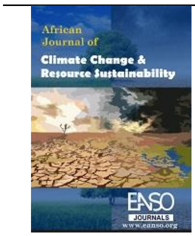

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Original Article

Comparative Effects of Site-specific and Blanket Fertilizer Application on Soil Physicochemical properties and Maize (Zea *mays* L.) Yield at Mikalango in Chikwawa District, Southern Malawi

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ABSTRACT

Malawi's economy predominantly relies on agriculture. However, continuous soil degradation threatens crop production, food security, and nutrition. The use of fertilizers in soil fertility amendment has not been as effective due to blanket application, which does not adequately address Malawi's diverse soil nutrient deficiencies. This can also lead to over-fertilization, which can generate greenhouse gas emissions contributing to climate change. The experiment, set up in a randomized complete block design, compared site-specific and blanket fertilizer applications having 5 treatments and 5 replications, where a single maize seed variety was planted uniformly. Data was collected from the site's soil physicochemical properties, maize growth, and yield components and analyzed using JMP SAS software version 14.0.0. Results indicated that site-specific fertilizer application significantly differed from blanket fertilizer application at a 5% level of significance. Phosphorus (0.31 ppm), Sulphur (24.2 ppm), and Zinc (1.92 ppm) were significantly higher due to site-specific fertilizer application. Similarly, plant biomass (3.41 t/ha) and grain yield (7.03 t/ha) were also significantly higher due to site-specific fertilizer application. Hence, the study concluded that site-specific soil fertility management is ideal for efficient nutrient replenishment and attaining optimum yields while mitigating climate change in maize farming systems.

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INTRODUCTION

The soil is not fertile enough to provide essential macro and micronutrients to plants in sufficient quantities (ALnaass et al., 2021). Fertilizers and manures play a crucial role in agriculture by replenishing nutrients in the soil, thereby enhancing crop yields. Fertile soils form a basis for increased production of food for human consumption and survival (FAO, 2019). The ecosystem services provided by soil can be categorized as supporting, such as primary production and biodiversity, or regulatory, including erosion control, water infiltration, nutrient retention, atmospheric gas regulation, and pest control (Baer and Birge 2018). Sustainable soil management is thus profoundly important for humanity's welfare in numerous intricate ways. Nonetheless, with the global population growing rapidly, there's increasing pressure to generate sufficient food to sustain this population using the limited arable land available. According to the United Nations (UN), the global population of 6.7 billion is expected to reach 9.2 billion by 2050 (Roberts, 2009). The rapid increase in human population will therefore exacerbate problems of soil degradation and climate change due to continuous cultivation on small land sizes, hence threatening food security (White, 2019).

Malawi is one of the developing countries in Sub-Saharan Africa that is being severely impacted by soil degradation and climate change caused by human activity due to continuous cultivation on small pieces of land and overdependence on small-scale rainfed agriculture. The population continues to grow while the scope for expanding the amount of land under cultivation seems very near or already at the frontier of its potential (Muyanga et al., 2020). At over 186 people per square kilometer, Malawi has one of the highest rural population densities in Sub-Saharan Africa (National Statistical Office, 2018). Estimations suggest that farm sizes are relatively diminutive, as 76 percent of the farming population manages farms smaller than one hectare.

Smallholder farming and commercial estate farming are the two primary sub-sectors that makeup Malawi’s agricultural industry (Mutegi et al., 2015). The smallholder sub-sector in Malawi consists of a substantial number of small-scale farmers primarily growing food crops for their consumption. Additionally, they cultivate certain cash crops such as coffee, tobacco, macadamia, and cotton. On the other hand, the estate sector comprises a much smaller number of large-scale farmers who focus predominantly on producing crops for the export market. Hence, there exists an enduring and urgent need for cooperative efforts aimed at increasing agricultural yield within the smallholder sub-sector, particularly focusing on subsistence food crops.

Maize is the primary food crop and holds significant importance as the staple crop in Malawi. It is predominantly grown by smallholder farmers on marginal land sizes (FAO, 2018). Crop cultivation plays a vital role in Malawi, serving as a critical catalyst for the local economy. The food security situation in Malawi is primarily influenced by the patterns observed in small-scale maize farming. The subsistence farming system, associated with low crop diversification, has not only left the food system vulnerable to the vagaries of climate change, pests, and animal diseases but has also witnessed stagnation in productivity (FAO et al., 2023). The country faces a substantial constraint in soil and nutrient depletion, which poses a significant obstacle to achieving food security and fostering economic growth at a national level. The available data for Malawi suggests that 36.7% of the population still faces challenges accessing an adequate food supply (Aberman et al., 2018).

