Yield Response and Nutrient use Efficiencies of Maize (*Zea mays* L.) As Determined through Nutrient Omission trial in Jimma Zone, Southwestern Ethiopia

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Abstract: *Appropriate fertilization based on actual limiting nutrients and crop requirements is economic and judicious for sustainable crop production. A field experiment was conducted to identify yield-limiting nutrients, to determine yield response, nutrient uptake and use efficiencies of maize (Zea mays L.) through nutrient omission technique in the Nitisols of Omo Nada District Southwestern Ethiopia for one cropping season (2019/20). The experiment was laid out in Randomized Complete Block Design with four replications. The treatments were control, NP, PKS (-N), NKS (-P), NPS (-K), NPK (-S), NPKS, NPKSZn (-B), NPKSB (-Zn) and NPKSZnB. One composite soil sample was collected from an experimental plot at a depth of 0-20cm before treatment application and analyzed to estimate the inherent N, P, K, S, Zn and B supplying capacity of the soil. Grain and straw samples were collected to determine N, P, K, S, Zn and B contents. Maize yield and yield components, nutrient uptake and agronomic efficiencies of maize were subjected to ANOVA using SAS 9.3 software. The LSD test was used to separate means at a 5% level of significance. The results of soil showed moderately acidic, sandy clay loam texture, low total N, available P and medium in K, S, Zn, B, OC, OM and CEC. Grain yield and yield components, nutrient uptake and agronomic efficiency of each nutrient were significantly affected due to nutrient omitting. Accordingly, the highest grain yield response of maize (5909.1kg ha^{-1}) was obtained from N fertilized plots indicating N was the most yield-limiting nutrient. Owing to the magnificent yield response to N fertilizer in the current study, proper management of N is very essential for the intensification of maize productivity. The maximum total nutrient uptake of N (87.38), P (40.40), K (114.95), S (22.22), Zn (2.67), B (0.28) and agronomic efficiencies of N (55.6), P (166.9), K (166.9), S (333.7), and Zn (1359.8) was obtained from integrated use of macronutrients (NPKS) with Zn.*

Keywords: Agronomic efficiency, Nutrient combination, Nutrient recovery, Nutrient uptake

1. Introduction

Soil nutrient depletion and inadequacy of current fertilizer recommendations due to ignoring soil fertility status and excluding major nutrients other than nitrogen (N) and phosphorus (P) from the recommended dose continuously decreased soil quality and crop production. In most areas, nutrients available in soil are rarely present in adequate amounts and are most probably of unbalanced proportion to meet the nutrient requirements of crops. To increase productivity and subsequently improve food security in Ethiopia, it is imperative to identify soil nutrients limiting maize growth and production. The national soil inventory data (EthioSIS, 2013) also revealed that in addition to N and P, sulfur (S), boron (B) and zinc (Zn) deficiencies are widespread in Ethiopian soils in general and in Southwestern parts of Ethiopia in particular. Therefore, future gains in food grain production will be more difficult and expensive considering the increasing problem of multi-nutrient deficiencies unless immediate action is taken.

Maize (*Zea mays* L.) is one of the most important staple food crop in Ethiopia and its production and consumption have grown widely across regions. However, current average yield is 3944 kgha^{-1} (CSA, 2017), which is much lower than its yield potential. The deficiency of essential elements has been implicated to limit the uptake of the nutrients, growth and yields of crops. In Ethiopia, regional fertilizer recommendations have been developed for maize which is slightly region-specific excluding the nutrient status of the soil Wakene *et al.* (2011). Yet cropping systems, management practices, soil type, fertility status, climatic conditions and other factors governing yield response to nutrients vary considerably in space and time Kiara *et al.* (2016). Due to such localized differences in crop growing conditions and the soils' indigenous nutrient supply capacity, grain yield and nutrient use efficiencies vary across maize producing regions of the country Tesfaye *et al.* (2019).

Recognition of this variability has prompted many researchers to consider managing this variability. Research that aims to improve soil fertility management and productivity of small-scale farmers has to reckon with soil variation by identifying the most limiting nutrient elements and coming up with flexible recommendations rather than blanket recommendations. Flexible recommendations could be based on variations in soil characteristics that affect productivity and yield responses. Thus, the nutrient omission technique (all the other nutrients are supplied other than the nutrient in question) is a useful tool to quantify soil nutrient supply capacity and to identify yield-limiting nutrients in a given area. Therefore, this experiment was conducted (i) to identify the most yields limiting nutrient for maize (ii) to determine the yield response of maize through the nutrient combination (iii) to determine maize nutrient uptake and agronomic efficiencies of N, P, K, S and Zn in Omo Nada District, Jimma Zone.

2. Materials and Methods

2.1. Description of the study areas

The experiment was conducted on farmers' fields in Nitisols of Goroseden Kebele, Omo Nada District South-western Ethiopia during the main cropping season (2019/20). The experimental site was selected systematically to cover a wide range of major maize growing areas in the district. Geographically, the experimental site was located between 070 40' 09 3" N latitude, 0370 14' 41.5" E longitudes and an altitude of 1750 meters above sea level. According to the data from Jimma Meteorological Station (2019), the average minimum and maximum temperature and mean annual rainfall of the experimental sites were 12.64 °C, 28.36 °C and 1198 mm, respectively. The predominant soil type of the study area, in particular, is Nitisols which have a reddish colour with moderately acidic in reaction. On average, the soil is deep and highly weathered well-drained, sandy clay in texture and strong to moderately acidic in a reaction as reported by Wispelaere *et al*. (2015).

2.2. Soil sampling and laboratory analysis procedures

One representative composite soil sample (0-20cm depth) was collected using an auger before treatment application. The collected sample was analyzed for soil pH, organic carbon (OC), total nitrogen (TN), available phosphorus (Av. P), available potassium (K), available sulfur (S), cation exchange capacity (CEC), and micronutrients (B and Zn) at Jimma Soil and Tissue Analysis Laboratory based on procedures described in Van Reeuwijk (2006). The pH-H_2O was measured at 1:2.5 soils to solution suspension using a pH meter. The Walkley and Black method functioned to determine the OC content while the Kjeldahl method was employed to determine total nitrogen Bremner and Mulvaney (1982). Available P was determined using the Bray II method by Bray and Kurtz (1945). Available S, B, and Zn and exchangeable K of the soil were extracted by the Mehlich-III multi-nutrient extraction method Mehlich (1984) and measured with their respective wavelength range by Inductively Coupled Plasma Optical Emission Spectrometer.

