Heliyon 9 (2023) e22933

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Impact of silicate fertilizer on soil properties and yield of bread wheat in Nitisols of tropical environment

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ARTICLE INFO

Keywords:
Mineral fertilizers
Silicate
Soil acidity
Wheat and yield

ABSTRACT

Purpose: Soil acidity and depletion of essential plant nutrients are among the major abiotic stresses that constrained wheat productivity in Ethiopia. Silicates and silicate by-products can be used as alternative source for amendment of soil acidity and improvement of crop yields. Surface application of water-soluble silicate fertilizer alone and the integrated application with full does of recommended N and P from mineral fertilizers can reduce the extent of soil acidity and improve phosphorous availability in the soil, soil pH and exchangeable acidity and can enhance the yield attributes and yield of bread wheat. A field experiment was conducted under rain-fed condition from July to December of 2020 to evaluate the role of soil and foliar application of water-soluble silicate fertilizer without and with reduced or full doses of recommended nitrogen (N) and phosphorus (P) (RNP) from mineral fertilizers on soils chemical attributes, yield components and yield of bread wheat sown under moderately to strongly acidic condition in south-eastern Ethiopia.
Methods: The experiment comprised sole silicate (40 kg + 18 L/ha^{-1}), and its integration with full dose of RNP (92–30 kg N–P ha^{-1}), three quarters dose of RNP (69–23 kg N–P ha^{-1}) and half dose of RNP (46–15 kg N–P ha^{-1}) from mineral fertilizers. Full dose of RNP from mineral fertilizers and a negative control with no silicate and mineral fertilizer inputs included as controls, resulting in a total of six treatments. The experiment was laid out in randomized complete block design, replicated three times.
Results: The combined application of silicate with mineral fertilizers significantly influenced soil properties, yield attributes and yield of bread wheat. Integrated applications of silicate fertilizers and full dose of RNP increased grain yield, biomass yield, and available soil P by 108, 115, and 23 % respectively relative to untreated soil.
Conclusions: Integration of silicate with mineral fertilizers can be considered as a viable and alternative option for acid soils amendment. Generally, the result of the current study revealed that combined application of water soluble granular and liquid silicate at the rate of (40 kg + 18 L)/ha with full dose of recommended nitrogen (92 kg ha^{-1}) and phosphorus (30 kg ha^{-1}) significantly reduced exchangeable acidity, tended to increase soil reaction, increased available soil phosphorus content and boosted yield of bread wheat compared to their sole applications. Thus, application of water-soluble silicate fertilizer with recommended rate of nitrogen and

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https://doi.org/10.1016/j.heliyon.2023.e22933
Received 4 March 2023; Received in revised form 20 November 2023; Accepted 22 November 2023
Available online 28 November 2023

phosphorus is better in enhancing plant nutrition and yield of bread wheat in the highlands of Ethiopia and other similar agro-ecologies.

1. Introduction

Wheat (*Triticum aestivum*) is one of the most widely cultivated and traded cereal crops worldwide due to its broader adaptability to diverse agroeclogies and soils. The total area dedicated to wheat was estimated at 219 million hectares with a global production of 761 million tons of grain [1]. It is the main staple food crop for 35–40 % of the world's population because it provides more carbohydrates, proteins, minerals and vitamins than any other cereal crops [2,3]. Compared to other cereal crops such as rice and maize, the nutritional value of wheat is superior, with 60–80 % starch and 8–15 % protein [4,5].

Ethiopia is the largest wheat producer in sub-Saharan Africa (SSA) [6,7] because of its favorable agro-ecologies and soils [7,8]. Out of the total area of 2.96 million (M) hectare devoted to wheat production in SSA in 2018 and 2.21 M ha in East Africa in 2020, 60 and 83 %, respectively was cultivated in Ethiopia [1,9]. Despite the great production, national wheat productivity in Ethiopia (3 t ha^{-1} [10]; is still very low compared to the world average of 3.5 t ha^{-1} [1] and 6.6 t ha^{-1} of the top producing country in the continent, Egypt [1]. Thus, increasing wheat productivity has been a major issue to meet the ever-increasing demand of the growing population in Ethiopia [7].

Soil acidity and depletion of essential plant nutrients are among the major abiotic stresses that constrained wheat productivity in Ethiopia in general and in the study area in particular [11–16]. About 43 % of the cultivable land in Ethiopia is affected by soil acidity [12], of which about 28 % is categorized under strongly acidic (pH $<$ 5.5) (11). Soils of Arsi highlands, where this study was conducted, are very strongly to strongly acidic (pH–H_2O: 4.49–5.3) [17]. The soil acidity and nutrients depletion in this region could attribute to diverse factors including but not limited to high amount of precipitation, which leached appreciable amounts of exchangeable bases from the soil surface, nitrogen fertilizers, conventional cultivation without balanced nutrients replacement and severe soil erosion [12]. Thus, soil acidity amendment and mitigation of nutrients depletion are essential to offset their negative influences; thereby, enhance wheat productivity in the study area (13, 14, 15, 16,17, 18,].

