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Effect of liming on soil physicochemical properties and yield of some spring wheat (*Triticum aestivum* L.) cultivars in acid soils of South-Eastern Nigeria

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Abstract

This study was conducted to evaluate the varietal performance of some spring wheat cultivars and lime application on soil properties, growth, physiology and yield of wheat under acidic soil condition in Calabar, Nigeria. A factorial experiment was laid in a completely randomized design with three lime rates (0.0, 0.5 and 1.0 ton/ha) and four spring wheat cultivars (Imam, Sc. Sahai, Norman and WZ 272-2015). Soil physicochemical properties, growth variables, photosynthetically active radiation, yield-related and yield attributes were measured. The pre-soil analysis showed that the soil was strongly acidic and characterized by low organic carbon, total nitrogen, available phosphorus and exchangeable bases, but high in exchangeable aluminum. Application of lime significantly ($p \leq 0.05$) improved soil pH, increased calcium and magnesium availability and reduced ($p \leq 0.05$) aluminum toxicity at the 0.5 ton/ha lime rate. Among the cultivars, WZ 272-2015 and Norman were most ($p \leq 0.05$) responsive to lime, recording superior performance in growth, spikelet formation, dry matter partitioning, and overall yield at the 0.5 ton/ha lime rate. Lime application also enhanced light interception at 4 and 8 WAS and was highest ($p \leq 0.05$) at 0.5 and 1.0 ton/ha in WZ 272-2015 and Norman, compared to the control (0.0 ton/ha). Liming at 0.5 ton/ha could be sufficient to ameliorate soil acidity for soil nutrient availability for enhanced wheat performance in the study location. WZ 272-2015 and Norman are recommended for cultivation in lime-amended soils following their adaptability and superior yield responses to acidity.

Keywords: *Triticum aestivum* L., calcium carbonate, soil properties, spring wheat, acid sands

Introduction

Wheat (*Triticum aestivum* L.), an important global grain and ranked as the second most important cereal crop after rice (Naja *et al.*, 2018). It is cultivated mainly in temperate and sub-temperate regions of the world. Although several varieties are recognized across the globe, there are only three cultivars namely, *Triticum aestivum* (Bread wheat), *Triticum durum* (Macaroni wheat) and *Triticum dicoccum* (Emmer wheat) that are commercially cultivated

(Sendhil *et al.,* 2012). Globally, wheat crops are the leading sources of carbohydrates (about 71 %) and protein (about 13 %) in human food (Udhayan *et al.*, 2023). Over the years, wheat consumption has steadily increased in conjunction with the global population growth rate, which is estimated to exceed 80 billion by 2030 with a resultant 55 % rise in food consumption (FAO, 2022).

Historically, wheat cultivation in Nigeria has been concentrated in the northern states, where cooler temperatures during the dry season allow for optimal growth. However, studies are underway to develop heat-tolerant and disease-resistant varieties that can be grown in other agro-ecological zones (Bamiro *et al.*, 2020). Over the years, the Nigerian government's efforts to increase wheat production led to the ban on wheat importation in 1987, and the Accelerated Wheat Production Programme (AWPP) was implemented to encourage local production. The lowest local production and the highest import quantities were recorded in 2020 (55,000 tonnes and 5.7 million tonnes, respectively) (FAO, 2022). Similarly, the ratio of local production to import progressively declined from 1.41 % in 2016 to 0.93 % in 2020 (FAOSTAT, 2021). To meet this demand, Nigeria is expected to produce over 160,000 tonnes of wheat to promote sustainability prospects in wheat production.

Soil acidity is the primary constraint that affects agricultural productivity, particularly in tropical regions (Brady and Weil, 2017), characterized by high rainfall, weathering of parent materials, and excessive nitrogenous fertilizers application. The soils are usually low in pH due to higher concentrations of aluminum (Al^{3+}) and hydrogen (H^+) cations. Although the use of organic and inorganic inputs could increase soil fertility, the benefits are generally short-lived in tropical soils because of rapid decomposition of soil organic matter and leached bases such as calcium, magnesium, potassium and sodium (Agegnehu *et al.*, 2019; Agegnehu *et al.*, 2021). Agricultural limes are naturally occurring minerals that contain mainly calcium compounds and are capable of neutralizing soil acidity. These minerals include calcium carbonate ($CaCO_3$), hydrated lime [$Ca(OH)_2$], calcium oxide (CaO), and slag lime ($CaSiO_3$) (Kalkhoran *et al.*, 2021). Adding liming materials helps to reduce soil acidity by neutralizing acid reactions in the soil. The carbonate component reacts with hydrogen ions present in the soil solution and raises the soil pH; it is the most utilized long-term technique of soil acidity amelioration, and its effectiveness is well established (Bürge *et al.*, 2021). Although wheat is grown in the northern part of Nigeria on a very limited scale, there is a need to identify varieties that can adapt to a wide range of ecologies in the country. We propose to identify tolerant wheat cultivars that could withstand soil acidity. This study is aimed to evaluate the effect of liming on soil physicochemical properties and yield of some spring wheat cultivars grown to an acid soil in Cross River State, South-Eastern Nigeria.

