

# Diagnostic Trials on Sorghum (*Sorghum bicolor* L. Moench) for Developing Site-specific Nutrient Management Practices in the Lowlands of Eastern Amhara, Ethiopia

Habtemariam Teshome<sup>\*A</sup>, Samuel Adissie<sup>A</sup>, Kassa Sisay<sup>A</sup> and Tadesse Hailu<sup>A</sup>

<sup>A</sup> Sirinka Agricultural Research Center, Woldia, Ethiopia

\*Corresponding author; email: [teshomehabte@gmail.com](mailto:teshomehabte@gmail.com)

## Abstract

Soil fertility heterogeneity significantly influences crop productivity and the effectiveness of nutrient management strategies. In Ethiopia, various types and sources of inorganic fertilizers are distributed to enhance crop production. Therefore, selecting appropriate fertilizers based on specific soil nutrient deficiencies is essential. A field experiment was conducted in Kobo using sorghum as the test crop to identify yield-limiting nutrients through crop response. The experiment employed a randomized complete block design with farmers' fields serving as replications. Biological yield data were collected and analyzed using analysis of variance (ANOVA). When significant differences among treatments were detected, means were separated using the LSD test at  $P \leq 0.05$ . Results showed that omitting nutrients from inorganic fertilizers, either individually or in combination, significantly reduced grain yield. The highest grain yield was achieved with the combined application of NPS (nitrogen, phosphorus, sulphur) fertilizer and farmyard manure (FYM). In contrast, the lowest yield occurred in the control treatment, where all nutrients were omitted. Biomass yield did not differ significantly between treatments across both years. The study indicates that applying farmyard manure in combination with inorganic fertilizers, such as NPS, NPSK (NPS + potassium), and NPSKZn (NPSK + Zinc), effectively meets the nutrient requirements of sorghum. Grain yield under nutrient omission treatments ranked as follows: NPS + FYM > NPS > NPSK > NPSKZn > NP > NS > PS > N > S > P. Among the nutrients tested, farmyard manure had the greatest impact on yield, followed by nitrogen, sulphur, and phosphorus fertilizers.

Keywords: crop response, farmyard manure, nitrogen, omission

## Introduction

Soil fertility heterogeneity in smallholder farming systems is a major factor that affects productivity and the suitability of crop and nutrient management recommendations for different locations at various spatial scales. The availability of nutrients and soil fertility levels are substantially affected by nutrient management approaches and cropping practices (Asan et al., 2023). Site-specific nutrient management (SSNM) aims to enable the dynamic adjustment of fertilizer use between high-yielding crop nutrient requirements and nutrient supply from organic sources (Bekele et al., 2022). The site-specific nutrient management concept (SSNM) helps optimize the management of fertilizers, including N, P, K, S, and micronutrients, in heterogeneous production systems. SSNM integrates soil, agronomic, and climate information to provide location-specific guidelines on nutrient requirements (Oyinbo, 2019). It aims to (a) account for indigenous nutrient sources, including crop residues and farmyard manure; and (b) apply balanced fertilizer at optimal rates and at critical growth stages to meet the deficit between the nutrient needs of a high-yielding crop and the indigenous nutrient supply.

Optimum productivity of any cropping system depends on an adequate supply of plant nutrients. Even if all other factors of crop production are optimal, the fertility of the soil largely determines the ultimate yield. The blanket recommendation is inadequate for optimal crop production due to unbalanced nutrient proportions in the soil (Chivenge et al., 2022). Soil does not supply sufficient nutrients for normal plant development and optimum productivity, as a result, application of supplemental nutrients is required. Fertilizer is one of the most essential sources to meet this requirement. The indiscriminate use of fertilizers, however, may cause adverse effects on soils and crops, both in terms of nutrient toxicity and deficiency,

resulting from overuse or inadequate use (Ray et al., 2000). Diagnostic techniques including identification of deficiency symptoms, soil and plant analysis and biological tests are helpful in determining specific nutrient stresses and quantity of nutrients needed to optimize the yield (Havlin et al., 2007). Diagnostic/omission techniques describe omitting or excluding specific essential nutrients from the fertilization schedule to observe their impact on crop production by keeping the supply of other limiting nutrients in ample quantity (Majumder et al., 2024). Omission trial supports the identification of specific nutrients that are the most yield-limiting.