Lime (limestone) is the most commonly used product for soil acidity amendments and increase crop yields in Ethiopia [17,18] and many countries throughout the world [19,20]. Lime; however, is a slowly soluble product, and its dissociated components such as carbonate show restricted mobility within the uppermost soil profile; thus, its neutralizing effects are usually limited to the applied and incorporated layers [21,22]. Surface application of lime with low solubility can restrict root development within the surface layers and consequently suppress the potential yield of crops due to subsurface potential acidity and low availability of exchangeable cations [22, 23].

Silicates and silicate by-products, such as steel industry slags (basically composed of calcium or magnesium silicate), can be used as alternative source even more advantageously for amendment of soil acidity and improvement of crop yields due to their neutralizing constituent of silicate, higher solubility, alkalinity and silicon (Si) supply to the soil and several Si-accumulating crops [24–27]. Silicates have greater reaction rate due to their particle characteristics, presenting greater specific surface [22,24] Because of higher reaction rate and mobility, the dissociated products of silicates can reach down to deeper soil layers [22], indicating their higher potential for amelioration of thicker layers of acid soils. [28], for example, reported that silicate from slag (calcium/magnesium silicate) is 6.78 times more soluble (0.095 g dm^{-3}) than calcium carbonate (0.014 g dm^{-3}). Given higher reactivity, silicate is more efficient for phosphorus availability in acidic soils; thereby, improve nutrition acquisition to crops and reduce toxic cations such as aluminum [22].

Apart from their benefits for soil acidity amendment, silicates have a high level of silica and can be used as a nutrient source for plants since successive cropping reduces Si concentration in soil [29]. Moreover, silicate impacts uptake, translocation and availability of several mineral nutrients in plants such as phosphorus, potassium, calcium and magnesium and alleviating mineral nutrition deficiencies [30–35].

This study was, thus, conducted based on the following hypotheses: (i) surface application of water soluble silicate fertilizer alone can reduce the extent of soil acidity and improve phosphorous availability in the soil, and (ii) the integrated application of water soluble silicate and full does of recommended N and P from mineral fertilizers are more efficient to improve soil available P, soil pH and exchangeable acidity and can enhance the yield attributes and yield of bread wheat. In summary, the present study aimed to evaluate the role of soil and foliar application of water-soluble silicate fertilizer on soils chemical attributes, yield components and yield of bread wheat under moderately to strongly acidic condition in southeastern Ethiopia.

Table 1
Description of the experimental sites.

S/No	Testing site	Latitude	Longitude	Altitude [m above sea level]
1	Site 01 [Wadji Chilalo]	07°49'44.4"	039°10'54.3"	2840
2	Site 02 [Wadji Chilalo]	07°49'40.6"	039°10'09.7"	2757
3	Site 03 [Shala Chabeti]	07°50'80.5"	039°07'9.6"	2668
4	Site 04 [Shala Chabeti]	07°50'03.7"	039°07'11.0"	2543
5	Site 05 [Haro Bilalo]	07°52'16.9"	039°08'18.5"	2680
6	Site 06 [Haro Bilalo]	07°52'37.0"	039°08'45.2"	2723

2. Materials and methods

2.1. Description of the study area

A field experiment was conducted from July to December of 2020 at six farmers' fields in Tiyo district of Arsi zone in the southeast of Ethiopia. The geographical locations of the sites are shown in Table 1. The dominant soil type of the sites is classified as Nitisol [36]. It is reddish in color and moderately to strongly acidic in reaction.

The study area has bimodal rainfall pattern with the short rainy season occurs during the months of February to end of April, whereas the long rainy season extends from June to September. Since none of the experimental sites have meteorological station, the weather variables were estimated from the NASA database (https://power.larc.nasa.gov). The estimated weather variables during the cropping season in 2020 are shown in Table 2. Thus, the annual precipitation was 1106 mm. The mean seasonal wind speed, relative humidity, maximum and minimum temperatures were 1.8 m s^{-1}, 77.6 %, 20.0 °C and 9.8 °C, respectively (Table 2). The maximum monthly precipitation (282 mm), relative humidity (85.9 %) and minimum temperature (11.5 °C) were observed during the month of August. The maximum monthly wind speed (2.2 m s^{-1}) and maximum temperature (21 °C) were recorded in December (Table 2). The lowest monthly precipitation (33 mm) was estimated in November whereas the lowest relative humidity (63.4 %) and minimum temperature (6.7 °C) were observed during the month of August. July and September were the period that recorded the lowest wind speed (1.2 m s^{-1}) and maximum temperature (19 °C), respectively (Table 2). Generally, the study area is characterized by high precipitation and humidity but lower temperature.