2.3. Treatments and experimental design

Ten treatments of different rates of six single nutrients (N_{120}, P_{40}, K_{40}, S_{20}, Zn_5 and $B_{2.5}$ kg ha^{-1}) were used in the present study. Each fertilizer rate was set based on the recommendation given by Tesfaye *et al. (*2019) and the rate of each nutrient indicated in Table 2. Even though farmers are not growing maize without fertilizer, control treatment was included for comparison among the rest of the treatments. The treatments were laid out in a randomized complete block design in four replications. The gross plot area was 18 m^2 (6 m x 3 m), which accommodated 8 rows and 10 plants per row while the net plot area was 10.8 m^2 (4.5 m x 2.4 m).

Table 1: Soil Physicochemical properties of experimental site before treatment application

Soil Properties	Value	Rating	Reference
pH (1:2.5 H_2O)	5.40	Moderately acidic	Tekalign, 1991
Soil BD (g cm^{-3})	1.23	Optimum	Hunt and Gilkes,1992
CEC (cmol(+)Kg^{-1})	16.06	Medium	Hazelton and Murphy, 2007
Total N (%)	0.18	Medium	Tekalign, 1991
Available P (mg kg^{-1})	8.18	Low	FAO, 2008
Available K (mg kg^{-1})	249.62	High	Horneck *et al.* (2011)
Available S (mg kg^{-1})	6.10	Medium	Horneck *et al.* (2011)
B (mg kg^{-1})	0.61	Medium	Horneck *et al.* (2011)
Zn (mg kg^{-1})	1.47	Marginal	Jones, 2003
OC (%)	2.83	Medium	Tekalign, 1991
OM (%)	4.88	Medium	Tekalign, 1991
Sand (%) Silt (%) Clay (%)	60 5 35	Soil Textural Class: Sandy clay loam, which is ideal	Onwueme and Sinha, 1991

Table 2: Treatments used in the present study

Treatments	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	S (kg ha^{-1})	Zn (kg ha^{-1})	B (kg ha^{-1})
T_1 = Control	0	0	0	0	0	0
T_2 = NP	120	40	0	0	0	0
T_3 = PKS (-N)	0	40	40	20	0	0
T_4 = NKS (-P)	120	0	40	20	0	0
T_5 = NPS (-K)	120	40	0	20	0	0
T_6 = NPK (-S)	120	40	40	0	0	0
T_7 = NPKS	120	40	40	20	0	0
T_8 = NPKSZn (-B)	120	40	40	17.6	5	0
T_9 = NPKSB (-Zn)	120	40	40	20	0	2.5
T_{10} = NPKSZnB	120	40	40	17.6	5	2.5

2.4. Experimental materials and planting procedures

High yielding (BH-661) maize variety was used as a test crop in the study, which was released from Bako Agricultural Research Center. The variety is popularly accepted and grown by farmers. The full doses of all fertilizers in the respective treatments except the nutrient to be omitted were applied at planting. Urea was applied in splits where the half rate at planting and the remaining half rate was applied (3-4 weeks after planting) when the plant attains at knee height stage. Urea, Triple Super Phosphate (TSP), Murata of Potash (KCl), Calcium Sulfate ($CaSO_4.2H_2O$), Zinc Sulfate ($ZnSO_4.7H_2O$) and Borax ($Na_2B_4O_7.5H_2O$) were used as sources of N, P, K, S, Zn and B, respectively. All cultural practices were done uniformly for all treatments, as per the recommendation for maize production in the area. Harvesting was done manually from the net plot area when the crop physiologically matured.

2.5. Data collection

2.5.1. *Maize yield and yield components*

Data on a plant basis was recorded from the six central harvestable rows (3.75mx2.4m=9m^2). The collected data include leaf area index (LAI), grain yield, ear length, number of kernel rows cob^{-1}, number of kernels cob^{-1} and biomass yield. The LAI was calculated as the ratio of the total leaf area of ten plants (cm^2) per area of land occupied by these plants. Cob length was measured from ten randomly selected cobs per plot at harvesting and the average value was recorded for each plot. The number of kernel rows cob^{-1} was counted from ten randomly selected ears and the average value was recorded for each plot. The number of kernels cob^{-1} was determined by counting the number of kernels cob^{-1} from ten randomly taken cobs and the average value was registered. Grain yield (economic yield) was determined from the entire net plot and converted into kilogram per hectare where the actual grain yield was adjusted to 12.5% moisture level, which is the standard moisture content of cereal crops. Above-ground biomass (Biological yield) was measured from the weight of above-ground biomass for plants in a net plot area and converted to kilogram per hectare. Harvest Index (%) was determined as a ratio of grain yield to above-ground biological yield on a dry weight basis in percentage Singh and Stoskopf (1971) as described in the following formula.

$$HI = \left(\frac{Grain\ yield}{Above\ ground\ biomass}\right) * 100 \quad [1]$$

2.5.2. *Determination of agronomic efficiency*

Agronomic efficiency (AE) refers to the additional produce obtained in kg kg^{-1} of an applied nutrient which was calculated using the formula of Fageria *et al.* (2010) as follows:

$$AE = \frac{Grain\ yield\ (fertilized\ plot) - Grain\ yield\ (no\ fertilizer)}{Fertilizer\ applied\ kg/ha} \quad [2]$$

2.5.3. *Apparent nutrient recovery efficiency*

The apparent nutrient recovery efficiency of nutrients was determined as the quantity of nutrient uptake per unit of nutrient applied then finally changed to a percentage using the formula indicated below [3]. Grain and straw samples were collected randomly from the net plot area during harvesting from each plot and bulked over replication to determine N, P, K, S, and Zn contents.

$$ARE\ (\%) = \frac{(Nf - Nu)}{Na} x100 \quad [3]$$

Where

ARE = Apparent nutrient recovery efficiency

Nf = total nutrient uptake (grain plus straw) of the fertilized plot (kg ha^{-1})

Nu = total nutrient uptake (grain plus straw) of the unfertilized plot (kg^{-1})

Na = quantity of nutrient applied (kg ha^{-1})

2.6. Data Analysis

The collected data were subjected to analysis of variance (ANOVA) appropriate to RCBD using SAS Institute (2012) 9.3 version software and the interpretations were made following the procedure described by Gomez and Gomez (1984). The least significant difference (LSD) test at a 5% probability level was used for treatment mean comparison when the ANOVA showed significant differences among treatments.