To increase the productivity of the crop of smallholder farms and therefore improve food security in the study sites there is a need to identify the soil factors that constrain crop growth. Additionally, one or two types of fertilizer recommendations apply to the entire district or a wide region. To increase the use efficiency of applied nutrients and the cost-effectiveness of resource input, there is a need to target interventions, whether related to soil amendments to improve soil condition or to fertilizer application to address nutrient requirements. Knowing the limiting soil factors would inform about the right inputs needed. Therefore, this research was conducted to find out the yield-limiting nutrients based on sorghum response using the nutrient omission technique and to develop 'Site Specific Nutrient Management Practices' under variable soil fertility and climatic conditions.

## Materials and Methods

### Site Description

The experiment was conducted at Kobo, located 54 km north of Woldia. Its altitude ranges from 1000 to

2800 m above sea level. It has an agroecology of hot to warm, sub-moist valleys and escarpments. The study district is located at a geographical coordinate point with latitudes ranging from 12.03 ° to 12.08 ° N and longitudes from 39.28 ° to 39.42 ° E. Annual rainfall, minimum, and maximum temperature of the study area are 649 mm, 29°C, and 15°C, respectively. The major crops grown in the region are sorghum, teff, and maize (Asamenew, 1993), and nowadays most of the irrigable area is shifted to horticultural crops. The livelihood of the population is dependent on mixed farming and crop production, with about 96% of its population engaged in agriculture. However, due to various constraints, Kobo is one of the food-insecure woredas of Amhara National Regional State.

### Experimental Treatments and Design

The experiment was conducted over two years, in the 2016 and 2017 main cropping seasons, at Abuare, Aradom, and Ayub kebeles of the district. The design for the experiment was a randomized complete block design. The farmer's field was considered a replication. Twelve treatments with 3 m by 4.5 m net plot size were used. Sites were carefully selected to ensure a good representation of cropping systems. During harvesting, grain yield and biomass yield were measured by taking the weight of the grains for the plant in a plot by excluding two rows as a border side and one plant at the first and end of each row, and converting it to kg per hectare. Finally, the grain yield was also adjusted to a moisture content of 12.5% using grain moisture analysis.

### Nutrient Application Rates

Nutrients were applied at rates required to achieve the expected attainable yield without nutrient limitation in each location. Nutrient application rates depend on

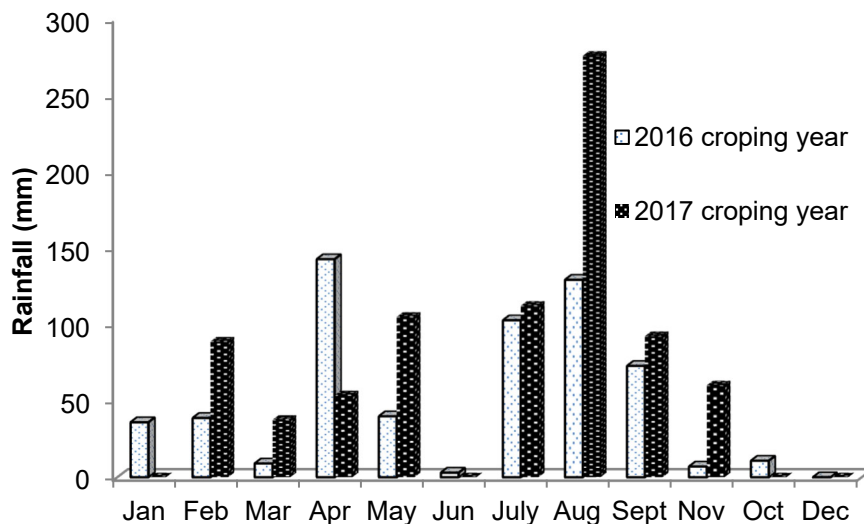


Figure 1. Monthly rainfall distribution of the study area during the two cropping years

the maximum achievable yield, as determined by rainfall and agro-ecological potential. The sources of S&K were CaSO<sub>4</sub> and KCl, respectively. Locally available cattle farmyard manure was collected and applied at a rate of 12 t.ha<sup>-1</sup>, and 69 kg.ha<sup>-1</sup> nitrogen and 69 kg.ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> containing fertilizer was used

as the recommended fertilizer rate for the study area (Office of Woreda Agriculture manual 2008, unpublished) (Table 2).

