 2005. Recuperação e manutenção da fertilidade dos solos. Visão Agrícola, 1: 48-59. Available at: https://www.esalq.usp.br/visaoagricola/sites/default/files/cana-adubos-e-corretivos.pdf

Dick, W. A., Kost, D.; Nakano, N. 2006. A review of agricultural and other land application uses of flue gas desulfurization products. Electric Power Research Institute, Palo Alto, CA. Report 101385. 97 p.

Dubrovina, T. A.; Losev, A. A.; Karpukhin, M. M.; Vorobeichik, E. L.; Dovletyarova, E. A.; Brykov, V. A.; Brykova, R. A.; Ginocchio, R.; Yáñez, C.; Neaman, A. 2021. Gypsum soil amendment in metal-polluted soils-an added environmental hazard. Chemosphere, Oct; 281: 130889. https://doi.org/10.1016/j.chemosphere.2021.130889

Duke, J. A. 1983. Handbook of energy crops. Perdue University. Available at www.hort.purdue.edu/newcrop/duke_energy/dukeindex.html

Ekholm, P.; Ollikainen, M.; Punttila, E.; Ala-Harja, V.; Riihimäki, J.; Kiirikki, M.; Taskinen, A.; Begum, K. 2024. Gypsum amendment of agricultural fields decreases phosphorus losses – evidence on a catchment scale. SSRN, 59 p. http://dx.doi.org/10.2139/ssrn.4694131

Ellington, A. 1986. Effects of deep ripping, direct drilling, gypsum and lime on soils, wheat growth and yield. Soil and Tillage Research, 8; 29-49. https://doi.org/10.1016/0167-1987(86)90321-1

Endale, D. M.; Schomberg, H. H.; Fisher, D. S.; Franklin, D. H.; Jenkins, M. B. 2014. Flue gas desulfurization gypsum: implication for runoff and nutrient losses associated with broiler litter use on pastures on ultisols. Journal of Environmental Quality, 43(1): 281-289. https://doi.org/10.2134/jeq2012.0259

Ernani, P.R.; Cassol, P.C.; Peruzzo, G. 1992. Eficiência agronômica do gesso agrícola no sul do Brasil. In: II Seminário sobre o Uso do Gesso na Agricultura, Uberaba, 1992. Anais. Uberaba, IBRAFOS. 1: .263-276.

Farina, M. P. W.; Channon, P. 1988. Acid-subsoil amelioration: II. Gypsum effects on growth and subsoil chemical properties. Soil Science Society of America Journal, 52(1): 175-180. https://doi.org/10.2136/sssaj1988.03615995005200010031x

Favaretto, N.; Norton, L. D.; Johnston, C. T.; Bigham, J.; Sperrin, M. 2012. Nitrogen and phosphorus leaching as affected by gypsum amendment and exchangeable calcium and magnesium. Soil Science Society of America Journal, 76: 575-585. https://doi.org/10.2136/sssaj2011.0223

Fernando, M. S. W.; Silva, S. H. S. A.; Kanchana, S. 2021. Influence of gypsum application in disease management of onion (*Allium cepa* L.). International Journal of Innovative Science and Research Technology, 6(8): 900-905. Available at: https://ijisrt.com/assets/upload/files/IJISRT21AUG592.pdf

Ferreira, C. F.; Bassaco, M. V. M.; Pereira, M.; Pauletti, V.; Prior, S. A.; Motta, A. C. V. 2020. Dendrometric analysis of early development of *Eucalyptus urophylla* x *Eucalyptus grandis* with gypsum use under subtropical conditions. FLORAM, 27(1): e20190095. http://dx.doi.org/10.1590/2179-8087.009519

Fleuridor, L.; Herms, C.; Culman, S.; Dick, W. A.; Paul, P. A.; Doohan, D. 2021. Short-term responses of soils and crops to gypsum application on organic farms. Agronomy Journal, 113(5): 4220-4230. https://doi.org/10.1002/agj2.20669

Fontoura, S. M. V.; Pias, O. H. C.; Tiecher, T.; Cherubin, M. R.; Moraes, R. P.; Bayer, C. 2019. Effect of gypsum rates and lime with different reactivity on soil acidity and crop grain yields in a subtropical Oxisol under no-tillage. Soil & Tillage Research, 193: 27-41. https://doi.org/10.1016/j.still.2019.05.005

Gabriel, C. A.; Cassol, P. C.; Simonete, M. A.; Moro, L.; Pfleger, P.; Mumbach, G. L. 2018. Lime and gypsum applications on soil chemical attributes and initial growth of eucalyptus. Floresta, 48(4): 573-582. https://doi.org/10.5380/rf.v48i4.57455

Garbowski, T.; Bar-Michalczyk, D.; Charazińska, S.; Grabowska-Polanowska, B.; Kowalczyk, A.; Lochyński, P. 2023. An overview of natural soil amendments in agriculture. Soil and Tillage Research, 225: 105462. https://doi.org/10.1016/j.still.2022.105462

Gharaibeh, M. A.; Eltaif, N. I.; Albalasmeh, A. A. 2011. Reclamation of highly calcareous saline sodic soil using *Atriplex halimus* and by-product gypsum. International Journal of Phytoremediation, 13(9): 873-83. https://doi.org/10.1080/15226514.2011.573821

Gingrich, C.; Hart, J.; Christensen, N. 2000. Hops fertilizer guide. Oregon State University Extension. Available at: https://catalog.extension.oregonstate.edu/fg79

Goiba, P. K.; Prakash, N. B.; Dhumgond, P.; Shruthi; Yogesh, G. S. 2023. Application of slag-based gypsum in rice crop and its effect on growth, yield and nutrient availability in acidic, neutral and alkaline soils. Communications in Soil Science and Plant Analysis, 54(11): 1510-1524. https://doi.org/10.1080/00103624.2022.2161558

Grego, C. R.; Coelho, R. M.; Vieira, S. R. 2011. Critérios morfológicos e taxonômicos de Latossolo e Nitossolo validados por propriedades físicas mensuráveis analisadas em parte pela geoestatística. Revista Brasileira de Ciência do Solo, 35(2): 337-350. https://doi.org/10.1590/S0100-06832011000200005