3. Results and Discussion

3.1. Grain yield response of maize to different nutrients

3.1.1. *Nitrogen*

Compared with tested nutrients highest grain yield response was obtained from the application of 120 kg ha^{-1}N indicating N is the most yield-limiting essential plant nutrient for maize production hence it needs special attention. This condition happened whenever the soil contains appropriate moisture because soil moisture is the solvent and medium of nutrient transport to the absorbing root zoon and plays a key role in influencing crop response to fertilizer application. This might be attributed due to the availability of N forms in the soil solution owing to sufficient soil moisture. When the soil contains optimum moisture there is high water flux both of which increase the mass flow of N ions to the root surface enhancing N uptake since mass flow rate is a function of both water flux in the root rhizosphere and nutrient concentration in the soil solution. The current result was in agreement with the findings of Tesfaye *et al.* (2019), who reported that the maximum yield response was recorded from plots treated with 120 kg ha^{-1} nitrogen.

3.1.2. *Phosphorous*

Yield response to P was significantly higher at a rate of 40 kg ha^{-1} however, not as high as the yield response to N application and such a lesser yield response to P application can be attributed due to the P fixing nature of the weathered Nitisols and calcareous soils of the high rainfall areas. In areas having appropriate moisture conditions, a higher fractAion of available P goes to the soil solution and is hence transported to the root surface via diffusion since the rate of diffusion depends on both water availability in the root rhizosphere and the concentration of the nutrient ions in the soil solution. The current result was in line with the finding of Tesfaye *et al.* (2019) who reported that the maximum yield response was obtained from plots treated with 40 kg ha^{-1} P.

3.1.3. *Potassium*

Concerning K, 1470.8 kg ha^{-1}maize grain yield response was recorded when supplying 40kg ha^{-1}K even though the response was not as higher as compared to NP. The result showed that to increase the production of cereal crops including maize, increasing the appropriate use of all essential nutrients containing K is an option. Since plant growth and crop production require an adequate supply and balanced amounts of all nutrients to maximize productivity by optimizing the plant nutrient uptake, adding K fertilizer can increase fertilizer use efficiency and grain yield for different cereal crops. Therefore, improving the nutrient content of the fertilizer that fits the needs of the crops is required to improve the productivity of maize due to the presence of synergetic interaction of K with macronutrients (N and P) and micronutrients (Zn) but it has antagonistic interaction with B which was in confirmed with the finding of Malakouti (2008).

3.1.4. *Sulfur*

The remarkable grain yield response to the application of S cannot attribute compared to other major macronutrients. This might be due to the presence of magnesium and calcium that hides the effects of sulfur as supported by Sumner (1981). However, the result of pre-planting soil samples showed that soil S content as medium critical soil sulfur level of 6.10 mg kg^{-1}, which may confirm that the grain yield response is less likely due to S application compared to other major macronutrients.

3.1.5. *Micronutrients (Zn, B)*

The grain yield response due to micronutrients especially (Zn) was observed even if it is not as remarkable as compared with macronutrients. However, the application of B does not give a yield response, which might be the presence of an optimum level of B in the soil. Thus, the grain yield response could be due to Zn application since the Zn content of all fields was below the critical level (1.5 mg kg^{-1}) soil as suggested by Horneck *et al*. (2011) for maize. However, there is need for a further study to understand the impact of each of the secondary macronutrients and micronutrients on maize production.

3.2. Effects of nutrient omitting on yield and yield components of maize

3.2.1. *Growth parameters*

Leaf area index values ranged from 2.3 to 4.6, recording the lowest value from control while the maximum from the application of (NPKSZn). The reason for an increase in LAI might be due to the development of more expanded leaves produced in response to the balanced application of nutrients that enhanced vegetative growth. This showed that the balanced application of mineral nutrients on maize increased leaf size (to maximize light interception) and maximize the overall plant economy of the crop. Fertilization of balanced nutrients to crops up to optimum level helps efficient utilization of nutrients that leads to high photosynthetic productivity and accumulation of high dry matter. This ultimately increases plant growth and development, which may result in improved yield attributes like leaf length and leaf size, thereby increasing production as supported by (Mikos-Szymańska, 2018). The result was in line with the finding of Kumar *et al.* (2005).

The ANOVA result showed that fertilizer treatments had a highly significant effect ($P < 0.01$) on the number of rows cob^{-1}. The highest number of rows cob^{-1} (14.0) was recorded from the application of NPKSZn while, the lowest (12.9) was obtained from the control, N and P-omitted plots (Table 3). Application of major macronutrients (NPKS) in combination with micronutrients (Zn) increased the number of rows cob^{-1} by 8.5% compared to control, N and P-omitted plots. In agreement with this result, Adediran and Kogbe (2003) reported that maize production depends mainly on the availability of essential nutrients. On the other hand, there was no significant difference observed between numbers of rows cob^{-1} due to the application of B indicating B did not bring a significant difference, which might due to the presence of a medium quantity of B in the soil of study sites.

The maximum cob length (20.0cm) was obtained from the application of NPKSZn, which is statistically at par with plots treated with NPK (19.3cm), and NPKS (19.98cm), NPKSB (19.6cm) and NPKSZnB (19.6cm). The minimum cob length (12.5cm and 12.8cm) was obtained from control and N-omitted plots respectively. The highest ear length development might be due to an increase in photosynthetic activities on the account of an adequate supply of N and P. The current result was in agreement with the finding of Ahmad *et al.* (2018) who reported that a significant increase in cob length with increased rates of N and P. Nitrogen is required for ear growth if the soil is nourished through mineral fertilizer which had an impact on yield. To do so the maximum assimilates supply should be available during maize grain filling with a split application of N Arif *et al.* (2010). Moreover, when the environmental condition allows for optimum utilization of solar radiation, there is higher assimilation production and its conversion to starches results in higher cob length as reported by Derby *et al.* (2004).

The highest number of grains of cob-1 (589.8) was recorded from the application of NPKSZn, while the lowest number (355.5) was obtained from the control (Table 3). Application of NPKSZn increased the number of grains per row by65.9%, 58.8% and 16.8%, over control, N-omitted and NP, respectively. This might be due to an increase in the number of grains row^{-1}, ear length and a number of rows cob^{-1} with higher and balanced fertilization. The optimum availability of synthetic fertilizers, which might boost growth indices and consequently increase ear length as reported by Chapagain and Gurung (2010) which produced more grains cob^{-1}. The current result confirmed the findings of Redai *et al.* (2018) who reported that the maximum grain was recorded from the application of macronutrients (NPK) in combination with Zn.

The highest ear diameter (4.7cm) was recorded from the application of NPKS, which was statistically at par with NPK, NPKSZn and NPKSZnB treated plots (Table 3). On the other hand, the lowest cob diameter (4.1cm) was recorded from the control. The availability of essential nutrients from NPKS leads to improved cell activities, enhanced cell multiplication, enlargement and luxuriant growth. The result was in agreement with the finding of Baharvand *et al.* (2014) who reported that the ear diameter of maize increased due to the increasing rate of chemical fertilizers.

