



Review article

The Role of Lime (CaCO₃) in Soil Properties and Nutrient Availability: Implications for Greenhouse Gas Emissions and Climate Change

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Abstract

Calcareous soils, primarily characterized by the presence of calcium carbonate (CaCO₃) and associated carbonate minerals, play a fundamental role in regulating soil chemical equilibrium, pH regime, buffering capacity, nutrient availability, and structural stability. Through these interconnected mechanisms, calcareous conditions exert a direct influence on agricultural productivity as well as on broader environmental outcomes. Elevated soil pH values and the abundance of bicarbonate ions in calcareous systems promote the precipitation of phosphorus (P) and the reduced solubility or strong surface adsorption of essential micronutrients such as iron (Fe), zinc (Zn), and manganese (Mn). These processes frequently result in lime-induced chlorosis, yield reductions, and quality losses, particularly in fruit crops and nutritionally sensitive field crops. In contrast, acid soils, where carbonate content is absent or extremely limited, occupy a substantial proportion of the world's arable land. Under such low-pH conditions, nutrient availability is constrained, aluminum and manganese toxicity may occur, and the solubility of potentially toxic elements increases, leading to distinct limitations on crop growth and root development. In these systems, liming represents a classical and indispensable soil amelioration practice, as it raises soil pH, increases base saturation, improves cation exchange processes, enhances soil aggregation and structural resilience, and stimulates microbial and biological activity. Beyond agricultural production, soil inorganic carbon (SIC) associated with carbonates constitutes one of the largest carbon pools in terrestrial ecosystems and plays a complex role in greenhouse gas dynamics and climate regulation. Whether SIC functions as a net atmospheric carbon dioxide (CO₂) sink or source depends largely on the origin of calcium, fertilization intensity, and land management strategies. In acid soils, liming is commonly regarded as a practice that directly generates CO₂; however, the accompanying increase in soil pH may simultaneously reduce nitrous oxide (N₂O) emissions by altering nitrogen transformation pathways, while excessive liming can enhance ammonia (NH₃) volatilization. In this context, the use of biomass-derived ashes with low heavy-metal content and silicate-based materials such as feldspar and perlite offer promising integrated management options by improving nutrient availability while contributing to long-term CO₂ sequestration. Consequently, sustainable agriculture in both calcareous and acid soils should move beyond short-term yield-oriented approaches and adopt integrated environmental soil management strategies that explicitly account for greenhouse gas emissions, carbon sink potential, and climate change mitigation.

Keywords: Lime (CaCO₃), Calcareous Soils, Nutrient Availability, Soil Inorganic Carbon (SIC), Greenhouse Gas Emissions, Climate Change

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INTRODUCTION

Approximately 30% of the world's terrestrial surface consists of calcareous soils characterized by a high calcium carbonate (CaCO_3) content (Bontpart et al., 2024). These soils are particularly widespread in arid and semi-arid subtropical regions and may constitute more than half of the total land area in regions where agricultural production is intensive, such as the Mediterranean basin (López-Rayó et al., 2023; Wahba et al., 2019). In Türkiye, nearly one-third (33.48%) of cultivated agricultural soils are classified as calcareous soils containing more than 15% lime (Eyüpoğlu, 1999). In order to meet the increasing food demand of the growing global population, the reclamation and agricultural utilization of low-productivity calcareous lands located along desert margins has become a necessity for sustainable agricultural production (Wahba et al., 2019; Manikandan et al., 2024). However, calcareous and highly calcareous soils possess severe yield-limiting constraints in plant production due to their high carbonate content and the associated chemical limitations (Bolan et al., 2023b; Brownrigg et al., 2022; Manikandan et al., 2024).

Conversely, acid soils in which lime is absent or present only in trace amounts cover nearly half of the world's arable land and present a different set of production challenges as a result of low soil pH (Wang et al., 2021; Wenyika et al., 2025). Therefore, ensuring sustainability in agricultural production requires a comprehensive understanding of the relationship between soil properties and nutrient availability, given the widespread occurrence of both acid and calcareous soils and the direct control exerted by soil pH on the availability of plant nutrients in these systems (Meena et al., 2025).

Improving the quality of acid-reacting soils as a plant growth medium requires an increase in soil pH. For this purpose, liming materials are widely applied, and this practice is referred to as liming. Common liming materials include oxides, hydroxides, and carbonates of calcium (Ca) and magnesium (Mg) (Sims, 1996; Brady & Weil, 2017). The origin of soil lime may be lithogenic (primary), resulting from the physical disintegration of parent materials such as limestone, dolomite, or marl, or pedogenic (secondary), formed through re-precipitation processes within the soil profile during pedogenesis (Batool et al., 2024; Manikandan et al., 2024). Although calcareous soils are most common in arid and semi-arid regions due to limited leaching of soluble salts, they may also develop in humid and sub-humid climates on CaCO_3 -rich and relatively weakly weathered parent materials (Bolan et al., 2023b). Pedogenic lime formation in arid and semi-arid regions occurs through the process of calcification, whereby carbonates leached from upper horizons accumulate in lower layers, forming calcic or petrocalcic (caliche) horizons (Wahba et al., 2019; Manikandan et al., 2024). This accumulation may occur as a diffuse distribution throughout the soil matrix or appear as filaments, nodules, or discrete carbonate pockets.

Soil lime content and soil pH are regarded as “master variables” that directly govern a wide range of chemical reactions in soils (Penn & Camberato, 2019; Lal et al., 2021). In calcareous soils, pH is

buffered by reactions between CaCO_3 and atmospheric carbon dioxide (CO_2) and is generally stabilized within the range of 7.5–8.5 (Bontpart et al., 2024; López-Rayó et al., 2023). In contrast, in acid soils formed under high rainfall conditions, leaching of base cations may reduce soil pH to values below 5.5, triggering aluminum (Al) and manganese (Mn) toxicity while simultaneously decreasing the availability of phosphorus (P), calcium (Ca), and magnesium (Mg) (Wenyika et al., 2025; Penn & Camberato, 2019). In calcareous environments, the primary constraint is the combination of high pH and the abundance of bicarbonate (HCO_3^-) ions. These conditions promote the precipitation of micronutrients such as iron (Fe), zinc (Zn), manganese (Mn), boron (B), and copper (Cu) as insoluble oxides or their strong adsorption onto soil surfaces, thereby limiting their bioavailability (López-Rayó et al., 2023; Kaya & Uygur, 2019). Phosphorus availability is also severely restricted in calcareous soils, as phosphate anions readily react with Ca^{2+} and Mg^{2+} to form poorly soluble calcium phosphate compounds such as apatite (Penn & Camberato, 2019; Memon et al., 2024). From a physical perspective, calcareous soils are prone to structural problems, including surface crust formation, cementation of subsoil layers, and the consequent restriction of water infiltration (Wahba et al., 2019; Manikandan et al., 2024).