2.2. Experimental setup and procedures

The experiment had six treatments comprising of 100 % sole application of granular and liquid silicate fertilizer (40 kg + 18 L/ha) (Si-Star), full dose of recommended N & P (RNP) from NPS and urea ((92–30 kg N–P ha^{-1}), recommended granular and liquid silicate fertilizer (40 kg + 18 L/ha) with full dose of RNP from NPS and urea (92–30 kg N–P ha^{-1}), recommended granular and liquid silicate fertilizer (40 kg + 18 L/ha) with75 % of RNP from NPS and urea (69–23 kg N–P ha^{-1}), recommended granular and liquid silicate fertilizer (40 kg + 18 L/ha) with 50 % of RNP (46–15 kg N–P ha^{-1}) from NPS and urea and treatment with neither mineral nor silicate fertilizers (treatment with no input or negative control (Table 3). Each treatments were replicated three times across each six sites. The granular and liquid silicate fertilizer (Si-star) contained 20 % sodium silicate, 80 % auxiliary components and other essential trace elements that improve growth and yield (MyoungJeonBio Co. Ltd). Si-star is alkaline in its pH and has anion that reacts in the soil. The six treatments are shown in Table 3. The experiment was arranged in randomized complete block design with three replications. Bread wheat variety called '*Lemu*' was drilled by hand in rows with spacing of 20 cm in plot sizes of 7.8 m^2 (2.6 m length by 3 m width). The distance between blocks and plots were 1 m and 0.4 m, respectively.

The NPS blended fertilizer was used as a source of N and P; 125 kg (57.5 kg N) urea as a source of N to supplement the remaining amount that could not be met the recommended N by NPS fertilizer; and Si-star as a source of silicon (Si). All NPS and granular silicate fertilizers, and half dose of urea were applied at sowing as basal placement based on the treatment's arrangement. The remaining half dose of urea fertilizer was side dressed at tillering stage of the crop development as per the treatment setup. In addition to the granular form of silicate fertilizer, 18 L liquid silicate was also applied in three splits based on the recommendation set by the manufacture. The first round of liquid silicate fertilizer was injected in to the soil at a rate of 15 Liter ha^{-1} diluted in 15,152 L water ha^{-1} when the seedlings growth was 5–10 cm high. This is to make the seedling resistant to the early hard ship effect of soil acidity on root of newly germinated plant and to increase the efficiency of silicate fertilizer on reducing the soil acidity around the root zone. The second and third rounds of liquid silicate fertilizer were sprayed on the leaves of bread wheat plants three weeks before flowering (bud formation) and at flowering stages (on formation of blossom bud), respectively at a rate of 1.5 Liters ha^{-1} diluted in 1515 L water ha^{-1} for each round of foliar application.

For the control of weeds and fungal diseases, Pallas™ 45 OD (Pyroxsulam (Triazolopyrimidine), 45 g L^{-1}) and Rex®Duo (187 g L^{-1} Epoxiconazole and 310 g L^{-1} Thiophanate-methyl), respectively were applied. Pallas™ 45 OD was applied 21 days after planting for effective control of weeds by using a knap sack while Rex®Duo was applied two times, just after tillering and at booting stage as soon as the disease symptom observed and when the disease occurred using knap sack by man power. All other agronomic practices were kept uniform for all treatments as per the recommendation made for the wheat crop.

Table 2
Weather variables in the study area during 2020 cropping season.

Month	Precipitation [mm $month^{-1}$]	Wind speed [m s^{-1}]	Relative humidity [%]	Maximum temperature [°C]	Minimum temperature [°C]
June	158	1.3	79.6	20.7	11.3
July	209	2.0	84.3	19.0	11.1
August	282	1.7	85.9	19.1	11.5
September	258	1.2	83.8	19.7	11.3
October	97	2.0	76.0	19.8	8.8
November	33	2.2	70.2	20.6	7.7
December	69	2.2	63.4	21.0	6.7
Total	**1106**				
Average		**1.8**	**77.6**	**20.0**	**9.8**

Table 3
Description of treatments evaluated in the experiment.

S/No	Treatments	Amount of nutrients [kg (L) ha^{-1}]			
		N	P	SiO_3-granul	SiO_3-liquid
1	No input	0	0	0	0
2	100 % recommended N & P (RNP) from NPS and urea	92	30	0	0
3	100 % RNP from NPS and urea + recommended silicate	92	30	40	18
4	75 % RNP from NPS and urea + recommended silicate	69	22	40	18
5	50 % RNP from NPS and urea + recommended silicate	46	15	40	18
6	Recommended silicate	0	0	40	18

Note: N, P and SiO_3 are nitrogen, phosphorous and silicate, respectively.

2.3. Soil sample collection and analyses

Surface (~0–20) soil samples were collected using auger after land preparation prior to sowing from the experimental plots and composited into one sample per each site for the purpose of soil characterization. Soil samples were also collected after harvesting of the crop from each plot. The collected soil samples were air dried, crushed with a mortar and pestle and passed through a 2-mm mesh sieve. The samples were analyzed for potential of hydrogen (pH), total nitrogen (N), available phosphorous (P) and exchangeable acidity following standard procedures. The pH of the soil was determined in 1:2.5 (weight/volume) soil to water ratio using a glass electrode attached to digital pH meter [37]. Total N was determined using Kjeldahl method as described by Ref. [38]. Available P was determined by Bray II method. Exchangeable acidity was determined by saturating the soil samples with 1 N potassium chloride (KCl) solution and the filtrate was titrated with 0.02 N sodium hydroxide (NaOH) and 0.02 N hydrochloric acid (HCl), respectively [39].