Materials and Methods

Experimental site

This research was conducted at the University of Calabar Research Farm (04° 57'-13°N, 08° 20' E, 39 m above sea level), Nigeria. The relative humidity is 60-90 %, while the mean annual temperature in the area ranges between 27 °C and 28 °C. Calabar soils are mainly acidic, derived from coastal plain sands and classified as *Typic Paleudult* in the *Ultisol* order of the USDA soil taxonomy (Ita *et al.*, 2025).

Collection and preparation of research materials

i) Wheat

The experimental wheat varieties *WZ 272 2015, Norman, Imam* and *Sc. Sahai* were sourced from Lake Chad Research Institute (LCRI), Maiduguri, Borno State. The LCRI mandates are focused on genetic improvement of crops, including wheat to mitigate production challenges and boost food security and yields in Nigeria.

ii) Soil sample collection and preparation

The test soil was collected from a previously cultivated plot at the Faculty of Agriculture Research Farm, University of Calabar. Soil samples (0-15 and 15-30 cm) were collected from nine (9) different spots in a fallow land, using a soil auger and bulked to form a composite sample. About 150 g was taken for routine physicochemical analysis using standard laboratory procedures as outlined in Udo *et al.* (2009) and Otie *et al.* (2025). The soil was air-dried and screened via a 4mm sieve, and fourteen kilograms (14.0 kg) of the soil was weighed into 36 plastic pots (experimental units), with height 30 cm and diameter of 25 cm. The pots were perforated at the base for drainage, and for seeding the wheat varieties. Cured poultry manure (PM), sourced from University of Calabar poultry farm, was shade-dried, crushed and analyzed for nutrient contents as described in Udo *et al.* (2009). The PM was basally applied to the soil at 1.0 ton/ha as recommended for wheat production in Nigeria (Ali and Wabekwa, 2024) to boost soil fertility.

Experimental design, planting and maintenance of experimental units

Four spring wheat cultivars (*WZ 272 2015, Norman, Imam* and *Sc. Sahai*) were factorially combined with three rates of calcium carbonate ($CaCO_3$), lime [0, Lm_0 = Control), 0.5 (Lm_1 = 3 g) and 1.0 (Lm_2 = 6 g) tons/ha] following the standard recommended rate of 500 kg/ha for acid soils of Southern Cross River State (Effa *et al.*, 2011; Otie *et al.*, 2018). The treatments were laid as a 4 x 3 factorial experiment, arranged in a completely randomized design (CRD). The total number of treatment combinations were 4 x 3 = 12, replicated three times to give a total of thirty-six (36) experimental units. Lime was tilled into the moist soil one week before wheat sowing to allow reactions to commence. For each pot, fifteen wheat seeds were sown at 2 cm deep and in 3 rows (five seeds per row) at 10 cm apart. Thereafter, the seedlings were thinned to nine vigorous seedling (3 seedlings per row) at 14 days after sowing (DAS). Irrigation was carried out twice daily at 700 mL per pot. The pots were weeded manually as the need arose. Harvesting was done at physiological maturity, dried and manually threshed.

Data Collection

The growth attributes studied were plant height, number of tillers, number of functional tillers, flag leaf area, and number of days to heading at 4, 6 and 8 WAS. The photosynthetically active radiation (PAR, µmol $m^{-2}s^{-1}$) was determined as spot measurement on the flag leaves periodically (4, 6 and 8 WAS) on sunny days, using the MQ-100: Quantum Integral Sensor with Handheld Meter (Apogee Instruments INC. USA). The length of spike, number of spikes per plant, number of spikelets per main spike and number of spikelets per main plant were measured at 10 WAS. The weight of spikes and plant dry weight were measured at harvest after oven drying at 75°C for 72 hours. Harvest index (%) was estimated as: $\mathrm{HI} = \frac{\text{Seed dry matter}}{\text{Plant dry matter}}$ x 100. The grain yield per plant was measured at harvest using a sensitive weighing balance (g).