Guimarães, A. M.; Caires, E. F.; Silva, K. S.; Rocha, J. C. F. 2015. Estimating gypsum requirement under no-till based on machine learning technique. Revista Ciência Agronômica, 46: 250-257. https://doi.org/10.5935/1806-6690.20150004

Hanger, B. C. 1979. The movement of calcium in plants. Communications in Soil Science and Plant Analysis, 10(1-2): 171-193. https://doi.org/10.1080/00103627909366887

HĀPI - Hop Research Center (ed.). 2019. Fertility guide for hops. Hāpi Research Ltd. 29 p. Available at: https://hapi.co.nz/wp-content/uploads/2019/10/Fertility-Guide-for-Hops-Oct-2019.pdf

Instituto Brasileiro de Mineração (IBRAM). 2020. Informações sobre a economia mineral brasileira 2020 (ano base 2019). 1. ed. Brasília: IBRAM. 80 p. Available at: https://portaldamineracao.com.br/wp-content/uploads/2021/03/Economia-Mineral-Brasileira-IBRAM-2020.pdf

Jan, M.; Shrivastava, M. 2017. Genetically modified plants: a systematic review. International Journal of Recent Scientific Research, 8(4): 16471-16481. http://dx.doi.org/10.24327/ijrsr.2017.0804.0155

Jayawardane, N. S.; Blackwell, J. 1986. Effects of gypsum-slotting on infiltration rates and moisture storage in a swelling clay soil. Soil Use and Management, 2(3): 114-118. https://doi.org/10.1111/j.1475-2743.1986.tb00693.x

Jin, M.; Zhou, Y.; Wen, B.; Liu, L.; Liu, H. 2023. Progresses of gypsums for the improvement of saline-alkaline soil. Journal of Nanjing Forestry University, 47(2): 1-8. 10.12302/j.issn.1000-2006.202209047

Karthik, A.; Maheswari, M. U. 2021. Smart fertilizer strategy for better crop production. Agricultural Reviews. 42(1): 12-21. https://doi.org/10.18805/ag.R-1877

Kilpatrick, L. A. 2012. Sustainable growth of Miscanthus on marginal lands amended with flue gas desulfurization gypsum and sewage biosolids. American Society of Agricultural and Biological Engineers, 12-1337624. 37 p. https://doi.org/10.13031/2013.41822

King, K. W.; Williams, M. R.; Dick, W. A.; LaBarge, G. A. 2016. Decreasing phosphorus loss in tile-drained landscapes using flue gas desulfurization gypsum. Journal of Environmental Quality 45, 1722-1730. https://doi.org/10.2134/jeq2016.04.0132

Kong, F.; Ying, Y.; Lu, S. 2023. Heavy metal pollution risk of desulfurized steel slag as a soil amendment in cycling use of solid wastes. Journal of Environmental Sciences, 127: 349-360. https://doi.org/10.1016/j.jes.2022.05.010

Kopittke, P. M.; Menzies, N. W. 2007. A review of the use of the basic cation saturation ratio and the “ideal” soil. Soil Science Society of America Journal, 71(2): 259-265. https://doi.org/10.2136/sssaj2006.0186

Kopittke, P. M.; Menzies, N. W.; Wang, P.; McKenna, B. A.; Lombi, E. 2019. Soil and the intensification of agriculture for global food security. Environment International, 132: 105078. https://doi.org/10.1016/j.envint.2019.105078

Koralegedara, N. H.; Pinto, P. X., Dionysiou, D. D., Al-Abed, S. R. J. J. 2019. Recent advances in flue gas desulfurization gypsum processes and applications - A review. Journal of Environmental Management, 251: 109572. https://doi.org/10.1016/j.jenvman.2019.109572

Korcak, R. F. 1993. High-gypsum byproducts as soil amendments for horticultural crops. HortTechnology, 3(2). 156-161. https://doi.org/10.21273/HORTTECH.3.2.156b

Koske, T. J.; Hall M.; Hinson, R.; Pollet, D.; Sanderlin, R. 2005. Commercial growing of greenhouse tomatoes. Available at: http://www.lsuagcenter.com/NR/rdonlyres/7D6AEFA5-E5C2-494A-AF3B-DE10DDC1ADBE/10421/pub1808greenhousetomatoes1.pdf

Kost, D.; Chen, L.; Guo, X.; Tian, Y.; Ladwig, K.; Dick, W.A. 2014. Effects of flue gas desulfurization and mined gypsums on soil properties and on hay and corn growth in eastern Ohio. Journal of Environmental Quality, 43: 312-321. https://doi.org/10.2134/jeq2012.0157

Kost, D.; Ladwig, K. J.; Chen, L.; DeSutter, T. M.; Espinoza, L.; Norton, L. D.; Smeal, D.; Torbert, H. A.; Watts, D. B.; Wolkowski, R. P.; Dick, W. A. 2018. Meta-Analysis of gypsum effects on crop yields and chemistry of soils, plant tissues, and vadose water at various research sites in the USA. Journal of Environmental Quality, 47(5): 1284-1292. https://doi.org/10.2134/jeq2018.04.0163

Kraamwinkel, C. T.; Beaulieu, A.; Dias, T.; Howison, R. A. 2021. Planetary limits to soil degradation. Communications Earth & Environment, 2: 249. https://doi.org/10.1038/s43247-021-00323-3

Krithika, L. B. 2022. Survey on the applications of blockchain in agriculture. Agriculture, 12, 1333. https://doi.org/10.3390/agriculture12091333

Kumaragamage, D.; Weerasekara, C. S.; Perry, M.; Akinremi, O. O.; Goltz, D. 2022. Alum and gypsum amendments decrease phosphorus losses from soil monoliths to overlying floodwater under simulated snowmelt flooding. Water, 14: 559. https://doi.org/10.3390/w14040559

Lantzke, N. 2018. Gypsum recommendations for horticulture in Carnarvon. Carnarvon Growers Association. Farmnote, number 3. 4 p. Available at: https://www.agric.wa.gov.au/sites/gateway/files/Farmnote%20-%20Gypsum%20recommendations.pdf