2.4. Yield attributes and yield data collection

The collected agronomic data included number of tillers $plant^{-1}$, spikes m^{-2}, spike length, plant height, number of seeds $spike^{-1}$, grain yield, above ground total biomass yield, harvest index, hectoliter and seed (kernel) weights. The number of tiller $plant^{-1}$ was counted from ten plants within each plot. Numbers of spikes m^{-2} were counted from ten 0.5 m long sampling points in each plot, and were converted to m^{-2} for the purpose of statistical analysis. Spike length was measured from ten randomly selected plant samples from each plot using a meter rule from the base of spike to its tip by excluding awns. The heights of ten plants in each plot at random were chosen and measured at physiological maturity as the wheat flag leaf and spikes turned from green to yellow and begun to dry from the soil surface to apex of spike by excluding awns. The number of seeds was counted from ten randomly selected spikes from each plot. The entire plot area of 7.8 m^2 was manually harvested for the above ground total biomass yield determination. The harvested samples were manually threshed, air-dried to uniform moisture content and after its moisture was checked by grain moisture tester, cleaned and the grain and straw samples were weighed using digital balance. The grain yields were adjusted to a standard moisture content of 12.5 % before the data were analyzed. The harvest index was computed from the percentage ratio of grain to biomass yields. For determination of hectoliter and kernel weights, samples were randomly taken from the collected and cleaned grains of each plot, and measured using sensitive balance (0.01 g).

2.5. Data analysis

The collected agronomic and soil data were subjected to analysis of variance using SAS computer software package version 9.0 (SAS Institute, Inc., Cary, NC). Mean comparison was performed using the least significant difference test at 5 % probability level. Simple regression analysis was also conducted using SAS statistical package to assess the relationship of improvements in soil chemical attributes and yield components with yield of bread wheat.

Table 4
Chemical properties of the soils of the experimental sites before sowing.

S/No	Testing site	pH	Total N [%]	Available P [mg kg^{-1}]	Exchangeable acidity [$cmole_{(+)}$ kg^{-1}]
1	Site 01 [Wadji Chilalo]	5.31	0.25	5.04	0.76
2	Site 02 [Wadji Chilalo]	5.31	0.25	9.70	0.74
3	Site 03 [Shala Chabeti]	5.39	0.23	13.25	0.34
4	Site 04 [Shala Chabeti]	5.10	0.23	10.82	0.82
5	Site 05 [Haro Bilalo]	5.29	0.27	9.89	1.34
6	Site 06 [Haro Bilalo]	5.11	0.34	9.33	0.70

Note: pH, N and P are soil reaction, nitrogen and phosphorus, respectively.

3. Results

3.1. Soil properties

The chemical analyses performed for the soil samples collected before sowing are presented in Table 4. The soil reaction (pH), total nitrogen (N), available phosphorous (av. P) and exchangeable acidity ranged from 5.1 to 5.4, 0.23–0.34 %, 5.0–13.2 mg kg^{-1} and 0.34–1.34 cmol $_{(+)}$ kg^{-1} (Table 4). Accordingly, soils of the study area can be categorized under moderately to strongly acidic [40], medium to high N [40], and very low to low av. P [41].

Sole and combined applications of silicate and mineral fertilizers significantly altered the exchangeable acidity of the soils (Table 5). Significant reduction in exchangeable acidity was recorded in the sole-silicate treated soils (0.87 cmol $_{(+)}$ kg^{-1}) compared to unfertilized (1.14 cmol $_{(+)}$ kg^{-1}) and fully fertilized (1.10 cmol $_{(+)}$ kg^{-1}) soils. The sole-silicate without mineral fertilizers reduced the level of exchangeable acidity by 24 % (0.27 cmol $_{(+)}$ kg^{-1}) and 21 % (0.23 cmol$_{(+)}$ kg^{-1}) compared to unfertilized and fully fertilized soils, respectively (Table 5). Silicate fertilizer integrated with reduced or full doses of nutrients from mineral fertilizers also significantly reduced the exchangeable acidity by 13–14 % (0.15–0.16 cmol $_{(+)}$ kg^{-1}) compared to unfertilized soil (Table 5).

Soil fertilization using water soluble silicate and its integration with mineral fertilizers also significantly improved the available phosphorous (av. P) contents in the soils (Table 5). The maximum amount of av. P (16.4 mg kg^{-1}) was extracted from the soil treated with full dose of RNP (92–30 kg N–P ha^{-1}) integrated with silicate fertilizer, which agreed well with the changes in exchangeable acidity (Table 5).

3.2. Yield attributes and yield

Soil fertilization using granular and liquid silicate fertilizers alone and in combination with mineral fertilizers significantly influenced most of the measured yield attributes and yield of bread wheat (Table 6). Despite the differences among the tested sites, the responses of bread wheat to the application of granular and liquid silicate fertilizer alone or along with mineral fertilizers were consistent across environments.

