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Granular and powdered lime improves soil properties and maize (*Zea mays* l.) performance in humic Nitisols of central highlands in Kenya

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ABSTRACT

Acidic soils pose a major challenge for crop production in heavily weathered tropical soils, especially due to the high toxicity of aluminum (Al), low cation exchange capacity, and low availability of phosphorus (P) to plants. Lime application was recommended to alleviate soil acidity problems. Granular $CaCO_3$ lime was introduced into the Kenyan market as an alternative to powdered $CaCO_3$ and CaO-lime for small Kenyan farms, providing uniform distribution and efficient application. The aim of this study was therefore to investigate the effectiveness of different types of powdered and granular lime individually and in combination with mineral fertilizers in improving soil properties and maize yield. The study was conducted at two sites, Kirege (extremely acidic) and Kangutu (moderately acidic). Experiments were conducted in a randomized complete block design repeated four times in two consecutive seasons: long rain (LR) in 2016 and short rain (SR) in 2016. Three types of lime were applied before planting. Selected chemical properties of the soil were analyzed before and after the experiment. Maize and stover yield data were collected and analyzed. Results showed that lime application significantly increased soil pH and decreased exchangeable acidity. Powdered calcium carbonate ($CaCO_3$) showed the highest pH increase in both extreme (+19%) and moderate (+14%) acid sites. All types of lime and fertilizer applications alone significantly increased the available soil P at both the seasonal and site levels. However, maize grain yield was lower with fertilizer alone or lime alone than with lime and fertilizer combination. Powdered $CaCO_3$+ fertilizer was found to give the highest grain yields on both very acidic (5.34 t ha^{-1}) and moderately (3.71 t ha^{-1}) acid sites. In the study, combining powdered $CaCO_3$ lime with fertilizers was most effective in improving acidic soils by decreasing soil acidity and increasing available phosphorus, which ultimately increased grain yield. The results of this study recommend the use of powdered $CaCO_3$ as an effective and practical solution for farmers facing soil acidification problems.

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1. Introduction

Agriculture plays a vital role in the economy of Kenya, employing more than half of the population and making a significant contribution to the country's Gross Domestic Product (GDP) (25% GDP) [1], However, the agricultural productivity of the country faces various challenges, such as limited access to quality inputs, climate change, and soil acidity [2].

Acidic soils pose a significant problem in Sub-Saharan Africa (SSA) and specifically in Kenya, where they cover 29% and 13% of the total land area, respectively [3,4]. In Kenya, the acidic soils are found in the highly productive croplands of the central and western regions, with 70% of the soils in maize-growing areas having a pH below 5.5 [5,6]. These acidic soils are characterized by high levels of aluminum (Al) and hydrogen (H) ions, which are toxic to soil microbial activity and lead to a deficiency of essential nutrient elements, thereby inhibiting plant growth [7].

Maize is a crucial staple crop in Kenya, providing food for millions of people [8]. It is also a major cash crop, accounting for 40% of the country's total cereal production [9]. However, the improved maize varieties and landraces commonly used by Kenyan farmers are sensitive to low phosphorus (P) levels (<5 mg P kg-1) and high aluminum toxicity (>20% Al3+ saturation) [8] In soils deficient in phosphorus, maize grain yields are reduced by approximately 16%, and in soils with high aluminum toxicity, the reduction is about 28% [5]. To address nutrient deficiencies, the application of mineral fertilizers has become necessary, but this has exacerbated soil acidity, leading to poor maize grain yields ranging from 0.5 to 1.5 t ha-1 yr-1 in the region [10–14].

The use of lime has been proposed as a method to improve the fertility of highly acidic and weathered soils with low available phosphorus (P) [15]. Previous research has shown that lime application raises soil pH, as well as the levels of calcium (Ca) and magnesium (Mg), base saturation, and P uptake by plants in soils that tend to fix P [15,16]. The efficacy of different liming materials in soil improvement may differ depending on their source, particle size, nutrient content, and neutralizing capacity [17]. Smallholder farmers in Kenya have scarce use of liming materials, which could enhance their crop yields, possibly due to insufficient knowledge on lime application, access, and high transport costs [6]. There is also inadequate information on effectiveness of different lime types in enhancing soil chemical properties. The manual application of powdered lime is a common practice in smallholder farming in Kenya, The practice of manually spreading lime is often used on small farms, although it can be strenuous and not recommended during windy weather conditions. To address these challenges, MEA Ltd, a Kenyan fertilizer blending company, introduced granular $CaCO_3$ lime to the local market. Granular lime has several advantages over powdered $CaCO_3$ and CaO, such as more even distribution and easier blending with fertilizers for effective row application. However, the price of granular lime is higher than that of powdered limes requiring an evaluation of its effectiveness. Therefore, the aim of this study was to examine the agronomic effectiveness of three types of lime, one granular and two powdered on acidic Nitisols and maize yields in Tharaka Nithi County.

2. Materials and methods

2.1. *Description of study sites*

The experiment was carried out in Kirege and Kangutu in Meru South Sub-County of Tharaka Nithi County, Kenya. Meru South sub-county is situated in the Upper Midland zone 2 (UM2) agro-ecological zone with an annual rainfall range of 1200–1400 mm [18]. Kirege site is located at a latitude of 0°20′16.7″S, longitude 37°36′51.7″E, 1500 m above sea level and Kangutu is located at an laltitude of 0°33′84″S and longitude 37°68′31 E, 1468 m above sea level (a.s.l.). Rainfall distribution pattern is bimodal, the long rains (LR) fall from March to May and short rains (SR) from October to December each year [18].