Laxmanarayanan, M.; Prabhudev, D.; Shruthi; Jahir Basha, C. R.; Supriya, S.; Prakash, N. B. 2022. Influence of yellow gypsum on nutrient uptake and yield of groundnut in different acid soils of Southern India. Scientific Reports, 12: 5604. https://doi.org/10.1038/s41598-022-09591-1

Lebedev, V. G.; Popova, A. A.; Shestibratov, K. A. 2021. Genetic engineering and genome editing for improving nitrogen use efficiency in plants. Cells, 10(12): 3303. https://doi.org/10.3390/cells10123303

Lecourieux, D.;, Ranjeva, R.; Pugin, A. 2006. Calcium in plant defense-signaling pathways. The New Phytologist, 171(2): 249-269. https://doi.org/10.1111/j.1469-8137.2006.01777.x

Lee, Y. B.; Bigham, J. M.; Dick, W. A.; Jones, E. S.; Ramsier, C. 2007. Influence of soil pH and application rate on the oxidation of calcium sulfite derived from flue gas desulfurization. Journal of Environmental Quality, 36: 298-304. https://doi.org/10.2134/jeq2006.0050

Lemes, E. M; Azevedo, B. N. R; Domiciano, M. F. I.; Andrade, S. L. 2021. Improving soybean production using light supplementation at field-scale: a case study. Journal of Agricultural Studies, 9(3): 259-275. https://doi.org/10.5296/jas.v9i3.18890

Li, C.; Dong, Y.; Yi, Y.; Tian, J.; Xuan, C.; Wang, Y.; Wen, Y.; Cao, J. 2023. Effects of phosphogypsum on enzyme activity and microbial community in acid soil. Scientific Reports, 13: 6189. https://doi.org/10.1038/s41598-023-33191-2

Liu, S.; Liu, W.; Jiao, F.; Qin, W.; Yang, C. 2021. Production and resource utilization of flue gas desulfurized gypsum in China - A review. Environmental Pollution, 288: 117799. https://doi.org/10.1016/j.envpol.2021.117799

Lorenzetti, J. M.; Rodrigues, J. C.; Morales, S. H.; Dematté, J. L. I. 1992. Uso de calcário e gesso em soqueira de cana-de-açúcar. STAB, 10: 14-18. http://www.stab.org.br/revista.html

Lorenzi, J. O.; Monteiro, P. A.; Miranda Filho, H. S.; Van Raij, B. Raízes E Tubérculos. In: Van Raij, B.; Cantarella, H.; Quaggio, J. A.; Furlani, A. M. C. (Eds.) 1997. Recomendações de adubação e calagem para o Estado de São Paulo. Campinas: Instituto Agronômico de Campinas, p. 221-229. (IAC. Boletim Técnico, 100). Available at: https://www.iac.sp.gov.br/publicacoes/boletim100.php

Mackelprang R.; Lemaux, P. G. 2020. Genetic engineering and editing of plants: an analysis of new and persisting questions. Annual Review of Plant Biology, 71(1): 659-687. https://doi.org/10.1146/annurev-arplant-081519-035916

Mahibha, G.; Balasubramanian, P. 2023. Impact of artificial intelligence in agriculture with special reference to agriculture information research. Current Agriculture Research Journal, 11(1). Available at: https://bit.ly/3xx30KC

Malavolta, E.; Romero, J. P.; Liem, T. H.; Vitti, G. C. 1979. Gesso agrícola: seu uso na adubação e correção do solo. São Paulo: ULTRAFÉRTIL, 32 p.

Mao, Y.; Li, X.; Dick, W. A.; Cao, L. 2022. Use of flue gas desulfurization gypsum to reduce dissolved phosphorus in runoff and leachate from two agricultural soils. Soil Ecology Letters. https://doi.org/10.1007/s42832-022-0135-5

Marchesan, E.; Tonetto, F.; Teló, G. M.; Coelho, L. L.; Aramburu, B. B.; Trivisiol, V. S. 2017. Soil management and application of agricultural gypsum in a Planosol for soybean cultivation. Ciencia Rural, 47, 1-7. https://doi.org/10.1590/0103-8478cr20161102

Marchis, D.; Badulescu, C.; Nistor, M.-C. 2016. Benefits of using FGD gypsum from S.E. Turceni in agriculture. Research Journal of Agricultural Science, 48(4): 247-253. Available at: https://rjas.ro/download/paper_version.paper_file.8023d1dc03b3fb93.6d617263686973322e706466.pdf

Martins, O. C.; Novais, R. F.; Alvarez, V. V. H.; Ribeiro, A. C.; Barros, N. F. 2002. Respostas à aplicação de diferentes misturas de calcário e gesso em solos. I. Alterações químicas no perfil do solo. Revista Ceres, 49: 123-35. Available at: http://www.ceres.ufv.br/ojs/index.php/ceres/article/view/2798/0

Matveeva, V. A.; Smirnov, Y. D.; Suchkov, D. V. 2022. Industrial processing of phosphogypsum into organomineral fertilizer. Environ Geochem Health, 44: 1605-1618. https://doi.org/10.1007/s10653-021-00988-x

Mayer, J. F. 1768. Die Lehre vom Gyps als einem vorzüglich guten Dung zu allen Erd-Gewächsen auf Aeckern und Wiesen, Hopfen- und Weinbergen [Instruction in gypsum as an ideal good manure for all things grown in soil on fields and pastures, hops yards and vineyards]. Anspach, (Germany): J.J. Palm. p. 61. https://doi.org/10.3931/e-rara-45060

McBride, M. B. 1994. Environmental chemistry of soils. Oxford University Press, New York. 406 p.

McGrath, J. M.; Penn, C. J.; Coale, F. J. 2013. A modeling approach to the design of in situ agricultural drainage filters. Soil Use Management, 29, 155-161. https://doi.org/10.1111/j.1475-2743.2011.00381.x

McIntyre, D.S.; Loveday, J.; Watson, C.L. 1982. Field studies of water and salt movement in an irrigated swelling clay soil. I. Infiltration during ponding. II. Profile hydrology during ponding. III. Salt movement during ponding. Australian Journal of Soil Research, 20: 81-90, 91-99, 101-105. https://doi.org/10.1071/SR9820081, https://doi.org/10.1071/SR9820091, https://doi.org/10.1071/SR9820101

McKibben, W. 2012. The art of balancing soil nutrients: A practical guide to interpreting soil tests. Acres, U.S.A. 304 p.