The maximum grain (6617 kg ha^{-1}) and biomass (15379 kg ha^{-1}) yields of bread wheat were harvested from the application of full dose of RNP and silicate fertilizers (Table 6). Integration of silicate with mineral fertilizers yielded 284 (4 %) and 709 kg ha^{-1} (5 %) grain and biomass yield increments, respectively relative to the sole application of mineral fertilizers (Table 6). Statistically equivalent grain (6333 kg ha^{-1}) and biomass (14670 kg ha^{-1}) yields were also obtained from the sole application of full dose of RNP (Table 6). The maximum number of tiller $plant^{-1}$ (4), spikes per m^{-2} (383) and plant height (97.6 cm) were also obtained from the integrated application of full dose of RNP along with granular and liquid silicate fertilizer (Table 6). The supplement of silicate to the full dose of RNP also produced higher spike length (8.2 cm) and seed weight (42.9 mg), which were statistically similar to the values obtained from the sole application of full dose of RNP (8.2 cm and 43.2 mg, respectively) (Table 6).

Results further presented that integrated application of water-soluble silicate with three-fourth dose of RNP (69–23 kg N–P ha^{-1}) produced 5922 and 13559 kg ha^{-1} grain and biomass yields, respectively (Table 6). Similarly, the combined use of silicate with half dose of RNP (46–15 kg N–P ha^{-1}) provided 5376 and 12684 kg ha^{-1} grain and biomass yields, respectively (Table 6). The grain yields obtained from reduction of full dose of RNP to three-fourth (69–23 kg N–P ha^{-1}) and half (46–15 kg N–P ha^{-1}) were statistically lower by 695 (11 %) and 1241 (19 %) kg ha^{-1}, respectively than the full dose of RNP. The corresponding reductions for the biomass yields were 1820 (12 %) and 2695 (18 %) kg ha^{-1} (Table 6). Similarly, integrated application of silicate with half dose of RNP gave 546 (9 %) and 875 (6 %) kg ha^{-1} grain and biomass yields, respectively decline compared to the three-fourth dose of RNP (Table 6).

Table 5
Soil chemical properties as influenced by the application of silicate and its integration with mineral fertilizers.

Factors	Soil reaction	Total Nitrogen (%)	Available phosphorous [mg kg^{-1}]	Exchangeable acidity [cmol$_{(+)}$ kg^{-1}]
Location				
Site 01 [Wadji Chilalo]	5.49^{a}	0.283^{a}	15.6^{b}	1.529^{b}
Site 02 [Wadji Chilalo]	5.06^{cd}	0.279^{a}	17.4^{a}	1.744^{a}
Site 03 [Shala Chabeti]	5.22^{b}	0.244^{b}	15.6^{b}	0.632^{d}
Site 04 [Shala Chabeti]	5.13^{bc}	0.238^{bc}	14.2^{bc}	1.116^{c}
Site 05 [Haro Bilalo]	5.08^{cd}	0.224^{c}	12.9^{c}	0.685^{d}
Site 06 [Haro Bilalo]	4.99^{d}	0.199^{d}	12.9^{c}	0.357^{e}
Treatments				
No input	5.07	0.24	13.3^{b}	1.141^{a}
100 % RNP	5.13	0.25	16.3^{a}	1.097^{ab}
100 % RNP + Silicate	5.18	0.24	16.4^{a}	0.990^{bc}
75 % RNP + Silicate	5.17	0.24	15.6^{a}	0.984^{bc}
50 % RNP + Silicate	5.18	0.25	13.5^{b}	0.982^{bc}
Silicate	5.23	0.25	13.6^{b}	0.869^{c}
CV [%]	3.2	16.8	14.8	18.8
LSD [0.05]	0.11	0.0273	1.46	0.13

Note: (1) (1) CV and **LSD** stand for coefficient of variation and **least significant difference at p<0.05 level of probability**, respectively, **and** (2) means with the same letter within column are not statistically different among each other.

Table 6
Yield and yield attributes of bread wheat as influenced by the integrated application of silicate and mineral fertilizer in the southeastern highlands of Ethiopia.