Statistical analysis

The data obtained were subjected to analysis of variance using GenStat software 15.1 Edition to partition the effects of the two factors and their interactions. Treatment means were compared using Duncan's new multiple-range test at a 5 % level of probability.

Results and Discussions

Soil properties

The soil analysis (Table 1) had a pH (H_2O) of 5.4. The soil organic carbon (OC) of the plow layer (0-30 cm) was 1.01 %, total nitrogen (TN) was 0.09 % and available P (Av. P) was 4.56 mg/kg. The exchangeable base values (cmol/kg) were 3.93 for Ca, 0.86 for Mg, 0.10 for Na and 0.08 for K. The values (cmol/kg) of exchangeable acidity were 2.54 for Al^{3+} and 0.77 for H^+. There were significant varietal and liming effects on the chemical properties of the soil after harvest. The pH was significantly ($p \leq 0.05$) higher in soils planted with *WZ 272 2015* (6.4) and *Norman* Oba-98 varieties than those of *Imam* (6.1) and *Sc. Sahai* (5.8). Soil under *WZ 272 2015* had higher ($p \leq 0.05$) OC (1.69 %), Av. P (17.89 mg/kg) and exchangeable Ca (1.97 cmol/kg) and Mg (0.28 cmol/kg) relative to soils under other varieties. Total nitrogen was highest ($p \leq 0.05$) in soils sown to *Norman* varieties, relative to others. Soils sown to *WZ 272 2015* recorded the lowest ($p \leq 0.05$) exchangeable acidity (Al^{3+}, 0.53 cmol/kg; H^+, 0.92 cmol/kg) and highest ($p \leq 0.05$) ECEC (7.35 cmol/kg) and base saturation (BS) (78.83 %) compared to others. At the 0.5 ton/ha rate, liming boosted ($p \leq 0.05$) the soil nutrients and significantly reduced exchangeable acidity. There was significant ($p \leq 0.05$) interaction effect with *WZ 272 2015* performance in soils treated with 0.5 ton/ha relative to other varieties.

Effect of spring wheat cultivars and lime on wheat growth attributes

The main and interaction effects of spring wheat cultivars and lime on plant growth attributes (plant height, number of tillers, number of functional tillers, number of days to heading and flag leaf area) are presented in Table 2. There was a significant varietal ($p \leq 0.05$) effect in plant height at 8 WAS across the wheat cultivars. *WZ 275-2015* showed the best ($p \leq 0.05$) performance on most growth attributes (Table 2). Wheat cultivars vary widely in their tolerance to Al^{3+} toxicities whose primary symptoms are rapid inhibition of root growth and disruption of root morphology (Rasel *et al.*, 2013). Low fertility is a major limitation of acid soil to crop production, especially on highly weathered and leached soils (Kochian *et al.*, 2004). The superior performance of *WZ 275-2015* over other wheat cultivars may suggest tolerance to Al^{3+} toxicities. This finding aligns with those of Shaon *et al.* (2023), who reported substantial reductions in wheat root length under Al stress, accompanied by diminished shoot length, plant height, and seedling weight. The application of lime at the 0.5 ton/ha (Lm_1) significantly boosted all the growth attributes across the cultivars, highlighting the role of lime in improving nutrient availability, particularly calcium and magnesium, which are vital elements for cell elongation and vegetative growth (Mugo *et al.*, 2020). The interaction of Lm x V showed that liming at Lm_1 (0.5 ton/ha) facilitated plant height, functional tillers and flag leaf area of *WZ 275-2015* relative to other cultivars. For the number of days to heading, *WZ 272-2015* significantly ($p \leq 0.05$) headed in fewer (51.13) days under Lm_1 (0.5 ton/ha) compared with other cultivars. Liming may have removed the deleterious effects of Al and ensured adequate supply of calcium for cell wall strengthening and plant vigor (Wan *et al.*, 2021). Over-liming (higher lime application) had negatively impacted wheat performance relative to where lower rate was applied. This could possibly be due to nutrient lockup, as phosphorus and other essential trace elements become tied up and unavailable to the plants (Wenyika *et al.*, 2025).