The highest HI (47.2%) was recorded from the application of NPKSZnB which was statistically at par with the value obtained from the application of NPKSB (47%). The lowest HIs (37.3% and 39.7%) were recorded from the control and N-omitted plots. The current result was in the acceptable range of HI (40 to 60%) for maize Hay (1995). Thus, an adequate supply of balanced nutrients including micronutrients is important in optimizing the partitioning of dry matter between grain and other parts of a maize plant. Optimum utilization of solar radiation, higher assimilation production and its conversion to starch results in higher biomass and grain yield leading to a higher harvest index. This finding was supported by Obsa *et al.* (2021) who reported that the highest HI (47.36%) was obtained from the application of NPK + CaMgSZnB while the lowest HIs (33% and 34%) were recorded from the control and N-omitted plots from the same soil type.

Table 3: Effect of nutrient omission on number of rows and grains, ear length, and ear diameter of maize

Treatments	LAI	Rows cob^{-1}	Ear Length (cm)	Grain cob^{-1}	Ear Diameter (cm)	HI (%)
Control	2.28^{f}	12.90^{b}	12.50^{d}	355.50^{d}	4.10^{c}	37.30^{c}
NP	3.83^{cd}	13.50^{ab}	16.80^{c}	505.00^{c}	4.30^{bc}	42.10^{b}
PKS (-N)	2.70^{e}	12.90^{b}	12.80^{d}	371.50^{d}	4.10^{c}	39.70^{bc}
NKS (-P)	3.73^{d}	12.90^{b}	17.90^{b}	502.90^{c}	4.50^{ab}	43.30^{ab}
NPS (-K)	4.13^{bc}	13.40^{ab}	18.00^{b}	515.10^{c}	4.40^{ab}	43.70^{ab}
NPK (-S)	4.48^{ab}	13.40^{ab}	19.30^{a}	567.50^{ab}	4.60^{a}	43.30^{ab}
NPKS	4.38^{ab}	13.70^{ab}	19.98^{a}	576.70^{ab}	4.70^{a}	44.00^{ab}
NPKSZn (-B)	4.63^{a}	14.00^{a}	20.00^{a}	589.80^{a}	4.70^{a}	43.90^{ab}
NPKSB (-Zn)	4.35^{ab}	13.60^{ab}	19.60^{a}	567.20^{ab}	4.50^{ab}	47.10^{a}
NPKSZnB	4.35^{ab}	13.40^{ab}	19.70^{a}	565.80^{b}	4.60^{a}	47.20^{a}
Mean	3.89	13.37	17.66	511.70	4.45	43.16
LSD (0.05)	0.38	0.90	0.90	23.60	0.30	4.56
CV (%)	6.82	4.46	3.68	3.18	4.14	7.28

Means followed by a common superscript letter within a column are not significantly different from each other at $P<0.05$

3.2.2. *Grain Yield*

It is evident from the result that the grain yield of maize ranged from 2028.5 to 8702.6 kg ha^{-1}, recording the lowest yield from the control and N-omitted treatment while the highest yield from the application of (NPKSZn) nutrients up to optimum level (Figure 2). There were 329.0% and 29.8% grain yield advantages obtained due to the application of NPKSZn compared to control and existing NP recommendations. Application of NPKSZn produced grain yield advantage 350 kg ha^{-1} compared to the application of NPKS, which is obvious associated with the application of 5 kg ha^{-1} Zn. Thus, one can conclude that adding micronutrients such as Zn results a significant grain yield difference whereas adding up B on NPKS have no significant grain yield advantages. This might probably be due to the optimum content of boron on the initial soil of the experimental site.

Treatments omitting N, P, K, S or Zn resulted in a marked yield loss compared to the full application of NPKSZn, indicating the significance of replenishment of these nutrients for achieving a high yield target. Compared to the NPKSZn, which recorded the highest yield, yield reductions were 5910, 2540, 1470, 1200 and 500 kg ha^{-1} in the omission of N, P, K, S, and Zn plots, respectively. Although treatments receiving the existing recommended NP dose of fertilizer had higher grain yield over control, it showed 2000 $kgha^{-1}$ yield reduction compared to the NPKSZn treatment. The lowest yield from the control plot indicates that the indigenous soil is unable to supply a sufficient amount of nutrients while the lower yield of N - omitted plots indicates that application cannot be substituted by any other nutrient and has the highest contribution to maize yield. This confirms that N is the most limiting nutrient for maize production. It could be due to the effect of N on chlorophyll formation, photosynthesis and assimilated production because N stress reduces crop photosynthesis by reducing leaf area development and leaf photosynthesis rate by accelerating leaf senescence thereby reducing the final yield Diallo *et al.* (1997). Unlike the current study, Tesfaye *et al.* (2019), however, did not observe any significant positive effect of micronutrients on maize grain yield from the same district and this could probably be due to the soil application, especially of higher boron doses.

The second most yield-limiting nutrient following N was P. Phosphorus omitted treatments gave numerically lower yield compared to other treatments except control and N-omitted plots, meaning that P deficiency also limits maize yield. Its deficiency is a common crop growth and yield-limiting factor in unfertilized soils and affects leaf growth dynamics in maize (Ibrikci *et al.*, 2005; Rehman *et al.*, 2011). The present result revealed that P-omitted plots showed reduced maize growth characters compared to NPKSZn treated plots and 2540$kgha^{-1}$ yield reduction was recorded indicating that the soil might be unable to supply sufficient amount of P that is required for proper growth and development of plants.