Factors	Tillers plant^{-1} [No]	Spike m^{-2} [cm]	Spike length [cm]	Plant height [cm]	Seeds spike^{-1} [No]	Grain yield [kg ha^{-1}]	Biomass yield [kg ha^{-1}]	Seed weight [mg]
Location								
Site 01 [Wadji Chilalo]	4.4^{a}	372^{bc}	9.0^{a}	99.6^{a}	51^{a}	7117^{a}	15944^{a}	44.8^{a}
Site 02 [Wadji Chilalo]	3.4^{b}	310^{e}	7.7^{c}	83.5^{bc}	42^{b}	4263^{d}	10087^{d}	43.9^{b}
Site 03 [Shala Chabeti]	2.6^{c}	385^{b}	7.1^{d}	81.3^{c}	43^{b}	4064^{d}	9717^{d}	40.6^{e}
Site 04 [Shala Chabeti]	3.6^{b}	426^{a}	7.5^{cd}	90.8^{b}	49^{a}	6346^{b}	14341^{b}	42.6^{c}
Site 05 [Haro Bilalo]	2.3^{c}	329^{d}	7.4^{cd}	80.9^{c}	48^{a}	3572^{e}	8513^{e}	39.4^{f}
Site 06 [Haro Bilalo]	2.7^{c}	354^{c}	8.3^{b}	87.6^{bc}	42^{b}	5581^{c}	12692^{c}	41.6^{d}
Treatments								
No input	1.9^{c}	343^{b}	7.0^{b}	77.1^{c}	42^{cd}	3179^{d}	7154^{c}	40.1^{b}
100 % RNP	3.9^{a}	381^{a}	8.2^{a}	93.1^{ab}	51^{a}	6333^{ab}	14670^{a}	43.2^{a}
100 % RNP + silicate	4.1^{a}	383^{a}	8.2^{a}	97.6^{a}	45^{cd}	6617^{a}	15379^{a}	42.9^{a}
75 % RNP + silicate	3.7^{ab}	379^{a}	8.5^{a}	91.3^{ab}	46^{bc}	5922^{b}	13559^{b}	43.2^{a}
50 % RNP + silicate	3.4^{b}	354^{b}	8.0^{a}	89.4^{b}	50^{ab}	5376^{c}	12684^{b}	42.9^{a}
Silicate	2.1^{c}	336^{b}	7.0^{b}	75.1^{c}	41^{d}	3517^{d}	7848^{c}	40.6^{b}
CV [%]	19.4	7.9	10.9	13.4	13.5	12.3	12.7	2.5
LSD [0.05]	0.4114	19.085	0.5647	7.7493	4.1065	420.43	1005.6	0.6977

Note: (1) CV is coefficient of variation, LSD is least significant difference at $p < 0.05$ level of probability and RNP is recommended rate of nitrogen and phosphorous, which is equivalent to 92–30 kg N–P ha^{-1} and (2) means with the same letter within column indicated insignificant difference.

The unfertilized treatment produced the lowest yield attributes and yield of bread wheat (Table 6). Growing bread wheat without any sources of fertilizers produced only 3179 and 7154 kg ha^{-1} grain and biomass yields, respectively (Table 6). The sole application of granular and liquid silicate fertilizers without the addition of mineral fertilizers also produced lower yield attributes and yield, which were statistically not different from the unfertilized plot (Table 6).

3.3. Spatial differences

The response of bread wheat to integrated applications of silicate and mineral fertilizers varied significantly across the six testing sites (Table 6). The maximum grain yield (7117 kg ha^{-1}), biomass yield (15944 kg ha^{-1}), seed weight (44.8 mg), number of seeds spike^{-1} (51), plant height (99.6 cm), spike length (9 cm), spikes m^{-2} (372) and number of tillers plant^{-1} (4) were obtained from site 1 (Table 6). The lowest grain yield (3572 kg ha^{-1}), biomass yield (8513 kg ha^{-1}), seed weight (39.4 mg), plant height (80.9 cm) and number of tillers plant^{-1} (2), however, were obtained from site 5 (Table 6).

Table 7
Correlation coefficients for yield attributes and yield of bread wheat, and soil properties as influenced by integrated use of silicate and mineral fertilizers in the southeastern highlands of Ethiopia.

Variables	SPM	SPL	PH	NSPS	GY	SW	pH	AP	EA
NTPP	0.93**	0.96**	0.98**	0.73^{ns}	0.99***	0.97**	0.18^{ns}	0.85**	0.02^{ns}
SPM	1	0.91**	0.93**	0.58^{ns}	0.94**	0.86*	−0.04^{ns}	0.95**	0.22^{ns}
SPL		1.0	0.93**	0.72^{ns}	0.95**	0.98***	0.13^{ns}	0.77^{ns}	0.03^{ns}
PH			1.0	0.70^{ns}	0.98**	0.93**	0.07^{ns}	0.83*	0.12^{ns}
NSPS				1	0.72ns	0.82*	−0.07^{ns}	0.42^{ns}	0.27^{ns}
GY					1	0.96**	0.17^{ns}	0.87*	0.03^{ns}
SW						1	0.22^{ns}	0.73^{ns}	−0.03^{ns}
pH							1	0.05^{ns}	−0.97**
AP								1	0.12^{ns}

Note: (1), NTPP, SPM, SPL, PH, NSPS, GY, SW, pH, AP and EA are number of tiller plant^{-1}, spike m^{-2}, spike length, plant height, number of seeds spike^{-1}, grain yield, seed weight, soil reaction, available phosphorous and exchangeable acidity, respectively; (2) ns indicated not significant at $p < 0.05$, whereas *, ** and *** indicated significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