Table 1: Effect of spring wheat cultivars and lime on soil chemical properties

Treatment	Soil depth (cm)	pH (H_2O)	OC (%)	TN (%)	Av. P (mg/kg)	Ca	Mg	K	Na	Al^{3+} (cmol/kg)	H^+	ECEC	BS (%)
Wheat cultivars (V) Imam (V_1)	0-30	6.1^{bc}	1.05^{d}	0.11^{c}	15.50^{d}	2.87^{c}	1.13^{c}	0.10^{a}	0.07^{a}	0.80^{a}	1.19^{a}	5.98^{c}	68.00^{c}
Sc. Sahai (V_2)	0-30	5.8^{c}	1.46^{b}	0.12^{c}	15.73^{c}	2.87^{c}	1.00^{d}	0.10^{a}	0.07^{a}	0.67^{b}	1.11^{b}	5.72^{d}	68.00^{c}
Norman (V_3)	0-30	6.3^{ab}	1.31^{c}	1.17^{a}	16.48^{b}	3.13^{b}	1.73^{b}	0.11^{a}	0.09^{a}	0.60^{c}	1.03^{c}	6.51^{b}	72.67^{b}
WZ 272-2015 (V_4)	0-30	6.4^{a}	1.69^{a}	1.08^{b}	17.89^{a}	3.40^{a}	1.97^{a}	0.10^{a}	0.08^{a}	0.53^{d}	0.92^{d}	7.35^{a}	78.83^{a}
Lime rate (Lm)													
Lm_0 =0.0 ton/ha	0-30	4.8^{c}	1.13^{c}	0.08^{c}	16.27^{c}	1.75^{c}	0.75^{c}	0.09^{a}	0.07^{a}	1.18^{a}	1.21^{a}	5.06^{c}	59.76^{c}
Lm_1 = 0.5 ton/ha	0-30	5.7^{a}	1.58^{a}	0.14^{a}	16.84^{a}	3.80^{a}	2.05^{a}	0.11^{a}	0.08^{a}	0.10^{c}	0.88^{c}	7.15^{a}	89.84^{a}
Lm_2 = 1.0 ton/ha	0-30	5.4^{b}	1.35^{b}	0.11^{b}	16.80^{b}	3.65^{b}	1.50^{b}	0.10^{a}	0.07^{a}	0.67^{b}	1.10^{b}	7.02^{b}	75.25^{b}
Lm x V													
$Lm_0 V_1$	0-30	4.7^{de}	0.36^{j}	0.08^{g}	10.31^{j}	1.20^{f}	1.00^{cd}	0.09^{a}	0.07^{a}	1.60^{a}	1.40^{b}	3.76^{j}	43.00^{i}
$Lm_0 V_2$	0-30	4.6^{de}	0.88^{h}	0.04^{h}	$I0.62^{j}$	1.00^{f}	0.80^{d}	0.08^{a}	0.06^{a}	1.36^{c}	1.26^{c}	4.46^{i}	43.00^{i}
$Lm_0 V_3$	0-30	4.8^{d}	0.64^{i}	0.07^{g}	11.00^{i}	2.40^{e}	0.40^{e}	0.10^{a}	0.08^{a}	1.24^{d}	1.68^{a}	3.90^{j}	46.00^{h}
$Lm_0 V_4$	0-30	4.8^{d}	1.00^{g}	0.11^{f}	13.06^{h}	2.40^{e}	0.80^{d}	0.10^{a}	0.08^{a}	1.52^{b}	1.60^{ab}	2.50^{k}	52.00^{g}
$Lm_1 V_1$	0-30	5.8^{bc}	1.54^{e}	0.52^{cd}	16.00^{e}	3.60^{c}	0.40^{e}	0.11^{a}	0.07^{a}	0.28^{h}	0.48^{h}	7.86^{c}	79.00^{d}
$Lm_1 V_2$	0-30	5.7^{bc}	1.64^{d}	0.57^{c}	18.52^{ab}	3.30^{c}	0.40^{e}	0.09^{a}	0.07^{a}	0.12^{j}	0.48^{h}	7.34^{d}	86.00^{b}
$Lm_1 V_3$	0-30	6.0^{b}	1.79^{b}	0.85^{b}	17.98^{c}	4.00^{a}	3.60^{a}	0.12^{a}	0.10^{a}	0.00^{k}	0.56^{g}	8.50^{b}	92.00^{ab}
$Lm_1 V_4$	0-30	6.2^{a}	2.15^{a}	1.06^{a}	18.94^{a}	4.00^{a}	3.80^{a}	0.11^{a}	0.09^{a}	0.00^{k}	0.42^{i}	9.48^{a}	94.00^{a}
$Lm_2 V_1$	0-30	5.6^{bc}	1.44^{f}	0.42^{d}	15.19^{f}	3.80^{bc}	2.00^{b}	0.10^{a}	0.07^{a}	0.40^{g}	0.96^{e}	5.56^{h}	81.00^{c}
$Lm_2 V_2$	0-30	5.1^{c}	1.46^{f}	0.53^{cd}	14.75^{g}	4.00^{a}	1.80^{b}	0.12^{a}	0.09^{a}	0.44^{f}	0.60^{f}	6.84^{f}	77.00^{e}
$Lm_2 V_3$	0-30	5.1^{c}	1.71^{c}	0.55^{c}	18.12^{bc}	3.00^{d}	1.20^{c}	0.10^{a}	0.08^{a}	0.24^{i}	0.52^{gh}	7.14^{e}	61.00^{f}
$Lm_2 V_4$	0-30	5.6^{bc}	1.56^{e}	0.32^{e}	17.00^{d}	3.80^{bc}	1.00^{cd}	0.09^{a}	0.07^{a}	0.60^{e}	1.17^{d}	6.58^{g}	82.00^{c}