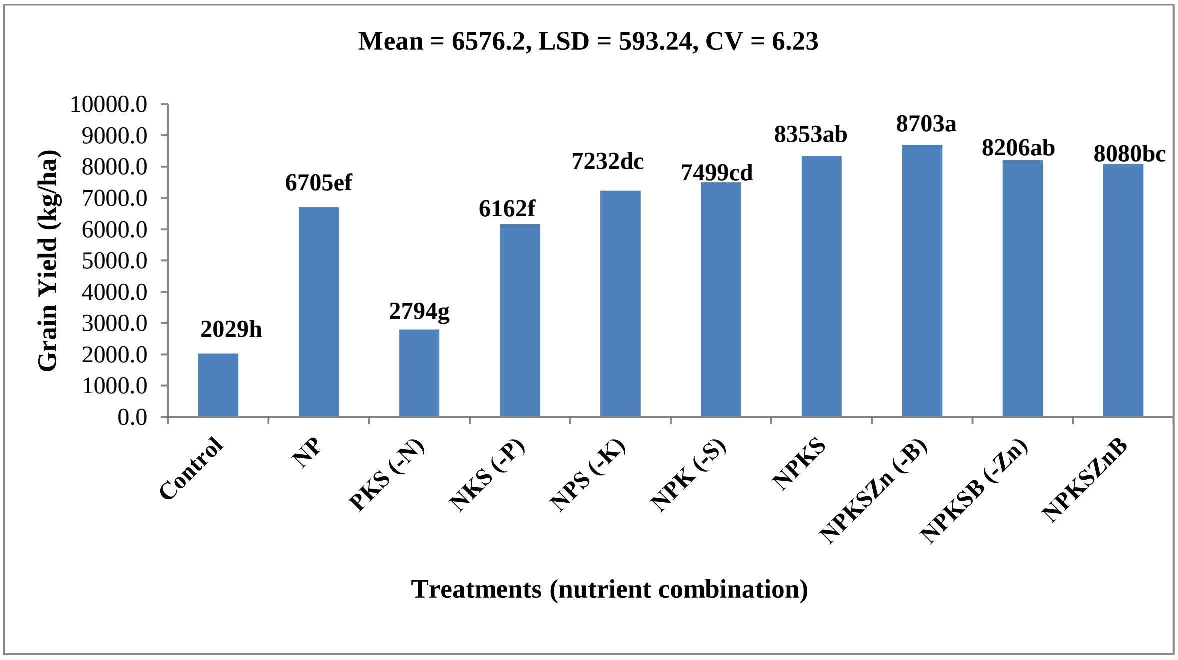

Figure 2: Effect of nutrient combination on maize grain yield at Jimma area
Note: Different small letters denote significant differences between treatments at $P<0.05$

3.3. Total nutrient uptake

The highest total N uptake (87.38 kg ha^{-1}) was recorded from the application of NPKSZn, which was statistically at par with the application of NPKSB (83.29). Due to the application of NPKSZn, 659.83% and 374.12% of total N uptake increments were recorded compared to unfertilized and N-omitted plots. The increment in total uptake might be due to the efficient use of N from fertilizer applied. Total uptake of N supplied from fertilizer can increase by increasing yield and efficient use of N Haney *et al.* (2015). A higher amount of N uptake or accumulation in grain is important because crop yield is directly associated with N accumulated in grain. Higher N uptake in straw is also desirable because if straw has a higher N concentration, during crop growth N is translocate to grain when plant demand increases, thereby improving yield. A similar finding was also obtained by (Lopez-Bellido *et al.* 2003; Dagne 2016) for Nitisols of Western Ethiopia who reported that the application of macronutrients in combination with micronutrients produced the highest N concentration and uptake.

The maximum total P-uptake (40.40 $kgha^{-1}$) was obtained from the application of NPKSZn, while the lowest (8.07 $kgha^{-1}$) was recorded from the control. Application of NPKSZn improved total p uptake by 400.62% and 59.32% compared to control and P-omitted plots, respectively. These results showed that there was a positive effect of P on maize grain and straw yields and the improvement of grain and straw P contents by application of balanced fertilizers including P containing sources. Moreover, the highest nutrient uptake recorded might be due to the positive interaction of P with other nutrients, because the existence of synergetic nutrient interactions is an important factor in improving the yield of field crops where the presence of one element facilitates the uptake of other Wilkinson (2000). Phosphorus has a positive significant interaction with N, K and S. This positive interaction gives rise to improvement in growth and yield of crop plants with P fertilization. Phosphorus also has synergistic interaction with micronutrients. Among micronutrients, P-Zn interaction is widely reported by Wilkinson (2000) where, Zn deficiency in this situation is associated with the rapid growth of plants, and soil-available Zn cannot fulfill the demands of rapidly growing plants, which makes Zn deficiency, induced P toxicity.

Total nutrient uptake of K ranges from 20.43 to 114.95$kgha^{-1}$ recording the lowest uptake from unfertilized plots, while the highest K uptake is from plots treated with NPKSZn. The highest nutrient uptake is based on the concept that the concentration of an essential nutrient in a plant or part of a plant indicates the soil's ability to supply that nutrient and the positive interaction that exists among the nutrients applied Hillel (2005). Maximum total K uptake enhanced under NPKSZn fertilization is an indication of synergetic interaction of K with macronutrients (N and P) and micronutrients (Zn) but it has antagonistic interaction with boron. Kalpana and Krishnarajan (2002) noticed that the application of increasing levels of K up to 50 kg ha^{-1} significantly increased N and K uptake in baby corn. This illustrated that NPKSZn fertilization was better for improving N, P and K accumulation. The lower K uptake and concentrations from the control and K - omitted plots might therefore be due to low K availability in the experimental soil, as was confirmed by soil analysis results before planting.

Concerning S, the maximum total S uptake (22.22 kg ha^{-1}) was obtained from the application of NPKSZn, while the minimum (4.74 $kgha^{-1}$) was obtained from the control. This evidence indicates that the application of macronutrients (NPKS) including Zn improves S uptake by 368.78% and 299.79% advantages compared with control and S omitted plots respectively. An increase in the availability of S in soil and its absorption by the crop due to NPKSZn might be the release of more soil S from the absorption site because of ion exchange synergistically as reported by Gowda *et al.* (2001). Moreover, maximum S uptake in grain and straw was higher at a high N rate compared to the low rate of N, indicating improvement in S use efficiency with the integrated application of N. The efficiency of nutrient absorption is often determined by the ability of the plants to absorb a certain element at a low level of soil stocks or the nutrient medium Dawson *et al.* (2008).

The maximum total Zn uptake (2.67$kgha^{-1}$) was obtained from the application of NPKSZn which was statistically at par with treated NPKS (2.47), while the minimum total Zn uptake (0.67kg ha^{-1}) was obtained from control. The current result was confirmed by the finding of (Jain and Dahama, 2005) who noticed that N, P, K, S and Zn contents and uptake in maize were significantly higher at

9kgha^{-1}. Azab (2015) also proved that combined application of Zn and NPK fertilizer significantly improved N, P, K and Zn content and uptake as compared to plots fertilized only NPK.

Boron uptake in grain ranged from 0.04 to 0.28kg ha^{-1}, recording the lowest value from unfertilized crops and N - omitted plots while the highest value from the application of NPKS, NPKSZn and NPKSZnB. Comparing the average B uptake values from the application of NPKS, NPKSZn and NPKSZnB no significant difference was observed, but there is a slight numerical B uptake difference between treatments. From this, it can be concluded that adding up B has a small but non-significant difference observed, which might be an overdose of this nutrient and antagonistic interactions among the applied elements.