To achieve food security, one of the key focus areas has been the implementation of agricultural subsidy programs in Malawi. The strategy has been implemented by the Government through supporting resource-poor farmers to access adequate farm inputs, specifically maize seed and fertilizers for maize production since the 1990s. The program later evolved into a large-scale subsidy program in which private-sector companies were permitted to directly sell fertilizer to farmers in exchange for coupons (Kaiyatsa et al., 2018). The very first large subsidy program in recent years, the Farm Input Subsidy Program (FISP) was the much-publicized program implemented in 2005 targeting smallholder farmers with subsidized maize seed and fertilizers across the country (Nhlengethwa et al., 2023). Under the initiative, each farm household received coupons to purchase two bags of 50 kg of nitrogen fertilizers and 5 kg of maize seed (Logistic Unit, 2016).

The Ministry of Agriculture in Malawi reported that maize yield increased across the country following the implementation of the FISP. For example, maize yields were less than 1.3 metric tons (mt) per hectare (ha) before 2005/06 and increased to just above 2.0 mt per ha with the introduction of the Farm Input Subsidy Program (FISP) in the 2005/06 production season (MOAIWD, 2016). However, evidence depicts that the effects of the subsidy program on poverty were mixed. Chirwa (2010) found that those who received FISP inputs had an 8.2% increase in per capita incomes, but then again Ricker-Gilbert and Jayne (2012) found no substantial and significant effect on the household assets, total income, or off-farm income. Nevertheless, the increase in maize yield in the subsequent season prompted the acknowledgment of the FISP as a feasible strategy for enhancing the overall food security of the nation. Consequently, in the 2006/2007 agricultural season, the program was expanded to encompass a larger number of smallholder farmers. This expansion involved collaborating with suppliers with extensive retail networks and maintaining substantial fertilizer reserves after the season (IFDC, 2018). In 2007, a consortium comprising 20 prominent private manufacturers, importers, and synthetic (NPK) fertilizer suppliers established the Fertilizer Association of Malawi (FAM). Since its inception, FAM has played a pivotal role in facilitating the effective distribution of fertilizers through the Affordable Inputs Program (AIP). This program aims to provide subsidized agricultural inputs, specifically maize seed, and nitrogen fertilizers, targeting 4,279,100 smallholder farmers.

Regardless of the decades-long efforts in implementing agricultural subsidy programs to increase access to fertilizer by smallholder farmers, soil degradation and climate change remain significant challenges to attaining food security in Malawi. According to a report by GOM (2021), a staggering 5.4 million people in Malawi - both in rural and semi-urban areas - are currently classified as severely chronically food insecure. In the short term, climate change may benefit maize production but increased maize production may worsen soil degradation (Stevens and Madani, 2016). Msowoya et al. (2016) show that maize production may drop by 14% in central Malawi by 2050 and by 33% by the end of the century. Over the long term, climate change will drive down yields, as well as the nutritional content of plants (Challinor et al., 2014; Smith and Myers, 2018). The depletion of major nutrients, particularly nitrogen (N), severely affects soil fertility and maize productivity in Malawi (FAO, 2018).

The state of soil fertility in SSA is deteriorating rapidly, compounding the already dire situation (Mgomezulu et al., 2024). Although applying fertilizer is a method for rapidly restoring depleted soil nutrients, and indeed, the primary aim of the Malawi Government's subsidy programs, there's a necessity to encourage farmers to use fertilizers efficiently. This is crucial for addressing soil degradation and the declining yields of maize in a sustainable manner. Current fertilizer application is based on blanket recommendations that focus on N and P, and to a lesser extent S, although there are indications for the need to address soil acidity and deficiency of other nutrients to match the wide variability of soil types and nutrient levels across Malawi (Mutegi et al., 2015). Emissions from extensively fertilized agricultural soils due to blanket application may contribute to rising temperatures and exacerbate the decline in maize yields over the medium to long term. Over a quarter of farmers surveyed in the 2006/2007 and 2008/2009 Agricultural Inputs Support Surveys (AISS) reported yield loss due to adverse weather conditions (Snapp et al., 2014).

Since the 1990s, Malawi has maintained very low standard fertilizer application rates for maize which are either 69 kg or 92 kg of nitrogen fertilizer per hectare following the blanket recommendation. According to Amali and Namo (2014), for hybrid maize, 400 kg per hectare of NPK is recommended to be applied just before planting, which should be followed up four weeks after planting with 250 kg of CAN per hectare as side dressing. Such a rate can be achieved through site-specific fertilizer application following a soil test report to ensure fertilizer use efficiency. Chilimba and Nkosi (2014) reported that in recent attempts to develop specific fertilizers, the Department of Agricultural Research Service (DARS) developed soil fertility maps but had not yet linked these to site-specific fertilizer recommendations.

