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Increasing yield and mitigating environmental emissions by applying suitable magnesium fertilizer in forage production

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KEYWORDS

Carbon footprint, forage production, magnesium fertilizers, magnesium leaching, magnesium release

HIGHLIGHTS

- Mg blended formulations combine benefits of both fast- and slow-release Mg fertilizers.
- Mg fertilizer application boosted perennial ryegrass yield and Mg uptake.
- Mg blended formulations had relatively lower greenhouse gas emissions.
- Tailored Mg strategies could enhance forage yield in China.

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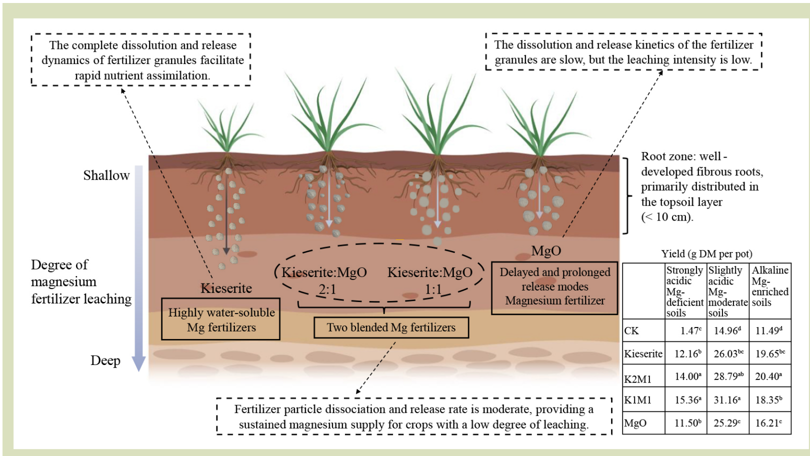
GRAPHICAL ABSTRACT



ABSTRACT

The scarcity of high-quality forage remains a major constraint to sustainable ruminant production in China. The effectiveness of different magnesium fertilizers under varying soil conditions has not been fully investigated in forage production. This study evaluated the agronomic and environmental effects of rapid-release fertilizer of kieserite ($MgSO_4 \cdot H_2O$), slow-release fertilizer of calcined magnesite (MgO) and Mg blended formulations (kieserite:MgO 1:1, K1M1; and kieserite:MgO 2:1, K2M1) on forage yield, Mg release dynamics and leaching characteristics in strongly acidic Mg-deficient soils, slightly acidic Mg-moderate soils and alkaline Mg-enriched soils. This investigation was conducted as pot experiments, soil incubation trials and soil column leaching simulations. Mg fertilizer application increased forage yield by 41%–946% and Mg uptake by 22%–5407% than the CK, with the most substantial improvements occurring in strongly acidic Mg-deficient soils. Mg blended formulations had relatively better performance in forage production than kieserite or MgO. These have characteristics of solubility in water, release, and leaching for various Mg fertilizers. Kieserite has a rapid release rate and the highest exchangeable Mg^{2+} accumulation, simultaneously with the highest leaching rate (16%–30%). In contrast, MgO has a slow-release rate and the lowest leaching rate (–2.4% to 3.8%). K1M1 and K2M1 have moderate release rate to support forage growth, a low magnesium leaching rate and mitigate soil acidification in acidic soils. Also, Mg application reduced greenhouse gas emissions per unit of forage by 14%–90%. Optimized Mg fertilizer application has the potential to increase annual perennial ryegrass production by 4.64 Tg in China. This research provides a scientific foundation for optimizing Mg fertilizer types for forage production in various soils to achieve green agricultural development.

1 Introduction

Ruminant systems effectively convert low-grade biomass into nutritious products, reducing food-feed competition[1]. Increasing ruminant production by 12% could lower GHG emissions while feeding 525 million more people[2]. Despite growing demand in China, domestic productivity lags behind some European levels due to insufficient high-quality forage supply, leading to significant imports[3].

High-quality forage, although non-edible to humans, improves feed digestibility, promotes faster growth of animals and enhances meat quality[4,5]. Nevertheless, China faces challenges such as low forage yield, high nutrient losses during hay processing and lower feed quality than imported forage. Also, magnesium deficiency could lead to disorders such as puerperal hypocalcemia and grass tetany in ruminants[6]. Mg fertilizer application has been shown to significantly increase forage yield and uptake, especially in acidic soils[7,8]. Although existing studies have preliminarily shown the agronomic benefits of Mg fertilizer application for forage productivity, existing knowledge remains fragmented. This is because most studies focus on specific fertilizer types or isolated soil pH conditions-leaving important gaps in understanding the synergies of blended Mg sources and optimal application ratios in pasture systems. Therefore, there is an urgent need to determine the most effective Mg fertilizer types and blending ratios to optimize forage productivity under specific soil pH and Mg content regimes.

Growing awareness of the agronomic and ecological importance of Mg has spurred more intensive investigation into its environmental fluxes, particularly leaching losses. Due to its smaller ionic radius and relatively larger hydrated radius, Mg^{2+} is highly mobile in soils. This causes weak adsorption by soil colloids, significant leaching losses and ultimately major Mg^{2+} depletion[9,10]. Synchronizing fertilizer Mg release with crop uptake remains a central challenge. Although slow-release Mg fertilizers offer sustained nutrient supply (especially in Mg-deficient and acidic soils[11]), rapid-release fertilizers deliver immediate Mg[12]. However, the nutrient release kinetics and leaching dynamics of mixed Mg fertilizers (e.g., kieserite and MgO in various ratios) remain poorly characterized, particularly under different soil conditions. Thus, more research is required into these dynamics to optimize Mg-use efficiency and forage yield while minimizing environmental loss.

As a key driver of sustainable forage production, Mg fertilizer application enhances grassland productivity and carbon sequestration[13], which is important for terrestrial ecosystems storing 34% of global terrestrial carbon[14]. However, Mg fertilizer production generates GHG emissions[15], and emission trade-offs between fertilizer types remain unresolved. Optimizing Mg application strategies across soil types is therefore essential to minimize GHG emissions in forage systems. Life cycle assessment (LCA) provides a comprehensive framework for evaluating the environmental impacts of agricultural inputs and outputs across the full life cycle.

Previous LCA studies have compared the carbon footprint of various forage crops (e.g., alfalfa vs ryegrass)[16]. Building on this foundation, the present study used LCA to quantify the carbon footprint of forage production under different Mg fertilizer application strategies and soil pH conditions.

The objective of this study is to evaluate how different Mg fertilizers (single and blended) affect Mg release dynamics, leaching characteristics, forage yield and environmental performance across soil types. The specific research aims were: (1) elucidating Mg release patterns and migration-leaching behaviors of single and blended Mg fertilizers to guide optimal fertilizer application; and (2) assessing how Mg fertilizer types and blending ratios impact forage yield and carbon footprint under different soil pH conditions.

2 Materials and methods

2.1 Tested Mg fertilizers and soils

The Mg fertilizers comprised two types with contrasting solubility characteristics: rapid-release fertilizer of kieserite (natural $MgSO_4 \cdot H_2O$) and slow-release fertilizer of calcined magnesite (MgO). Kieserite is highly water-soluble Mg fertilizer and MgO is characterized by a delayed and prolonged release pattern. Kieserite is a naturally derived mineral product manufactured using proprietary electrostatic separation technology of K+S AG (Kassel, Germany). It offers several agronomic advantages, including controlled nutrient release, environmental sustainability, excellent storage stability and the simultaneous provision of multiple essential nutrients. Compared with chemically synthesized magnesium sulfate and other Mg- or K-based fertilizers, kieserite has superior physicochemical properties and agronomic performance[17]. In contrast, MgO requires hydrolysis for nutrient release, resulting in a slower yet extended availability of Mg[18]. The release behavior of both fertilizers can be influenced by soil pH and moisture conditions.

Three soil types were selected to represent a range of pH conditions: (1) strongly acidic Mg-deficient soils, classified as lateritic red soil, collected from Zhangzhou City, Fujian Province; (2) slightly acidic Mg-moderate soils, classified as paddy soil, collected from Wuxue City, Hubei Province; and (3) alkaline Mg-enriched soils, classified as fluvo-aquic soil, collected from Xinxiang City, Henan Province. The initial physicochemical properties of these soils are given in Table 1.