Table 4: Total nutrient uptake of maize as affected by nutrient combinations

Treatments	Total nutrient uptake (kgha^{-1} nutrient applied)				
	N	P	K	S	Zn
Control	11.50^{g}	8.07^{e}	20.43^{e}	4.74^{f}	0.67^{f}
NP	48.56^{d}	30.38^{c}	72.55^{d}	17.14^{cd}	2.02^{bc}
PKS	18.43^{f}	11.14^{e}	27.67^{e}	6.80^{e}	0.79^{f}
NKS	43.72^{e}	25.57^{d}	74.06^{d}	15.20^{d}	1.80^{cd}
NPS (-K)	60.68^{c}	29.47^{c}	88.60^{c}	17.37^{c}	1.25^{e}
NPK (-S)	63.44^{c}	32.39^{c}	100.64^{b}	18.95^{bc}	1.84^{cd}
NPKS	74.12^{b}	36.56^{b}	102.70^{b}	19.81^{b}	2.47^{a}
NPKSZn (-B)	87.38^{a}	40.40^{a}	114.95^{a}	22.22^{a}	2.67^{a}
NPKSB (-Zn)	83.29^{a}	36.04^{b}	93.19^{bc}	20.40^{ab}	1.41^{de}
NPKSZnB	70.26^{b}	37.53^{ab}	97.61^{b}	20.55^{ab}	2.35^{ab}
Mean	56.14	28.75	79.39	16.18	1.73
LSD (0.05)	4.52	3.16	8.30	1.97	0.45
CV (%)	5.54	7.57	7.22	8.33	18.02

Means followed by a common letter/s within a column are not significantly different at $P<0.05$

3.4. Agronomic efficiencies

Agronomic efficiency (AE) of each nutrient was highly significantly ($P < 0.01$) affected due to nutrient combination where the application of NPKSZn resulted in the highest value. Nutrient use efficiency was increased via increasing crop nutrient uptake and use efficiency by decreasing nutrient losses from the soil-plant system. This improvement was attributed due to nutrient uptake increment through the integrated application of macronutrients with micronutrients in nutrient deficient soil as a result enhanced nutrient use efficiency of crops thereby boosting yield and productivity Redai *et al*.(2018).

Accordingly, the highest agronomic efficiency of nitrogen (AEN) (55.6 kg kg^{-1}) was obtained from the application of NPKSZn. The lowest AEN (34.5 kg kg-1) was recorded from the application of NKS (-P) indicating the combined application of N and P is especially very important since the absence of one of these nutrients remarkably reduced the AE of other nutrients (Table 5). Selecting a fertilizer combination that confers the highest AE of each nutrient is quite important, which is in agreement with the findings of Kurwakumire *et al.* (2014). On the other hand, the highest AEN might be attributed due to the synergetic interaction effect of N with P, K, S and Zn. Even though, N interaction with micronutrients depends on the forms of N absorbed and the soil pH changes in the rhizosphere. If N is absorbed in the form of NH_4^+, soil pH may decrease, and uptake of most micronutrients increases. If N is mainly absorbed as NO_3^-, soil pH may increase, and uptake of most micronutrients decreases Wilkinson (2000).

The highest agronomic efficiency of phosphorus (AEP) (166.9 kg kg^{-1}) was obtained from the application of NPKSZn and the least (19.1 kg kg^{-1}) was recorded from N-omitted plots. Application of NPKSZn increased ATP by 42.7% and 772.7% compared with NP and N-omitted plots, respectively. Omitting N (i.e. PKS treatment) extraordinarily reduced AEP, which might be reduced root growth and negatively influences the absorption of water and nutrients. This showed that the application of P in the absence of N cannot improve the AEP which was confirmed by the finding of Tesfaye *et al.* (2019).

The highest agronomic efficiency of potassium (AEK) 166.5kgkg^{-1} was obtained from the application of NPK indicating positive interactions of K with N and P, while the lowest AEK (19.1 kg kg^{-1}K) was recorded from plots treated with PKS (-N) indicating N-deficiency negatively affects AEK of crops. Similarly, the same trend was observed in the case of S and Zn agronomic efficiencies. Higher AE is generally obtained if the yield increment per unit of nutrient applied is high (Obreza and Rhoads, 1988) which supports the finding of the current study. On the other hand, a lower yield response indicates higher soil indigenous nutrient supply or higher soil fertility, resulting in lower agronomic efficiency.

In general, higher agronomic efficiencies would be obtained if the yield increment per unit of nutrient applied were high, nevertheless what amount can be considered as high AE is not exactly identified Robert (2008). Further increasing nutrient levels beyond crop requirement may decrease agronomic efficiency of a nutrient by the crops, which indicates a higher amount of fertilizer application over optimum dose in luxury nutrient uptake might not contribute to physiological processes and hence yield.

Table 5: Agronomic efficiency of N, P, K, S, Zn and B as affected by omitted nutrients

Treatments	Agronomic Efficiency (kg grain kg^{-1} nutrients applied)				
	N	P	K	S	Zn
Control	-	-	-	-	-
NP	38.97^{f}	116.9^{g}	-	-	-
PKS (-N)	-	19.1^{h}	19.1^{f}	38.3^{g}	-
NKS (-P)	34.50^{g}	-	103.3^{e}	206.7^{f}	-
NPS (-K)	43.40^{e}	130.1^{f}	-	260.2^{e}	-
NPK (-S)	45.60^{d}	136.8^{e}	136.8^{d}	-	-
NPKS	52.70^{b}	158.1^{b}	158.1^{b}	316.2^{b}	-
NPKSZn (-B)	55.60^{a}	166.9^{a}	166.9^{a}	333.7^{a}	1359.8^{a}
NPKSB (-Zn)	51.50^{bc}	154.4^{c}	154.4^{bc}	308.9^{c}	-
NPKSZnB	50.40^{c}	151.3^{d}	151.3^{c}	302.6^{d}	1210.3^{b}
Mean	46.58	129.20	127.13	252.36	1285.06
LSD (0.05)	1.36	2.36	4.12	4.42	42.64
CV (%)	4.25	3.41	4.52	5.36	6.88

Means followed by a common letter/s within a column are not significantly different at $P<0.05$

3.5. Apparent recovery of nutrients

The apparent recovery efficiency of each nutrient showed a positive response due to the inorganic fertilizer combination. The highest recovery fraction of N (0.64), P (80.2), K (236.32), S (87.40) and Zn (40.10) was recorded from the application of NPKSZn. The increment of recovery fraction might due to the integrated use of macronutrients (NPKS) with micronutrients (Zn) in the appropriate form of fertilizer. The result was in line with the finding of Jones *et al.* (2011) who reported that matching appropriate essential macronutrients in combination with micronutrients with crop nutrient uptake could optimize nutrient use efficiency thereby apparent recovery of nutrients.