Mesías-Ruiz, G. A.; Pérez-Ortiz, M.; Dorado, J.; Castro, A. I.; Peña, J. M. 2023. Boosting precision crop protection towards agriculture 5.0 via machine learning and emerging technologies: a contextual review. Frontiers in Plant Science, 14: 1143326. https://doi.org/10.3389/fpls.2023.1143326

Messenger, B. J.; Menge, J. A.; Pond, E. 2000. Effects of gypsum soil amendments on avocado growth, soil drainage, and resistance to *Phytophthora cinnamomi*. Plant Disease, 84: 612-616. https://doi.org/10.1094/PDIS.2000.84.6.612

Morelli, J. L.; Dalben, A. E.; Almeida, J. O. C.; Dematte, J. L. I. 1992. Calcário e gesso na produtividade da cana-de-açúcar e nas características químicas de um Latossolo de textura média álico. Brasileira de Ciência do Solo, 16: 187-194. http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=4316645

Morelli, J. L.; Nelli, E. J.; Dematte, J. L. I.; Dalben, A. E. 1987. Efeito do gesso e do calcário nas propriedades químicas de solos arenosos álicos e na produção de cana de açúcar. STAB, 6(1): 24-31. http://www.stab.org.br/revista.html

Muller, M. M. L.; Tormena, C. A.; Genu, A. M.; Kramer, L. F. M.; Michalovicz, L.; Caires, E. F. 2012. Structural quality of a no-tillage red latosol 50 months after gypsum application. Revista Brasileira de Ciência do Solo 36, 1005-1013. https://doi.org/10.1590/S0100-06832012000300030

Murphy, P. N. C.; Stevens, R. J. 2010. Lime and gypsum as source measures to decrease phosphorus loss from soils to water. Water Air Soil Pollut Water, Air, & Soil Pollution, 212: 101-111. https://doi.org/10.1007/s11270-010-0325-0

Narasimhan, V.; Ramadoss, N.; Sridhar, V. V.; Kareem, A. A. 1994. Using gypsum to manage sheath rot in rice. International Rice Research Newsletter, 19(2): 27-28. Available at: https://eurekamag.com/research/003/007/003007204.php

Niaz, S.; Wehr, J. B.; Dalal, R. C.; Kopittke, P. M.; Menzies, N. W. 2023. Wetting and drying cycles, organic amendments, and gypsum play a key role in structure formation and stability of sodic Vertisols. SOIL, 9: 141-154. https://doi.org/10.5194/soil-9-141-2023

Nora, D. D.; Amado, T. J.; Bortolotto, R. F.; Ferreira, A. O.; Keller, C.; Kunz, J. 2014. Alterações químicas do solo e produtividade do milho com aplicação de gesso combinado com calcário. Magistra, 26(1): 1-10. Available at: https://www3.ufrb.edu.br/magistra/index.php/magistra/article/view/432/114

Norton, L. D. 2008. Gypsum soil amendment as a management practice in conservation tillage to improve water quality. Journal of Soil and Water Conservation, 63: 46A-48A. https://doi.org/10.2489/jswc.63.2.46A

Okolie, C. C.; Danso-Abbeam, G.; Groupson-Paul, O.; Ogundeji, A. A. 2023. Climate-smart agriculture amidst climate change to enhance agricultural production: a bibliometric analysis. Land, 12: 50. https://doi.org/10.3390/land12010050

Oliveira, M. W.; Freire, F. M.; Macêdo, G. A. R.; Ferreira, J. J. 2007. Nutrição mineral e adubação da cana-de-açúcar. Informe. Agropecuário, 28: 30-43. Available at: http://www.nutricaodeplantas.agr.br/site/downloads/unesp_jaboticabal/oliveira_cana_informeagropec.pdf

Oster, J. 1982. Gypsum usage in irrigated agriculture: a review. Fertilizer Research. 3: 73-89. https://doi.org/10.1007/BF01063410

Outbakat, M.; Choukr-Allah, R.; Bouray, M.; EL Gharous, M.; EL Mejahed, K. 2023. Phosphogypsum: properties and potential use in agriculture. In: Choukr-Allah, R.; Ragab, R. (eds) Biosaline Agriculture as a Climate Change Adaptation for Food Security. Springer, Cham. https://doi.org/10.1007/978-3-031-24279-3_12

Panday, D.; Ferguson, R. B.; Maharjan, B. 2018. Flue gas desulfurization (FGD) gypsum as soil amendment. In: Rakshit, A.; Sarkar, B.; Abhilashis, P. C. (Eds.), Soil Amendments for Sustainability: Challenges and Perspectives. CRC Press, FL, pp 199-208. Available at: https://digitalcommons.unl.edu/agronomyfacpub/1245

Paolinelli, M. T.; Oliveira, P. M.; Santos, P. R. R, S.; Leandro,V. P.; Moraes, W. Y. 1986. Aplicação direta do fosfogesso. In: Seminário Sobre o Uso de Gesso na Agricultura, 1., Brasília. Anais... Brasília: DDT, p.197-207.

Pauletti, V.; Motta, A. C. V. 2017. Manual de adubação e calagem para o estado do Paraná. Sociedade Brasileira de Ciência do Solo - Núcleo Estadual Paraná, Curitiba. 289 p.