Table 1 Physicochemical characteristics of the three experimental soils classified by texture (silty clay loam, silty loam and sandy loam) and pH (acidic, neutral, alkaline)

Soil physical and chemical property	Soil type		
	Lateritic red soil (Fujian)	Paddy soil (Hubei)	Tidal soil (Henan)
Texture	Silty clay loam	Silty loam	Sandy loam
Soil particle composition			
Sand grain (0.02–2 mm) (%)	2.58	15.76	36.68
Silt (0.002–0.02 mm) (%)	78.28	79.27	57.65
Clay particle (< 0.002 mm) (%)	19.14	4.97	5.67
pH	4.33	6.26	8.36
Soil organ material ($g \cdot kg^{-1}$)	5.23	18.27	8.34
NO_3-N ($mg \cdot kg^{-1}$)	50.97	11.27	4.01
NH_4^+-N ($mg \cdot kg^{-1}$)	29.90	2.10	35.47
Available phosphorus ($mg \cdot kg^{-1}$)	2.03	27.26	78.35
Available potassium ($mg \cdot kg^{-1}$)	38.37	309.07	199.93
Exchangeable calcium ($mg \cdot kg^{-1}$)	83.1	801.83	6179.83
Exchangeable magnesium ($mg \cdot kg^{-1}$)	9.58	155.81	244.07

Note: the soil texture is categorized based on the international standard for soil texture classification.

These three soil types were chosen for their wide distribution across major agricultural and forage production regions in China. The lateritic red soil is predominant in the southern provinces, a key area for forage development; the paddy soil is widespread in the central Yangtze River basin; and the fluvo-aquic soil covers the vast North China Plain[19]. Together, they represent a significant proportion of the area where perennial ryegrass is cultivated, ensuring the findings of this study have broad applicability.

The experimental design included five treatments: a no-Mg-fertilizer application control (CK), rapid-release kieserite, slow-release MgO, and two blended Mg formulations (K1M1, kieserite:MgO 1:1; and K2M1, kieserite:MgO 2:1). These ratios were selected to examine synergistic effects between fast- and slow-release Mg sources: K1M1 (1:1) represents a balanced blend, designed to supply Mg both immediately and sustainably; and K2M1 (2:1) prioritizes greater initial Mg availability, potentially more beneficial in soils with high Mg fixation capacity.

A preliminary experiment was conducted to determine the optimal physical form of Mg fertilizers. We compared granular and powder formulations of K1M1 and K2M1 across key indicators: Mg fertilizer nutrient release rate, soil Mg leaching amount and rate, soil pH, soil exchangeable Mg content, ryegrass yield and ryegrass Mg concentration. No significant differences ($p > 0.05$) were observed between the two forms for all measured parameters. Therefore, granular fertilizers, which are easier to handle and apply in agricultural production, were adopted for the main experiment to ensure the practical relevance of the findings.

Mg fertilizers were granular formulations supplied by K+S AG. Each treatment was applied to the three soil types and we used a completely randomized design, resulting in 15 distinct treatment combinations (3 soil types × 5 treatments).

2.2 Soil incubation experiment

Each treatment was replicated four times, resulting in 60 experimental containers total. A 500-g portion of air-dried soil (passed through a 1-mm sieve) was placed into 750 mL polyethylene containers. All soil incubation treatments received a uniform Mg application rate of 200 mg·kg^{-1} MgO dry soil. For the 500 g soil per container, this rate translates to 100 mg MgO (equivalent to 60 mg elemental Mg). The specific mass of each fertilizer type was then calculated to meet this 60 mg elemental Mg target, accounting for their respective Mg concentrations. This resulted in the application of 375 mg of kieserite, 229 mg of the K2M1, 182 mg of the K1M1 and 120 mg of MgO, which were then uniformly mixed with the soil. Soil moisture was maintained at 65% of the maximum field water-holding capacity by periodic watering. Soil samples were collected at 1, 3, 5, 7, 10, 15, 20, 30, 45 and 60 days after the start of incubation. This sampling schedule was designed to capture the characteristic biphasic release pattern of Mg^{2+} from fertilizers, which typically involves a rapid initial release phase followed by a slower, long-term release and stabilization phase. High-frequency sampling in the first 10 days aimed to accurately characterize fast-release dynamics and identify the peak release time, and subsequent extended intervals monitored the gradual decline and final stabilization of exchangeable Mg^{2+} concentrations. This approach aligns with established methodologies for studying fertilizer nutrient release kinetics[20]. Exchangeable Mg^{2+} concentrations were determined by inductively coupled plasma optical emission spectrometry (ICP-OES), enabling characterization of the temporal Mg release dynamics for each fertilizer type.

2.3 Laboratory-based soil column leaching experiment for Mg transport

The soil column leaching experiment used 45 devices (15 treatments × 3 replicates), comprising five magnesium application regimes for each of three soil types. The leaching apparatus consisted of rigid polyvinyl chloride tubes (internal diameter 3 cm and length 50 cm), each fitted with a centrally located 1 cm diameter drainage outlet at the base. Each column was uniformly packed with 300 g of air-dried and pulverized soil, stratified into three 100 g layers. A stratified sampling design was adopted for the experiment, with layer depths adjusted based on soil texture and properties. Strongly acidic, Mg-deficient soils were stratified into 15 cm thick layers (0–15 cm topsoil, 15–30 cm subsurface and 30–45 cm subsoil) to accommodate their aggregation stability. In contrast, slightly acidic Mg-moderate and alkaline Mg-rich soils, with more uniform textures, were partitioned into 10 cm layers (0–10 cm topsoil, 10–20 cm subsurface and 20–30 cm subsoil). This depth-adaptive stratification ensured representative sampling of the distinct pedogenic horizons of each soil while maintaining methodological consistency across treatments. The topsoil layer was homogeneously mixed with Mg fertilizers applied at MgO-equivalent rates of 74.9 mg for kieserite, 45.8 mg for the K2M1, 36.4 mg for the K1M1 and 24.0 mg for MgO.

An intermittent leaching protocol was adopted to simulate regional annual precipitation patterns: 1200 mm for strongly acidic Mg-deficient soils, 800 mm for slightly acidic Mg-moderate soils, and 400 mm for alkaline Mg-enriched soils. The annual rainfall data is from the National Meteorological Bureau and represents the climatic characteristics of eastern China, the middle and lower reaches of the Yangtze River, and the North China Plain, respectively. Ten leaching events were conducted at 6-day intervals, with leachates collected in conical flasks after each event. A schematic of the experimental setup is given in Fig. 1.

Collected leachates were filtered through 0.45 μm membrane filters into 10 mL centrifuge tubes. The Mg^{2+} concentration in the filtered leachates was determined using ICP-OES (Optima 7300DV, PerkinElmer, Shelton, CT, USA). Instrument parameters were: RF power of 1300 W, plasma gas (argon) flow of 15 $L\cdot min^{-1}$, auxiliary gas flow of 0.2 $L\cdot min^{-1}$ and nebulizer gas flow of 0.8 $L\cdot min^{-1}$. The Mg emission line at 285.213 nm was used for quantification.

The Mg leaching rate was calculated as:

$$\text{Ratio}_{\text{Leaching}} = (\text{LeachingMg}_{\text{T}} - \text{LeachingMg}_{\text{CK}})/\text{ApplicationMg}_{\text{T}} \times 100 \quad (1)$$

where, $\text{Ratio}_{\text{Leaching}}$ (%) is the Mg leaching rate, $\text{LeachingMg}_{\text{T}}$ and $\text{LeachingMg}_{\text{CK}}$ (mg) are Mg leaching amounts in treatments and control, respectively, and $\text{ApplicationMg}_{\text{T}}$ (mg) is the total Mg applied for each treatment.

2.4 Pot experiments

2.4.1 Experimental setting

The test plant was perennial ryegrass (*Lolium perenne*), a representative forage species. Four replicates were used per treatment, resulting in 60 pots total (15 treatments × 4 replicates). A randomized block design was used, with circular plastic pots (top diameter 18 cm, bottom diameter 14 cm and height 18 cm) each filled with 2.5 kg of air-dried soil.