Maize (*Zea mays* L.) is the main crop cultivated in the area. Humic Nitisols are the predominant soil types; they are typically deep and highly weathered with moderate to high inherent fertility [18]. The extremely acidic site (Kirege) received higher cumulative rainfall compared to the moderately acidic site (Kangutu). In Kirege, 541 mm and 317 mm was received in LR2016 and SR2016, respectively (Fig. 1). In Kangutu, the cumulative rainfall for LR2016 and SR2016 was 448 mm and 283 mm. Rainfall declined

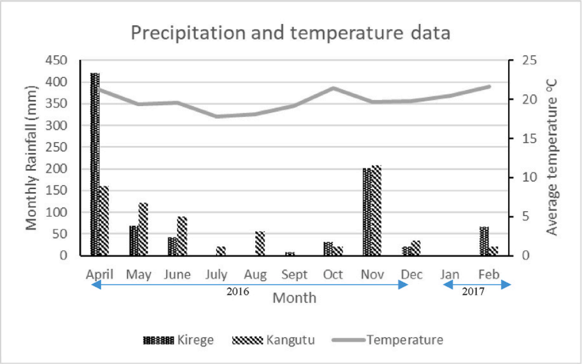

Fig. 1. Average rainfall during the 2016 long rains (LR2016) and short rains (SR2016) in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya.

throughout the cropping season in both sites . Drought spells frequently occurred, for example, a seven-week drought ensued six weeks after planting during the SR2016 season (Fig. 1).

Rainfall was insufficient during the peak water demand period; for example, most rainfall (>90%) had occurred at 50% flowering in SR2016 Kirege.

2.2. Experimental design

The experiment was laid in a randomized block experimental design (RCBD) with eight treatments replicated four times per site. The treatments included control, fertilizer only treatment, sole lime, and fertilizer plus lime. The treatments are shown in Table 1.

Plots sizes of 4.5 m by 3.0 m were marked and guard rows set with 1.0 m spacing. The liming materials consisted of powdered calcium carbonate ($CaCO_3$) and CaO limes from Homa Lime Company Limited and granulated lime $CaCO_3$ from MEA Ltd. The limes were manually distributed evenly one month before planting at the recommended rate of 2 t ha^{-1} in the first season (2016 long rain). Diammonium phosphate (DAP) fertilizer was added at planting, and four weeks after planting, urea fertilizer was added in both seasons. The rates used followed the recommendations for optimal crop production in the area P fertilizer at 60 kg P_2O_5 ha^{-1} [19] and lime at 2 t ha^{-1} [6], [20]. Maize variety H516 was the test crop and it was planted with the rows spaced at 50 cm within and 75 cm between them. Disease, weeds, pests, and cultural management practices were done through the seasons.

2.3. Soil sampling and analysis

Soil sampling was conducted both prior to the experiment and after harvest in each season using an Edelman soil auger. The zigzag method was used to collect samples from the 0–20 cm depth [21]. Five sub-soil samples were collected from each treatment area and combined to create a composite soil sample. These composite soil samples were accurately labeled, placed into plastic bags, and transported to the National Agricultural Research Laboratories (NARL) for analysis. The soil samples were later air-dried, finely crushed to fit through a 2 mm sieve, and analyzed for various properties such as soil texture, soil pH, organic carbon, exchangeable acidity, available phosphorus, total nitrogen, and exchangeable bases (K^+, Mg^{+2}, Ca^{2+}) Additionally, a portion of the soil samples were sieved using a 0.5 mm sieve to determine the quantities of organic carbon and total nitrogen present.

The soil's texture was analysed using the Bouyoucos hydrometer method [22]. The pH of the soil-water mixture was measured using a 1:2.5 soil-water ratio [23]. Exchangeable acidity was determined utilizing a titration method as described by Ref. [22]. To extract the essential cations (calcium, magnesium, and potassium), ammonium acetate was used at a soil pH of 7. Atomic absorption spectrophotometry was used to measure the exchangeable calcium and magnesium in the extract, while flame photometry was used for the determination of exchangeable potassium. The determination of organic carbon content involved the utilization of the Walkley and Black sulfuric acid-dichromate digestion method, followed by back titration with ferrous ammonium sulfate. Total nitrogen and phosphorus were determined through calorimetry of the digests. Available phosphorus, on the other hand, was determined using the Mehlich double acid method. Soil organic carbon content was determined using the modified Walkley-Black method [24,25]. The total nitrogen content in the sampled soil was determined by employing the Kjeldahl digestion, distillation, and titration procedure as outlined in Ref. [26].

2.4. Data collection and analysis

Agronomic data like maize above-ground biomass, grain yields were collected. Maize was harvested, and data on total stover fresh weight, grain moisture content, and after drying stover (t ha^{-1}) and grain yield (t ha^{-1}) was taken. Maize grain yield was expressed at a 12.5% moisture level.

Data on agronomic variables, such as the above-ground biomass of maize and grain yields, were collected. Following the maize harvest, measurements were taken for the total fresh weight of stover, moisture content of the grains, as well as the stover (t ha^{-1}) and grain yield (t ha^{-1}) after drying. The grain yield of maize was reported based on a moisture level of 12.5%.

The collected data was subjected to analysis of variance (ANOVA) utilizing the General Linear Model (GLM) feature of the SAS software [27]. Means separation was done using Duncan's Multiple Range Test (DMRT). For pairwise comparisons of the initial and final soil property parameters, the student t-test was applied.

Table 1
Treatments at Kangutu and Kirege experimental sites, Meru South, Kenya.