The link between calcareous soils, climate change, and greenhouse gas emissions is critical within the context of the global carbon (C) budget. Liming of acid soils neutralizes soil H^+ ions but simultaneously leads to direct CO_2 emissions, which represent a significant component in greenhouse gas inventories (Lal et al., 2021). In naturally calcareous soils, however, the processes are more complex, as soil inorganic carbon (SIC) may function both as a carbon source and as a potential carbon sink (Naorem et al., 2022; Manikandan et al., 2024). The precipitation of calcium derived from silicate weathering as carbonate constitutes a long-term sink for atmospheric CO_2 (Manikandan et al., 2024). In contrast, soil acidification induced by excessive nitrogen fertilization can dissolve these carbonates, resulting in CO_2 release to the atmosphere (Abdollahpour et al., 2025; Raza et al., 2020). These dynamics demonstrate that the carbon sequestration potential of calcareous soils is closely linked to fertilization strategies and that unbalanced nitrogen management may pose a substantial risk in the context of climate change. A clear trade-off exists: while intensive fertilization aimed at increasing crop yields may accelerate inorganic carbon losses, balanced fertilization practices combined with the use of biochar or other organic amendments can promote more stable carbon retention in soils (Abdollahpour et al., 2025; Liang et al., 2025).

Recent studies further indicate that liming practices play a dual role in soil–climate interactions. In acid soils, liming enhances crop productivity and food security through pH regulation while simultaneously contributing to climate change mitigation by reducing nitrous oxide (N_2O) emissions (Wang et al., 2021). Moreover, it has been demonstrated that well-managed lime layers or lime-based systems may facilitate the binding of atmospheric CO_2 in carbonate form, thereby offering a direct carbon removal potential (Hawrot & Renforth, 2025). These findings emphasize the central role of soils in regulating the climate system through both organic and inorganic carbon pools and highlight that

calcareous soils and limed acid soils may serve as strategic management components in climate change mitigation efforts (Lal et al., 2021).

The primary objective of this review is to examine nutrient availability constraints encountered in lime-free (acid) soils and in highly calcareous soils, together with modern management strategies developed to address these limitations. By doing so, this review aims to emphasize that such soils and related management practices should not be viewed solely as production constraints, but also as potential strategies for reducing greenhouse gas emissions and contributing to climate change mitigation.

EFFECTS OF LIME AND LIMING ON SOIL PROPERTIES

Soil calcareous is a term generally used to describe the presence of calcium carbonate (CaCO_3) and related carbonate minerals, such as magnesium carbonate, in soils. Carbonate minerals in natural systems predominantly occur as calcite (CaCO_3), dolomite [$\text{CaMg}(\text{CO}_3)_2$], and aragonite (a polymorph of CaCO_3), whereas siderite (FeCO_3) occurs less frequently (Batool et al., 2024; Naorem et al., 2022). When these compounds are present in soils in free form, they release CO_2 gas and produce effervescence upon treatment with hydrochloric acid (HCl), which is a classical diagnostic reaction for carbonates (Wahba et al., 2019).

The origin of soil calcareous may be lithogenic (primary) or pedogenic (secondary) (Kapur et al., 2000). Lithogenic carbonates are directly inherited from carbonate-rich parent materials such as limestone or dolomite, whereas pedogenic carbonates are reshaped within the soil profile as a result of soil-forming processes, including weathering, dissolution, and re-precipitation (Batool et al., 2024). Pedogenic lime formation is generally associated with the process of calcification, whereby carbonates leached from upper horizons accumulate in lower layers (typically the B or C horizon), forming calcic or petrocalcic (caliche) horizons (Wahba et al., 2019). Such accumulations may occur as diffuse distributions throughout the soil mass or appear in the form of filaments, nodules, or discrete carbonate pockets.

In calcareous soils, the carbonate–bicarbonate equilibrium is the principal determinant of soil pH and buffering capacity. Calcium carbonate reacts with water and carbon dioxide to form bicarbonate ions [$\text{Ca}(\text{HCO}_3)_2$], and through this process, soil pH is commonly buffered within the range of 7.5–8.5 (George et al., 2012; Bontpart et al., 2024). This equilibrium can be summarized by Reaction (1) and is closely linked to the partial pressure of CO_2 in the soil atmosphere (Sanderman, 2012; Naorem et al., 2022):



The concept of “active lime” refers to the fine-grained and highly reactive fraction of calcareous that can interact more rapidly with the soil solution (López-Rayó et al., 2023). Total soil calcareous

content is commonly determined using calcimetry (Scheibler method) by measuring the volume of CO₂ released following the addition of HCl. This method is widely accepted as a reliable and standardized approach, particularly for monitoring relatively small changes in SIC stocks (Silva et al., 2024).

The most pronounced chemical effect of lime is the neutralization of soil acidity through an increase in soil pH and base saturation (Wenyika et al., 2025; Abdollahpour et al., 2025). Liming practices enhance cation exchange capacity (CEC) by promoting the replacement of H⁺ and Al³⁺ ions on colloidal surfaces with Ca²⁺ or Mg²⁺ (Wenyika et al., 2025; Kant et al., 2006). However, excessive lime content may increase electrical conductivity (EC) and alter the ionic strength of the soil solution, thereby disturbing the balance of other nutrients (Wahba et al., 2019; Kaya & Uygur, 2019). Moreover, in calcareous and highly calcareous soils, elevated pH and the bicarbonate/carbonate equilibrium can limit the availability of several nutrients, particularly phosphorus (P), Fe, Zn, Mn, and under certain conditions, B. Iron deficiency under such conditions may lead to the development of “lime-induced chlorosis,” often resulting in significant yield losses (Wahba et al., 2019).

In acid soils, agricultural activities are associated not only with low base saturation but also with insufficient organic matter content, which can lead to severe degradation of soil structure. Organic matter deficiency weakens granular and aggregate structure, favoring the dominance of massive (structureless) soil conditions; this, in turn, reduces water infiltration and deteriorates soil physical properties (Sumner & Noble, 2003; Shaaban, 2024).