The following guidelines (Table 2) were used to determine nutrient application rates.

Table 1. Treatments description

Plot	Description
Control	No fertilizer application. Used to measure grain yield as an indicator of the adequate indigenous NPS supply from soil, rainwater, crop residue, and atmosphere.
N	Provide sufficient N only; other nutrients are assumed to come from the soil.
P	Provide sufficient P only; other nutrients are assumed to come from the soil.
S	Provide sufficient S only; other nutrients are assumed to come from the soil.
PS	N omission plot with sufficient P and S amounts applied. Used to measure grain yield as an indicator of the adequate indigenous N supply from soil, rainwater, crop residue and atmosphere.
NS	P omission plot with sufficient N and S amounts applied. Used to measure grain yield as an indicator of the adequate indigenous P supply from soil, rainwater, crop residue and atmosphere.
NP	S omission plot with sufficient N and P amounts applied. Used to measure grain yield as an indicator of the adequate indigenous S supply from soil, rain water, crop residue and atmosphere.
NPS	Full NPS input to estimate the nutrient-limited yield gap and evaluate agronomic use efficiencies of N, P, and S. Fertilizer N is applied in two splits.
NPSK	This treatments will be used to assess the contribution of K with primary nutrients.
NPKSZn	This treatments will be used to assess the contribution of secondary and micronutrients to Sorghum productivity. The secondary nutrient rates have already been determined from existing work
NPS+FYM	This treatments will be used to assess the contribution of farmyard manure to Sorghum and Teff productivity through its multiple effects, including the addition of organic matter and the regulation of nutrient supply, water, and air circulation.

Notes: N = nitrogen, P = phosphorus, S = sulphur, K = potassium, Z = zinc, FYM = farmyard manure.

Table 2. Amount of nutrients applied

Treatments	Nutrient application rates (kg.ha <sup>-1</sup> )								
	N	P	P <sub>2</sub> O <sub>5</sub>	K	K <sub>2</sub> O	S	Zn	ZnSo <sub>4</sub>	FYM
Control	0	0	0	0	0	0	0	0	0
N	150	0	0	0	0	0	0	0	0
P	0	55	125	0	0	0	0	0	0
S	0	0	0	0	0	20	0	0	0
PS	0	55	125	0	0	20	0	0	0
NS	150	0	0	0	0	20	0	0	0
NP	150	55	125	0	0	0	0	0	0
NPS	150	55	125	0	0	20	0	0	0
NPSK	150	55	125	60	72	20	0	0	0
NPSKZn	150	55	125	60	72	20	5	25	0
NPS+FYM	150	55	125	0	0	20	0	0	12 t.ha <sup>-1</sup>
R.NP	69	30	69	0	0	0	0	0	0

Notes: R.NP= recommended nitrogen and phosphorous; N = nitrogen, P = phosphorus, S = sulphur, K = potassium, Z = zinc, FYM = farmyard manure.

## Data Collection

### Grain and biomass

Grain yield was measured from the innermost rows harvested and was adjusted to 12.5% moisture content. Fresh biomass weight was measured by weighing the fresh total above-ground biomass and the head of the harvestable rows. Plant height was measured at maturity from five random plant samples of the harvestable rows, from ground level to the tip of the head.

### Soil sampling

Composite soil samples were taken before planting at a depth of 0-20 cm for laboratory analysis, including total N, available P, organic carbon (OC), texture, and pH.

The methods of analysis of the collected soil samples are described below. Soil pH was determined using a glass electrode pH meter in a 1:2.5 soil-to-water suspension, after stirring for 30 minutes, as described by Piper (1966). Organic carbon was estimated by the wet digestion method of Walkley and Black (1934). Available P in soil was extracted by Olsen et al. (1954), and P in the extract was determined by the ascorbic acid method. The total available nitrogen in the soil was determined using the wet digestion procedure of the Kjeldahl method. Soil texture was determined by hydrometer method.

### Data Analysis

The data obtained were subjected to analysis of variance using Statistic 10 software, and treatment effects were compared using Fisher's Least Significant Differences test at a 5% level of significance.