Treatment:	Description
Control	No inputs
Fertilizer	DAP (60 kg P ha^{-1}) + Urea (60 kg N ha^{-1})
Pw-$CaCO_3$	Powdered 2 t ha^{-1} $CaCO_3$
CaO	2 t ha^{-1} CaO
Pw-$CaCO_3$+Fertilizer	2 t ha^{-1} $CaCO_3$ + (60 kg P ha^{-1} + 60 kg N ha^{-1})
CaO + Fertilizer	2 t ha^{-1} CaO + (60 kg P ha^{-1} + 60 kg N ha^{-1})
Gr-$CaCO_3$	2 t ha^{-1} Granulated $CaCO_3$
Gr-$CaCO_3$ +Fertilizer	2 t ha^{-1} Granulated $CaCO_3$ + (60 kg P ha^{-1} + 60 kg N ha^{-1})

3. Results and discussion

3.1. Characteristics of experimental soil and before planting

Table 2 presents the soil data, indicating that both study sites had clay soils. The soil in Kirege was classified as extremely acidic, while the soil in Kangutu was categorized as strongly acidic. Additionally, the soils exhibited low levels of soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), and exchangeable sodium, based on the ratings provided by Ref. [28]. The levels of exchangeable magnesium (Mg) and potassium (K) were classified as medium [29]. The initial soil characterization data for Kangutu and Kirege is presented below.

3.1.1. Characteristics of the limes

Analyses of the limes indicated that the amounts of Calcium Carbonate Equivalent, Ca, and Ca + Mg varied among the limes as shown in Table 3.

In the Kenyan market, calcium oxide (CaO) and ground limestone, primarily composed of calcium carbonate ($CaCO_3$), are widely utilized as liming materials [30]. According to Ref. [31] the incorporation of $CaCO_3$ along with inorganic fertilizers resulted in a significant increase in maize grain yield, elevating it from 0.5 metric tons per hectare to 5 metric tons per hectare. The use of powdered lime offers the advantage of increased surface area, leading to a faster soil reaction. However, it poses challenges in terms of even application on the soil surface and potential uneven distribution due to the drift of its fine particles [32]. To address these challenges, granulated lime, which involves finely grinding limestone and processing it into fertilizer-sized pellets, can be utilized [33,34].

3.2. Effect of lime on selected soil chemical properties

3.2.1. Soil pH-H_2O

There was a significant variation ($p < 0.05$) in soil pH among treatments before and after the experimental period. Treatments involving lime application led to a significant increase in soil pH, while the sole fertilizer and control treatments showed a decrease in soil pH. In Kirege, the highest pH increase compared to the baseline was observed during the LR2016 (+11.1%) and SR2016 (+19.8%) seasons in the Pw-CaCO3 treatment ($p < 0.001$). Similarly, in Kangutu, the Pw-CaCO3 and Pw-CaCO3 + fertilizer treatments exhibited the highest pH percentage increase during the SR2016 (+14.1%) and LR2016 (+6.26%) seasons (Table 4).

The initial high soil acidity levels are likely to pose challenges associated with acidic soils, including aluminum (Al) toxicity, deficiencies in essential nutrients, and reduced phosphorus (P) availability, which are common when soil pH drops below 5. However, the application of lime in Kangutu resulted in achieving an optimal soil pH for maize productivity by the end of the experiment. According to Ref. [35], a pH range of 5.5–7.1 is considered optimal for maize growth. The increase in pH can be attributed to the presence of basic cations (Ca^{2+} and Mg^{2+}) and anions (CO_3^{2-}) in lime, which effectively exchange H+ ions in exchange sites, leading to the formation of water (H_2O) and carbon dioxide (CO_2) [36]. It is worth noting that significant chemical changes occur in the soil within 4–6 weeks following lime application when sufficient soil moisture is present, as reported by Ref. [37].

The use of Pw-$CaCO_3$ lime resulted in significant increases in pH, which can be attributed to its high quality, particularly its elevated Calcium Carbonate Equivalent (CCE). On the other hand, the low pH changes observed in treatments with CaO may be attributed to its low CCE. Treatments with Gr-$CaCO_3$ lime, despite containing a high amount of calcium, showed lower increases in pH compared to Pw-$CaCO_3$ treatments. This discrepancy could be due to the larger particle sizes of the granular lime, which had a lower surface area and were not adequately broken down due to insufficient soil moisture. The limited moisture can be attributed to the inadequate distribution of rainfall during both seasons. The presence of binding agents in Gr-$CaCO_3$ lime may have slowed down the

Table 2
Initial soil physical and chemical properties of Kirege and Kangutu soils (0–20 cm), Meru South Sub-County of Tharaka Nithi County, Kenya.

Soil Parameters	Kirege	Kangutu
Soil pH-H_2O	4.14	5.08
Ex. Ac (C mol kg^{-1})	0.49	0.29
TN (%)	0.18	0.16
SOC (%)	1.7	1.51
AP (Mehlich) mg kg^{-1}	22.65	16.25
K^+ (C mol kg^{-1})	0.19	0.29
Ca^{2+} (C mol kg^{-1})	2.30	2.80
Ma^{2+} (C mol kg^{-1})	1.14	3.76
Na^+ (C mol kg^{-1})	0.19	0.21
Sand (%)	4.88	10.44
Silt (%)	11.50	16.75
Clay (%)	83.62	72.81
Texture Class	Clay	Clay

soil pH = soil reaction; Exch. Ac = exchangeable acidity; SOC = soil organic carbon; TN = total nitrogen; AP = available phosphorus; Ca^{2+}, Mg^{2+}, K^+ and Na^+ = exchangeable calcium; magnesium; potassium and sodium respectively.

Table 3
Selected chemical properties of lime types used in the experiment.

Lime type	Ca	Mg	Ca + Mg	CCE
Pw-CaCO3	29.23	5.4	34.63	86.58
CaO	32.33	0.63	32.6	82.58
Gr-CaCO3	33.41	1.53	34.94	87.35

*CCE- Calcium carbonate equivalent.