4. Discussion

The use of silicate fertilizers reduced soil acidity and improved soil conditions for plant growth as clearly verified by analytical results (Table 5). The mechanism underlying the significant reduction in exchangeable acidity could be due to changes in concentrations of hydrogen (H^+) and aluminum (Al^{3+}) ions. The addition of silicate induced chemical reaction; thereby, the hydroxyl (OH^{-1}) anions were released from the exchangeable sites and their concentrations increased, resulting in the reduction of exchangeable acidity (H^+ and Al^{3+}) in the studied soil solution [22]. The silicates used ameliorated soil acidity in the same way as lime by providing silicate anions (SiO_3^{-2}) and releasing of hydroxyl (OH^{-1}) anions in soil solution, and can also decrease iron, manganese and aluminum toxicity [24]. In agreement with the current results, Castro and Crusciol [22] also observed a significant decrease in H^+ and Al^{3+} concentrations down to 0.60 m soil depth after 18 months from silicate application. Ur Rahman et al. [35] also stated significant reduction of toxicity induced by soil acidity in the roots of wheat seedlings due to treatment with silicate fertilizers. Kostic et al. [44] also reported that silicon ameliorated low soil pH and high Al^{3+} comparable to the effect of liming. Thus, use of silicate can be considered as an alternative option to ameliorate soil acidity.

The use of silicate showed the tendency to increase in soil reaction (Table 5). This could likely be attributed to the decline in exchangeable acidity (Table 5), and justified by the strong but negative correlation (-0.97; $p < 0.01$) it established with exchangeable acidity (Table 7). In agreement with the current result, Frayssinet et al. [20] reported that application of liquid silicate fertilizer brought a significant increase in soil reaction from 6.21 to 6.81, which could be ascribed to basicity of the product (pH$\sim$14). Castro and Crusciol [22] and Crusciol et al. [19] also observed increase in soil pH down to 0.10 m soil layer after 3 months and 0.40 m soil layer after 18 months, respectively owing to application of calcium (Ca)/magnesium (Mg) silicate. Kostic et al. [42] demonstrated a significant increase in rhizosphere soil pH by about 2.5 and 2.0 units in KCl and water (H2O) extracts, respectively due to use of silicate. The effective raise in soil pH in response to the addition of silicate from slag was also reported by Nolla et al. [29] and White et al. [43], which could be due to its inherent high liming potential since it is a by-product containing other elements such as Ca and Mg. When summarized, the addition of silicon to the soil tended to increase soil reaction, which partly accounted to its reduced exchangeable acidity.

The addition of water-soluble silicate and its integration with mineral fertilizers significantly improved available phosphorous (av. P) contents in the soils (Table 5). The explanation for the increase in av. P content in soils resulting from the combined application of silicate and mineral fertilizers could be attributed to the (i) addition of the available nutrient from NPS fertilizer, and (ii) availability of the added nutrients, particularly P, from the NPS source, and the soil itself as a consequence of reduction in exchangeable acidity of amended soil (Table 5). The fact that availability of nutrients from the soil can be justified by a 3 % increase in av. P content of soil amended with sole-silicate compared to untreated soil (Table 5). The mechanism behind the increase in av. P in amended soil was due to desorption of P from the exchangeable site as silicon anions (H_3SiO^{4-}) replaces it, which compete for the same sorption sites of soil colloids with phosphate anions (H_2PO^{4-}). Consequently, the P sites are saturated by the silicate anions, phosphate ions are released to soil solution and improved its availability [44]. Corroborating the current results, Kostic et al. [42] demonstrated a 40 % increase in rhizosphere water-soluble P compared to the treatment with no silicate. Castro and Crusciol [22] also observed increased av. P levels down to 0.20 m after 6th and persisted until 18th months due to application of silicate fertilizer. Stephano et al. [34] indicated that application of 45 kg Si ha^{-1} along with 240–100–100 kg N–P_2O_5–K_2O ha^{-1} increased the total plant P uptake, P recovery efficiency, agronomic efficiency of P, and partial factor productivity by 15.3 %, 16.7 %, 34.7 %, and 4.8 %, respectively compared to untreated treatments. Thus, the role of silicate in improving availability of P in soil is indispensable as observed in the results of the current study.

Combined application of full dose of RNP and silicate fertilizers provided maximum grain and biomass yields of bread wheat (Table 6). The enhanced yield attributes and yield of bread wheat with co-application of water soluble silicate and mineral fertilizers could be attributed to (i) direct addition of nutrients from mineral (NPS and urea) and silicate fertilizers, (ii) direct addition of av. P through desorption from exchangeable sites by silicate anions, and (iii) indirect benefit from reduction in exchangeable acidity and its concomitant increase in soil pH and av. P in soil solution, and their contribution towards improved P utilization by wheat. Agreeing with the current results, White et al. [43] also observed significantly higher grain yield of wheat ($\sim$7 t ha^{-1}) with silicate slag and N at rates of 9 t ha^{-1} and 145 kg ha^{-1}, respectively. These results demonstrated that integrating silicate with mineral fertilizers at full dose had synergetic effect towards increasing wheat yield.