It has also been shown that applications of rapidly soluble reactive lime materials, such as CaO can increase aggregate stability over relatively short periods (Keiblinger, 2016). Nevertheless, under conditions of excessive lime, aggregation alone is not sufficient to ensure favorable soil physical behavior. The relationship between lime content and infiltration must be evaluated in conjunction with soil texture, silt-to-clay ratio, and crusting susceptibility. A classical rainfall simulator study demonstrated that CaCO₃ content and texture significantly influence infiltration rates in crusted soils (Ben-Hur et al., 1985). Under calcareous conditions, intense rainfall may promote surface crust formation and/or the development of compacted layers resulting from tillage or cementation (hardpan or petrocalcic horizons), which can adversely affect infiltration and root development. Therefore, organic matter management and appropriate tillage practices play a critical role in sustaining soil physical quality (Manikandan et al., 2024).

The absence of calcareous in soils indicates acidic conditions in which the carbonate buffer system is lacking and soil pH declines below 5.5. Under such conditions—particularly in humid regions subject to intense leaching and acidifying fertilization—Al³⁺ solubility may increase, leading to toxicity that restricts root growth; in addition, certain micronutrients (e.g., Mn) may become excessively available and pose toxicity risks (Hede et al., 2001). Acidic soil conditions can also increase the solubility of heavy metals [e.g., lead (Pb), cadmium (Cd)], facilitating their uptake by plants and

subsequent entry into the food chain, thereby posing risks to animal and human health (Bolan et al., 2023a). In acid soils, liming is therefore regarded as a classical reclamation practice, as it raises soil pH and reduces both aluminum toxicity and acidity-related nutritional constraints (Wenyika et al., 2025).

Lime application in acid soils creates more favorable conditions for microbial and enzymatic activity, thereby accelerating organic matter mineralization and nitrification (Wenyika et al., 2025). In contrast, organic matter content in naturally calcareous soils is often low, as high calcium concentrations may stabilize organic matter in mineral–organic complexes, making decomposition more difficult (Manikandan et al., 2024; Wenyika et al., 2025). The presence or absence of lime in soils also influences soil biodiversity by shaping the dominance of acidophilic or calcicolous plant and microbial communities adapted to acidic or calcareous conditions, respectively (Bontpart et al., 2024).

PROPERTIES OF CALCAREOUS SOILS AND PLANT NUTRIENT AVAILABILITY

The terms “calcareous”, “calcisols”, and/or “calcids” are used to describe soils rich in calcium carbonate or calcium and magnesium carbonates (Wahba et al., 2019). Calcareous soils are defined as soils containing more than 15% CaCO_3 and are widely distributed across arid, semi-arid, humid, and sub-humid regions (Bolan et al., 2023b). In the field, the presence of lime is diagnosed based on the intensity of effervescence observed when 10% hydrochloric acid (HCl) is applied; soils are classified along a qualitative scale ranging from “no effervescence” (non-calcareous) to “very strong effervescence” (calcareous soils). In laboratory analyses, lime content is determined using the Scheibler calcimeter method; soils containing 15–30% CaCO_3 are classified as calcareous, those with 30–50% as marl soils, and soils containing more than 50% CaCO_3 are referred to as lime soils (Bolan et al., 2023b).

According to Soil Taxonomy, calcareous soils are characterized by the presence of calcium carbonate in the parent material and/or by a calcic horizon (lime layer) (USDA, 2014). This horizon represents a zone of secondary accumulation of calcium and/or magnesium carbonates. Accumulation may occur within the C horizon or in various other horizons. The calcic horizon must be at least 15 cm thick and contain 15% or more CaCO_3 equivalent carbonates. If this layer overlies the parent material (C horizon), its carbonate content must exceed that of the underlying layer by at least 5%. Visible evidence of secondary carbonate accumulation, such as nodules and/or concretions, must be present. If the calcic horizon overlies limestone, marl, or other highly calcareous materials containing 40% or more CaCO_3 equivalent, a decrease in carbonate content with depth is not required.

Soils are commonly classified according to their lime content as shown in Table 1 (Nelson, 1982).

Table 1. Classification of soils according to lime content.

Lime content (%)	Class
0–1	Slightly calcareous
1–5	Calcareous
5–15	Moderately calcareous
15–25	Highly calcareous
>25	Very highly calcareous

Calcareous soils are typically buffered within an alkaline pH range, a condition that substantially reduces the availability of phosphorus (P) and molybdenum (Mo) (Meena et al., 2025). Phosphorus availability declines due to precipitation as calcium phosphate. Water-soluble P applied via phosphorus fertilizers readily reacts with Ca to form less soluble Ca-phosphate compounds, thereby reducing plant-available P (Wahba et al., 2019). However, phosphorus chemistry is not strictly unidirectional. Particularly at higher pH ranges, competition between carbonate and phosphate for Ca may reverse Ca-phosphate solubility under certain conditions, indicating that pH–CaCO₃–P relationships can exhibit threshold-type behavior (Penn et al., 2019). This explains why decisions regarding fertilizer dose, form, and placement is critical for phosphorus management in calcareous environments.

A strong relationship between soil pH and plant phosphorus uptake has been reported. While the primary orthophosphate ion (H₂PO₄⁻) predominates under strongly acidic conditions, the secondary orthophosphate ion (HPO₄²⁻) is more common in soils with pH values around neutrality. In acidic soils, these ions precipitate with Fe and Al as insoluble phosphate compounds, whereas in soils with pH values above 7, they precipitate with Ca to form insoluble Ca-phosphates. The optimal soil pH range for phosphorus availability has been identified as 6.5–7.3 (Brady & Weil, 2017). One of the most effective approaches to improving phosphorus availability in calcareous soils is the addition of organic matter. Studies have demonstrated that applications of fresh organic residues and organic acids can significantly enhance phosphorus availability (Ström et al., 2002). Similarly, increases in soil organic matter content have been shown to markedly increase Olsen-P extractable phosphorus (Braschi et al., 2003).

Localized acidification of a portion of the root zone through the placement of chemical fertilizers and other acidifying soil amendments offers potential for increasing phosphorus solubility in calcareous soils by exploiting the pH-lowering effects of fertilizers (Shen et al., 2011). In particular, hydrogen ions (H⁺) released during nitrification of ammonium (NH₄)-based fertilizers, such as ammonium sulfate, may locally decrease soil pH, enhance Ca-phosphate solubility, and improve phosphorus availability (Brownrigg et al., 2022). Among these practices, sulfur (S) application for pH reduction is one of the most widely known approaches (Akay et al., 2019; Maltaş et al., 2022; Orman & Kaplan, 2000). However, its effectiveness is transient and depends on the amount, particle size, timing, oxidation status of the applied sulfur, as well as environmental conditions.