## Results and Discussion

### Physicochemical Properties of the Soil

The first-year results of soil analysis (Table 3) showed that the soil had total nitrogen content in the range of 0.11-0.32 (%). According to Tekalign et al. (1991), soil total N availability of < 0.05% was considered as very low, 0.05-0.12% as poor, 0.12-0.25% as moderate,

and more than 0.25% as high. Based on this, the experimental site showed moderate to high content of total nitrogen. The soil has an organic matter content ranging from 1.26% to 2.75%, which is categorized as low to medium (Debele, 1980). According to Debele, soil organic matter content of less than 0.7% is considered very low, 0.7-2.6% as low, 2.6-5.2% as medium, and more than 5.2% as high. The laboratory results also indicated that the textural class of the experimental site was clay based on USDA textural classification. Thus, the textural class of the experimental soil is ideal for sorghum production, and the soil reaction (pH) of the experimental site ranges from 6.4 to 6.9, which shows a neutral range (Tekalign, 1991). Still, it is within the optimum range for sorghum production, i.e., 5.5 to 7.0.

The second-year results of soil analysis (Table 3) showed that the soil had total nitrogen content in the range of 0.1-0.25 (%), which is categorized under poor to moderate total nitrogen content. The soil has an organic matter content ranging from 0.88% to 2.2%, which is considered low (Debele, 1980). The soil test result reveals that the available phosphorus content of the soil, as rated by Olsen et al. (1954), is in the high range. As described in Table 3 below, the existing available soil phosphorus content in the area is adequate for optimal crop production (Bai et al., 2013). Thus, phosphorus fertilizer application is not advisable (Delgado et al., 2024). In conformity with the soil data Wang et al. (2023) confirmed that 17.06 mg.kg<sup>-1</sup> soil P was the agronomic threshold of cereals. The laboratory results also indicated that the textural class of the experimental site was clay based on USDA textural classification and the soil reaction (pH) of the experimental site was ranges from 6.5-6.8 which shows neutral range (Tekalign, 1991), but it is within the optimum range for sorghum production, i.e., 5.5 -7.0.

### Sorghum Grain Yield and Biomass Yield

The data on sorghum grain yield as affected by the application of different inorganic fertilizers is presented in Table 4. As indicated in Table 4, grain yield was significantly affected by the application of the inorganic fertilizers in combination or alone at (P<0.05). Compared to the control treatment, the highest sorghum yield was obtained from NPS plus Farmyard manure application, without a significant

Table 3. pH, organic matter content, total N, available P, and textural class of soil samples taken at planting at Kobo in the year 2016 and 2017.

Year	pH	% organic matter	%Total nitrogen	Available phosphorus (ppm)	Textural class
2016	6.4-6.9	1.26-2.75	0.11-0.32	30.8-34.4	Clay
2017	6.5-6.8	0.88-2.2	0.1-0.25	33.85-44.45	Clay

difference from the NPS, NPSK, and NPSKZn treatments (Table 4), and a 21-quintal yield advantage over the control treatments in the first year. In Table 4, the NP higher rate is lower than the recommended NP rates. This implies that the recommended NP rate is sufficient for that site, and adding additional NP results in a yield penalty, either due to the logging effect or toxicity.

Like the first-year results, the second-year results showed that sorghum grain yield was affected by the application of different inorganic fertilizers, as presented in Table 5. As indicated in Table 5, grain yield was significantly affected by the application of inorganic fertilizers, either in combination or alone ( $P < 0.05$ ). Compared to the control treatment, the highest sorghum yield was also obtained from NPS plus Farmyard manure application, without a significant difference from the NPS, NPSK, and NPSKZn treatments (Table 5), and a 21-quintal yield advantage over the control treatments. Unlike the first year, the second year indicates an addition of a higher rate of NP gives a higher grain yield than the recommended NP rate, which means the recommended rate is lower than the crop requirement.