Table 4
Changes in soil pH water and Exchangeable Acidity (C mol kg^{-1}) under various treatments in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya.

Treatment	soil pH water					Exchangeable Acidity (C mol kg^{-1})				
	Initial	LR2016	T-test, p^{a}	SR2016	t-test, p^{b}	Initial	LR 2016	T-test, p^{a}	SR 2016	T-test, p^{b}
Kirege										
Pw-CaCO$_3$	4.05^{bc}	4.5^{ab}	0.003	4.85^{ab}	0.006	0.5^{a}	0.425^{bc}	0.057	0.237^{b}	0.0002
Pw-CaCO$_3$+Fert	4.25^{a}	4.63^{a}	0.011	4.98^{a}	0.001	0.48^{a}	0.4^{c}	0.05	0.25^{b}	0.002
CaO	4.08^{abc}	4.43^{ab}	0.0008	4.78^{ab}	<0.001	0.5^{a}	0.425^{bc}	0.05	0.275^{b}	0.002
CaO + fert	4.1^{abc}	4.45^{ab}	0.0009	4.8^{ab}	0.0001	0.5^{a}	0.425^{bc}	0.057	0.262^{b}	0.004
Gr-CaCO$_3$	3.95^{c}	4.33^{b}	0.005	4.68^{b}	0.0008	0.5^{a}	0.425^{bc}	0.057	0.275^{b}	0.002
Gr-CaCO$_3$+Fert	4.3^{ab}	4.64^{a}	0.0007	4.99^{a}	<0.0001	0.45^{a}	0.4^{c}	0.18	0.262^{b}	0.015
Fertilizer	4.1^{abc}	4.08^{c}	0.162	3.98^{c}	0.823	0.48^{a}	0.5^{b}	0.39	0.5^{a}	0.391
Control	4.13^{abc}	4.05^{c}	0.982	4.0^{c}	0.569	0.5^{a}	0.56^{a}	0.057	0.57^{a}	0.181
%CV	*3.34*	*3.4*		*2.8*		*6.62*	*10.95*		*15.39*	
P value	*0.04*	*< .0001*		*< .0001*		*0.262*	*0.0004*		*< .0001*	
Kangutu										
Pw-CaCO$_3$	5.06^{a}	5.45^{a}	0.004	5.77^{a}	0.003	0.3^{a}	0.175^{b}	0.015	0.17^{b}	0.015
Pw-CaCO$_3$+fert	5.11^{a}	5.43^{a}	0.04	5.67^{ab}	0.03	0.27^{a}	0.175^{b}	0.091	0.15^{b}	0.039
CaO	5.072^{a}	5.31^{a}	0.019	5.5^{b}	0.04	0.3^{a}	0.2^{b}	0.091	0.175^{b}	0.013
CaO + fert	5.11^{a}	5.3^{a}	0.08	5.55^{ab}	0.015	0.25^{a}	0.2^{b}	0.181	0.175^{b}	0.041
Gr-CaCO$_3$	5.03^{a}	5.26^{a}	0.03	5.55^{ab}	0.002	0.27^{a}	0.225^{b}	0.181	0.2^{b}	0.048
Gr-CaCO$_3$+fert	5.01^{a}	5.23^{a}	0.007	5.47^{b}	0.006	0.28^{a}	0.23^{ab}	0.091	0.2^{b}	0.006
Fertilizer	5.1^{a}	5.09^{c}	0.89	4.86^{b}	0.018	0.27^{a}	0.325^{a}	0.05	0.35^{a}	0.18
Control	5.03^{a}	4.96^{b}	0.39	4.94^{c}	0.85	0.3^{a}	0.32^{ab}	0.391	0.325^{a}	0.391
%CV	*3.36*	*2.75*		*2.73*		*22.48*	*29.27*		*33.41*	
P value	*0.92*	*< .0001*		*< .0001*		*0.575*	*0.018*		*0.003*	

Means not sharing a common letter in a column in each site are significantly different at 5% Probability level.
Note: LR 2016 = Long Rains 2016, SR 2016 = Short Rains 2016, CV = Coefficient of variation.

[a] Pairwise *t*-test comparison between baseline value and LR2016.

[b] Pairwise *t*-test comparison between baseline value and SR2016.

reaction compared to Pw-CaCO$_3$ lime, which reacted more rapidly in the soil.

The observed decline in soil pH in the sole fertilizer treatment during the LR season in both sites aligns with the findings reported [38,39]. which indicate that the application of mineral fertilizers can lead to a reduction in pH. Mineral fertilizers have been known to contribute H^{+} ions to the cation exchange complex of the soil, resulting in increased soil acidity [39].

3.2.2. *Soil exchangeable acidity (C mol kg^{-1})*

The application of different lime types resulted in a significant decrease in soil exchangeable acidity by the end of the experiment. In Kirege, the Pw-CaCO$_3$ treatment exhibited the highest percentage decrease of −52.6% during the SR2016 season and −15.5% during the LR2016 season. Similarly, in Kangutu, the sole Pw-CaCO$_3$ treatment showed the highest percentage decrease of −50% during the SR2016 season and −41.67% during the LR2016 season. In contrast, the sole fertilizer and control treatments demonstrated increases in exchangeable acidity in both seasons and sites. (Table 4).

The application of both lime, with or without fertilizer, resulted in a significant decrease in soil exchangeable acidity compared to the initial levels. Exchangeable acidity plays a crucial role in determining aluminum phytotoxicity, as it is closely associated with the concentration of exchangeable aluminum [40]. Ref. [41] reported that the application of lime leads to a substantial reduction in exchangeable acidity in the soil. This reduction can be attributed to the precipitation of aluminum ions (Al^{3+}) as aluminum hydroxide ($Al(OH)_3$), which effectively removes the exchangeable acidity from the soil.