Soil amendments such as aluminum sulfate and iron sulfate, used to reduce soil reaction, can alter calcium chemistry in calcareous systems by lowering soil pH (Haynes, 1986). The reaction of iron (II) sulfate (FeSO_4) with Ca may result in the formation of more soluble salts [e.g., calcium sulphate (CaSO_4)], thereby reducing Ca participation in phosphorus precipitation reactions. Furthermore, the formation of organic matter–phosphorus complexes involving Fe^{2+} (Fe–OM–P) may limit secondary reactions between P and Ca, positively affecting the chemical stability and availability of phosphorus (Grigatti et al., 2017).

In calcareous soils, the dominance of Ca^{2+} and Mg^{2+} ions in the soil solution due to high CaCO_3 content may create cationic competition or antagonism with potassium ion (K^+), limiting potassium (K) uptake by plant roots even when sufficient available K is present in the soil. In this context, ionic imbalance represents a major factor reducing potassium availability (Zengin et al., 2009; Behera et al., 2021; Memon et al., 2025). It has also been reported that soil pH in calcareous-alkaline soils significantly affects crop yield and fruit quality and that optimizing soil pH improves nutrient uptake by plants (Güneri et al., 2009).

In calcareous soils, CaCO_3 buffers soil pH within the alkaline range through the carbonate–bicarbonate system, thereby controlling both nutrient precipitation–dissolution equilibria and the solubility of micronutrients such as Fe, Zn, and Mn (Sparks, 2003). Unlike liming in acidic systems, this “carbonate buffer” makes it difficult to lower pH in calcareous soils, often leading to chronic nutritional disorders. Micronutrients (Fe, Zn, Mn, B, Cu) tend to precipitate as insoluble oxides and hydroxides or become strongly adsorbed onto soil surfaces under calcareous conditions (López-Rayó et al., 2023; Kaya & Uygur, 2019). Moreover, in calcareous and highly calcareous soils, elevated pH and the bicarbonate/carbonate equilibrium can limit the availability of several nutrients, particularly P, Fe, Zn, Mn, and under certain conditions, B. Iron deficiency under such conditions may lead to the development of “lime-induced chlorosis,” often resulting in significant yield losses (Wahba et al., 2019).

Iron availability is strongly dependent on soil pH, as the reduction and uptake of Fe^{3+} by plants becomes increasingly constrained under alkaline conditions (Arcas et al., 2024). Iron deficiency is the primary cause of lime-induced chlorosis, disrupting chlorophyll synthesis and resulting in yield losses (Bontpart et al., 2024; Tarakçioğlu & Uzun, 2024). Beyond its effects on Fe metabolism, CaCO_3 influences mineral nutrition across a broad spectrum, inducing chlorosis and yield reductions, while climatic variables such as soil moisture, CO_2 concentration, and temperature affect CaCO_3 equilibria and plant tolerance mechanisms (Bontpart et al., 2024). Under high CaCO_3 and bicarbonate conditions, Fe solubility and, less frequently, Mn uptake decline, a phenomenon particularly associated with chlorosis in fruit crops and certain legumes (López-Rayó et al., 2023). In calcareous systems, the effectiveness of chelates such as Fe-EDDHA for mitigating iron chlorosis has been well documented (Papastylianou, 1990; Roosta et al., 2015). Similarly, Zn is a micronutrient whose solubility decreases

under high pH conditions, placing calcareous soils at high risk of Zn deficiency (Martínez-Ríos et al., 2024; Duffner et al., 2012).

Comparative evaluations across crop groups indicate that legumes (e.g., faba bean, common bean) and maize are particularly sensitive to Fe and Zn deficiencies, whereas fruit and vineyard crops such as citrus, peach, apple, and grapevine frequently experience severe iron chlorosis and quality losses under highly calcareous conditions (López-Rayó et al., 2023; Tarakçıoğlu & Uzun, 2024). For example, while maize yield in acidic soils can be increased by raising soil pH, yield improvements in calcareous soils are achievable only through the use of chelated micronutrients or by improving soil physical properties (Kant et al., 2006; Wahba et al., 2019).

Soil management strategies applied to support plant growth under excessively calcareous conditions exhibit both beneficial and adverse effects. In chemical fertilization, the use of ammonium-based nitrogen fertilizers may enhance nutrient uptake by inducing localized acidification through H⁺ release during nitrification (Abdollahpour et al., 2025). However, this practice may also lead to CO₂ release from SIC stocks (Abdollahpour et al., 2025). Applications of organic matter and compost can reduce soil pH while improving nutrient availability through enhanced microbial activity, whereas acidifying agents such as sulfur are effective in neutralizing carbonates and lowering pH in calcareous soils (Wahba et al., 2019). Irrigation and fertigation practices, particularly drip irrigation, facilitate direct nutrient delivery to the root zone and may reduce surface crust formation. From a tillage perspective, deep loosening practices extending to depths of up to 60 cm can improve root development by breaking cemented layers (Wahba et al., 2019).

Boron adsorption is pH-sensitive and tends to approach a maximum at pH values around 7–8 in many systems; in calcareous soils, calcite surfaces and carbonate minerals may play a role in boron adsorption (Goldberg & Forster, 1991). Consequently, the deficiency–toxicity window for boron may narrow under calcareous conditions, necessitating more sensitive management in regions with boron accumulation derived from irrigation water or parent material. Boron deficiency is commonly reported in coarse-textured (sandy) acidic soils, following excessive liming, in soils rich in carbonates and/or Fe- and Al- oxides and hydroxides, and in soils with low organic matter content (Niaz et al., 2011; Ryan et al., 2013).

High calcium saturation in calcareous soils tends to enhance the formation and stability of micro- and macro-aggregates through flocculation processes among soil colloids. Following aggregation, increased biological activity may promote the formation of water-stable aggregates, thereby improving water infiltration and aeration (Wenyika et al., 2025).

In a study simulating high lime content, Abdulwahhab and Şeker (2020) reported that increasing lime application rates to clay and sandy loam soils resulted in higher pH, bulk density, particle density, and CaCO₃ content in both textures, while electrical conductivity and liquid limit values decreased. The

effects of lime applications on soil structure varied with texture: in clay soils, low lime doses improved aggregate properties, whereas high doses caused structural degradation; in sandy loam soils, aggregate stability was affected to a more limited extent. The greater increase in organic carbon mineralization observed in sandy loam soils suggested that clay soils may possess a relatively higher carbon storage capacity.