Basal fertilizers were uniformly incorporated into the soil and included urea (46% N) at 345 mg, monoammonium phosphate (12.5% N, 60.5% P_2O_5) at 302.5 mg, and potassium sulfate

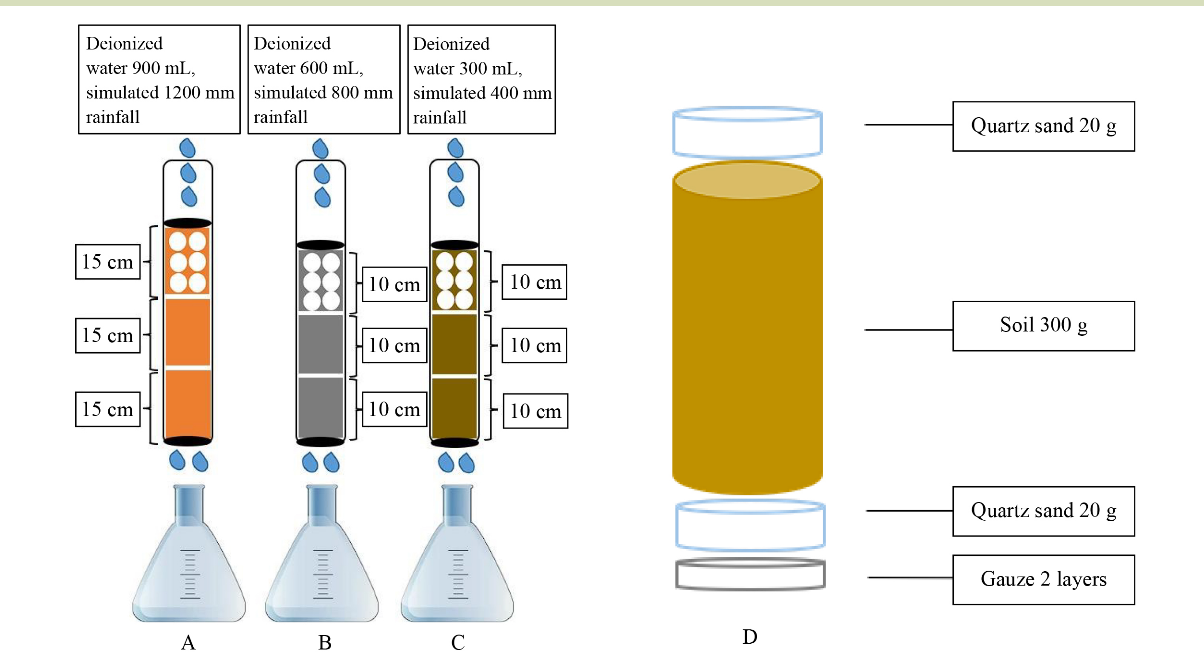


Fig. 1 Schematic of the soil column leaching apparatus simulating region-specific rainfall patterns: A, in strongly acidic Mg-deficient soils; B, in slightly acidic Mg-moderate soils; C, in alkaline Mg-enriched soils; and D, the structures of soil columns.

(52% K_2O) at 520 mg per pot. Mg treatments were applied as: kieserite at 3.13 g, K2M1 at 1.92 g, K1M1 at 1.52 g and MgO at 1.00 g per pot. To ensure sufficient micronutrient availability during the experiment, a balanced nutrient solution was applied periodically. Its composition and application rates (per kg soil) were: $CaCl_2$ (126 mg·kg^{-1} soil), EDTA-FeNa (5.8 mg·kg^{-1} soil), $MnSO_4·4H_2O$ (6.67 mg·kg^{-1} soil), $ZnSO_4·7H_2O$ (10 mg·kg^{-1} soil), $CuSO_4·5H_2O$ (2 mg·kg^{-1} soil), H_3BO_3 (0.67 mg·kg^{-1} soil), and $(NH_4)_6Mo_7O_{24}·4H_2O$ (0.26 mg·kg^{-1} soil).

The ryegrass was sown in late March 2023 and harvested four times at 25-day intervals (stubble height: 3–5 cm), with the final harvest in early July. Post-final harvest, soil samples were collected to analyze pH and exchangeable Mg^{2+} concentrations. Plant samples were dried (65 °C, 48 h), ground (< 1 mm), and subsampled (100 ± 5 mg). Acid digestion was performed with 12 mL HNO_3:$HClO_4$ (4:1 v/v) at 180 °C until clear; after cooling, the solution was diluted to 50 mL with ultrapure water, filtered, and Mg quantified by ICP-OES (Optima 7300DV, PerkinElmer).

2.4.2 Calculation of magnesium use efficiency

The Mg use efficiency (MUE) was calculated as:

$$\mathrm{Mg_{UE}} = (\mathrm{MgUptake_T} - \mathrm{MgUptake_{CK}})/\mathrm{MgApplication_T} \times 100\% \quad (2)$$

where, Mg_{UE} (%) is the Mg fertilizer use efficiency; $MgUptake_T$ and $MgUptake_{CK}$ (mg) are total Mg uptake by plants in the treatment and control, respectively, and $MgApplication_T$ (mg) is the total Mg applied in the treatment.

2.5 Carbon footprint

The carbon footprint was assessed in terms of GHG emissions, including carbon dioxide, nitrous oxide and methane, across subsystems of agrochemicals production and pot experiment management. The agricultural input subsystem included GHG emissions from fertilizer manufacturing (Table 2). The pot management subsystem accounted for CO_2 and direct/indirect N_2O emissions from fertilizer application during the experiment. Energy expenditures (irrigation, climate control and other pot cultivation practices) were excluded from the system boundary. The functional unit for carbon footprint calculation was defined as GHG emissions per gram of dry grass biomass.

The calculation of GHG emissions in forage production is:

$$\mathrm{GE_{AP}} = \sum (\mathrm{AC}_j \times \mathrm{EF}_j) \quad (3)$$

where, GE_{AP} (g per pot) is GHG emissions per pot from agrochemicals production, AC_j (g per pot) is the agrochemicals consumption in pot experiments and EF_j (g·g^{-1} CO_2-eq dry matter) is the CO_2 emission factor of the production corresponding to agrochemicals (Table 2).

$$\mathrm{GE_{PM}} = \mathrm{AC_{urea}} \times \mathrm{EF_{ureaCO_2}} \times 44/12 + (\mathrm{N_2O_{direct}} + \mathrm{N_2O_{indirect}}) \times 44/28 \times 273 \quad (4)$$

where, GE_{PM} (g per pot) is GHG emissions per pot from pot management, EF_{ureaCO_2} (%) is the emission factor for CO_2-C emission from urea application in pot management, the emission factor is 20%[21], 44/12 is the molecular conversion factor of CO_2-C emission to CO_2 emission, N_2O_{direct} and $N_2O_{indirect}$ (g N per pot) are the direct and indirect N_2O-N

Table 2 The emission factors of agrochemicals production and pot management

Subsystem	Abbreviation	unit	Emissions factor	Reference
Agrochemicals production				
N fertilizer	EF_N	g CO_2-eq g^{-1} N	11.9	[23]
P fertilizer	$EF_{P_2O_5}$	g CO_2-eq g^{-1} P_2O_5	2.55	[24]
K fertilizer	EF_{K_2O}	g CO_2-eq g^{-1} K_2O	0.84	[24]
Mg fertilizer	EF_{MgO}	g CO_2-eq g^{-1} MgO	3.8	[15]
Pesticide	$EF_{Pesticide}$	g CO_2-eq g^{-1}	18	[25]
Pot management				
Direct N_2O	$EF_{direct-N_2O}$	%	1	[21]

Note: The unit g CO_2-eq g^{-1} denotes grams of carbon dioxide equivalent per gram, used to quantify greenhouse gas emission intensity per unit mass of the research subject.

emissions from pot management (Table 2) with indirect N_2O emissions derived from 1% of volatilized NH_3-N and 0.75% of the leached NO_3-N[21], 44/28 is the molecular conversion factor of N_2O-N emission to N_2O emission., and 273 is the global warming potential of N_2O for the 100-year period[22].

The carbon fixed in underground roots was included in the calculation of soil organic carbon change. The root biomass was estimated to multiply the forage yield by its root-shoot ratio.

$$MC_{undergroundroot} = Yield \times 0.37 \times 0.45 \quad (5)$$

$$CS = MC_{undergroundroot} \times 9.7/100 \times 44/12 \quad (6)$$

where, $MC_{undergroundroot}$ is the carbon content of the underground root, Yield (g per pot) is dry matter grass yield per pot, CS is the CO_2 emissions avoided due to carbon sequestration of roots in ryegrass production, 9.7 is the emission reduction potential of soil organic carbon sequestration in 100 years[26], 0.37 is the mean root-shoot ratio for ryegrass[27], and 0.45 is the carbon content of the underground root of ryegrass[28].

$$GE = GE_{AP} + GE_{PM} \quad (7)$$

$$GHG_{grass} = (GE_{AP} + GE_{PM} - CS)/Yield \quad (8)$$

where, GE is GHG emissions per pot and GHG_{grass} ($g \cdot g^{-1}$ CO_2-eq dry matter) is net GHG emissions per unit of dry matter grass.