Malawian smallholder farmers have been producing maize as a staple food crop for many generations. The soil remains inherently fertile, although they are increasingly depleted of organic matter and certain nutrients such as N, P, and S (Waddington et al., 2015). However, blanket application of fertilizers to improve soil fertility is also environmentally hazardous, particularly due to emerging evidence suggesting increased accumulation of greenhouse gases in the upper atmosphere due to excessive application of fertilizer. This phenomenon is believed to contribute to climate alterations (Sejian et al., 2015). Therefore, specific fertilizer applications to match soil nutrient deficiencies may help realize a synergy for simultaneously addressing the current concerns of soil degradation and climate change in maize production systems.

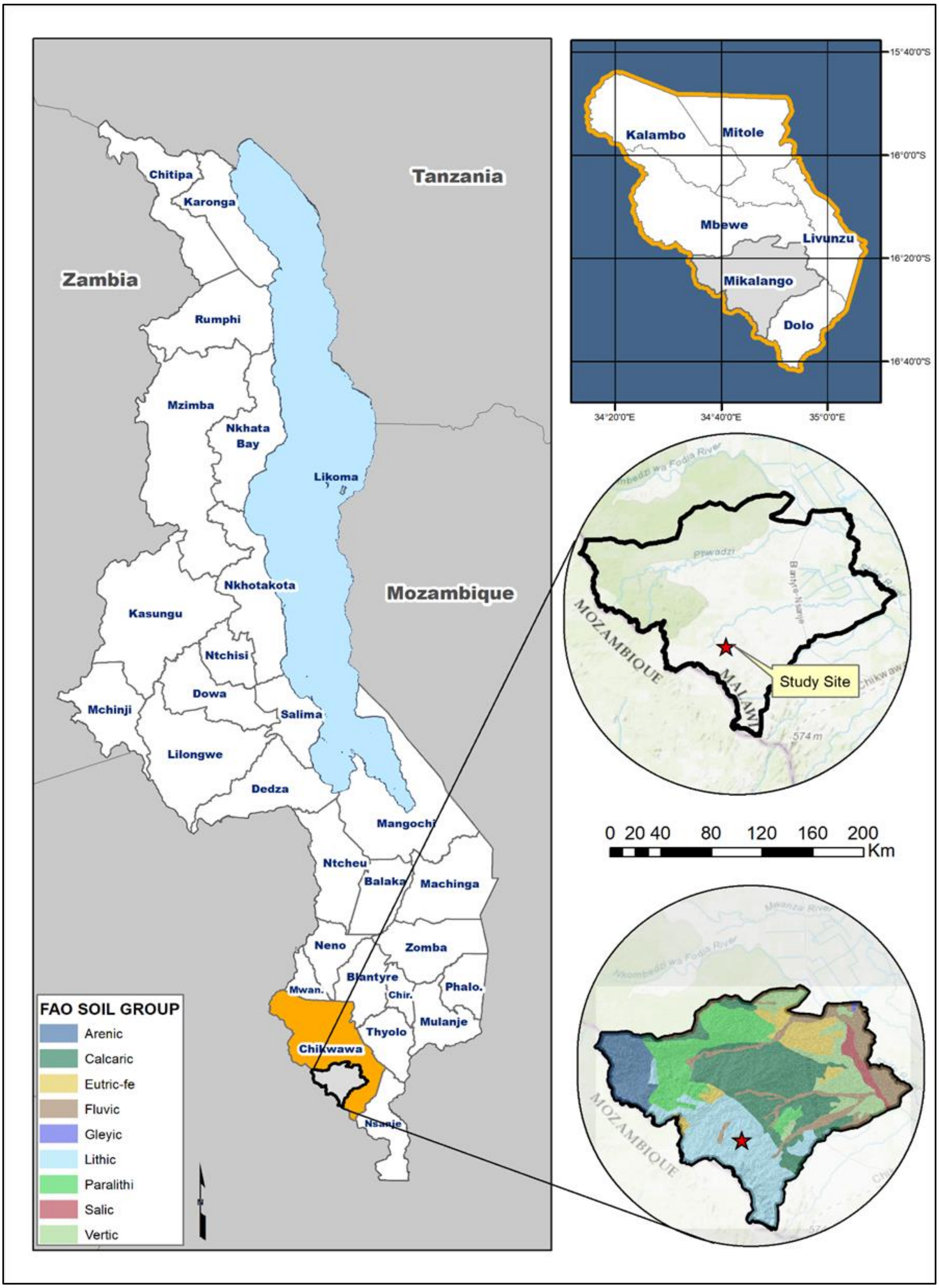
METHODOLOGY

Study Area

The study was conducted at Mikalango in Chikwawa district, Southern Malawi, located at latitude -16° 47' 07" South and longitude 34° 76' 24" East (Figure 1). The area's climatic conditions are generally warm, with mean monthly temperatures ranging between 27°C to 40°C and mean annual rainfall ranging between 0 to 600 mm, coinciding with Malawi's lakeshore, middle, and upper shire agroecological zone (Benson, 1998). Food crops grown by farmers include sorghum and millet, while maize is rarely produced due to the site's soil fertility status and extreme climatic conditions.

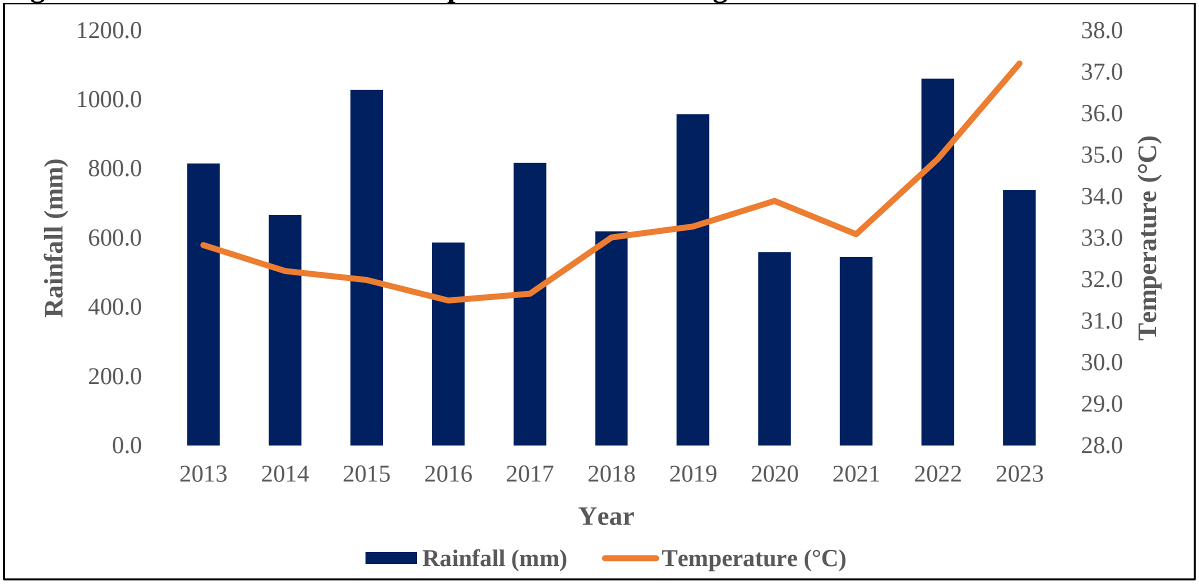