To unlock the production potential of calcareous soils, the key management axis emphasized in this section includes: (i) appropriate selection and placement of fertilizers, particularly phosphorus and micronutrients; (ii) organic matter additions to promote stable aggregate formation, suppress dispersion, and enhance resistance to crusting; and (iii) practices such as deep ripping to disrupt compacted pan layers. Achieving full production potential further requires careful irrigation and fertilization management (Bolan et al., 2023b).

PROPERTIES OF ACID SOILS AND PLANT NUTRIENT AVAILABILITY

Soil pH is fundamentally defined on a 0–14 scale, with values below 7 indicating acidic conditions, 7 representing neutrality, and values above 7 indicating alkaline conditions (Soil Survey Division Staff, 2017). Agronomic classification further subdivides this range into functional categories that more closely reflect nutrient availability and toxicity thresholds, ranging from strongly acidic soils (pH < 5.0) to slightly acidic (pH 6.1–6.5), neutral (pH 6.6–7.3), and alkaline soils (pH > 7.3), as summarized in Table 2 (Brady & Weil, 2017; Soil Survey Division Staff, 2017).

In this study, acid soils are defined as soils with surface horizon pH (H₂O) values below 5.5, following the widely accepted agronomic and pedological convention that identifies this threshold as critical due to the onset of aluminum toxicity, reduced nutrient availability, and significant constraints on plant growth, rather than solely relying on the chemical definition of acidity (pH < 7).

At the global scale, acid soils are distributed within two major geographical belts. The first occurs in the humid northern temperate zone, which is predominantly covered by coniferous forests and characterized mainly by Spodosols, Inceptisols, Histosols, Entisols, and dystric Alfisols. The second belt is found in the humid tropics, currently or historically dominated by savannas and tropical rainforests, where Oxisols and Ultisols are the prevailing soil orders (Uexküll & Mutert, 1995). FAO–IAEA (2006) emphasizes that areas with the highest potential for agricultural expansion are predominantly located on acid-reacting Oxisols and Ultisols, and that soil acidification in these systems is further intensified by increasing atmospheric CO₂ concentrations and the long-term use of ammonium-based nitrogen fertilizers.

Table 2. Classification of Soil Reaction Based on pH Ranges

Soil Reaction Class	Soil pH Range
Ultra Acidic	< 3.5
Extremely Acidic	3.5 – 4.4
Very Strongly Acidic	4.5 – 5.0
Strongly Acidic	5.1 – 5.5
Moderately Acidic	5.6 – 6.0
Slightly Acidic	6.1 – 6.5
Neutral	6.6 – 7.3
Slightly Alkaline	7.4 – 7.8
Moderately Alkaline	7.9 – 8.4
Strongly Alkaline	8.5 – 9.0

The absence of lime in soils indicates acidic conditions in which the carbonate buffer system is lacking and soil pH declines below 5.5. Under such conditions—particularly in humid regions subject to intense leaching and acidifying fertilization— Al^{3+} solubility may increase, leading to toxicity that restricts root growth; in addition, certain micronutrients (e.g., Mn) may become excessively available and pose toxicity risks (Hede et al., 2001). Acidic soil conditions can also increase the solubility of heavy metals (e.g., Pb, Cd), facilitating their uptake by plants and subsequent entry into the food chain, thereby posing risks to animal and human health (Bolan et al., 2023a). In acid soils, liming is therefore regarded as a classical reclamation practice, as it raises soil pH and reduces both aluminum toxicity and acidity-related nutritional constraints (Wenyika et al., 2025).

Phosphorus deficiency is widely recognized as one of the most important nutritional constraints in acid soils worldwide (Hinsinger, 2001; Sanchez, 2010). Despite the presence of substantial total phosphorus reserves, its availability to plants is severely limited under acidic conditions. This limitation primarily arises from strong chemical interactions between phosphate anions—predominantly dihydrogen phosphate (H_2PO_4^-) and, to a lesser extent, hydrogen phosphate (HPO_4^{2-}) and soluble Al^{3+} and Fe^{3+} ions released at low soil pH. These interactions promote the rapid formation of sparingly soluble aluminum and iron phosphate compounds, such as variscite and strengite, which effectively immobilize phosphorus in soil matrices (Ro & Cho, 2000; Verma et al., 2005). In addition to precipitation reactions, phosphate ions are strongly adsorbed onto the surfaces of Fe- and Al-oxides and hydroxides that dominate the clay fraction of many acid soils, further reducing plant-available P (Redel et al., 2008). As soil pH declines, the solubility and activity of Al^{3+} and Fe^{3+} increase markedly, intensifying both precipitation and sorption processes and leading to chronic phosphorus deficiency. Consequently, phosphorus fertilization efficiency in acid soils is often low unless combined with soil management practices such as liming or organic amendments that reduce Al and Fe activity and improve P availability.

Tuyisenge (2021) demonstrated that liming applied to a wide range of acid soils induced significant transformations among P fractions, particularly within the more plant-available pools. These inter-fractional transfers were shown to vary as a function of soil physicochemical properties, the rate of lime application, and incubation time. In addition, long-term fertilization history emerged as a key determinant governing the relationships among P fractions. Overall, the results indicated that liming practices can partially regulate both the availability and mobility of phosphorus in acid soils.

In addition to its role in neutralizing soil acidity, lime application substantially modifies soil chemical properties and nutrient dynamics (Wenyika et al., 2025; Abdollahpour et al., 2025). Liming practices enhance CEC by promoting the replacement of H^+ and Al^{3+} ions on colloidal surfaces with Ca^{2+} or Mg^{2+} (Wenyika et al., 2025; Kant et al., 2006). However, excessive lime content may increase EC and alter the ionic strength of the soil solution, thereby disturbing the balance of other nutrients (Wahba et al., 2019; Kaya & Uygur, 2019). Soil pH strongly controls nutrient availability and dominant chemical reactions in soils (Table 3) (Brady & Weil, 2017; Havlin et al., 2014).