During the LR2016 season in Kirege, the application of lime treatments did not lead to a significant change in exchangeable acidity. This lack of significant change could be attributed to the high levels of aluminum ions present in the soil. Ref. [42] suggests that aluminum ions have a buffering effect on soil pH, which may have contributed to the observed lack of significant change in exchangeable acidity. However, there were no significant differences observed between the different lime types in terms of their ability to decrease exchangeable acidity. It is likely that the application of different lime types caused most of the aluminum to precipitate, resulting in the measured exchangeable acidity being primarily due to H+ ions.

On the other hand, Pw-$CaCO_3$ lime proved to be highly effective in reducing exchangeable acidity by reacting with both aluminum ions Al^{3+} and H^+ ions. This effectiveness can be attributed to the quality of Pw-$CaCO_3$ lime, particularly its high Calcium Carbonate Equivalent. Ref. [43] suggests that a higher Calcium Carbonate Equivalent indicates greater effectiveness of the lime in reducing exchangeable acidity.

3.2.3. *Soil available P (Mehlich) ppm*

In both seasons and sites, there was a significant increase ($p < 0.0001$) in soil available phosphorus (P) across all treatments compared to the control. The treatments that involved lime application, with or without fertilizer, showed considerable improvements in soil available P. Specifically, the Pw-$CaCO_3$+fert treatment exhibited the highest percentage increase in soil available P in both sites and seasons. as shown in Table 5.

The initial levels of soil available phosphorus (P) in both Kirege and Kangutu were below the critical level required for maize (*Zea mays* L.) growth [44]. However, during the SR2016 season, there were relatively higher amounts of soil available P compared to the first season, LR2016. This increase in soil available P could be attributed to the residual effects of P fertilizer and lime application. According to Ref. [37], P from phosphate fertilizer is rapidly adsorbed onto the surface of soil particles, followed by a slower conversion into less available forms, such as mineral phosphates. Consequently, the residual effects of P fertilizer and lime can be observed in the first season and subsequent seasons after their application. The application of lime helped elevate soil P levels to an adequate range by counteracting the effects of acidic soils, which are typically deficient in soil available P. Ref. [45] observed that low pH levels result in the immobilization of applied P due to the precipitation of insoluble aluminum phosphates. However, through the application of both fertilizer and lime, significantly higher soil P availability was achieved compared to the sole application of either. Ref [3] found that lime reduces P sorption, thereby enhancing the availability of both native P and applied fertilizer for plant uptake. In the acidic soils of Kakamega County, Kenya. Ref. [46] noted that the use of 0.8 t ha^{-1} Pw-$CaCO_3$ lime in combination with 52 kg P ha^{-1} led to an increase in available phosphorus (Bray) from 3 to 8 mg P kg^{-1}.

3.2.4. *Exchangeable calcium; magnesium*

The application of lime had diverse effects on the levels of Ca^{2+} in the soil. In Kirege, the treatments of Pw-$CaCO_3$+fert (+65%) and Pw-$CaCO_3$ (+60%) resulted in the highest increases in Ca^{2+} levels. On the other hand, the control and sole fertilizer treatments exhibited a decline in Ca^{2+} levels. In Kangutu, the Pw-$CaCO_3$ treatment showed the highest increase (+60%) in Ca^{2+} levels, while the control and sole fertilizer treatments displayed a decrease in Ca^{2+} levels.

Furthermore, the application of lime led to significant increases in Mg saturation. In Kirege, the Pw-$CaCO_3$ treatment exhibited the highest significant increase ($p = 0.0342$) in Mg saturation (+202%), while the sole fertilizer and control treatments showed decreases of (−23%) and (−36%), respectively. Similarly, in Kangutu, all treatments resulted in increases in Mg saturation, with the Pw-$CaCO_3$

Table 5
Changes in available P, exchangeable calcium; magnesium under various treatments in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya.