The combined analysis of the results indicates that sorghum grain yield was affected by the application of different inorganic fertilizers, which is presented in Table 6. As shown below, grain yield was significantly affected by the application of the inorganic fertilizers in combination or alone at ( $P < 0.05$ ). Compared to the control treatment, the highest sorghum yield was obtained from NPS plus farmyard manure application, without a significant difference from the NPS, NPSK,

and NPSKZn treatments (Table 6), and a 21.8 quintal yield advantage over the control treatments. The mean grain yields of sorghum were significantly affected by the different treatments imposed. The omission of N, P, and S significantly reduced the grain and straw yields of sorghum compared to the treatment that received all nutrients. The highest grain yield ( $5490.3 \text{ kg}\cdot\text{ha}^{-1}$ ) was recorded from NPS + FYM, and the lowest grain yield ( $3316.7 \text{ kg}\cdot\text{ha}^{-1}$ ) was associated with the omission of all nutrients (no fertilizer), the difference being significant. Grain yields with the addition of N, P, and S were increased by 857, 401, and 495  $\text{kg}\cdot\text{ha}^{-1}$ , respectively, and were significantly higher than the control (no fertilizer) treatment.

The total biomass yields of sorghum were not significantly affected ( $P < 0.05$ ) by the application of different fertilizer treatments in the years 2016 and 2017, nor by the combined data over the two years. This result contrasts with the use of mineral fertilizer, which has improved the biomass yield of the crop.

A nutrient omission trial aims to find out the most limiting nutrients for the growth of a crop plant. If any element is omitted while other components are applied at suitable rates and plants grow weakly, then the tested element is a limiting factor for crop growth. Conversely, if any element is omitted but plants are healthy, then that element is not a limiting factor for crop production. When a nutrient is deficient in the soil, then the growth of a crop plant and ultimately the yield is affected.

Table 4. Effect of different nutrients on sorghum grain and biomass yield at Kobo in 2016

Treatments	Grain yield ( $\text{kg}\cdot\text{ha}^{-1}$ )	Biomass ( $\text{kg}\cdot\text{ha}^{-1}$ )
Control	3366.8 <sup>c</sup>	9949
N	3816.7 <sup>bc</sup>	9854
P	3453.3 <sup>bc</sup>	10,051
S	3548.7 <sup>bc</sup>	9122
NP	3825.4 <sup>bc</sup>	9736
NS	3619 <sup>bc</sup>	8915
PS	4076.7 <sup>abc</sup>	9198
NPS	4302.7 <sup>abc</sup>	11,118
NPSK	4979 <sup>ab</sup>	11,780
NPSKZn	4932.9 <sup>abc</sup>	12,861
NPS +FYM	5538.1 <sup>a</sup>	12,441
Rec NP	4503 <sup>abc</sup>	9069
CV (%)	31.56	34.4
LSD (0.05)	1688.4	4138.9

Notes: N = nitrogen, P = phosphorus, S = sulphur, K = potassium, Z = zinc, FYM = farmyard manure.

Table 5. The effects of different nutrients on sorghum grain and biomass yield at Kobo in 2017

Treatments	Grain yield (kg.ha <sup>-1</sup> )	Biomass( kg.ha <sup>-1</sup> )
Control	3266.2 <sup>c</sup>	11,034
N	4888.9 <sup>abc</sup>	11,665
P	4192 <sup>abc</sup>	8390
S	4337.6 <sup>abc</sup>	12,068
NP	5092 <sup>ab</sup>	12,830
NS	4654.6 <sup>abc</sup>	11,317
PS	4144.2 <sup>abc</sup>	8271
NPS	4674.9 <sup>abc</sup>	10,290
NPSK	4613.9 <sup>abc</sup>	13,002
NPSKZn	4673.4 <sup>abc</sup>	13,089
NPS +FYM	5448.6 <sup>a</sup>	12,779
Rec NP	3440 <sup>bc</sup>	8565
CV (%)	22.34	36.53
LSD (0.05)	1684.2	6871.3

Notes: N = nitrogen, P = phosphorus, S = sulphur, K = potassium, Z = zinc, FYM = farmyard manure.

Table 6. Effect of different nutrients on sorghum yield at Kobo in 2016 and 2017

Treatments	Grain yield (kg.ha <sup>-1</sup> )	Biomass yield (kg.ha <sup>-1</sup> )
Control	3316.7 <sup>c</sup>	10311
N	4174.1 <sup>bc</sup>	10458
P	3717.9 <sup>bc</sup>	9805
S	3811.7 <sup>bc</sup>	9081
NP	4294.0 <sup>bc</sup>	10767
NS	4001.0 <sup>bc</sup>	8887
PS	4099.2 <sup>bc</sup>	8889
NPS	4426.8 <sup>abc</sup>	11666
NPSK	4857.3 <sup>ab</sup>	11578
NPSKZn	4829.2 <sup>ab</sup>	11920
NPS +FYM	5490.3 <sup>a</sup>	12531
Rec NP	4148.6 <sup>bc</sup>	9476
CV (%)	28.02	33.63
LSD (0.05)	1196.3	3574.4

Notes: N = nitrogen, P = phosphorus, S = sulphur, K = potassium, Z = zinc, FYM = farmyard manure.