Pauletti, V.; Pierri, L.; Ranzan, T.; Barth, G.; Motta, A. C. V. 2014. Efeitos em longo prazo da aplicação de gesso e calcário no sistema de plantio direto. Revista Brasileira de Ciência do Solo 38: 495-505. https://doi.org/10.1590/S0100-06832014000200014

Penn, C. J.; Bryant, R. B. 2006. Application of phosphorus sorbing materials to streamside cattle loafing areas. Journal of Soil and Water Conservation, 61(5): 303-310. Available at: https://www.jswconline.org/content/61/5/303

Penn, C. J.; McGrath, J. M. 2014. Chemistry and application of industrial by-products to animal manure for reducing phosphorus losses to surface waters. In: He, Z., Zhang, H. (Eds.), Applied Manure and Nutrient Chemistry for Sustainable Agriculture and Environment. Springer, The Netherlands, pp. 211-238. https://doi.org/10.1007/978-94-017-8807-6_11

Pias, O. H. D. C.; Tiecher, T.; Cherubin, M. R.; Mazurana, M.; Bayer, C. 2019. Crop yield responses to sulfur fertilization in Brazilian no-till soils: a systematic review. Revista Brasileira de Ciência do Solo, 43: 1-21. https://doi.org/10.1590/18069657rbcs20180078

Pias, O. H. D. C.; Tiecher, T.; Cherubin, M. R.; Silva, A. G. B.; Bayer, C. 2020. Does gypsum increase crop grain yield on no-tilled acid soils?: A meta-analysis. Agronomy Journal, 112: 675-692. https://doi.org/10.1002/agj2.20125

Pivetta, L. A.; Castoldi, G.; Pivetta, L. G.; Maia, S. C. M.; Rosolem, C. A. 2019. Gypsum application, soil fertility and cotton root growth. Bragantia, 78(2): 264-273. https://doi.org/10.1590/1678-4499.20180183.

Popp, M.; Lindsay, K.; Ashworth, A.; Moore, P.; Owens, P.; Adams, T.; McCarver, M.; Roark, B.; Pote, D.; Pennington, J. 2021. Economic and GHG emissions changes of aeration and gypsum application. Agriculture, Ecosystems & Environment, 321: 107616. https://doi.org/10.1016/j.agee.2021.107616.

Prakash, N. B.; Dhumgond, P.; Shruthi.; Ashrit, S. 2020. Performance of slag-based gypsum on maize yield and available soil nutrients over commercial gypsum under acidic and neutral soil. Communications in Soil Science and Plant Analysis, 51: 1780-1798. https://doi.org/10.1080/00103624.2020.1791161

Qayyum, M. F.; Rehman, M. Z. U.; Ali, S.; Rizwan, M.; Naeem. A.; Maqsood, M. A.; Khalid, H.; Rinklebe, J.; Ok, Y. S. 2017. Residual effects of monoammonium phosphate, gypsum and elemental sulfur on cadmium phytoavailability and translocation from soil to wheat in an effluent irrigated field. Chemosphere, 174: 515-523. https://doi.org/10.1016/j.chemosphere.2017.02.006.

Qu, J.; Zhang, L.; Zhang, X.; Gao, L.; Tian, Y. 2020. Biochar combined with gypsum reduces both nitrogen and carbon losses during agricultural waste composting and enhances overall compost quality by regulating microbial activities and functions. Bioresour. Technol. 314, 123781.

Raimondi, G.; Maucieri, C.; Toffanin, A.; Renella, G.; Borin, M. 2021. Smart fertilizers: What should we mean and where should we go? Italian Journal of Agronomy, 16(2): 1794. https://doi.org/10.4081/ija.2021.1794

Raine, S. R.; Loch, R. J. 2003. What is a sodic soil? Identification and management options for construction sites and disturbed lands. In: Road, Structures and Soils in South East Queensland 29-30th (Department of Main Roads, Queensland). 14 p.

Ramos, B. Z.; Toledo, J. P. V. F.; Lima, J. M.; Serafim, M. E.; Bastos, A. R. R.; Guimarães, P. T. G.; Coscione, A. R. 2013. Gypsum applications to coffee: influence on calcium, magnesium and potassium contents and pH of the solution of a dystrophic red latosol Revista Brasileira de Ciências do Solo. 37(4): 1018-1026. https://doi.org/10.1590/S0100-06832013000400019

Rampim, L.; Lana, M. C.; Frandoloso, J. F.; Fontaniva, S. 2011. Atributos químicos de solo e resposta do trigo e da soja ao gesso em sistema semeadura direta. Revista Brasileira de Ciência do Solo, 35: 1687-1698. https://doi.org/10.1590/S0100-06832011000500023

Rashmi, I.; Mina, B. L.; Kumar, K.; Ali, S.; Kumar, A.; Kala, S.; Singh, R. K. 2018. Gypsum - an inexpensive, effective sulphur source with multitude impact on oilseed production and soil quality: A review. Agricultural Reviews, 39: 218-225. https://doi.org/10.18805/AG.R-1792

Rawat, A.; Kumar, R.; Singh, V. P.; Bhatt, B. 2020 Effect of plant based nano-sized gypsum on growth parameters and yield of wheat (*Triticum aestivum* L.). International Journal of Chemical Studies, 8(4): 2991-2993. https://doi.org/10.22271/chemi.2020.v8.i4aj.10105

Raza, A.; Mubarik, M. S.; Sharif, R.; Habib, M.; Jabeen, W.; Zhang, C.; Chen, H.; Chen, Z.-H.; Siddique, K. H. M.; Zhuang, W.; Varshney, R. K. 2023. Developing drought-smart, ready-to-grow future crops. Plant Genome, 16: e20279. https://doi.org/10.1002/tpg2.20279

Rehman, M.; Fahad, S.; Du, G.; Cheng, X.; Yang, Y.; Tang, K.; Liu, L.; Liu, F. H.; & Deng, G. 2021. Evaluation of hemp (*Cannabis sativa* L.) as an industrial crop: a review. Environmental Science and Pollution Research International, 28(38): 52832-52843. https://doi.org/10.1007/s11356-021-16264-5

Rezapour, S.; Asadzadeh, F.; Barin, M.; Nouri, A. 2021. Organic amendments improved the chemical-nutritional quality of saline-sodic soils. International Journal of Environmental Science and Technology, 19(6): 4659-4672. https://doi.org/10.1007/s13762-021-03599-2