Treatment	available P (Mehlich) ppm					Ca^{2+}			Mg^{2+}		
	Initial	LR2016	*t*-test p^a	SR2016	*t*-test, p^b	Initial	SR16	T test, *p*	Initial	SR16	T test, *p*
Kirege											
Pw-CaCO3	26.25^{a}	33.5^{bc}	0.032	37.73^{cd}	0.011	1.8^{a}	2.85^{ab}	0.013	0.39^{ab}	1.18^{a}	0.034
Pw-CaCO3+fert	21.25^{a}	47.37^{c}	0.001	61.5^{a}	0.003	1.9^{a}	3.15^{a}	0.038	0.21^{b}	0.96^{ab}	0.005
CaO	28^{a}	32.12^{abc}	0.024	40.25^{cd}	0.013	1.93^{a}	2.65^{ab}	0.018	0.78^{a}	1.14^{a}	0.003
CaO + fert	23.75^{a}	43.37^{d}	0.005	64^{d}	0.007	1.75^{a}	2.47^{bc}	0.022	0.46^{ab}	0.98^{ab}	0.003
Gr-CaCO3	27^{a}	34.37^{c}	0.013	37.75^{cd}	0.022	1.7^{a}	2.27^{c}	0.042	0.34^{ab}	0.99^{ab}	0
Gr-CaCO3+fert	25^{ab}	53.5^{ab}	0.006	68^{a}	0.009	1.77^{a}	2.37^{c}	0.023	0.45^{ab}	1.21^{a}	0.05
Fertilizer	28.75^{a}	54.87^{a}	0.004	70^{ab}	0.005	1.85^{a}	1.7^{d}	0.391	0.73^{ab}	0.56^{b}	0.178
Control	21.25^{a}	20.3^{d}	0.099	18.75^{e}	0.28	1.85^{a}	1.67^{d}	0.61	0.69^{ab}	0.44^{b}	0.121
%CV	35.65	13.4		15.59		16.12	22.34		65.05	38.01	
P value	0.076	<.0001		<.0001		0.95	0.007		0.02	0.0385	
Kangutu											
Pw-CaCO3	17.5^{a}	20.63^{bc}	0.003	21.752^{c}	0.02	1.975^{bc}	3.15^{ab}	0.003	1.3^{b}	3.92^{a}	0.002
Pw-CaCO3+fert	15.75^{a}	30.12^{a}	0.0001	34.5^{a}	0.0002	2.15^{abc}	3.4^{ab}	0.014	1.58^{ab}	3.93^{a}	0.004
CaO	17.5^{a}	19.85^{bc}	0.001	24.25^{bc}	0.004	1.95^{bc}	2.65^{bc}	0.029	1.78^{ab}	3.07^{ab}	0.007
CaO + fert	15^{a}	24.5^{b}	<.0001	30^{b}	<.0001	2.45^{a}	3.25^{ab}	0.011	2.11^{a}	3.85^{a}	0.028
Gr-CaCO3	16.75^{a}	19.35^{c}	0.001	19^{c}	0.018	2.35^{ab}	3.52^{a}	0.004	1.84^{a}	3.52^{a}	0.034
Gr-CaCO3+fert	15^{a}	24.25^{bc}	0.018	29.5^{b}	0.03	1.9^{bc}	2.83^{abc}	0.004	1.14^{b}	3.87^{a}	0.001
Fertilizer	15^{a}	21.88^{bc}	0.02	25.75^{bc}	0.05	1.75^{c}	1.68^{d}	0.86	1.96^{ab}	1.87^{c}	0.076
Control	17.5^{a}	15.55^{bc}	0.068	18^{c}	0.461	2.4^{ab}	2.12^{cd}	0.74	1.88^{a}	1.82^{bc}	0.075
%CV	16.96	11.96		15.41		0.025	18.38	27.58	27.58	19.13	0.744
P value	0.63	0.0009		<.0001		16.72	0.0003	0.046	0.046	0.0004	

Means not sharing a common letter in a column in each site are significantly different at 5% Probability level.
Note: LR 2016 = Long Rains 2016, SR 2016 = Short Rains 2016, CV = Coefficient of variation.

[a] Pairwise *t*-test comparison between baseline value and LR2016.

[b] Pairwise *t*-test comparison between baseline value and SR201.

treatment showing the highest increase (+201%).

The observed results align with expectations, as lime contains substantial amounts of Ca^{2+} and Mg^{2+} that are released into the soil upon application. This phenomenon is supported by Ref. [47], which states that lime application increases the saturation percentage of Ca^{2+} and Mg^{2+} on the exchange sites of soil colloid. Additionally, lime application raises the pH of the soil solution through carbonate reactions. The gradual effect of lime can be attributed to its slow reactivity in releasing Ca^{2+} and/or Mg^{2+} ions, which leads to a longer-lasting impact compared to other organic and inorganic inputs [48].

3.2.5. *Total nitrogen, total organic carbon and K*

In Kirege, significant increases in soil total nitrogen were observed compared to the baseline in the Gr-$CaCO_3$+ fert ($p = 0.008$), Pw-$CaCO_3$+fert ($p = 0.01$), and CaO + fert ($p = 0.018$) treatments. The elevated pH resulting from lime application may have contributed to the retention of more nitrogen in the soil as ammonium through cation exchange, reducing nitrogen loss through nitrate leaching and volatilization as ammonia [49,50].

In contrast, all treatments in Kangutu exhibited a decline in total nitrogen, although the decline was not significant. The sole fertilizer treatment showed the highest decline (−37.5%). The decrease in soil total nitrogen in Kangutu could be attributed to plant uptake and soil nitrogen immobilization processes [51] Table 6.

The application of different lime types with and without fertilizer did not result in a significant change in soil organic carbon compared to the baseline. The insignificant increase in soil organic carbon may be attributed to an increase in soil biological activity and plant productivity, which can lead to an accumulation of organic matter [52]. The low initial levels of total nitrogen and organic carbon in the soil [53] may have also contributed to the lack of significant results. According to Ref. [54] the decline in soil organic matter is often due to faster mineralization than accumulation, which is influenced by moist and warm conditions favoring decomposition. Additionally, the removal of crops and continuous cultivation can cause the breakdown of soil aggregates, resulting in the decomposition of soil organic matter [55].

On K saturation, the experimental soil demonstrated an adequate level of K saturation, and the observed changes were not significant. Ref. [56] suggested that a K saturation range of 1%–5% is suitable for maintaining soil productivity.

3.3. *Maize yields*

In Kangutu, throughout both seasons, treatments that included the application of fertilizer, either alone or in combination with lime, resulted in the highest stover and grain yields. This trend was similarly observed in Kirege. On the other hand, treatments with sole lime application showed yields that were comparable to the control .. A presentation of the yield data can be found in Table 7.

In Kangutu, the treatment receiving Pw-$CaCO_3$+fertilizer exhibited the highest maize stover yields of 5.27 t ha-1 in both the LR2016 and SR2016 seasons. Similarly, in Kirege, the Pw-$CaCO_3$+fertilizer treatment yielded the highest maize stover, with 5.16 t ha-1 in the LR2016 season and 3.38 t ha-1 in the SR2016 season. On the other hand, the control treatment consistently resulted in the

Table 6

Changes in total Nitrogen, Total Organic Carbon and K under various treatments in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya.