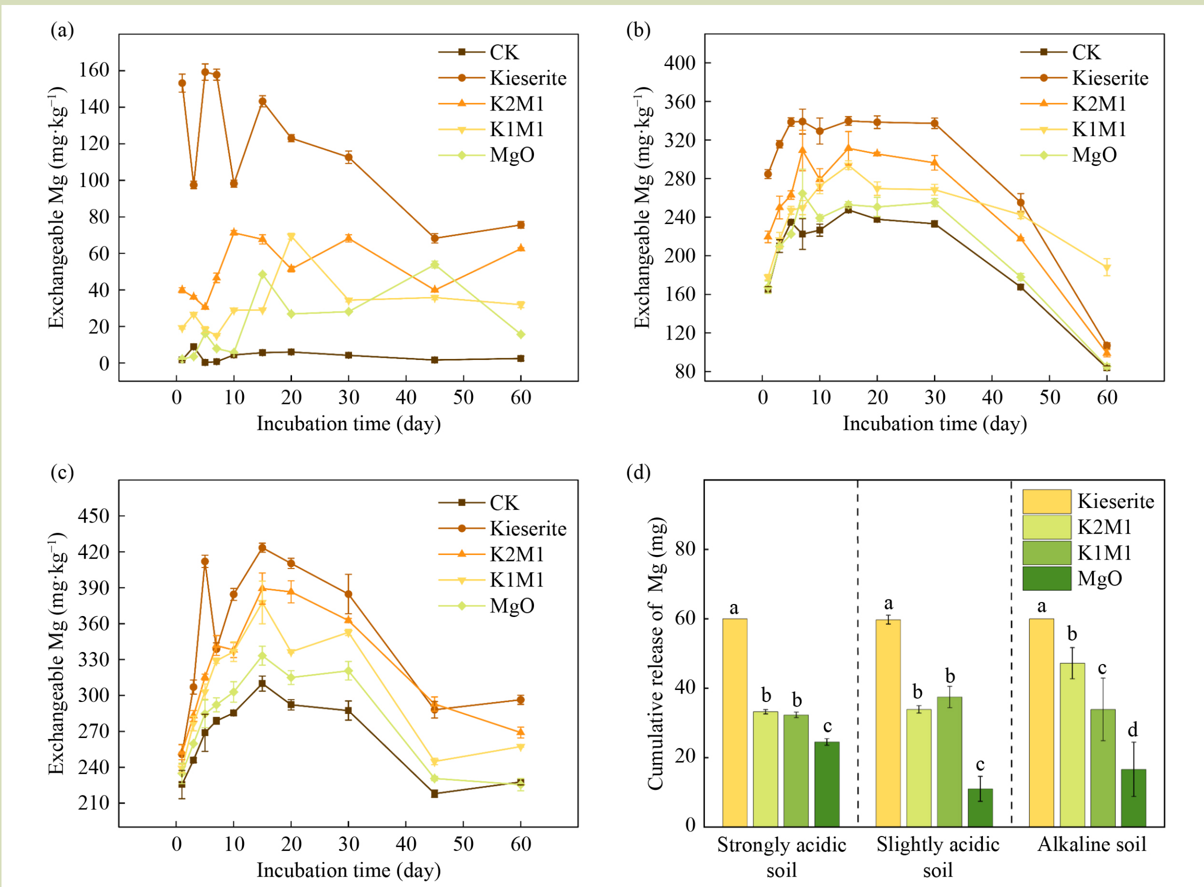


Fig. 2 Effects of Mg fertilizer treatments on exchangeable Mg concentration in a strongly acidic Mg-deficient soil (a), a slightly acidic Mg-moderate soil (b), and an alkaline Mg-enriched soil (c), effects of Mg fertilizer treatments on cumulative Mg release across three soil types (d). Means sharing the same letter for soil types in (d) show no significant difference (fail to reject the null hypothesis, $p > 0.05$); error bars indicate standard deviation.

2.6 Statistical Analysis

Data was analyzed using Microsoft Excel 2019 and SPSS 21 for descriptive statistics and analysis of variance (ANOVA). Before ANOVA, data normality was tested by the Shapiro-Wilk test, and variance homogeneity was verified with Levene's test. One-way ANOVA was used to identify significant differences among treatments for each measured variable; where the F-test was significant ($p < 0.05$), Duncan's multiple range test was applied for post hoc pairwise mean separation. Statistical significance was defined at $p < 0.05$. Results were graphically presented using Origin 2023.

3 Results

3.1 Release dynamics of various magnesium fertilizers across soils

The temporal dynamics of exchangeable Mg^{2+} concentration, cumulative release, and release rate differed significantly among Mg fertilizer treatments (Fig. 2).

The four Mg fertilizers all followed an initial rapid rise, a gradual decline, and eventual stabilization in the release pattern of exchangeable Mg^{2+}. However, the timing of peak Mg^{2+} concentration varied by treatment. Kieserite peaked earliest (5–15 days), followed by the blended formulations K2M1 and K1M1 (15–20 days), whereas MgO had the slowest release, with its peak occurring at 15–45 days. Kieserite consistently had the highest cumulative Mg release among treatments (Fig. 2(d)).

Kieserite released comparable amounts of Mg across the three soil types. In contrast, MgO had soil-dependent release: the highest release (25.4 mg) was observed in strongly acidic Mg-deficient soils, followed by alkaline Mg-enriched soils (16.6 mg) and slightly acidic Mg-moderate soils (11.0 mg). Cumulative Mg release from the blended fertilizers was intermediate between MgO and kieserite. Notably, under slightly acidic Mg-moderate conditions, K1M1 had a higher Mg release rate (62.5%) than K2M1 (56.5%); conversely, in both strongly acidic Mg-deficient and alkaline Mg-enriched soils, K2M1 outperformed K1M1 in release rate.

3.2 Leaching characteristics of various magnesium fertilizers across soils

Mg leaching dynamics and vertical distribution varied across treatments and soil types (Fig. 3 and Fig. 4). All treatments followed a typical leaching trend: an initial rapid increase in Mg losses, followed by a gradual plateau (Fig. 3(a–c)). Kieserite had the highest cumulative Mg leaching loss (5.8–20.28 mg), followed by the blended fertilizers K2M1 and K1M1, whereas MgO gave the lowest losses across the three soils. In the strongly acidic Mg-deficient soils, substantial Mg leaching occurred only with kieserite application. However, its total leaching loss was still lower than in the slightly acidic Mg-moderate soils and alkaline Mg-enriched soils. Under slightly acidic Mg-moderate conditions, the Mg leaching rate of K2M1 and K1M1 was lower than in alkaline Mg-rich soils. Notably, cumulative Mg leaching loss from MgO in slightly acidic Mg-moderate soils was lower than that of the CK ($p < 0.05$), leading to a calculated negative leaching rate. This phenomenon reflects an apparent reduction in leaching relative to the CK.

Mg fertilizer treatments significantly affected the exchangeable Mg content across soil layers (Fig. 4). In strongly acidic Mg-deficient soils, kieserite reduced topsoil exchangeable Mg content relative to other treatments. However, in subsurface and subsoil layers, kieserite increased soil exchangeable Mg content, with the greatest gains observed relative to the CK. In both slightly acidic Mg-moderate and alkaline Mg-rich soils, exchangeable Mg content across all layers was higher under kieserite and K2M1 than under K1M1 and MgO.

Also, Mg application significantly increased soil pH by 0.43–0.79 in the topsoil, 0.32–0.42 in the subsurface soil, and 0.43–0.57 in the subsoil compared to the CK in the strongly acidic Mg-deficient soil (Fig. 5). In slightly acidic Mg-moderate soils, Mg fertilizers also raised pH in topsoil and subsurface compared to the CK. Notably, kieserite slightly reduced topsoil pH relative to the CK (Fig. 5).

3.3 Magnesium uptake and GHG emissions in perennial ryegrass production

Mg fertilizer application treatments had 41%–946% higher forage yield, 22%–5407% higher Mg uptake, and 14%–90% lower GHG emissions than the CK (Table 3). Compared to the CK, Mg fertilizer application raised soil pH by 0.1–0.27 in strongly acidic Mg-deficient soils and 0.13–0.26 in slightly acidic Mg-moderate soils, but caused a slight reduction (0.13–0.26) in alkaline Mg-rich soils.