4. Conclusion and Recommendation

Based on the results, we conclude that rational fertilizer promotions and recommendations based on actual limiting nutrients for a given crop are not only revealed to supply adequate plant nutrients but also helped to understand the long-term ecological and economic benefits of the studied crop. According to the result, it is possible to conclude that the inherent N supplying capacity of soil is very low and highly limits grain yield of maize followed by P in the study area. Therefore, the use of an optimum dose of N and P should take great attention to efficient nutrient uptake, which ultimately increases maize productivity. The wider variability in maize yield response to the application of different nutrient combinations observed in this study, suggests that site-specific nutrient management is fundamental to intensifying maize production and productivity. Therefore, we can conclude that N is the most yield-limiting nutrient followed by P in the study area.

Moreover, the results of this experiment have substantiated the importance of micronutrients (Zn) in combination with macronutrients NPKS for improving nutrient concentration and uptake and have confirmed the significant yield increase in maize. The highest total nutrient uptake, agronomic efficiency and apparent recovery of nutrients were obtained from plots treated with fertilizer containing NPKSZn. Therefore, it can be concluded that the application of macronutrients in combination with micronutrients increased maize yield and concomitantly improved N, P and K uptake and its nutrient use efficiency.

Further researches need across different locations and soil types and nutritional quality analysis are also recommended.

Conflict of Interest

The authors declared that there is no conflict of interest.

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References

Adediran, J.A. and J.O. Kogbe. (2003). Influence of nitrogen, phosphorus and potassium application on yield of maize in the savanna zone, Nigeria. *African Journal of Biotechnology. 2:* 345-349.

Ahmad, S., Khan, A., Kamran, M., Ahmad, I., Ali S. and Fahad, S. (2018). Response of maize cultivars to various nitrogen levels. *European Journal of Experimental Biology. 8 (1)*:1-4.

Arif, M, Amin I, Jan M.T, Munir I.Q, Nawab, K.H, Khan, N.U, and Marwat, K.B. (2010). Effect of plant population and nitrogen levels and methods of application on-ear characters and yield of maize. *Pakistan Journal of Biotechnology. 42 (3):*1959-67.

Azab, M.E. (2015). Increasing Zn ratio in a compound foliar NPK fertilizer in relation to growth, yield and quality of corn plant. *Journal of Innovations in Pharmaceuticals and Biological Science.2 (4):* 451-468.

Baharvand, A.Z., Zahedi, H., Sharghi, Y. and Seifolahi-Nik, S. (2014). Comparative assessment of conventional and organic nutrient management on yield and yield components of three corn cultivars. *International Journal of Biological Science. 4(12):* 281-287.

Bray, R.H. and Kurtz, L.T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *International Journal of Soil science, 59*(1): 39-46.

Bremner, J.M. and Mulvaney, C.S. 1982. *Methods of soil analysis of total Nitrogen. Part 2*: *Chemical and microbiological properties,* (Vol. 9, pp: 595-624). Madison: American Society of Agronomy.

Chapagain, T. and Gurung, G.B. (2010). Effects of integrated plant nutrient management practices on the sustainability of maize-based hill farming systems in Nepal. *Journal of Agricultural Science. 2 (3):*26-32.

CSA (Central Statistical Agency). (2017). Agricultural Sample Survey 2016/17.*Report on area and production of the major crop*. *Volume 1*. Bulletin No 586. Central Statistical Agency, Federal Democratic Republic of Ethiopia, Addis Ababa.

Dagn, C. (2016). Blended fertilizers effects on maize yield and yield components of Western Oromia, Ethiopia. *Journal of Agriculture, Forestry and Fisheries*, 5(5): 151-162.

Dawson, J.C., Huggins, D.R. and Jones, S. (2008). Characterizing nitrogen use efficiency in natural and agricultural ecosystems to improve the performance of cereal crops in low-input and organic agricultural systems. *Journal of Field Crops Research 107*(2): 89-101.

Derby, N.E., Casey, F.X, Knighton ,R.E. and Steele, D. (2004). Midseason N fertility management for corn based on weather and yield prediction. *Agronomy Journal. 96(2)*:494-501.

Diallo, A.O., Adam, A., Akanvou, R.K. and Sallah, P. (1997). Response of maize evaluated under stress and non-stress environments. Developing Drought tolerant and Low N-Tolerant Maize in Mexico. Batan, (EL) *Proceedings of a Symposium on "Developing Drought tolerant and Low N-Tolerant Maize variety", March, 25-29, Mexico*, 1996.

Ethiopian Soils Information System. (2013). Status of soil resources in Ethiopia and priorities for sustainable management for Eastern and Southern Africa. *25-27 March, Nairobi, Kenya.*

Fageria, N.K. Morais, O.P, and Santos A.B. (2010). Nitrogen use efficiency in upland rice genotypes. *International Journal of Plant Nutrition.33(6):*1696 -1711.

FAO (Food and Agriculture Organization of the United Nations). (2008). *Guide to laboratory establishment for plant nutrient analysis. Fertilizer and Plant Nutrition Bulletin 19.*FAO, Rome, Italy.

Gomez, K.A., and Gomez, A.A. (1984). *Statistical procedures for agricultural research*. International Rice Research Institute: John Wiley and Sons Inc.

Gowda, D., Mahesh, B. and Gowda, S. (2001). Zinc-catalyzed ammonium format reductions: rapid and selective reduction of aliphatic and aromatic nitro compounds.

Haney, R.L. and Haney, E. B. (2015). Estimating potential nitrogen mineralization using the Solvita soil respiration system. *Open Journal of Soil Science. 5*(12): 319.

Hay, R.K.M. (1995). Harvest index: A review of its use in plant breeding and crop physiology. *Annals of applied biology*. *126 (1):* 197-216.

Hazelton, P. and B. Murphy, (2007.) Interpreting soil test results: What do all the numbers mean? 2nd edition. CSIRO Publishing. p152.

Hillel, D. and Hatfield J. L. (2005). *Encyclopedia of Soils in the Environment* (Vol. 3). Amsterdam: Elsevier.

Horneck, D.A. Sullivan D.M, Owen, J.S. and Hart J.M. (2011). Soil test interpretation guideline. Oregon State University, Extension Service.

Hunt N. and Gilkes, R. (1992). Farm monitoring handbook. *A practical down-to-earth manual for farmers and other land users*. University of Western Australia: Netherland. pp. 62. *American Society of Agronomy*.