Topographically, the area is characterized by low elevation and flat terrain, situated at an altitude of 37 meters above sea level. The soil type is heavy clay, also known as vertosols and typically associated with low plant-available nutrients are common in the area. Before setting up the experiment, soil samples were collected randomly from the site using an auger at 0-40 cm depths. Subsequently, a composite sample weighing 1 kg was made from these collected samples to conduct laboratory analysis on the soil, aiming to characterize its physicochemical properties and determine its fertility status. A second round of soil sampling was conducted after harvesting by collecting soil samples from the treatment plots on the site to assess the treatment effects on physicochemical properties.

Figure 1: Location Map of Mikalango EPA, Chikwawa, Malawi



Data Source: Landscape portal

Figure 2: Annual Rainfall and Temperatures at Mikalango in the last decade



Data Source: Ngabu, Chikwawa Weather Station

Treatments and Experimental Design

A randomized complete block design (RCBD) consisting of 5 treatments and 5 replications was used to set up the experiment. Treatments included Malawi's nationally recommended maize fertilizer blend (23:10:5+6S+1Zn as basal dress and 46% N as top dress), site-specific fertilizer blend (23:18:0+6S+2Zn), mixed fertilizer (NPK 13:6:3+5S+1Zn) consisting of a mixture of the national fertilizer and chicken organic manure, and finally chicken organic manure alone (NPK 2:0.8:1.2+5S+0.6Zn). The control condition (0:0:0) did not involve any fertilizer application. A hybrid maize variety, specifically DK 8033, introduced by Bayer Seed Company in 2017, renowned for its early maturation, resistance to drought, and high yield potential ranging from 6 to 10 t/ha, was utilized.