In both strongly acidic Mg-deficient and slightly acidic Mg-

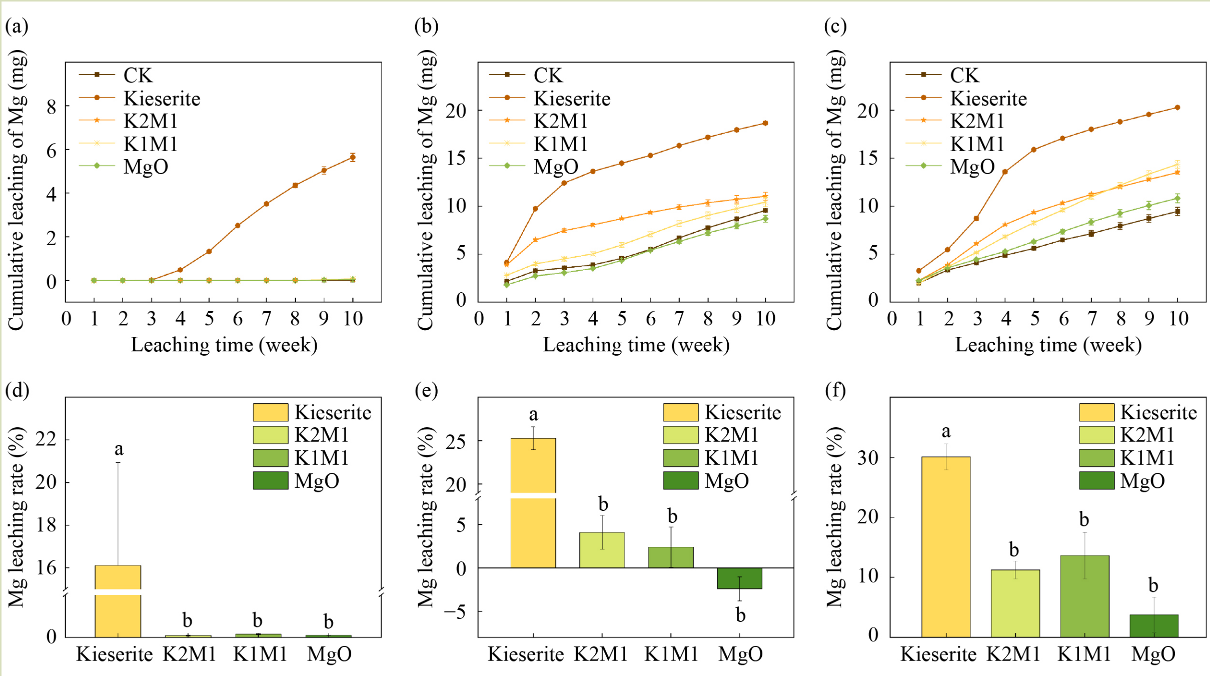


Fig. 3 Cumulative leaching of Mg and Mg leaching rate in strongly acidic Mg-deficient soils (a, d), slightly acidic Mg-moderate soils (b, e), and alkaline Mg-enriched soils (c, f). Means with the same letter within soil types in (d, e and f) are not significantly different (null hypothesis not rejected, $p > 0.05$); error bars indicate standard deviation.

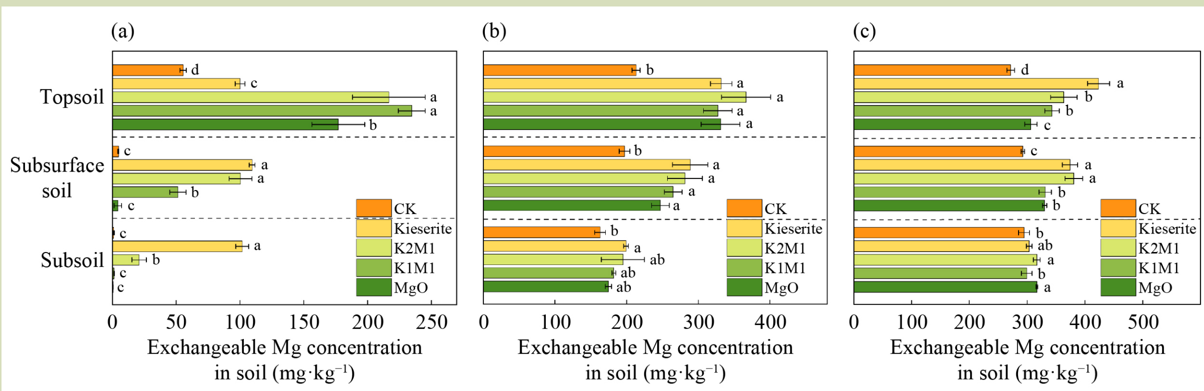


Fig. 4 Effects of different Mg fertilizers on exchangeable Mg concentrations across soil layers in strongly acidic Mg-deficient soils (a), slightly acidic Mg-moderate soils (b), and alkaline Mg-enriched soils (c). Means sharing the same letter within soil types show no significant difference (null hypothesis not rejected, $p > 0.05$); error bars indicate standard deviation.

moderate soils, the K1M1 treatment gave the highest ryegrass Mg uptake and MUE, and lowest GHG emission of all the treatments. In the alkaline Mg-rich soil, the K2M1 treatment was most effective, improving forage yield by 3.79%–11%.

Compared to strongly acidic Mg-deficient and alkaline Mg-rich soils, ryegrass grown in the slightly acidic Mg-moderate soils had markedly better performance and lower GHG emissions. Optimized Mg fertilizer application, applying K1M1 in acidic

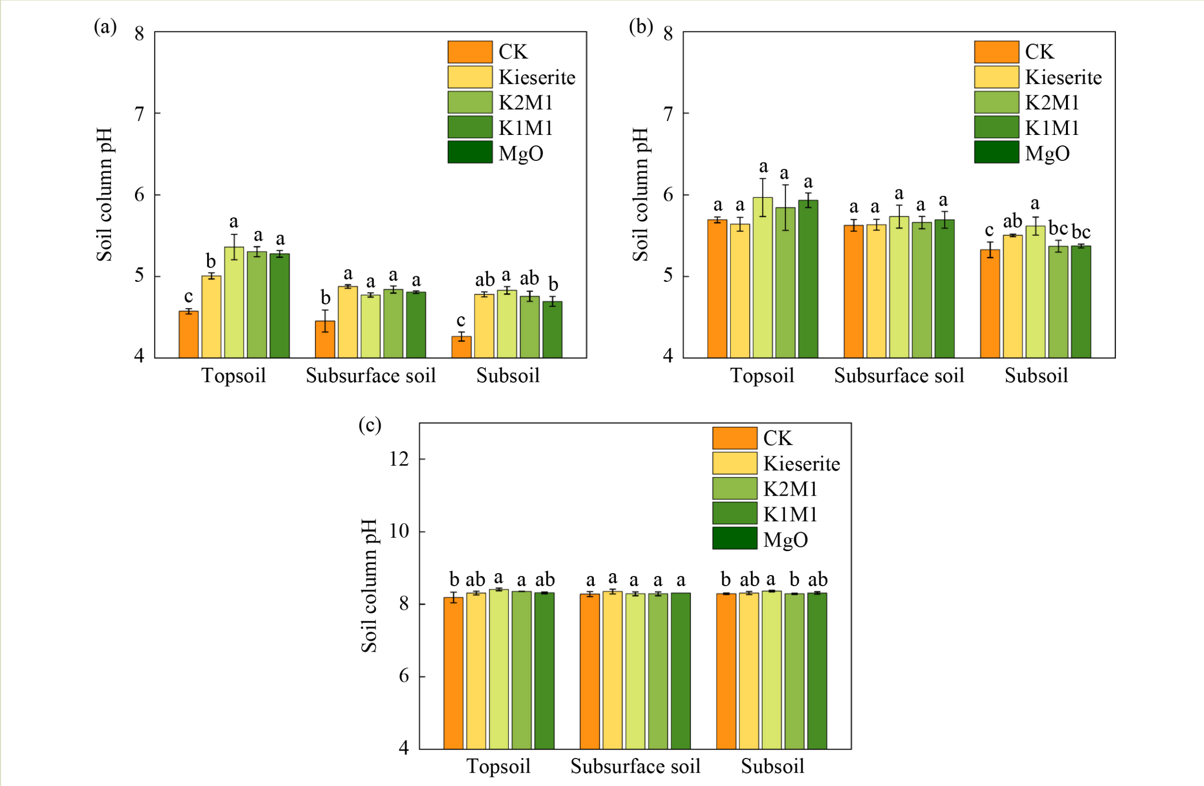


Fig. 5 Effects of various magnesium fertilizers on soil pH values in strongly acidic Mg-deficient soils (a), slightly acidic Mg-moderate soils (b), and alkaline Mg-enriched soils (c). Means sharing the same letter within soil types show no significant difference (null hypothesis not rejected, $p > 0.05$); error bars indicate standard deviation.

soil and using K2M1 in alkaline soil, has the potential to increase annual ryegrass production by 4.64 Tg in China (Fig. 6), especially in Sichuan and Yunnan Provinces.