Sole-application of silicate and its integration with reduced rates of RNP from mineral sources provided statistically lower yield of bread wheat. On the hand, the lowest yield attributes and yield of bread wheat were harvested from the unfertilized treatment (Table 6). This indicated that the soils of the study area are highly deprived of nutrients and yield of bread wheat could not be optimized without addition of external inputs. The relatively higher yield with Si nutrition compared to the untreated plots could be associated with the beneficial role Si played in ameliorating soil acidity and maintaining physiological and biochemical processes when the crop underwent through NP deficiency [45]. Silicon may affect photosynthesis and sugar metabolism; thus, enhancing growth-related responses of plants grown under deficient conditions of nutrients [45]. Overall, these results demonstrated that silicate fertilizer both in granular and liquid forms can be supplements, but not substitutes to nitrogen, phosphorus and sulfur nutrients.

The enhanced yield of bread wheat owing to sole application of full dose of RNP from mineral sources and their integration with granular and liquid silicate fertilizer was the function of improved yield components (Table 7). All correlations were found significant indicating the vital contributions of yield attributes for boosting bread wheat yield. In line with the current results, White et al. [43] reported that the improved yield of wheat resulting from co-application of Si and N were ascribed to the increase in number of spike

m^{-2} and grain number $spike^{-1}$. Sattar et al. [46] also observed that foliar application of Si enhanced plant height, number of grains $spike^{-1}$ and 1000-grains weight of wheat by 9 %, 20 % and 14 %, respectively under terminal drought stress as compared to control treatment. Similarly, Ali et al. [30] reported significant improvement of spikes of wheat by 34–87 % in foliar spray and 25–69 % in soil applied Si nanoparticles relative to the control. Thus, it can be summarized that the enhanced yield of bread wheat in response to co-application of silicate and mineral fertilizers was attained due to improved yield attributes.

Spatial variations and initial statuses of soils significantly impacted the entire parameters measured for soil (Table 5) and bread wheat (Table 6). The six testing sites situated in different geographical locations (Table 1). The soil also varied in their chemical properties (Table 4), which could primarily be accounted to a number of factors including but not limited to farmers' practices, previous cropping history and weather differences. The maximum yield attributes and yield of bread wheat from site 1 could partially be ascribed to its situation at higher altitudes compared to other five sites (Table 1). That location had relatively longer growing season, which could enable the crop to extract nutrients from the soil for relatively extended period and to gradually fill its grains. In agreement with current results, the positive correlation of longer growing period with enhanced grain yield of wheat for most of the locations in North America and Eurasia was reported by Morgounov et al. [47]. It could also be attributed to the relatively higher soil reaction (5.49) and av. P (15.6 mg kg^{-1}) contents of the soil (Table 5). The lowest yield attributes and yield of bread wheat from site 5 (Table 6) could be linked to its location at relatively lower elevations compared to other five sites (Table 1). The site had relatively shorter growing period to extract nutrients and fill the grain compared to others. It could also be due to the relatively lower contents of av. P (12.9 mg kg^{-1}) and lower soil reaction (5.08) (Table 5). Thus, the current results demonstrated that spatial variations and initial statuses of soils determined yield of bread wheat.

5. Conclusions

Soil properties, yield attributes and yield of bread wheat varied significantly among silicate and mineral fertilizers treatments. Our results showed that combined use of water-soluble silicate with full dose of recommended nitrogen (92 kg N ha^{-1}) and phosphorous (30 kg P ha^{-1}) significantly reduced exchangeable acidity, tended to increase soil reaction, increased available soil phosphorous content of the soil and boosted yield of bread wheat compared to their sole applications. On the other hand, applications of sole-silicate and its integration with reduced rates of nitrogen and phosphorous from mineral sources resulted in statistically lower yield attributes and yield of bread wheat, and soil chemical parameters except for soil acidity indicating that it can be a supplement, but not a substitute for essential nutrients. Reliant on the findings of this study, it can be suggested that integration of granular and liquid silicate at the rate of (40 kg + 18 L) ha^{-1} with full dose of recommended nitrogen (92 kg ha^{-1}) and phosphorus (30 kg ha^{-1}) can be considered as a possible alternative for acidic soils amendment, and enhancing plant nutrition; thereby, boosting the yield of bread wheat in the highlands of tropical environment.

Funding

This study was funded by EKOS STEEL MILL PLC, Korean.

CRediT authorship contribution statement

Gobena Negasa: Data curation, Investigation, Supervision, Writing - original draft, Writing - review & editing. **Kassu Tadesse:** Data curation, Formal analysis, Investigation, Software, Supervision, Writing - original draft, Writing - review & editing. **Dugasa Gerenfes:** Supervision. **Dawit Habte:** Writing - review & editing. **Anbessie Debebe:** Supervision. **Mengistu Chemeda:** Supervision. **Getnet Adugna:** Conceptualization, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge Kulumsa Agricultural Research Center (KARC) for the provision of logistics required for the conduct of this study. The authors would also like to acknowledge all staffs in the Natural Resources Management Research division of KARC for their technical expertise and support during the research period.

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