Ibrikci, H., Ryan, J., Ulger, A.C., Buyuk, G., Cakir, B., Korkmaz, K. and Konuskan, O. (2005). Maintenance of phosphorus fertilizer and residual phosphorus effect on corn production. *Nutrient Cycling in Agro ecosystems. 72*(3): 279-286.

Jain, N.K., and Dahama, A.K. (2005). The residual effect of phosphorus and zinc on yield, nutrient content, uptake and economics of pearl millet (*Pennisetum glaucum* L.) and wheat (*Triticum aestivum* L.) cropping system. *Indian journal of agricultural science*, *75*(5): 281-284.

Jones, C., Olson, R and Dinkins, C. (2011). Nutrient uptake timing by crops: to assist with fertilizing decisions. Montana State University, 2-8

Jones, J.B. (2003). Agronomic Handbook: Management of Crops, Soils, and their Fertility: CRC, Boca Raton. 450

Kalpana, R. and Krishnarajan J. (2002). Effect of dose and time of potassium application on yield and quality of baby corn (*Zea mays* L.). *International Journal of Agricultural Science. 22*(1): 59-60.

Kihara, J., Nziguhebab, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C. and Huising J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *International Journal of Agricultural Ecosystems and Environment. 229*:1-12.

Kumar, A., Gautam, R.C., Singh, R. and Rana, K.S. (2005). Growth, yield and economics of maize (*Zea mays* L)-wheat (*Triticum aestivum* L.) cropping sequence as influenced by integrated nutrient management. *Indian journal of agricultural science*, *75*(11): 709-711.

Kurwakumire, N., Chikowo, R., Mtambanengwe, F., Mapfumo P., Johnston A. and Zingore S. (2014). Maize productivity, nutrient and water use efficiencies across soil fertility domains on smallholder farms in Zimbabwe. *Journal of Field Crops Research*. *164*:136-147.

López-Bellido, R.J., López-Bellido, L., López-Bellido, F.J. and Castillo, J.E. (2003). Faba bean (*Vicia faba* L.) response to tillage and soil residual nitrogen in a continuous rotation with wheat (*Triticum aestivum* L.) under rain fed Mediterranean conditions. *Journal of Agronomy.95* (5): 1253-1261.

Malakouti, M.J. (2008). Determining the effect of micronutrients in ensuring efficient use of macronutrients. *Turk Journal of Agricultural Science*, *32*:215-220.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in soil science and plant analysis.15* (12):1409-1416.

Mikos-Szymańska, M., Borowik, M., Wyzińska, M. and Rusek, P. (2018). Effects of different fertilizer treatments on grain yield and yield components of spring wheat. *Research for Rural Development.2:* 100-106.

Obreza, T.A and Rhoads, F.M. (1988). Irrigated Corn Response to Soil-Test Indices and Fertilizer Nitrogen, Phosphorous, Potassium, and Magnesium. *Soil Science Society of America Journal. 52 (3)*:701-706.

Obsa, A., Tesfaye, B., and Alemayehu, R. (2021). Effect of Nutrient Omission on Grain Yield and Yield Components of Maize (*Zea mays* L.) at Kersa District, Jimma Zone, Southwestern Ethiopia. *Journal of Agriculture, Forestry and Fisheries, 1(10):* 7-15.

Onwueme, I. C., and Sinha, T. D. (1991). Field crop production in tropical Africa. Technical Centre for Agricultural and Rural Cooperation.

Redai, W., Tesfaye, A. and Yamane G. (2018).Effect of NPK and Blended Fertilizer Application on Nutrient Uptake and Use Efficiency of Selected Sorghum (*Sorghum bicolor* L.) Varieties Under Rain-fed Condition in Sheraro District, Northern Ethiopia. *Ethiopian Journal of Science*. *1(10):*140-156.

Rehman, A., Salem, M.F., Safdar M.E., Hussain, S. and Akhtar N. (2011). Grain quality, nutrient use efficiency and bio-economics of maize under different sowing methods and NPK levels. *Chilean Journal of Agricultural Research.71(4):* 586–593.

Robert, TL. (2008). Improving nutrient use efficiency. *Turkish Journal of Agriculture and Forestry*. 32 (3):177-82.

SAS (Statistical Analysis System) Institute (2012).*SAS/AF® 9.3: Procedure guide, 2nd edition*: Cary, NC: USA.

Shiferaw, B., Mulugeta, H., Atinafu, A. and Abay, A. (2018). Macro and micronutrients for optimizing maize production at Hawassa Zuria District, Southern Ethiopia. *Journal of Biology, Agriculture and Healthcare.8* (5): 27-31.

Singh, I.D., and N.C. Stoskopf. (1971). Determination of Harvest index in cereals. *Agronomy Journal*. *63 (2):* 224-226.

Sumner, M. E. (1981). Diagnosing the sulfur requirements of corn and wheat using foliar analysis. *Soil Science Society of America Journal*. *45*(1): 87-90.

Tekalign, M. (1991). Soil, plant, water, fertilizer, animal manure and compost analysis manual. Plant division working document 13. Addis Ababa, Ethiopia: ILCA.

Tesfaye, B., Rurinda, J., Kebede, M., Mutegi, J., Hailu, G., Tufa, T., Abera, T. and Sida T. (2019). Yield response and nutrient use efficiencies under different fertilizer applications in maize (*Zea mays* L.) in contrasting agro ecosystems. *International Journal of Plant and Soil Science, 29 (3)*:1-9.

Van Engelen, V. W. P., Verdoodt, A., Dijkshoorn, J. A. and Van Ranst, E. (2006).*Soil and terrain database of Central Africa (DR Congo, Burundi, Rwanda) Rwanda (SOTERCAF, version 1.0)* (No. 2006/07). ISRIC-World Soil Information.

Wakene, N., Tolera, A., Minale, L., Tolesa, D., Tenaw, W., Assefa, M. and Zerihun, A. (2011). Soil fertility management technologies for sustainable maize production in Ethiopia. *Proceeding of the 3rd National Maize Workshop of Ethiopia. On "Soil fertility management technologies for sustainable maize production". pp. 123-127*.

Wilkinson, S.R. (2000). Nutrient interactions in soil and plant nutrition. In: M.E. Sumner (Ed.), Handbook of Soil Science, CRC Press, Boca Raton, pp. 89-D112.

Wispelaere, L., Marcelino, V., Alemayehu, R., De Grave, E., Dumon, M., Mees, F. and Van Ranst, E. (2015). Revisiting nitic horizon properties of Nitisols of Southwestern Ethiopia. *Geoderma* 243-244: 69-79.