4 Discussion

This study investigated the release and leaching characteristics of different magnesium fertilizers and their combinations and quantitatively assessed their advantages and limitations in supplying nutrients for perennial ryegrass growth.

4.1 Release dynamics of magnesium fertilizer

Soil incubation experiments revealed significant differences in the exchangeable Mg^{2+} release patterns among the four Mg fertilizers (kieserite, K2M1, K1M1 and MgO). These Mg fertilizers followed a characteristic three-phase release curve: an initial increase, a subsequent decline and eventual stabilization. This pattern is largely governed by Mg fixation processes involving layered silicate minerals (e.g., vermiculite and montmorillonite) and Fe/Al oxides. During dry and wet cycling, Mg^{2+} migrates into the interlayer spaces of 2:1-type clay minerals, where it is dehydrated and converted into non-exchangeable Mg forms[29]. Additionally, amorphous Fe/Al oxides immobilize Mg^{2+} through surface complexation, especially in acidic soils[30].

Kieserite, a water-soluble and fast-acting Mg fertilizer, had the most rapid release and the highest cumulative Mg^{2+} release. Kieserite has fast dissolution stems from direct dissociation into Mg^{2+} and $SO_4{}^{2-}$. Also, the accompanying $SO_4{}^{2-}$ anions competitively inhibit Mg^{2+} fixation by occupying adsorption sites on soil colloids[17]. In contrast, MgO showed pronounced slow-release behavior, with the latest release peak and lowest cumulative release. Its dissolution involves multiple steps from

Table 3 Yield, utilization of Mg, and GHG emissions under different Mg fertilizer treatments across various soil conditions in ryegrass production

Soil type	Treatment	Yield (g DM per pot)	Mg uptakes (mg per pot)	MUE (%)	Soil pH	GE (g CO_2-eq per pot)	CS (g CO_2-eq per pot)	GHG (g CO_2-eq per pot)
Strongly acidic Mg-deficient soils	CK	1.47 ± 0.14^c	1.02 ± 0.13^c	/	4.23 ± 0.083^c	11.70	0.09 ± 0.01^c	7.98 ± 0.76^a
	Kieserite	12.16 ± 1.28^b	37 ± 7.64^b	12.08 ± 2.58^b	4.38 ± 0.063^b	12.08	0.72 ± 0.08^b	0.95 ± 0.11^b
	K2M1	14.00 ± 1.07^a	49 ± 6.57^a	16.10 ± 2.19^a	4.50 ± 0.065^a	12.59	0.83 ± 0.06^a	0.85 ± 0.07^b
	K1M1	15.36 ± 1.22^a	56 ± 9.77^a	18.42 ± 3.23^a	4.38 ± 0.041^b	12.84	0.91 ± 0.07^a	0.78 ± 0.07^b
	MgO	11.50 ± 0.87^b	33 ± 4.92^b	10.79 ± 1.63^b	4.33 ± 0.045^b	13.60	0.68 ± 0.05^b	1.13 ± 0.09^b
Slightly acidic Mg-moderate soils	CK	14.96 ± 0.39^d	65 ± 3.61^c	/	5.54 ± 0.043^c	11.95	0.89 ± 0.02^d	0.74 ± 0.02^a
	Kieserite	26.03 ± 0.46^{bc}	154 ± 6.07^a	29.79 ± 2.12^a	5.71 ± 0.067^{ab}	12.33	1.54 ± 0.03^{bc}	0.41 ± 0.01^c
	K2M1	28.79 ± 1.23^{ab}	158 ± 14^a	31.13 ± 5.41^a	5.67 ± 0.061^b	12.84	1.70 ± 0.07^{ab}	0.39 ± 0.02^c
	K1M1	31.16 ± 1.67^a	169 ± 18^a	34.64 ± 6.02^a	5.80 ± 0.028^a	13.09	1.85 ± 0.10^a	0.36 ± 0.02^c
	MgO	25.29 ± 3.48^c	120 ± 12^b	23.00 ± 2.24^b	5.73 ± 0.087^{ab}	13.85	1.50 ± 0.21^c	0.50 ± 0.09^b
Alkaline Mg-enriched soils	CK	11.49 ± 0.45^d	70 ± 6.1^d	/	7.97 ± 0.109^a	11.95	0.68 ± 0.03^d	1.01 ± 0.05^a
	Kieserite	19.65 ± 0.63^{ab}	157 ± 6.4^a	29.14 ± 2.29^a	7.78 ± 0.041^{bc}	12.33	1.16 ± 0.04^{ab}	0.57 ± 0.02^d
	K2M1	20.40 ± 1.39^a	143 ± 7.8^b	24.83 ± 0.46^b	7.77 ± 0.042^{bc}	12.84	1.21 ± 0.08^a	0.57 ± 0.05^d
	K1M1	18.35 ± 0.41^b	107 ± 5.8^c	12.36 ± 2.49^c	7.84 ± 0.080^b	13.09	1.09 ± 0.02^b	0.65 ± 0.02^c
	MgO	16.21 ± 0.82^c	85 ± 6.5^d	5.12 ± 1.90^d	7.71 ± 0.025^c	13.85	0.96 ± 0.05^c	0.79 ± 0.04^b
Source of variance								
Soil type (S)		**	**	**	**	n.a.	**	**
Treatment (T)		**	**	**	*	n.a.	**	**
S×T		**	**	**	**	n.a.	**	**

Note: DM means dry matter; MUE means magnesium use efficiency. CS means the amount of CO_2 emissions avoided due to carbon sequestration of root in ryegrass production. GE means GHG emissions per pot. GHG represents net GHG emissions per dry matter of grass. Different lowercase letters indicate significant differences ($p < 0.05$) in mean of yield, utilization of Mg, and GHG emissions in ryegrass production among different fertilizer treatments. Significant interactions in the two-way ANOVA were denoted: * meas $p < 0.05$; ** meas $p < 0.01$; n.a. means not applicable.

MgO to Mg^{2+} and is constrained by hydrolysis kinetics. In slightly acidic and alkaline soils, MgO readily forms sparingly soluble blends such as $Mg(OH)_2$ or basic $MgCO_3$, reducing the effective Mg conversion rate to below 60%[31,32]. In alkaline soils, MgO-based fertilizers undergo enhanced fixation by precipitation with carbonate ions[33]. Notably, in alkaline Mg-rich soils, the initially high Mg^{2+} concentration from kieserite accelerates fixation, leading to a steeper late-stage release decline than MgO[34–36].

Soil pH is important in the modulation of Mg release. MgO released significantly more Mg in strongly acidic Mg-deficient soils (25.4 mg) than in alkaline Mg-enriched soils (16.6 mg), driven by a proton-promoted dissolution mechanism. Under acidic conditions, H^+ ions significantly accelerate MgO hydrolysis, increasing the reaction rate by 2–3 orders of magnitude relative to neutral environments[37]. Conversely, kieserite maintained relatively stable release across the three soil types, as SO_4^{2-} anions are not readily adsorbed under either acidic or alkaline conditions[31]. In slightly acidic Mg-moderate soils, K1M1 had enhanced hydrolysis efficiency, higher Mg^{2+} release (62.5%) and reduced leaching losses[12] than K2M1 in Mg availability. In strongly acidic Mg-deficient soils, K2M1 had higher kieserite content, which facilitated MgO dissolution by localized acidification from SO_4^{2-} hydrolysis[31,32]. In alkaline soils (pH > 7.5), K2M1 benefitted from SO_4^{2-}-mediated inhibition of $Mg(OH)_2$ precipitation[32], resulting in higher Mg^{2+} release than K1M1 under both strongly acidic and alkaline conditions.