Accordingly, the yield obtained from the control treatment was significantly lower ( $P \leq 0.05$ ) than the yields obtained due to the application of all the different fertilizers. This implies that the grain yield was low without the application of either of the soil fertility amendment mechanisms. In this aspect, the results of this work align with those of Kanchikerimath and Singh (2001), who reported that the balanced application of nutrients and manure enhances nutrient availability. Similarly, Azharuddin BR et al. (2022) reported that higher grain and stover yields of sorghum were achieved through the application

of 50:25 Kg N :P ha<sup>-1</sup> + 3 t.ha<sup>-1</sup> FYM + 15 Kg.ha<sup>-1</sup> ZnSO<sub>4</sub> with irrigation in a vertisol. The same authors also confirmed that nitrogen omission is the most yield-limiting nutrient, followed by phosphorus and potassium.

The results are in close agreement with the earlier finding by Shahi et al. (2020), who reported that the application of 100% NP + FYM yielded the maximum maize gain. The results are in close agreement with those of Doldt et al. (2023), who confirmed that ISFM can play a crucial role in enhancing productivity. Rani

et al. (2023) also reported that omission of PK, NK, and NP resulted in significant yield reductions.

Similar findings were reported by Rathod et al. (2022) who revealed that application of balanced fertilization with NPK and comprised used of FYM increased crop productivity and Singh et al. (2020) reported that omission of N reduced the yield by 47.64 %; P omission by 40.82 % and S omission caused yield reduction of 19.51 %. This finding aligns with several studies conducted in Ethiopia (Alemayehu et al., 2023; Bazie et al., 2024; Bekele et al., 2022; Sebnie et al., 2024; Teshome et al., 2023; Wodaje et al., 2024) on sorghum, rice, tef, and wheat.

## Conclusions

Both inorganic fertilizers and farmyard manure (FYM) play important roles in soil fertility management, but neither alone can supply all the nutrients and growth conditions required for optimal sorghum production. The increased grain and biomass yields observed in this study are likely due to the enhanced supply of essential nutrients through combined fertilization. The results showed that among the various combinations of inorganic fertilizers and FYM, sorghum responded best to the application of NPS (nitrogen, phosphorus, sulphur) combined with FYM. Omitting all inorganic fertilizers, either alone or in combination, significantly reduced sorghum grain yield in both districts. In conclusion, organic sources, such as FYM, when applied in conjunction with inorganic fertilizers like NPS and NP-based treatments (NPS, NPSK, and NPSKZn), effectively meet the nutrient requirements of sorghum. Grain yield under different nutrient omission treatments followed this order: NPS + FYM > NPS > NPSK > NPSKZn > NP > NS > PS > N > S > P. This ranking highlights the critical importance of FYM as the most yield-limiting factor, followed by nitrogen, sulfur, and phosphorus fertilizers. For the study area, it is advisable to prioritize the use of nitrogen- and phosphorus-containing fertilizers over secondary and micronutrients to improve sorghum production and productivity. However, since yield reductions were observed even with recommended nitrogen and phosphorus rates, future research should focus on determining optimal fertilizer rates tailored to local conditions. Different crops respond uniquely to nutrient availability. Therefore, similar trials using indicator plants are recommended to identify limiting nutrients in various cropping systems accurately.

## Acknowledgement

The authors thank farmers for their willingness to provide the farm for the experimental trial and data collection. Finally, the authors would like to express their appreciation to the Kobo Agricultural Subcenter and the staff of the soil laboratory for their unwavering collaboration and assistance during the soil analysis.