Means within a column follow by the same letter(s) are not significantly different at 5 % probability level according to Duncan's multiple range test; V = Wheat cultivars; V_1 = *Imam*; V_2 = *Sc. Sahai*; V_3 = *Norman*; V_4 = *WZ 272 2015*; Lm = lime rate; Lm_0 =control (0 ton/ha); Lm_1 =0.5 ton/ha (3.0 g); Lm_2 =1.0 ton/ha (6.0 g)

Table 2: Effect of spring wheat cultivars and lime on growth variables

Treatment	Plant height (cm) 8WAS	Number of tillers 4WAS	Number of Functional tillers 8WAS	Number of days to heading 6WAS	Flag leaf area (cm^2) 6WAS
Wheat cultivars (V)					
Iman (V_1)	42.76^c	1.99^c	1.32^c	61.09^a	4.29^{cd}
Sc. Sahai (V_2)	42.94^c	1.13^{cd}	1.40^c	61.89^a	5.92^c
Norman (V_3)	54.86^b	2.77^b	2.64^b	57.97^b	8.54^b
WZ 272-2015 (V_4)	62.72^a	4.69^a	3.28^a	43.57^c	11.11^a
Lime rate (Lm)					
Lm_0 = 0.0 ton/ha	38.24^c	1.33^c	0.66^c	57.55^a	5.36^c
Lm_1 = 0.5 ton/ha	52.17^a	3.36^a	2.88^a	40.48^c	9.73^a
Lm_2 = 1.0 ton/ha	45.05^b	2.97^b	1.40^b	51.86^b	7.56^b
Lm x V					
Lm_0V_1	41.10^e	2.20^a	1.13^{de}	66.33^a	2.41^i
Lm_0V_2	37.33^g	2.40^a	1.10^{de}	64.43^{ab}	3.81^{gh}
Lm_0V_3	40.43^{ef}	1.90^a	1.17^d	63.50^{ab}	5.52^f
Lm_0V_4	42.00^d	2.83^a	1.13^{de}	62.83^{ab}	4.39^g
Lm_1V_1	47.93^{cd}	1.20^a	3.33^{ab}	56.00^{de}	8.35^c
Lm_1V_2	48.00^c	1.60^a	3.40^{ab}	54.47^e	9.25^b
Lm_1V_3	56.00^{ab}	2.23^a	3.60^{ab}	53.67^{ef}	10.48^{ab}
Lm_1V_4	58.83^a	2.83^a	4.17^a	51.13^f	12.23^a
Lm_2V_1	43.23^d	2.57^a	3.00^b	55.10^{d-f}	7.52^d
Lm_2V_2	46.23^{cd}	2.40^a	2.40^{cd}	58.23^d	6.73^e
Lm_2V_3	45.90^{cd}	2.07^a	2.67^c	56.73^{de}	7.63^d
Lm_2V_4	51.33^b	2.40^a	1.33^d	61.10^c	6.66^{ef}

Means within a column follow by the same letter(s) are not significantly different at 5 % probability level according to Duncan's
multiple range test. V= Wheat cultivars; V_1 = *Imam*; V_2= *Sc.Sahai*; V_3= *Norman*; V_4= *WZ 272 2015*; Lm =lime rate; Lm_0 = control
(0 ton/ha); Lm_1 =0.5 ton/ha (3.0 g); Lm_2 = 1.0 ton/ha (6.0 g); WAS= weeks after sowing