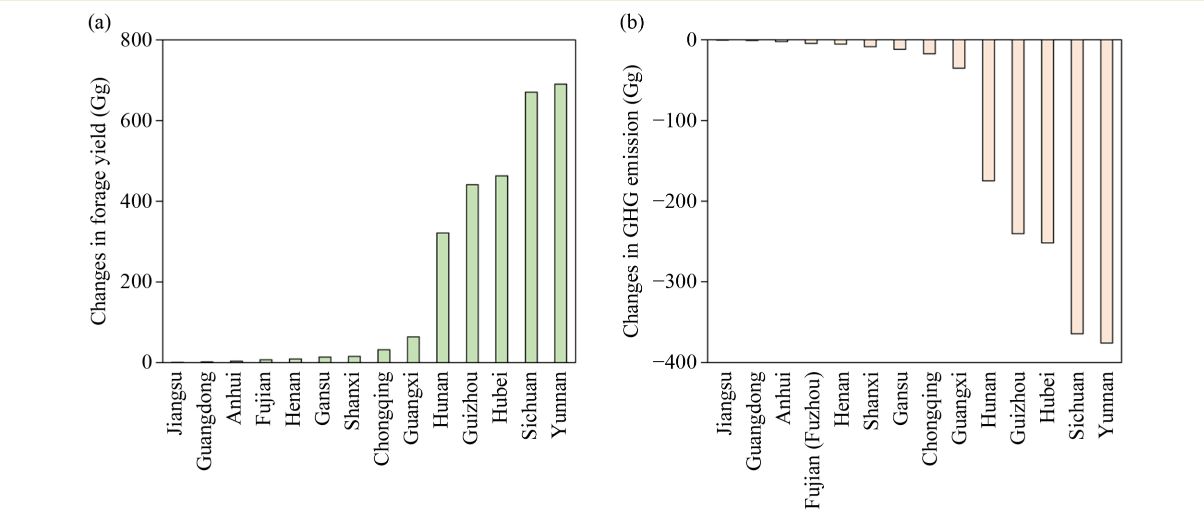


Fig. 6 Projected provincial impacts of optimized magnesium fertilizer application. (a) Forage yield enhancement (Gg) and (b) greenhouse gas (GHG) emissions mitigation (Gg CO_2-eq) in different regions after magnesium fertilization. Bars represent the predicted value for each region.

In stark contrast to their high efficacy in acidic soils, the performance of Mg fertilizers was constrained in alkaline soils, primarily due to mechanisms that immobilize Mg and reduce its availability. First, in alkaline Mg-rich soils, abundant CO_3^{2-} and OH^- ions react with dissolved Mg^{2+} to form sparingly soluble $MgCO_3$ and $Mg(OH)_2$[38–40]. This precipitation removes Mg from the soil solution, creating a direct chemical barrier to plant uptake. Second, enhanced adsorption at high pH drives fixation. As soil pH exceeds the point of zero charge, negative charge density on clay minerals and organic matter increases, strengthening electrostatic binding of Mg^{2+}. Although this reduces leaching, the strongly held Mg becomes less exchangeable and thus less accessible to plant roots[41]. Third, the Ca competition is important. Alkaline soils typically have high exchangeable Ca^{2+}, which competes with Mg^{2+} for root uptake channels and exchange sites. Given its often higher concentration, Ca^{2+} outcompetes Mg^{2+}, which induces functional Mg deficiency even when total soil Mg is not limiting[42].

4.2 Leaching dynamics of magnesium fertilizer

Across the three soil types, kieserite had significantly higher Mg leaching losses and rates than other Mg fertilizers (Fig. 3), whereas MgO consistently showed the lowest. Kieserite has higher leaching stems from its rapid dissolution, when, upon contact with water, kieserite dissociates readily into Mg^{2+} and SO_4^{2-}. The SO_4^{2-} anions compete with Mg^{2+} for soil adsorption sites, reducing Mg^{2+} specific adsorption and boosting its mobility in the soil profile. This gives sulfate-based Mg fertilizers greater leaching potential than other formulations[31].

Notably, Mg leaching losses of kieserite were lowest in strongly acidic Mg-deficient soils (5.81 mg) among the three soil types. This reduction is attributed to enhanced adsorption of Mg^{2+} onto protonated surfaces of Fe/Al oxide minerals in acidic soils[31,34,43]. Also, higher clay content in these soils boosts Mg^{2+} retention capacity, further reducing leaching[34]. In contrast, slightly acidic Mg-moderate soils, with higher silt content and elevated exchangeable Al^{3+}, promote Mg^{2+} physical entrapment in $[Al(OH)_x]$ polymer-derived micropores, also having lower leaching than alkaline Mg-enriched soils. Additionally, in strongly acidic Mg-deficient soils, kieserite-treated topsoil has significantly lower exchangeable Mg due to combined leaching and mineral fixation. Acidic-soil kaolinite with low interlayer charge fails to retain Mg effectively in topsoil, so kieserite-released Mg^{2+} migrates rapidly to deeper layers with water flow[44]. Amorphous Fe/Al oxides also form Al-O-Mg^+ specific adsorption complexes in acidic conditions (especially topsoil), further lowering exchangeable Mg^{2+}[30].

In contrast, MgO had the lowest Mg leaching losses across the three soils, which was primarily due to its low solubility and slow-release trait, as Mg^{2+} becomes available only gradually by multistep hydrolysis. In acidic soils, released Mg^{2+} is rapidly fixed by Fe/Al oxide surface complexation[30]; in alkaline Mg-rich soils, it precipitates as $Mg(OH)_2$[32]. Notably, MgO had a negative leaching rate in slightly acidic Mg-moderate soils. Compared to the CK, the apparent leaching reduction from the chemical response in soil to the alkaline MgO amendment. MgO hydrolysis consumes protons and raises pH. When pH exceeds 6.0, negative charge density on clay and organic matter surfaces increases, enhancing electrostatic adsorption and retention of soil-solution Mg^{2+}. This stabilizes the native soil Mg pool, reducing its mobility and leachability. Thus, while the control loses Mg baseline, MgO-treated soils gain retention capacity, which manifests as negative leaching in calculations. This finding is consistent with previous research reporting that slow-release Mg fertilizers can improve soil Mg retention and prevent leaching losses[45].

Our study extends this by confirming that the low-leaching trait in MgO is not only in acidic soils but also in alkaline Mg-rich soils. Also, the negative leaching rate we observed for MgO in slightly acidic soils, attributed to increased soil pH enhancing native Mg retention[46], provides a complementary mechanism to the adsorption-desorption kinetics described by Gransee & Führs[45]. Collectively, this confirms MgO as a sustainable Mg source for minimizing nutrient losses. Similarly, our results on the superior performance of blended formulations align with the findings of Lu et al.[12], who noted that Mg-fortified macronutrient fertilizers with both fast- and slow-release components improve plant growth with lower Mg leaching, validating the synergistic approach of our K1M1 and K2M1 treatments.

The blended fertilizers K2M1 and K1M1 had intermediate Mg leaching losses, with K2M1 (11.0–14.4 mg) consistently exceeding K1M1 (8.70–10.8 mg). This pattern reflects synergy between their two Mg sources; kieserite provides rapidly soluble, leaching-prone Mg^{2+}, whereas MgO releases Mg^{2+} gradually by interfacial reactions. Some of this released Mg^{2+} is temporarily adsorbed onto undissolved MgO particles, forming a buffering layer that regulates Mg availability and loss[31,32].

Across the treatments, Mg fertilizers most notably raised pH in strongly acidic Mg-deficient soils, primarily by Mg^{2+} displacing H^+ and Al^{3+} on soil colloids, alleviating Al toxicity and increasing base saturation[47]. Notably, kieserite slightly lowered topsoil pH due to SO_4^{2-} hydrolysis-induced acidification, but this effect was transient and diminished with continued leaching[48]. In contrast, MgO in blended formulations counteracted this by hydrolyzing to release OH^-, resulting in a net profile-wide pH increase (Fig. 5). This synergy explains acidification mitigation under K1M1/K2M1 in acidic soils.

Specifically, compared to other treatments, kieserite increases the exchangeable Mg concentration, ranging from 8.97% to 2490% in subsurface soil and 387% to 19,855% in subsoil in strongly acidic Mg-deficient soils. These unusually high percentages are accurate, stemming from the extremely low baseline exchangeable Mg content in the acidic Mg-deficient control: even small absolute Mg increases translated to substantial relative changes. It is crucial to interpret these large percentage increases in the context of the very low initial Mg concentrations. The substantial relative changes highlight the effectiveness of Mg fertilizer application in ameliorating severe deficiency, but they also underscore the proportion amplification effect where a small absolute gain translates into a large relative increase when the starting point is near zero. Thus, both absolute and relative changes should be considered for a comprehensive assessment of Mg dynamics in such soils.