Table 3. Soil pH ranges in relation to nutrient availability and predominant chemical processes governing element solubility and toxicity.

pH Range	Nutrient Availability Status,	Predominant Chemical Mechanism
4.0 - 5.0	Extremely low P, Ca, Mg, Mo	Al/Fe precipitation; Ca, Mg intense leaching
5.0 - 5.5	Low P, K; High Al, Mn	Ligand exchange; Al dissolution
6.0 - 7.0	Optimal for most nutrients	Maximum solubility of P, Balanced base status
> 7.5	Low P, Fe, Mn, Zn, B	Carbonate precipitation; Low solubility

GREENHOUSE GAS EMISSIONS AND CLIMATE CHANGE IMPLICATIONS OF CALCAREOUS AND LIMED SOILS

Forms of carbonate present in soils, collectively referred to as soil inorganic carbon, constitute the second largest terrestrial carbon pool after soil organic carbon (SOC), with an estimated global stock of approximately 950 Pg C (Batool et al., 2024; Lal et al., 2021). Whether SIC functions as a net sink or a source of atmospheric CO_2 largely depends on the origin of calcium involved in carbonate formation (Monger et al., 2015; Sanderman, 2012). When calcium is supplied through the weathering of silicate minerals, as described by the Ebelmen–Urey reaction, atmospheric CO_2 is permanently immobilized in the form of pedogenic carbonates, representing a net and long-term carbon sink (Monger et al., 2015; Lal et al., 2021). In a case study examining the distribution of carbonate pools and the formation of pedogenic carbonates in Mediterranean soils, Kapur et al. (2000) reported that carbonate accumulation may occur through both lithogenic inheritance and pedogenic processes.

Soils with high carbonate content have the capacity to capture atmospheric CO_2 and store it as stable calcium carbonate ($CaCO_3$) minerals. This process is recognized as a component of soil inorganic carbon sequestration and may contribute to climate change mitigation over extended timescales (Monger

et al., 2015; Beerling et al., 2020). The carbonate–silicate cycle facilitates the formation of carbonates through silicate weathering, thereby contributing to reductions in atmospheric CO₂ concentrations on geological timescales (Taylor et al., 2016; Beerling et al., 2020). However, in contrast to the rapid carbon cycle, these processes operate over thousands to millions of years (Walker et al., 1981; Taylor et al., 2016).

Land use and soil management practices can substantially modify this balance. Intensive nitrogen fertilization may induce soil acidification, leading to the dissolution of native carbonates and the release of CO₂ to the atmosphere. Conversely, management practices such as irrigation and organic matter amendments can enhance carbon storage potential by promoting bicarbonate leaching into deeper soil layers and/or the precipitation of secondary carbonates (Abdollahpour et al., 2025; Manikandan et al., 2024).

Supporting this view, Cai et al. (2018) demonstrated in a long-term field study on calcareous soils of the Chinese Loess Plateau that agricultural management and nitrogen input rates exerted strong controls on soil carbon stocks. Under appropriate management conditions, SOC stocks increased, whereas excessive nitrogen inputs in some cases stimulated carbonate dissolution, resulting in measurable losses of SIC.

RELATIONSHIP BETWEEN LIMING AND GREENHOUSE GASES/CLIMATE CHANGE

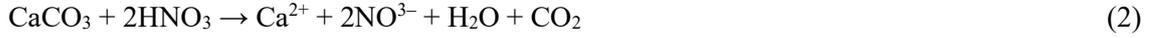
Carbonate-based soil amendments widely used in agriculture, particularly limestone (CaCO₃) and dolomite [CaMg(CO₃)₂], inherently possess the potential to release CO₂ owing to their chemical composition. In theory, complete dissolution of these materials would result in the transfer of carbonate-bound carbon to the atmosphere as CO₂, a process defined as the potential CO₂ emission. Under field conditions, however, incomplete dissolution of carbonates, together with partial retention of released CO₂ within the soil solution, bicarbonate systems, or through secondary recarbonation processes, generally limits atmospheric transfer. Consequently, the amount of CO₂ actually emitted to the atmosphere is commonly referred to as the realized net CO₂ emission.

Quantitative assessments indicate that the realized net carbon release per ton of applied limestone is approximately 0.059 metric tons of C (equivalent to about 0.22 tons of CO₂), whereas dolomite applications result in slightly higher values of around 0.064 metric tons of C (approximately 0.23–0.24 tons of CO₂). These estimates remain below the theoretical emission potential of carbonate materials and suggest that the contribution of agricultural liming to greenhouse gas budgets may be more limited than previously assumed (West & McBride, 2005).

The net climatic impact of liming is strongly influenced by the type of liming material (calcitic versus dolomitic), soil properties, and the temporal scale considered (Sanderman, 2012; Wenyika et al., 2025). Several studies emphasize that increased plant growth following liming and the resulting enhancement of organic carbon inputs to soil may partially or fully offset CO₂ losses associated with

carbonate dissolution, potentially leading to a net carbon gain at the system level (Sanderman, 2012; Lal et al., 2021).

Liming practices applied to reclaim acid soils may therefore exert bidirectional effects on the atmospheric CO₂ balance. On the one hand, CaCO₃ reacts with acidic ions in soil, leading to direct CO₂ release, as illustrated in Reaction 2 (Sanderman, 2012; Lal et al., 2021):



On the other hand, alternative liming materials such as calcium oxide (CaO) and calcium hydroxide [Ca(OH)₂] may contribute to greenhouse gas mitigation by actively taking up atmospheric CO₂ through carbonation reactions (Wu et al., 2024; Wang et al., 2021; Hawrot & Renforth, 2025). It should be noted, however, that CO₂ emissions also arise during the industrial production and processing of these materials due to energy consumption.

The dominant reaction pathways following application depend on soil moisture and chemical conditions. In the presence of sufficient moisture, CaO is rapidly hydrated (Reaction 3), whereas under dry conditions direct carbonation may occur (Reaction 4). In acidic environments, Ca(OH)₂ reacts with protons (Reaction 5), while under alkaline conditions with low moisture and elevated CO₂ concentrations, carbonation dominates (Reaction 6). The solubility and persistence of the resulting calcium carbonate are governed by particle size and soil pH.



Because oxidized forms of lime and biomass- or thermal power plant-derived ashes are alkaline and contain alkali and alkaline earth elements predominantly in oxide forms, their reactions in soil and associated CO₂ capture mechanisms are schematically illustrated in Figure 1.