Ritchey, K. D.; Feldhake, C. M.; Clark, R. B.; Sousa, D. M. G. 1995. Improved water and nutrient uptake from subsurface layers of gypsum-amended soils. In: Karlen, D. L. et al. (Ed.), Agricultural Utilization of Urban and Industrial By-Products. ASA Spec. Publ., vol. 58. ASA, CSSA, and SSSA, Madison. WI, pp. 157-181. https://doi.org/10.2134/asaspecpub58.c8

Ritchey, K. D.; Souza, D. M. G.; Lobato, E.; Correa, O. 1980. Calcium leaching to increase rooting depth in a Brazilian savannah oxisol. Agronomy Journal, 72: 40-44. https://doi.org/10.2134/agronj1980.00021962007200010009x

Robinson, M. J. C.; Dhar, A.; Naeth, M. A.; Nichol, C. K. 2023. Phosphogypsum impacts on soil chemical properties and vegetation tissue following reclamation. Environmental Monitoring and Assessment, 195: 769. https://doi.org/10.1007/s10661-023-11379-3

Rossato, O. B.; Foltran, R.; Crusciol, C. A. C.; Martello, J. M.; Rossetto, R.; Mccray, J. M. 2017. Soil fertility, ratoon sugarcane yield, and post-harvest residues as affected by surface application of lime and gypsum in southeastern Brazil. Bioscience Journal, 33(2): 276-287. https://doi.org/10.14393/BJ-v33n2-32755

Santos, C. A.; Carmo, M. G. F.; Bhering, A. S.; Costa, E. S. P.; Amaral Sobrinho, N. M. B. 2020. Use of limestone and agricultural gypsum in cauliflower crop management and clubroot control in mountain farming. Acta Scientiarum Agronomy, 42: 2-11. https://doi.org/10.4025/actasciagron.v42i1.42494

Santos, H. G.; Jacomine, P. K. T.; Anjos, L. H. C.; Oliveira, V. A.; Lumbreras, J. F.; Coelho, M. R.; Almeida, J. A.; Araújo Filho, J. C.; Oliveira, J. B.; Cunha, T. J. F. 2018. Sistema Brasileiro de Classificação de Solos. 5 ed. Brasília, DF: Embrapa. 356 p. Available at: https://www.infoteca.cnptia.embrapa.br/handle/doc/1094003

Schlossberg, M. J.; Miller, W. P.; Kruse, J. 2006. Turfgrass growth and water use in gypsum-treated Ultisols. The ASA-CSSA-SSSA International Annual Meetings. Indianapolis, IN. November 2006. Available at: https://acs.confex.com/crops/2006am/techprogram/P27169.HTM

Schultz, E.; Chatterjee, A.; DeSutter, T.; Franzen, D. 2017. Sodic soil reclamation potential of gypsum and biochar additions: influence on physicochemical properties and soil respiration. Communications in Soil Science and Plant Analysis, 48(15): 1792-1803. https://doi.org/10.1080/00103624.2017.1395449

Scott, W. D.; McCraw, B. D.; Motes, J. E.; Smith, M. W. 1993. Application of calcium to soil and cultivar affect elemental concentration of watermelon leaf and rind tissue. Journal of the American Society of Horticultural Science, 118: 201-206. https://doi.org/10.21273/JASHS.118.2.201

Shainberg, R.; Sumner, M.E., Miller, W.P., Farina, M.P.W., Pavan, M.A.; Fey, M.W. 1989. Use of gypsum on soils: a review. In: Stewart, B.A. (Ed), Advances in Soil Science, 9. Springer. p. 1-111 https://doi.org/10.1007/978-1-4612-3532-3_1

Shamshuddin, J.; Ismail, H. 1995. Reactions of ground magnesium limestone and gypsum in soils with variable-charge minerals. Soil Science Society of America Journal, 59: 106-112. http://dx.doi.org/10.2136/sssaj1995.03615995005900010017x

Soil Science Society of America. 1997. Glossary of soil science terms. SSSA, Madison (EUA). 134 p.

Somavilla, L.; Pinto, M. A. B.; Basso, C. J.; Da Ros, C. O.; Silva, V. R.; Brun, T.; Santi, A. L. 2016. Response of soybean and corn to soil mechanical intervention and agricultural gypsum application to the soil surface. Semina: Ciências Agrárias, 37, 95-102. https://doi.org/10.5433/1679-0359.2016v37n1p95

Song, W.; Yim, J.; Kurniadinata, O. F.; Wang, H.; Huang, X. 2018. Linking fruit Ca uptake capacity to fruit growth and pedicel anatomy, a cross-species study. Frontiers in Plant Science, 9: 575. https://doi.org/10.3389/fpls.2018.00575

Soratto, R. P.; Crusciol, C. A. C. 2008. Dolomite and phosphogypsum surface application effects on annual crops nutrition and yield. Agronomy Journal, 100, 261-270. https://doi.org/10.2134/agrojnl2007.0120

Sousa, D. M. G.; Lobato, E. 2004. Cerrado: correção do solo e adubação. 2. ed. Planaltina: Embrapa Cerrados. 416 p. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/555355

Sousa, D. M. G.; Lobato, E.; Ritchey, K. D.; Rein, T. A. 1992. Suggestions for diagnosis and recommendation of gypsum application for soil of the Cerrados. In: II Seminário Sobre o Uso do Gesso na Agricultura. Anais... IBRAFOS, Uberaba, Brazil, pp. 139-158.

Sousa, D. M. G.; Miranda, L. N.; Oliveira, A. S. 2007. Acidez do solo e sua correção. In: Novais, R. F.; Alvarez, V. V. H.; Barros, N. F.; Fontes, R. L.; Cantarutti, R. B.; Neves, J. C. L. (eds.) Fertilidade do Solo. Viçosa, MG: Sociedade Brasileira de Ciência do Solo. p. 205-274.