Effect of spring wheat cultivars and lime on photosynthetically active radiation

The main and interaction effect of spring wheat cultivars and lime on photosynthetically active radiation (PAR) is presented in Table 3. There was significant variation among the wheat cultivars, lime application and their interactions across the sampling periods, except at 6 WAS. *Norman* recorded the highest PAR at 4 WAS relative to other cultivars. At 8 WAS, *WZ 275-2015* significantly had higher PAR possibly due to its relatively higher growth rate and canopy structure for light interception, which is associated with greater biomass accumulation (Zhang *et al.,* 2020). Liming improved PAR across the varieties and was highest ($p \leq 0.05$) at 4 WAS under Lm_2 (1.0 ton/ha) application. Whereas, at 8 WAS, liming boosted PAR at the 0.5 ton/ha rate. Monitoring PAR for plant growth is a prerequisite for actual photosynthetic processes for healthy and productive plants (Otie *et al.,* 2018). Liming reduces Al^{3+} toxicity and enhances root growth, nutrient uptake, leaf chlorophyll content and photosynthetic gas exchange. Interactively, liming significantly ($p \leq 0.05$) increased the PAR of *Norman* (55.09 μmol $m^{-2}s^{-1}$) than other varieties at the 10 ton/ha lime rate.

However, PAR was better improved in *WZ 275-2015* at 8 WAS, under the 0.5 ton/ha lime application rate. Our finding is akin to other studies on lime application. Recent study suggested that lime application rate is critical to neutralizing exchangeable acidity that restricts root growth and nutrient acquisition in acidic soils (Fageria and Baligar, 2008; Otie *et al.*, 2018).

Table 3: Effect of spring wheat cultivars and lime on photosynthetically active radiation

Treatment	PAR 4WAS (μmol $m^{-2}s^{-1}$)	PAR 6WAS (μmol $m^{-2}s^{-1}$)	PAR 8WAS (μmol $m^{-2}s^{-1}$)
Wheat cultivars (V)			
Iman (V_1)	27.87^{b}	30.00^{a}	32.08^{c}
Sc. Sahai (V_2)	28.03^{b}	34.00^{a}	45.88^{b}
Norman (V_3)	39.90^{a}	34.00^{a}	45.71^{b}
WZ 272-2015 (V_4)	22.56^{c}	33.00^{a}	47.28^{a}
Lime rate (Lm)			
Lm_0 = 0.0 ton/ha	25.75^{c}	33.00^{a}	35.90^{c}
Lm_1 = 0.5 ton/ha	30.62^{b}	34.00^{a}	50.50^{a}
Lm_2 = 1.0 ton/ha	39.90^{a}	34.00^{a}	41.81^{b}
Lm x V			
Lm_0V_1	17.14^{g}	21.00^{a}	26.14^{i}
Lm_0V_2	39.16^{c}	41.00^{a}	66.70^{c}
Lm_0V_3	13.87^{ij}	23.00^{a}	30.69^{g}
Lm_0V_4	11.11^{Jk}	16.00^{a}	19.22^{j}
Lm_1V_1	25.11^{f}	22.00^{a}	39.97^{f}
Lm_1V_2	34.82^{d}	42.00^{a}	53.93^{d}
Lm_1V_3	14.66^{hi}	17.00^{a}	19.02^{j}
Lm_1V_4	28.40^{e}	38.00^{a}	89.93^{a}
Lm_2V_1	47.46^{b}	25.00^{a}	75.74^{b}
Lm_2V_2	10.11^{k}	13.00^{a}	17.00^{k}
Lm_2V_3	55.09^{a}	25.00^{a}	28.17^{h}
Lm_2V_4	28.17^{e}	38.00^{a}	46.33^{e}

Means within a column follow by the same letter(s) are not significantly different at 5 % probability level according to Duncan's multiple range test. V = Wheat cultivars; V_1 = *Imam*; V_2= *Sc. Sahai*; V_3= *Norman*; V_4= *WZ 272 2015*; Lm = lime rate; Lm_0 = control (0 ton/ha); Lm_1 = 0.5 ton/ha (3.0 g); Lm_2 =1.0 ton/ha (6.0 g); PAR = photosynthetically active radiation; WAS = weeks after sowing

Effect of spring wheat cultivars and lime on yield attributes

The effect of spring wheat cultivars and lime on yield attributes of wheat are presented in Table 4. Wheat cultivars differed significantly in their yield attributes (number of spikes/plant, number of spikelets/main spike, length of spike/plant and number of spikelets/plant). Across these traits, *Norman* was highest ($p \leq 0.05$) in number of spikelets/main spike and length of spike, while *WZ 275-2015* had more ($p \leq 0.05$) number of spikes/plant and number of spikelets/plant. These traits increase grain-bearing potential in wheat following sustainable soil nutrient management practices (Ali *et al.*, 2019). Spike traits depend strongly on genetic characteristics of varieties, and their stability under different environments for yield resilience (Shoaib *et al.*, 2020). Application of lime (0.5 ton/ha) increased the yield attributes across the varieties. Liming generally improves soil pH and nutrient availability. However, optimum lime application translates to reproductive gains due to cultivar-specific responses (Raza *et al.,* 2021). Lime application overcomes Al^{3+} toxicity, improves plant root growth, nutrients and water uptake from the soil for higher crop yields (Bürge *et al.,* 2021). The interaction of number of spikelets/plant showed that *WZ 275-2015* was significantly higher when treated with Lm_1 (0.5 ton/ha).