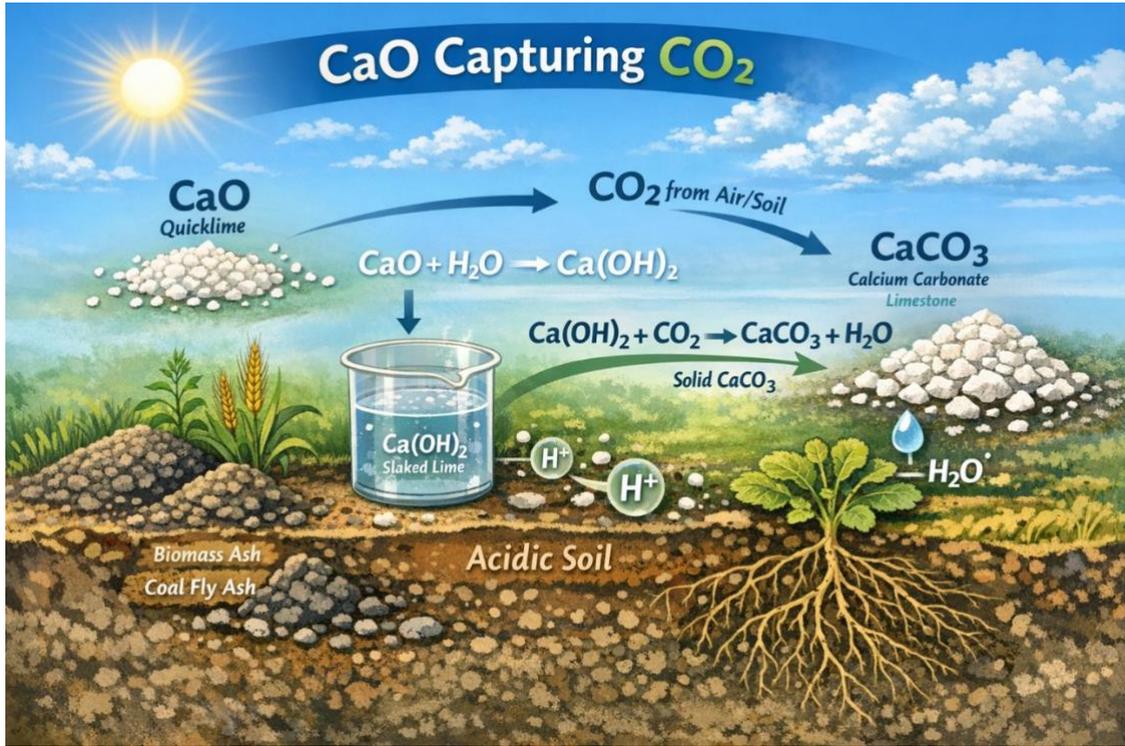


Figure 1. CO₂ capture from oxidized materials used in liming.

Although Intergovernmental Panel on Climate Change (IPCC) assumptions suggest that liming results in 100% CO₂ emissions, recent evidence indicates that this assumption likely overestimates actual emissions. A proportion of applied lime may dissolve and be transported to groundwater as bicarbonate, leading to effective CO₂ emissions that are estimated to be 14–34% lower than projected (Sanderman, 2012; Monger et al., 2015). In acid-reacting soils, liming increases soil pH, enhances plant growth and yield, and consequently increases the return of roots and crop residues to the soil. These processes raise organic matter inputs and may result in an increase in SOC stocks, indicating that liming not only improves soil fertility but can also indirectly contribute to carbon sequestration as part of integrated soil management strategies (Paradelo et al., 2015).

Biomass power plant ashes and thermal power plant ashes rich in alkaline and alkaline earth compounds, and characterized by low heavy-metal and radioactive element contents, show substantial potential as alternative liming materials (Basu et al., 2009; Wang et al., 2024; Sorrentino et al., 2023; Vassilev et al., 2021). When applied to acid soils, these materials can improve soil chemical reaction and promote CO₂ fixation through mineral carbonation processes. In addition, depending on their origin, such ashes may supply essential nutrients including K, Ca, Mg, P, B, and Zn. In Türkiye, chemical analyses of samples collected from a thermal power plant burning poultry litter and poultry manure (mean of five samples) revealed CaO, MgO, K₂O, and P₂O₅ contents of 26.14%, 5.82%, 19.74%, and 13.72%, respectively (Çöteli & Karahan, 2023). Because they both adjust soil pH to the desired level and contribute organic matter to the soil, mixtures of farmyard manure and lime have been recommended for the reclamation of acid-reacting soils (Çalış & Şeker, 2018). The agronomic and

environmental effects of these materials—applied either directly as liming agents or in combination with organic amendments—should be systematically evaluated across different soil texture classes, cropping systems, and under both rainfed and irrigated conditions.

Alternative liming materials such as zeolite and feldspar have also been evaluated for their acid-neutralizing capacity. In a laboratory study, the buffering capacities of finely ground zeolite (particle sizes of 1–0.5 mm, 0.5–0.25 mm, and <0.1 mm) and feldspar (<0.1 mm) were assessed using titration with HCl solutions of varying concentrations (Uygur, 2019). Zeolite exhibited significantly greater buffering capacity than feldspar across all particle-size fractions, with particle size exerting a strong influence on titration behavior. These findings suggest that zeolite and feldspar may serve as alternative liming materials for calcifuge crops, contributing both to acidity alleviation and to improvements in soil chemical properties.

Carbonate-based liming materials, silicate minerals, and biomass-derived ashes differ markedly in their interactions with climate-related processes. Conventional liming materials may directly emit CO₂, whereas silicate minerals represent carbon-free but slowly reacting alternatives. In contrast, biomass ash-based materials, when environmental safety criteria are met, offer a unique opportunity to simultaneously mitigate soil acidity, valorize waste streams, and enhance mineral CO₂ sequestration (Basu et al., 2009).

Owing to their high soluble salt contents and the presence of leachable macro- and micronutrients, fly ashes may also function as soil amendments capable of partially substituting for fertilizers and lime. However, when large quantities of alkaline fly ash are applied to neutralize soil acidity, adequate alkalinity must be ensured; otherwise, fly ash may gradually acidify and promote the release of elements at potentially toxic concentrations (Skousen et al., 2013). Beyond chemical effects, fly ashes can also improve soils with poor physical properties. Applications to coarse-textured or stony soils have been shown to enhance aggregate formation, water infiltration, and water-holding capacity, ultimately improving soil quality and crop yields without causing adverse effects in acid, neutral, or saline-sodic soils (Skousen et al., 2013).

The comparative assessment indicates that conventional liming materials provide rapid and effective correction of soil acidity; however, they are also associated with direct CO₂ emissions and an elevated risk of ammonia (NH₃) volatilization, particularly under ammonium-based fertilization regimes. In contrast, silicate-based materials such as feldspar represent carbon-free alternatives with long-term CO₂ sequestration potential through weathering processes, although their liming effectiveness is slower and more gradual. Biomass- and thermal power plant-derived ashes emerge as multifunctional soil amendments, as they simultaneously offer acid neutralization, nutrient supply, and high mineral carbonation potential, provided that environmental safety criteria—such as acceptable heavy metal contents are satisfied. Consequently, the selection of liming or alkalinity-providing materials should not

be based solely on short-term soil pH correction and yield response, but should also account for their greenhouse gas implications, carbon sequestration capacity, and compatibility with site-specific soil properties and nutrient management strategies. Integrating alternative liming materials into soil management frameworks may therefore enhance both agronomic sustainability and climate change mitigation outcomes.