## References

- Alemayehu, B., Adgo, E., and Amare, T. (2023). Nutrients limiting tef (*Eragrostis tef* (Zucc.) Trotter) crop yield on vertisols in Yilmana Densa, upper Blue Nile basin of Ethiopia. *Journal of Plant Growth Regulation* **42**, 2736–2748. DOI: <https://doi.org/10.1007/s00344-022-10741-y>.
- Asamenew, G.H., Beyene, H., Negatu, W., and Ayele, G. (1993). A survey of the farming systems of vertisol areas of the Ethiopian highlands. *CGIAR Research Centers*. DOI: <https://hdl.handle.net/10568/49995>.
- Asan, M.B., Santhi, R., Maragatham, S., Ravikesavan, R., Geetha, P., Gopalakrishnan, M., and Parimala, D.R. (2023). Impact of soil fertility characteristics on artificial fertility gradient approach developed using sorghum (*Sorghum bicolor*) in Alfisols. *Journal of Applied and Natural Science* **15**, 793–801. <https://doi.org/10.31018/jans.v15i2.4601>.
- Azharuddin BR, M., Bandiwaddar, T.T., and Shaila, H.M. (2022). Effect of nutrients omission on yield, nutrient uptake, and economics of rabi sorghum in vertisols under rainfed and irrigated conditions. *Journal of Cereal Research* **14**, Spl2. DOI: <https://doi.org/10.25174/2582-2675/2022/123721>.
- Bai, Z., Li, H., Yang, X., Zhou, B., Shi, X., Wang, B., and Zhang, F. (2013). The critical soil P levels for crop yield, soil fertility, and environmental safety in different soil types. *Plant and Soil* **372**, 27–37. DOI: <https://doi.org/10.1007/s11104-013-1696-y>.
- Bazie, Z., Amare, T., Alemu, E., Agegneu, G., Desta, G., Tenagne, A., and Wale, S. (2024). Identifying limiting nutrient(s) for better bread wheat and tef productivity in acidic soils of north-west Amhara, Ethiopia. *Agrosystems, Geosciences and Environment* **7**, e20516. DOI: <https://doi.org/10.1002/agg2.20516>.