Table 4: Effect of spring wheat cultivars and lime on yield attributes

Treatment	No. of spike/plant 10WAS	No. of spikelet/main spike 10WAS	Length of spike/plant (cm) 10WAS	No. of Spikelet/plant 10W
Wheat cultivars (V)				
Iman (V_1)	1.36^c	18.94^{ab}	5.74^d	25.60^c
Sc. Sahai (V_2)	1.36^c	18.62^b	6.32^c	24.48^d
Norman (V_3)	3.62^b	20.36^a	9.46^a	26.33^b
WZ 272-2015 (V_4)	4.50^a	17.67^b	8.58^{ab}	33.58^a
Lime rate (Lm)				
Lm_0 = 0.0 ton/ha	1.46^c	11.10^c	3.18^c	20.02^c
Lm_1 = 0.5 ton/ha	3.48^a	20.13^a	8.38^a	29.87^a
Lm_2 = 1.0 ton/ha	2.51^b	18.46^b	6.26^b	27.15^b
Lm x V				
Lm_0V_1	1.43^a	22.13^a	1.43^a	20.27^f
Lm_0V_2	1.40^a	21.33^a	6.07^a	24.33^{de}
Lm_0V_3	1.67^a	18.40^a	6.03^a	22.43^e
Lm_0V_4	1.33^a	18.67^a	6.67^a	22.67^e
Lm_1V_1	1.43^a	16.93^a	5.57^a	26.59^d
Lm_1V_2	1.57^a	20.67^a	6.40^a	30.50^c
Lm_1V_3	1.43^a	19.07^a	6.90^a	32.20^b
Lm_1V_4	1.50^a	17.17^a	6.67^a	37.10^a
Lm_2V_1	1.20^a	17.17^a	5.70^a	25.90^{de}
Lm_2V_2	1.40^a	19.07^a	$6,50^a$	26.57^d
Lm_2V_3	1.77^a	18.40^a	6.43^a	26.67^d
Lm_2V_4	1.67^a	17.17^a	6.40^a	25.33^{de}

Means within a column follow by the same letter(s) are not significantly different at 5 % probability level according to Duncan's
multiple range test. V= Wheat cultivars; V_1 = *Imam*; V_2= *Sc. Sahai*; V_3= *Norman*; V_4= *WZ 272 2015*
Lm = lime rate; Lm_0 = control (0 ton/ha); Lm_1 = 0.5 ton/ha (3.0 g); Lm_2 =1.0 ton/ha (6.0 g); PAR = photosynthetically active radiation; WAS = weeks after sowing

Effect spring wheat cultivars and lime on number of grains/plant, grain weight/plant, spike weight and plant dry weight

Table 5 shows the main and interaction effects of spring wheat cultivars and lime on number of grains/plant, grain weight/plant, spike weight/plant and plant dry weight. The number of grains/plant was highest ($p \leq 0.05$) in *WZ 275-2015* relative to other varieties for lime applied at 0.5 tons ha^{-1}. A similar trend occurred in grain weight/plant, spike weight and plant dry weight. The number of grains and grain weight per spike greatly affects wheat yield and vary considerably depending on the weather conditions and genetic characteristics of the variety (Dolferus *et al.,* 2011; Duvnjak *et al.,* 2023). Weight of spikes and plant dry weight were better ($p \leq 0.05$) under 0.5 ton/ha lime for *WZ 275-*

2015. Soil amendments, including agricultural limes, improve nutrient availability, uptake, root activity and yield formation in cereal crops (Kumar *et al.*, 2022). Such improvements in plant nutrition directly foster enhanced grain formation and overall productivity, mirroring reports from long-term field trials where liming led to yield increases of up to 37 % in wheat and depending on soil and crop variables (Tesfaye *et al.*, 2023). Calcium and magnesium supplied by liming are critical for better root health and nutrient uptake capacity, especially in cereal crops (Agegnehu *et al.*, 2021; Hosna *et al.*, 2024). Therefore, optimizing lime application rate based on varietal selection is crucial for enhancing wheat productivity. The interaction effect results indicate that *WZ 275-2015* had the highest yield and yield components when treated with lime at 0.5 ton/ha (Table 5) relative to other wheat varieties, and at any lime rate (Table 5).