4.3 Effects of Mg fertilizers on perennial ryegrass production

Building on the soil-level Mg release dynamics and chemical interactions given above, the pot trial revealed how these processes translated into distinct plant growth and environmental outcomes. The test plant, perennial ryegrass, has variable adaptability and growth across soil types, with an optimal pH range of 6.0–7.0[49]. Both soil type and Mg fertilizer type significantly affected its biomass production and Mg uptake (Table 3).

Across the three soils, the most striking improvement in yield occurred in strongly acidic Mg-deficient soils. Mg fertilizer application increased biomass yield by 946% and reduced unit-yield GHG emissions by 90%. This stems from three synergistic mechanisms. First Mg fertilizers raised soil pH by 0.1–0.27 by Mg^{2+} displacing Al^{3+}/H^+ on colloids, which mitigates proton toxicity and Al-induced root damage[31]. Also, MgO additionally consumes H^+ directly through hydrolysis[30]. Second, Mg fertilizer application reversed severe Mg limitation, which rapidly restored photosynthetic activity[50]. Finally, Mg enhanced photosynthetic carbon fixation and nitrogen cycling jointly boosted growth and reduced emissions[51]. In contrast, Mg fertilizer application in alkaline Mg-rich soils (initial Mg of 244 $mg \cdot kg^{-1}$) lowered pH by 0.13–0.26, likely due to H^+ release from plant roots during Mg^{2+} uptake to maintain charge balance[52].

In strongly acidic Mg-deficient soils, blended fertilizer K1M1 outperformed other Mg fertilizers, increasing Mg uptake by 9.68% to 26% and MUE by 14% to 82%. K1M1 enhanced the yield of ryegrass by maintaining topsoil Mg availability and offsetting pure rapid leaching of kieserite[53]. The forage achieved maximum Mg uptake in slightly acidic Mg-moderate soils through an optimal range of soil pH to boost root activity and mycorrhizal efficiency[49]; a favorable Ca/Mg ratio to avoid Ca-induced Mg inhibition[42], and low NH_4^+ (< 10 $mg \cdot kg^{-1}$) to reduce ionic competition and ensure Mg bioavailability[54]. In alkaline Mg-rich soils, the forage had lower biomass and Mg accumulation due to poor alkaline tolerance, suboptimal texture (prefers moist clay/clay loam with mild acidity)[49] and high Ca/Mg (Ca/Mg = 25, causing Mg antagonism)[55]. These issues were exacerbated by alkaline soil-specific constraints: high pH drove $Mg(OH)_2$ precipitation[36] and enhanced Mg^{2+} adsorption[41], further reducing Mg phytoavailability. K2M1 mitigated this by SO_4^{2-}-induced localized acidification. K2M1 achieved the highest yield, Mg uptake, and MUE through inhibiting $Mg(OH)_2$ precipitation[31,32,46] and lowering Ca/Mg (by SO_4^{2-} competing with Ca^{2+} for adsorption sites)[45,55].

Compared to the CK, Mg fertilizer application reduced GHG emissions by 14%–90%. Our comprehensive subsystem-level analysis provides a clear quantification of the GHG reduction pathways. The data unequivocally show that the primary driver for the observed reduction in GHG emission intensity was the substantial increase in forage biomass (up to 946%). This yield enhancement directly represents greater photosynthetic carbon fixation, which acts as the main denominator in the GHG. Although the absolute GE emissions from most subsystems remained relatively constant, the significant increase in yield diluted the emission intensity across the entire production chain. The yield-driven GHG emission reduction was further reinforced by synergistic mechanisms. First, Mg application elevated soil pH, especially in acidic soils, which enhances carbon sequestration by improved aggregate stability and mineral-associated organic carbon formation[56]. Second, Mg^{2+} optimizes nitrogen metabolism, cutting N_2O emissions by boosting nitrogen assimilation efficiency[46]. Integrating these agronomic-physiological responses with the dominant yield effect provides a coherent, data-driven explanation for lower GHG intensity.

K1M1 gave the lowest total GHG emissions in strongly/slightly acidic soils by MgO raised pH (supporting methanotroph activity, alleviating Al toxicity)[30,57] and kieserite rapidly supplied Mg^{2+} (enhancing denitrifying enzyme efficiency, promoting N_2O reduction)[46]. In alkaline Mg-rich soils, kieserite from K2M1 suppressed N_2O synthase by SO_4^{2-}-induced micro-acidification and resisted $Mg(OH)_2$ precipitation (ensuring sustained Mg supply to minimize nitrogen loss)[31,46]. This dual pathway synergistically reduces emissions and improves efficiency by adjusting soil pH and optimizing carbon-nitrogen cycling. Collectively, the results from the soil incubation and pot trials demonstrate a clear soil-plant continuum. The intrinsic properties of the Mg fertilizers governed their release dynamics in the soil, which in turn dictated Mg bioavailability, plant growth, and the overall environmental footprint of forage production.

4.4 Limitations

This study can be viewed as an initial step in quantitatively investigating the impacts of various Mg fertilizers on ryegrass yield, Mg release dynamics and leaching characteristics in various soils with distinct pH levels. Annual and perennial ryegrass develops an extensive root system, but the short duration of pot experiments limits further root development. Additionally, high plant density in pot trials restricts destructive dynamic soil sampling during cultivation, hindering precise root sampling and related physiological measurements. Therefore, future studies should validate optimal Mg fertilizer ratios through long-term pot trials or field experiments to account for root-soil interactions under more realistic growth conditions. Also, soil column leaching simulation used acrylic columns perforated at both ends and sealed laterally, allowing only stratified soil sampling and Mg concentration analysis post-leaching. To comprehensively capture Mg dynamics, time-series sampling during leaching cycles is recommended for future research, enabling real-time tracking of Mg migration and transformation. This study did not quantify specific Mg speciation (e.g., mineral-bound Mg, non-exchangeable Mg, exchangeable Mg and water-soluble Mg) in soils. Subsequent investigations should analyze Mg speciation to elucidate the transformation mechanisms between Mg pools after fertilizer application and identify the drivers of differential Mg fertilizer efficacy across Mg^{2+} availability levels. Also, the feasibility of incorporating various Mg fertilizers into compound fertilizers must be considered during promotion, ensuring scientifically sound production and application practices.

Second, extrapolating our pot experiment results to a national-scale 4.64 Tg annual forage production increase involves significant uncertainties. This calculation is based on current yield and cultivation area data from the China Grassland Statistical Yearbook 2020[58], specifically from the section on the artificial cultivation and production of perennial ryegrass in various regions for the year 2020. It is important to note that this figure represents a theoretical potential prediction under the key assumption that optimized management practices are fully adopted across all suitable areas without practical or economic constraints. Also, we assessed GHG emission by LCA relying on IPCC default emission factors (e.g., urea CO_2-C, indirect N_2O factors). Although internationally accepted and comparable, these values vary by local climate, soil conditions and management, which introduces uncertainty into absolute GHG estimates. Future research should include a sensitivity analysis to quantify how variations in these key parameters affect GHG emissions. This would enhance the robustness of conclusions and refine the model for region-specific applications.

Finally, the actual achievable gains may be lower due to real-world limitations, such as variable adoption rates, economic feasibility, climatic events, field variabilities (e.g., climate fluctuations, pests/diseases) and inconsistent management. Notably, our study ignored economic analysis. A comprehensive cost-benefit analysis (output: increased forage yield/quality; investment: blended Mg fertilizer and application costs) is important to assess financial attractiveness for forage producers. Future research should integrate economic modeling with large-scale field trials to validate agronomic benefits and provide evidence-based recommendations on the profitability and practicality of these tailored Mg fertilizer application strategies.

5 Conclusions

This study highlights the pivotal role of soil pH in governing the release dynamics, migration behavior, and uptake efficiency of magnesium fertilizers in ryegrass cultivation across diverse soil types. The results reveal that the agronomic performance of Mg fertilizers is highly dependent on soil pH and related physicochemical characteristics. Rapid-release Mg fertilizers, such as kieserite, provided immediate Mg availability but were prone to significant leaching losses, whereas slow-release Mg sources, notably MgO, ensured a more sustained Mg supply. Blended formulations of K1M1 and K2M1 demonstrated superior performance by balancing rapid nutrient supply with minimized leaching, leading to higher forage yields and greater Mg use efficiency. Also, Mg fertilizer application contributed to notable reductions in GHG emissions per unit of forage, particularly in strongly acidic soils. Our findings provide a robust scientific basis for optimizing Mg fertilizer strategies, specifically the use of K1M1 in acidic soils and K2M1 in alkaline soils, to enhance perennial ryegrass productivity and reduce environmental impacts within these specific agroecological contexts.

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Compliance with ethics guidelines

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