- Bekele, D., Gebreselassie, Y., and Tadesse, T. (2022). Yield response of upland rice (*Oryza sativa* L.) through nutrient omission trial in vertisols of Fogera districts, Northwest Ethiopia. *American Journal of Plant Biology* **7**, 30–40. DOI: <https://doi.org/10.11648/j.ajpb.20220701.15>.
- Debele, B. (1980). "The Physical Criteria and Their Rating Proposed for Land Evaluation in the Highland Region of Ethiopia." Land Use Planning and Regulatory Department, Ministry of Agriculture.
- Chivenge, P., Zingore, S., Ezui, K.S., Njoroge, S., Bunquin, M.A., Dobermann, A., and Saito, K. (2022). Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa. *Field Crops Research* **281**, 108503. DOI: <https://doi.org/10.1016/j.fcr.2022.108503>.
- Delgado, A., Quemada, M., Mateos, L., and Villalobos, F.J. (2024). Fertilization with phosphorus, potassium, and other nutrients. In "Principles of agronomy for sustainable agriculture", pp. 415–437. Springer International Publishing. DOI: [https://doi.org/10.1007/978-3-031-69150-8\\_28](https://doi.org/10.1007/978-3-031-69150-8_28).
- Doldt, J., Yilma, K., Ellis-Jones, J., Schulz, S., Thomson, A., and Barahona, C. (2023). The role of integrated soil fertility management in improving crop yields in the Ethiopian Highlands. *Experimental Agriculture* **59**, e24. DOI: <https://doi.org/10.1017/S0014479723000212>.
- Havlin, J.L., Tisdale, S.L., Beaton, J.D., and Nelson, W.L. (2007). "Soil Fertility and Fertilizers, An Introduction to Nutrient Management." Pp 175. Dorling Kindersley Pvt. Ltd. New Delhi, India,
- Kanchikerimath, M., and Singh, D. (2001). Soil organic matter and biological properties after 26 years of maize-wheat-cowpea cropping as affected by manure and fertilization in a Cambisol in the semiarid region of India. *Agriculture, Ecosystems and Environment* **86**, 155–162. DOI: [https://doi.org/10.1016/S0167-8809\(00\)00280-2](https://doi.org/10.1016/S0167-8809(00)00280-2).
- Majumder, S., Shankar, T., Maitra, S., Kumar, A., Gudade, B., Sagar, L., and Dash, S. (2024). Effect of nutrient omission plot technique-based nutrient management in rabi rice (*Oryza sativa*) on crop productivity, nutrient uptake, and soil health. *Indian Journal of Agronomy* **69**, 357–363. DOI: <https://doi.org/10.59797/ija.v69i4.5536>.
- Olsen, S.R., Cole, C.V., Watanabe, F.S., and Dean, L.A. (1954). "Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate". USDA, Washington.
- Oyinbo, O. (2019). "Site-specific Nutrient Management Advice and Agricultural Intensification in Maize-based Systems in Nigeria". Dissertation, KU Leuven.
- Piper, C.S. (1966). "Soil and Plant Analysis." Hans Publishers. Bombay.
- Rani, C.S., Rani, K.S., Shekar, K., and Sudhakar, C. (2023). Effect of nutrients omission on growth, yield, and economics of rabi sorghum (*Sorghum bicolor* L.) in vertisols under rainfed conditions. *International Journal of Environmental and Climate Change* **13**, 1095–1100. DOI: <https://doi.org/10.9734/ijecc/2023/v13i123773>.
- Rathod, P.H., Bhojar, S.M., Jadhao, S.D., Deshmukh, P.W., Lahariya, G.S., and Deshmukh, D.P. (2022). Yield and soil nutrient status as influenced by continuous sorghum-wheat cropping sequence in vertisols. *The Pharma Innovation International Journal* **11**, 1604–1610.
- Ray, P.K., Jana, A.K., Maitra, D.N., Saha, M.N., Chaudhary, J., Saha, S., and Saha, A.R. (2000). Fertilizer prescriptions on soil test basis for jute, rice, and wheat in a Typic Ustochrept. *Journal of the Indian Society of Soil Science* **48**, 79–84.
- Sebnie, W., Melak, E., and Lamesgn, H. (2024). Effects of nutrient omission on grain and biomass yield of irrigated wheat (*Triticum aestivum*) in Sekota district, Amhara region, Ethiopia. *Environmental Research Communications* **6**, 115013. DOI: <https://doi.org/10.1088/2515-7620/ad8f1e>.
- Shahi, U. P., Singh, V.K., Kumar, A., Singh, P., Dhyani, B.P., and Singh, A. (2020). Effect of site-specific nutrient management on productivity, soil fertility, and nutrient uptake in maize (*Zea mays*). *Indian Journal of Agronomy* **65**, 432–438. DOI: <https://doi.org/10.59797/ija.v65i4.3006>.
- Singh, S.P., Pakira, K.K., and Chanchala, R.P. (2020). Nutrient omission: A plant nutrient deficiency

- assessment technology of rice (*Oryza sativa*) in Inceptisols. *Journal of Pharmacognosy and Phytochemistry* **9**, 27–30.
- Tekalign, T., Haque, I., and Aduayi, E.A. (1991). "Soil, Plant, Water, Fertilizer, Animal Manure, and Compost Analysis Manual ". Working Document No. 13. Soil Science and Plant Nutrition Section, ILCA.
- Teshome, H., Molla, E., and Feyisa, T. (2023). Identification of yield-limiting nutrients for sorghum (*Sorghum bicolor* (L.) Moench) yield, nutrient uptake, and use efficiency on vertisols of Raya Kobo district, northeastern Ethiopia. *International Journal of Agronomy*, 5394806. DOI: <https://doi.org/10.1155/2023/5394806>.
- Walkley, A., and Black, I.A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29–38. DOI: <https://doi.org/10.1097/00010694-193401000-00003>.
- Wang, Y., Cui, Y., Wang, K., He, X., Dong, Y., Li, S., and Zhang, W. (2023). The agronomic and environmental assessment of soil phosphorus levels for crop production: A meta-analysis. *Agronomy for Sustainable Development* **43**, 35. DOI: <https://doi.org/10.1007/s13593-023-00887-8>.
- Wodaje, M., Fekadu, E., Abiye, W., Scopa, A., Abdel Rahman, M.A.E., and Moursy, A.R. (2024). Optimizing sorghum (*Sorghum bicolor*) yields in northwestern Ethiopia: A comprehensive study of key soil nutrient deficiencies. *Egyptian Journal of Soil Science* **64**. DOI: <https://doi.org/10.21608/ejss.2024.304108.1812>.