	Total Nitrogen %			Total Org. Carbon %			K (C mol kg^{-1})		
Treatment	Initial	2016SR	T-test,*p*	Initial	2016SR	T-test,*p*	Initial	2016SR	T-test,*p*
Kirege									
Pw-CaCO3	0.148^{b}	0.16^{a}	0.34	1.14^{c}	1.21^{b}	0.089	0.187^{a}	0.2^{a}	0.46
Pw-CaCO3+fert	0.165^{ab}	0.193^{a}	0.01	1.45^{ab}	1.82^{a}	0.158	0.175^{a}	0.225^{a}	0.34
CaO	0.165^{a}	0.175^{a}	0.219	1.45^{ab}	1.51^{ab}	0.134	0.17^{a}	0.175^{a}	0.63
CaO + fert	0.158^{a}	0.188^{a}	0.018	1.58^{ab}	1.78^{a}	0.268	0.175^{a}	0.18^{a}	0.63
Gr-CaCO3	0.135^{a}	0.14^{a}	0.135	1.50^{ab}	1.56^{ab}	0.485	0.175^{a}	0.195^{a}	0.09
Gr-CaCO3+fert	0.15^{a}	0.18^{a}	0.008	1.62^{a}	1.76^{ab}	0.198	0.185^{a}	0.175^{a}	0.18
Fert	0.16^{a}	0.175^{a}	0.101	1.41^{abc}	1.79^{a}	0.053	0.175^{a}	0.185^{a}	0.49
Control	0.177^{ab}	0.172^{a}	0.53	1.46^{bc}	1.27^{ab}	0.179	0.15^{a}	0.13^{a}	0.45
%CV	10.14	10.37		14.35	13.84		15.78	24.36	
P value	0.032	0.97		0.014	0.031		0.796	0.79	
Kangutu									
Pw-CaCO3	0.17^{a}	0.16^{a}	0.27	1.51^{a}	1.53^{a}	0.79	0.27^{a}	0.31^{a}	0.18
Pw-CaCO3+fert	0.17^{a}	0.16^{a}	0.31	1.49^{a}	1.55^{a}	0.52	0.35^{a}	0.39^{a}	0.01
CaO	0.17^{a}	0.14^{a}	0.15	1.34^{a}	1.59^{a}	0.21	0.34^{a}	0.36^{a}	0.81
CaO + fert	0.18^{a}	0.14^{a}	0.06	1.34^{a}	1.44^{a}	0.27	0.28^{a}	0.31^{a}	0.54
Gr-CaCO3	0.15^{a}	0.14^{a}	0.63	1.32^{a}	1.39^{a}	0.40	0.30^{a}	0.32^{a}	0.54
Gr-CaCO3+fert	0.16^{a}	0.14^{a}	0.31	1.32^{a}	1.43^{a}	0.38	0.26^{a}	0.29^{a}	0.60
Fert	0.16^{a}	0.1^{a}	0.34	1.34^{a}	1.46^{a}	0.47	0.26^{a}	0.265^{a}	0.86
Control	0.15^{a}	0.14^{a}	0.73	1.38^{a}	1.45^{a}	0.55	0.23^{a}	0.235^{a}	0.95
%CV	13.05	7.69		11.26	14.28		75.47	66.81	
P value	0.53	0.55		0.482	0.88		0.994	0.959	

Means not sharing a common letter in a column in each site are significantly different at 5% Probability level.
Note: LR 2016 = Long Rains 2016, SR 2016 = Short Rains 2016, CV = Coefficient of variation.

Table 7
Maize Stover and grain yields (t ha^{-1}) under different treatments at Kangutu and Kirege sites, Meru South Sub-County of Tharaka Nithi County, Kenya.

	LR2016		SR2016	
Treatment	Grain yield (t ha^{-1})	Stover yield (t ha^{-1})	Grain yield (t ha^{-1})	Stover yield (t ha^{-1})
Kangutu				
Pw-CaCO3+fert	2.55^{a}	4.66^{a}	1.22^{a}	5.27^{a}
Gr-CaCO3+fert	2.05^{ab}	3.60^{ab}	1.20^{a}	4.29^{ab}
CaO + fert	1.99^{ab}	3.17^{bc}	1.04^{ab}	4.39^{a}
Fert	1.90^{ab}	3.24^{bc}	1.18^{a}	4.24^{ab}
CaO	1.37^{b}	2.59^{bc}	0.44^{bc}	2.22^{b}
Pw-CaCO3	1.29^{b}	2.48^{bc}	0.46^{bc}	2.25^{bc}
Gr-CaCO3	1.19^{b}	2.37^{bc}	0.41^{bc}	2.00^{c}
Control	1.18^{b}	2.27^{c}	0.20^{c}	1.74^{c}
P value	0.019	0.004	0.008	0.003
CV (%)	34.22	26.28	58.42	40.78
	LR2016		**SR**2016	
Treatment	Grain Yield	Stover Yield	Stover Yield	
Kirege				
Pw-CaCO3+fert	3.11^{a}	5.16^{a}	3.38^{a}	
CaO + fert	2.24^{a}	5.13^{a}	2.25^{b}	
Fert	2.17^{a}	4.23^{a}	1.73^{b}	
Gr-CaCO3+fert	2.04^{a}	3.99^{a}	2.02^{b}	
CaO	0.45^{b}	0.97^{b}	0.40^{c}	
Pw-CaCO3	0.40^{b}	1.23^{b}	0.57^{c}	
Gr-CaCO3	0.38^{b}	0.97^{b}	0.43^{c}	
Control	0.24^{b}	0.67^{b}	0.28^{c}	
P value	<.0001	<.0001	<.0001	
%CV	57.42	37.24	51.81	

*.