Sousa, D. M. G.; Vilela, L.; Lobato, E.; Soares, W. V. 2001. Uso de gesso, calcário e adubos para pastagens no cerrado. Circular Técnica 12. Planaltina, DF: Embrapa Cerrados. 22 p. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/566086

Srivastava, S.; Pandey, V. K.; Singh, R.; Dar, A. H.; Dash, K. K.; Panesar, P. S. 2022. A critical review on artificial intelligence and robotic vision in food industry. International Journal of Science & Critics, 1(1): 8-17. Available at: https://www.sciencecritics.com/wp-content/uploads/2023/01/Review-Article-IJSC22D002.pdf

Sumner, M. E. 1993. Gypsum and acid soils - the world scene. Advances in Agronomy, 51(51): 1-32. https://doi.org/10.1016/S0065-2113(08)60589-1

Sumner, M. E.; Radcliffe, D. E.; McCray, M.; Carter, E.; Clark, R. L. 1990. Gypsum as an ameliorant for subsoil hardpans. Soil Technology, 3: 253-258. https://doi.org/10.1016/0933-3630(90)90005-N

Sun, L.; Ma, Y.; Liu, Y.; Li, J.; Deng, J.; Rao, X.; Zhang, Y. 2019. The combined effects of nitrogen fertilizer, humic acid, and gypsum on yield-scaled greenhouse gas emissions from a coastal saline rice field. Environmental Science and Pollution Research, 26: 19502-19511. https://doi.org/10.1007/s11356-019-05363-z

Syed-Omar, S. R.; Sumner, M. E. E. 1991. Effect of gypsum on soil potassium and magnesium status and growth of alfalfa. Communication in Soil Science and Plant Analysis, 22: 2017-2028. https://doi.org/10.1080/00103629109368554

Tavakkoli, E.; Uddin, S.; Rengasamy, P.; McDonald, G. K. 2021. Field applications of gypsum reduce pH and improve soil C in highly alkaline soils in southern Australia's dryland cropping region. Soil Use Management, 38: 466-477. https://doi.org/10.1111/sum.12756

Tayade, R.; Ghimire, A.; Khan, W.; Lay, L.; Attipoe, J. Q.; Kim, Y. 2022. Silicon as a smart fertilizer for sustainability and crop improvement. Biomolecules, 12(8): 1027. https://doi.org/10.3390/biom12081027

Thor, K. 2019. Calcium - nutrient and messenger. Frontiers in Plant Science, 10: 440. https://doi.org/10.3389/fpls.2019.00440

Tiecher, T.; Pias, O. H. C.; Bayer, C.; Martins, A. P.; Denardin, L. G. O.; Anghinoni, I. 2018. Crop response to gypsum application to subtropical soils under no-till in Brazil: a systematic review. Revista Brasileira de Ciência do Solo.42: e0170025. https://doi.org/10.1590/18069657rbcs20170025

Tirado-Corbalá, R., Slater, B. K., Dick, W. A., Bigham, J.; Muñoz-Muñoz, M. 2019. Gypsum amendment effects on micromorphology and aggregation in no-till Mollisols and Alfisols from western Ohio, USA. Geoderma Regional, 16, e00217. https://doi.org/10.1016/j.geodrs.2019.e00217

Tirado-Corbalá, R.; Slater, B. K.; Dick, W. A.; Bigham, J.; Mccoy, E. 2013. Hydrologic properties and leachate nutrient responses of soil columns collected from gypsum-treated fields. Soil and Tillage Research, 134, 232-240. https://doi.org/10.1016/j.still.2013.08.007

Toma, M.; Sumner, M. E.; Weeks, G.; Saigusa, M. 1999. Long-term effects of gypsum on crop yield and subsoil chemical properties. Soil Science Society of America Journal, 63: 891-895. https://doi.org/10.2136/sssaj1999.634891x

Tonetto de Freitas, S.; Mitcham, E. J. 2012. Factors involved in fruit calcium deficiency disorders. Horticultural Reviews (chapter 3), 40: 107-146. https://doi.org/10.1002/9781118351871.ch3

Truman, C. C.; Nuti, R. C.; Truman, L. R.; Dean, J. D. 2010. Feasibility of using FGD gypsum to conserve water and reduce erosion from an agricultural soil in Georgia. Catena, 81: 234-239. https://doi.org/10.1016/j.catena.2010.04.003

Tubail, K.; Chen, L.; Michel Jr., F. C.; Keener, H. M.; Rigot, J. F.; Klingman, M.; Kost, D.; Dick, W. A. 2008. Gypsum additions reduce ammonia nitrogen losses during composting of dairy manure and biosolids. Compost Science & Utilization, 16(4): 285-293. http://dx.doi.org/10.1080/1065657X.2008.10702390

USEPA (United States Environmental Protection Agency). 2023. Beneficial use evaluation: flue gas desulfurization gypsum as an agricultural amendment. United States Department of Agriculture (EPA Contract No. EP-W-15-005). Available at: https://www.epa.gov/system/files/documents/2023-03/FGD_Ben_Use_Eval_with_Appendices_March_2023_508.pdf

Van Raij, B. 2008. Gesso na agricultura. Campinas: Instituto Agronômico, Fundação IAC, n° 117. 233 p.

Van Raij, B. 2010. Melhorando o ambiente radicular em subsuperficie. In: Prochnow, L.I., Casarin, V., Stipp, S.R. ed. Boas práticas para uso eficiente de fertilizantes: contexto mundial e técnicas de suporte. v. 1. Piracicaba: INPI-Brasil, p. 349-382.

Van Raij, B.; Cantarella, H.; Quaggio, J. A.; Furlani, A. M. C. 1997. Recomendações de adubação e calagem para o Estado de São Paulo (Boletim Técnico, 100), 2 ed. Instituto Agronômico/Fundação IAC, Campinas. 285 p. Available at: https://www.iac.sp.gov.br/publicacoes/boletim100.php

Verma, K. K.; Song, X. -P.; Joshi, A.; Tian, D. -D.; Rajput, V. D.; Singh, M.; Arora, J.; Minkina, T.; Li, Y. -R. 2022. Recent trends in nanofertilizers for sustainable agriculture under climate change for global food security. Nanomaterials, 12: 173. https://doi.org/10.3390/ nano12010173

Vitti G. C.; Queiroz F. E. C.; Otto R.; Quintino T. A. 2005. Nutrição e adubação da cana-de-açúcar. Departamento de Solos e Nutrição de Plantas, ESALQ/USP, Piracicaba, SP. 78 p.