Table 4. Evaluation of different liming materials in terms of properties, effectiveness, and CO₂ emissions.

Evaluation Criterion	Conventional Liming Materials (CaCO ₃ / CaO / Ca(OH) ₂)	Feldspar / Silicate-Based Materials	Biomass and Thermal Power Plant Ashes
CO ₂ sequestration potential	Conditional (via carbonation and CaCO ₃ formation)	Indirect and long-term (through silicate weathering)	High (via mineral carbonation of alkaline oxides)
Rate of pH increase	High (rapid effect)	Low–moderate (slow effect)	Moderate–high (depending on CaO content of ash)
NH ₃ volatilization risk	High (especially with ammonium-based fertilizers)	Low–moderate	Moderate (dependent on CaO content and application rate)
Effect on N ₂ O emissions	Mostly reductive (promotion of complete denitrification)	Uncertain or weak	Potentially reductive (due to pH increase and Ca effects)
Effect on crop yield	Strong and short-term	Moderate to long-term	Moderate to strong (depending on pH correction and nutrient content)
Indirect carbon sequestration effect (SOC)	Present (yield increase → greater biomass return)	Present (yield improvement and structural enhancement)	Present (yield increase and ash-induced aggregation)
Carbon footprint from production/processing	Moderate–high (calcination and energy use)	Moderate (mining and grinding)	Low–moderate (waste material; dependent on additional processing requirements)

The interaction between nitrogen fertilization and liming is a critical determinant of N₂O emissions (Wenyika et al., 2025; Abdollahpour et al., 2025). By increasing soil pH, liming can raise the dinitrogen (N₂)/N₂O ratio during denitrification, thereby reducing emissions of N₂O, a potent greenhouse gas (Wenyika et al., 2025; Sanderman, 2012). Nevertheless, enhanced mineralization of soil organic matter following liming may induce a temporary increase in CO₂ emissions, which is commonly regarded as an emission trade-off (Sanderman, 2012; Lal et al., 2021). In systems relying on ammonium-based fertilizers, liming markedly increases NH₃ volatilization, underscoring the need for balanced lime application and carefully designed nitrogen management strategies (Wang et al., 2021).

Liming applied to regulate soil pH can influence greenhouse gas emissions both quantitatively and qualitatively through its effects on nitrogen transformation processes (Clough et al., 2004; Butterbach-Bahl et al., 2013). Under acidic conditions, denitrification tends to dominate, potentially leading to elevated N₂O formation, whereas increasing soil pH can constrain this pathway and reduce N₂O emissions (Baggs et al., 2010). Indeed, studies have shown that in limed soils where pH was raised to approximately 6.3, realized net N₂O emissions declined markedly relative to non-limed soils.

Conversely, as soil pH increases, the ammonium–ammonia equilibrium shifts toward NH_3 , resulting in greater gaseous nitrogen losses via volatilization (Mkhabela et al., 2006). Thus, although liming can function as an effective mitigation strategy for N_2O emissions, it simultaneously promotes NH_3 volatilization, creating a trade-off among gaseous nitrogen species with implications for overall reactive nitrogen losses and environmental impacts.

Recent evidence further demonstrates that liming does not universally reduce N_2O emissions across all soil and management scenarios and may even enhance emissions under certain conditions (Ribeiro et al., 2024). In particular, soils with moderately acidic or near-neutral initial pH values, or liming practices combined with specific nitrogen fertilizer forms, may experience increased microbial activity that stimulates N_2O production. In contrast, gypsum applications—supplying calcium and sulfate without directly increasing soil pH—tend to exert more limited and predictable effects on nitrogen transformation processes and have been reported to provide more consistent reductions in N_2O emissions. Collectively, these findings emphasize that the effects of liming on greenhouse gas emissions should not be regarded as universally beneficial; rather, they must be evaluated as context-dependent processes that require careful consideration of initial soil conditions, nitrogen sources, and site-specific management practices (Ribeiro et al., 2024).

CONCLUSIONS

Calcareous soils play a decisive role in regulating soil pH, buffering capacity, nutrient availability, and structural stability, thereby directly influencing both agricultural production performance and environmental outcomes. In calcareous soils, the carbonate–bicarbonate buffering system stabilizes soil reaction within the alkaline range, while simultaneously restricting the availability of phosphorus and several micronutrients, particularly iron, zinc, and manganese. These constraints commonly manifest as lime-induced chlorosis, yield reductions, and quality losses, especially in fruit crops and sensitive field crops. In contrast, in acid soils where carbonate buffering is absent, low pH–induced aluminum toxicity, suppression of root development, and increased solubility of potentially toxic elements constitute the main limiting factors; under such conditions, liming practices represent an indispensable reclamation strategy for restoring chemical balance and biological activity.

Beyond agricultural productivity, calcareous soil conditions and liming practices are closely linked to climate-related processes and greenhouse gas dynamics. Carbonate-associated soil inorganic carbon constitutes one of the largest carbon reservoirs in terrestrial ecosystems, and its role in the atmospheric CO_2 balance is strongly influenced by the origin of calcium, fertilization intensity, and land management practices. While pedogenic carbonate formation driven by silicate weathering may contribute to long-term carbon sequestration, intensive nitrogen fertilization can accelerate carbonate dissolution and CO_2 release. In acid-reacting soils, liming with carbonate-based materials has the potential to reduce N_2O emissions by influencing denitrification processes; however, it may

simultaneously increase NH₃ volatilization, giving rise to an unavoidable greenhouse gas emission trade-off. In this context, the use of biomass ashes with low heavy-metal contents and silicate-based materials such as feldspar or perlite may offer new opportunities for improving nutrient availability while enhancing CO₂ sequestration.

Accordingly, management strategies based on soil calcareousness should not be regarded solely as practices aimed at alleviating soil acidity or yield limitations, but rather as strategic components of integrated soil management. Site-specific approaches that incorporate appropriate selection of liming materials, balanced fertilization, organic matter additions, and careful irrigation management are critical for enhancing the sustainability of crop production while limiting environmental impacts and contributing to climate change mitigation.

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In this study,

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Conflicts of Interest

The author declares no conflict of interest.

Ethics Approval

In all processes of this study, the principles of Pen Academic Publishing Research Ethics Policy were followed.

This study does not require ethics committee approval as it does not involve any direct application on human or animal subjects.

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