Means not sharing a common letter in a column in each site are significantly different at 5% Probability level.
Note: LR 2016 = Long Rains 2016, SR 2016 = Short Rains 2016, CV = Coefficient of variation.

lowest stover yields across both seasons and sites. In terms of grain yields, the highest values were observed in Kangutu during the LR2016 season. The Pw-CaCO$_3$+fert treatment yielded 2.55 t ha^{-1}, corresponding to a 116% increase compared to the control. In the SR2016 season, the Gr-CaCO$_3$+fert and Pw-CaCO$_3$+fert treatments showed significant increases of 500% and 510% respectively, compared to the control, with grain yields of 1.2 t ha-1 and 1.22 t ha-1, respectively. In Kirege during the LR2016 season, the CaO lime + fertilizer treatment resulted in the highest maize grain yields. These results highlight the positive impact of fertilizer and lime applications on stover and grain yields, with the Pw-CaCO$_3$+fertilizer treatment consistently showing promising results in both sites.

The poor yields observed in both sites and seasons could be attributed to the erratic rainfall patterns, especially the prolonged drought experienced during the SR2016 season in Kirege, which led to a complete crop failure and no grain yields. Adequate and well-distributed rainfall is crucial for optimal crop growth and productivity in rain-fed agriculture, as highlighted by Refs. [57,58] Insufficient moisture availability can severely impact plant development and yield potential. However, it's worth noting that the combination of lime and P fertilizer showed promising results, as indicated by the higher yields observed in plots receiving lime with fertilizer compared to sole lime application. This suggests that the simultaneous application of lime and P fertilizer can improve soil fertility and nutrient availability, leading to enhanced crop growth and higher yields, as supported by studies on Kenyan acid soils [59,60].

The higher yields observed in treatments with fertilizers, particularly in combination with Pw-CaCO3 lime, can be attributed to the increased availability of essential nutrients like phosphorus (P) and nitrogen (N) in the soil. The application of lime, is known to have long-term residual effects on soil fertility, which may contribute to improved yields in subsequent seasons [61] Ref. [20] attributed increased maize yields to the combined application of Pw-CaCO$_3$ lime and inorganic fertilizers, with the order of yield performance as agricultural lime + fertilizer > fertilizer > lime > control. Similarly, ref [62] reported significantly higher grain yields with the use of CaO lime and P fertilizer compared to the control, while sole CaO application resulted in lower yields. Another study [63] found that a liming material with high CaO (73%) and MgO (2–3%)content significantly increased maize grain yield, with the highest yield recorded in the treatment with 6 t ha^{-1} of lime.

The superiority of Pw-CaCO$_3$+ fertilizer treatment in terms of reduction in soil acidity and maize yield compared to Gr-CaCO3+ fertilizer and CaO + fertilizer treatments can be attributed to the higher Calcium Carbonate Equivalent (CCE) of Pw-CaCO3 lime, which resulted in the release of more Ca and Mg into the soil. Pw-CaCO3 lime, being a fine powder, had better distribution and greater surface area contact with the soil, promoting faster and more efficient nutrient release. Moreover, ref. [64] noted that magnesium carbonate could reduce soil acidity than calcium carbonate.

The granulated lime (Gr-CaCO3) treatment, despite its high CCE, showed lower yields compared to Pw-CaCO3 lime. This could be attributed to the presence of lignosulfonate binding agents in the granular lime, which may have slowed down the reaction and nutrient release process. Additionally, the distribution pattern of granular lime may have resulted in concentrated spots, visually observed at the end of the study, which could have affected nutrient availability [65]. Microbial activity plays a crucial role in breaking down the binding agents and facilitating nutrient release from granular lime. However, under low rainfall and acidic soil conditions, microbial activity can be reduced, leading to a slower reaction rate of the granular lime. In contrast, fine powdery limes like CaO and Pw-CaCO3 have better contact with the soil due to their dust-like properties, resulting in higher surface area contact and potentially faster nutrient release [66].

4. Conclusion

The study highlights the potential for improving agricultural production in tropical sub-humid regions with erratic rainfall through the combined use of fertilizer and lime to restore soil fertility and increase yields. Among the lime types tested, powdered $CaCO_3$ lime (Pw-$CaCO_3$) had the greatest impact in alleviating soil acidity, increasing pH, improving soil available phosphorus (P), and promoting maize stover and grain yield. Therefore, t the combined use of fertilizer and Pw-$CaCO_3$ lime was the most effective option for smallholder farmers to address soil acidity, enhance soil available P, and enhance maize growth, stover, and grain yield. However, the study also notes that the differences in yield among the three lime types were marginal within the study period. It suggests the need for further research to investigate the long-term effects of these lime types on crop performance and soil properties in the sub-humid tropics. . In conclusion, the study provides evidence for the positive impact of combined fertilizer and lime application on soil fertility and crop yields in tropical sub-humid regions. It highlights the importance of choosing appropriate lime types, such as powdered $CaCO_3$ lime, andrecommends for further research to explore the long-term effects of different lime types. This knowledge can guide smallholder farmers in making informed decisions regarding soil management practices and contribute to sustainable agricultural development in the sub-humid tropics.

Author contribution statement

Peter Kibet: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. M.W Mucheru-Muna; F.K Ngetich; J.N Mugwe; N.K Korir: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. D.N Mugendi: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data associated with this study has been deposited at Kenyatta University Repository; http://ir-library.ku.ac.ke/handle/123456789/19246; 2019-03-22T07:35:25Z.

Additional information

Supplementary content related to this article has been published online at [URL].

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Peter Kibet reports equipment, drugs, or supplies was provided by Alliance for a Green Revolution in Africa.

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