Table 5: Effect spring wheat cultivars and lime on number of grains/plant, grain weight/plant, spike weight and plant dry weight

Treatment	Number of grains/plant	Grain weight/plant (g/plant)	Spike weight (g/plant)	Plant dry weight (g/plant)
Wheat cultivars (V)				
Imam (V_1)	13.14^{c}	4.15^{b}	9.20^{b}	11.24^{d}
Sc. Sahai (V_2)	13.79^{c}	4.16^{b}	10.01^{b}	12.39^{c}
Norman (V_3)	16.97^{b}	7.18^{ab}	13.23^{ab}	18.66^{b}
WZ 272-2015 (V_4)	18.24^{a}	8.21^{a}	14.25^{a}	21.89^{a}
Lime rate (Lm)				
Lm_0 = 0.0 ton/ha	4.81^{c}	4.10^{c}	4.20^{b}	8.32^{c}
Lm_1 = 0.5 ton/ha	12.30^{a}	8.23^{a}	7.25^{a}	14.90^{a}
Lm_2 = 1.0 ton/ha	10.49^{b}	7.18^{ab}	7.23^{a}	11.45^{b}
Lm x V				
Lm_0V_1	2.40^{e}	0.67^{e}	4.17^{d}	10.48^{e}
Lm_0V_2	3.27^{de}	2.11^{cd}	2.02^{ef}	10.35^{e}
Lm_0V_3	3.33^{de}	0.23^{bc}	2.17^{ef}	13.35^{d}
Lm_0V_4	2.33^{e}	1.80^{d}	3.24^{e}	12.08^{d}
Lm_1V_1	7.47^{b}	4.00^{bc}	5.99^{cd}	18.88^{b}
Lm_1V_2	8.02^{b}	4.24^{b}	6.22^{c}	21.99^{ab}
Lm_1V_3	7.87^{b}	6.17^{ab}	8.27^{ab}	21.58^{ab}
Lm_1V_4	11.70^{a}	6.25^{a}	9.29^{a}	22.13^{a}
Lm_2V_1	5.57^{c}	4.20^{b}	8.26^{ab}	21.62^{ab}
Lm_2V_2	5.00^{cd}	4.20^{b}	6.19^{c}	18.81^{b}
Lm_2V_3	3.70^{d}	3.15^{c}	5.25^{cd}	15.90^{c}
Lm_2V_4	5.77^{c}	3.10^{c}	5.20^{cd}	14.46^{cd}

Means within a column follow by the same letter(s) are not significantly different at 5 % probability level according to Duncan's multiple range test. V= Wheat cultivars; V_1 = *Imam*; V_2 = *Sc. Sahai*; V_3= *Norman*; V_4 = *WZ 272 2015*; Lm = lime rate; Lm_0 = control (0 ton/ha); Lm_1 = 0.5 ton/ha (3.0 g); Lm_2 = 1.0 ton/ha (6.0 g)

Conclusion

This study demonstrates that wheat varieties respond differently to soil acidity stress with significant variations in plant growth, physiology, yield and yield attributes. Lime applications improved the soil pH, exchangeable calcium and magnesium, and reduced aluminum toxicity accordingly. The soil was better improved in plots treated with 0.5 ton/ha lime. Plant height was significantly increased with 1.0 ton/ha of lime in *WZ 272-2015*. This cultivar also produced the highest number of tillers, functional tillers, flag leaf area and fewer days to heading at the 0.5 ton/ha lime rate. Though the application of lime at 1.0 ton/ha improved the plant height remarkably across the varieties. *Norman* recorded the highest PAR at 4 WAS at the 1.0 ton/ha lime rate, whereas *WZ 272-2015* was a better light interceptor at 8 WAS under the 0.5 ton/ha lime rate. The lime treatment boosted the photosynthetic traits of the plants at 0.5 ton/ha rate relative to non-limed plots (control = 0.0 ton/ha). *Norman* produced the highest number of spikelets per main spike and spike length, while *WZ 272-2015* had more spikes and spikelets per main plant, and were both influenced when the plants were treated with 0.5 ton/ha lime, relative to the control. The yield components varied significantly across the cultivars. *WZ 272-2015* recorded the highest number and weight of grains per plant across the cultivars. Similarly, the spike and plant dry weights were also better in *WZ 272-2015*. Thus, the grain yield components varied significantly in the order *WZ 273 2015 > Norman > Sc. Sahai > Imam*, highlighting the differential adaptation strategies of the tested cultivars under liming at 0.5 ton/ha. Thus, liming at 0.5 ton/ha could optimize *WZ 272-2015* and *Norman* production with further field trials to validate the findings.

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