Vitti, G. C.; Mazza, J. A. 2002. Planejamento, estratégias de manejo e nutrição da cultura de cana-de-açúcar. POTAFOS - Informações Agronômicas, n° 97. 16 p. Available at: http://www.ipni.net/publication/ia-brasil.nsf/0/504B40E488537AE083257AA2005EA7F6/$FILE/Encarte%2097.pdf

Vitti, G. S.; Luz, P. H. C.; Malavolta, E.; Dias, A. S.; Serrano, C. G. E. 2008. Uso de gesso em sistemas de produção. Piracicaba: GAPE, 104 p.

Wakchaure, M.; Patle, B. K.; Mahindrakar, A. K. 2023. Application of AI techniques and robotics in agriculture: a review. Artificial Intelligence in the Life Sciences, 3: 100057. https://doi.org/10.1016/j.ailsci.2023.100057

Walia, M. K.; Dick, W. A. 2018. Selected soil physical properties and aggregate-associated carbon and nitrogen as influenced by gypsum, crop residue, and glucose. Geoderma, 320: 67-73. https://doi.org/10.1016/j.geoderma.2018.01.022

Walker, M. E.; Csinos, A. S. 1980. Effect of gypsum on yield, grade and incidence of pod rot in five peanut cultivars. Peanut Science, 7 (2): 109-113. https://doi.org/10.3146/i0095-3679-7-2-13

Wallace, A. 1994. Use of gypsum on soil where needed can make agriculture more sustainable. Communications in Soil Science and Plant Analysis, 25(1-2): 109-116, https://doi.org/10.1080/00103629409369015

Wang, J. M.; Yang, P. L. 2018. Potential flue gas desulfurization gypsum utilization in agriculture: A comprehensive review. Renewable and Sustainable Energy Reviews, 82: 1969-1978. https://doi.org/10.1016/j.rser.2017.07.029

Wang, Y.; Wang, Z.; Liang, F.; Jing, X.; Feng, W. 2021. Application of flue gas desulfurization gypsum improves multiple functions of saline-sodic soils across China. Chemosphere, 277: 130345. https://doi.org/10.1016/j.chemosphere.2021.130345

Watts, D. B.; Dick, W. A. 2014. Sustainable uses of FGD gypsum in agricultural systems: Introduction. Journal of Environment Quality, 43(1): 246-252. https://doi.org/10.2134/jeq2013.09.0357

Watts, D. B.; Runion, G. B.; Torbert, H. A. 2021. Influence of flue gas desulfurization gypsum on phosphorus loss from a horticultural growth medium. Horticulturae, 7: 199. https://doi.org/10.3390/horticulturae7070199

White, P. J.; Broadley, R. 2003. Calcium in plants. Annals of Botany, 92: 487-511. https://doi.org/10.1093/aob/mcg164

Xu, X.; Wang, J.; Tang, Y.; Cui, X.; Hou, D.; Jia, H.; Wang, S.; Guo, L.; Wang, J.; Lin, A. 2023. Mitigating soil salinity stress with titanium gypsum and biochar composite materials: Improvement effects and mechanism. Chemosphere, 321: 138127. https://doi.org/10.1016/j.chemosphere.2023.138127

Yahya, K. E.; Jia, Z.; Luo, W.; YuanChun, H.; Ame, M. A. 2022. Enhancing salt leaching efficiency of saline-sodic coastal soil by rice straw and gypsum amendments in Jiangsu coastal area. Ain Shams Engineering Journal, 13(5): 101721. https://doi.org/10.1016/j.asej.2022.101721

Yamika, W. S. D.; Aini, N.; Setiawan, A.; Purwaningrahayu, R. D. 2018. Effect of gypsum and cow manure on yield, proline content, and K/Na ratio of soybean genotypes under saline conditions. Journal of Degraded and Mining Lands Management, 5(2): 1047-1053. https://doi.org/10.15243/jdmlm.2018.052.1047

Zahra, N.; Sarwar, G. 2015. Comparison of gypsum and potassium silicate for improving yield and yield components of rice. International Journal of Agricultural and Applied Sciences, 7(1): 1-6. Available at: https://www.academia.edu/download/49702340/comparison_of_gypsum_and_potassium_silic20161018-11950-1fp6o9v.pdf

Zambrosi, F. C. B.; Alleoni, L. R. F.; Caires, E. F. 2007. Gypsum application and ionic speciation of the solution from an oxisol under no-till system. Ciência Rural, 37: 110-117. https://doi.org/10.1590/S0103-84782007000100018

Zenda, T.; Liu, S.; Dong, A.; Duan, H. 2021. Revisiting sulphur - the once neglected nutrient: It's roles in plant growth, metabolism, stress tolerance and crop production. Agriculture, 11: 626. https://doi.org/10.3390/agriculture11070626

Zeng, H.; Dhiman, G.; Sharma, A.; Sharma, A.; Tselykh, A. 2023. An IoT and Blockchain-based approach for the smart water management system in agriculture. Expert System, e12892. https://doi.org/10.1111/exsy.12892

Zhao, Y.; Wang, S.; Li, Y.; Zhuo, Y.; Liu, J. 2019. Sustainable effects of gypsum from desulphurization of flue gas on the reclamation of sodic soil after 17 years. European Journal of Soil Science, 70(5): 1082-1097. https://doi.org/10.1111/ejss.12807

Zheng, Z. Z.; Shen, J. Q.; Pan, W. H.; Pan, J. W. 2013. Calcium sensors and their stress signaling pathways in plants. Hereditas, 35(7): 875-884. https://doi.org/10.3724/sp.j.1005.2013.00875

Zielonka, D.; Nierebiński, M.; Kalaji, H. M.; Augustynowicz, J.; Prędecka, A.; Russel, S. 2018. Efficiency of the photosynthetic apparatus in *Cannabis sativa* L. fertilized with sludge from a wastewater treatment plant and with phosphogypsum. Ecological Questions, 28: 55-61. https://doi.org/10.12775/EQ.2017.039

Zoca, S. M.; Penn, C. 2017. An important tool with no instruction manual. Advances in Agronomy, 144: 1-44. https://doi.org/10.1016/bs.agron.2017.03.001