The size of each plot was 7 by 3 meters which had 5 planting rows of 7 meters long with a plant spacing of 75 centimeters apart. The distance between plots within each block was 1 meter, while the distance between blocks was 2 meters to maintain a wide distance which minimizes errors arising from confounding results due to the proximity of the blocks. The hybrid maize seed variety was then planted uniformly in each planting row at the recommended rate of 1 seed per station at 25 centimeters spacing in all the plots, according to MOA (2020). The process of treatment randomization was carried out with rigorous adherence to the principles of experimental design. Each block, having 5 treatment plots, was randomly assigned 5 pieces of a written paper, each bearing the name of one of the 5 treatments having thoroughly mixed the papers.

Basal fertilizer application was done soon after plant emergence where national and site-specific fertilizers were applied using the nationally recommended cup size number 5 (5 grams), mixed fertilizer using cup number 8 (8 grams), and manure using two handfuls applied at 10 centimeters space from the planting station and 10 centimeters deep to achieve a recommended fertilizer application rate of between 69 to 200 kg per hectare for optimum maize yields according to MOA (2020) planting guidelines. Urea was similarly applied as a top-dressing fertilizer for the national fertilizer twenty-one days after the administration of basal dressing fertilizer while the rest of the treatments had the same treatment applied for top dressing at twenty-one days. Every routine site preparation and management procedure was executed consistently across all treatment plots, including applying fungicides, pre-emergence herbicides, and vegetation control.

Data Collection

Initial Soil Sampling and Formulation of Site-Specific Fertilizer

Soil samples were collected from the site randomly following a zig-zag pattern before setting up the experiment in October 2021. These were used to make a composite sample of 1 kg which was taken to Bvumbwe Agriculture Research Station under the Ministry of Agriculture in Malawi to determine the site's soil physicochemical properties (Table 1). These results were then used to formulate the site-specific fertilizer blend based on the observed nutrient deficiencies in the soil.

Effects on Soil Physicochemical Properties

Post-harvest samples collected from each treatment plot on the research site were analyzed using different soil laboratory procedures to determine the effect of each treatment. The Bouyoucos hydrometer was used to analyze soil texture following a procedure outlined by van Reeuwijk in 2002. The power of hydrogen (pH) was determined using a pH meter following a method described by Black in 1965. Total N (%) was analyzed using the Kjeldahl procedure described by Hesse in 1971, while available phosphorus (P) was analyzed following the Bray-1 procedure outlined by Bray and Kurtz in 1945.

The Walkley-Black procedure was employed to determine organic carbon (OC), while the conversion factor (% organic matter = 1.72 × % carbon) was employed to determine Organic Matter (OM) as described by USDA in 1982. Calcium (Ca), magnesium (Mg), and potassium (K) were analyzed using the ammonium acetate method following the procedure described by van Reeuwijk in 2002. Micronutrients, namely iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn), were analyzed using the DTPA extraction method in accordance with guidelines provided by FAO in 2022.

Effects on Maize Growth and Yield Components

Different metrics were employed to gather data on maize growth and yield components on each treatment plot. For maize growth parameters, maize height (m) was collected from each of the five treatment replications using a tape measure by manually measuring the height of three sampled maize plants from the three middle plant rows and calculating a mean height for the treatment using the formula below.

$$\text{Maize height (m)}=\sum(h1 \dots h5)/5 \qquad (1)$$

Where h is the mean height of three sampled maize plants from each treatment replication. Leaf area index (LAI) was determined for each of the five treatment replications by calculating the leaf area of three sampled leaves using tape measure length and width metrics and dividing the result by the ground area covered by each sampled plant. Finally, the overall mean was computed for each treatment. LAI is presented in the formula below.

$$\text{Leaf Area Index}=\sum(\frac{LA}{GA}1 \dots . \frac{LA}{GA}5)/5 \qquad (2)$$

LA is the mean leaf area of three sampled leaves, and GA is the mean ground area covered by the three maize plants on which the leaves were sampled per each treatment replication. Leaf color index (LCI) was determined on each of the five treatment replications using a leaf color chart on three sampled maize leaves from the three middle plant rows at 21 days after planting where on the chart, 1 represented yellow, 2 represented light green and 3 represented green as shown on the formula below.

$$\text{Leaf Color Index} =\sum(C1 \dots C5)/5 \qquad (3)$$

The variable C is the mean color index of three sampled leaves from the middle rows per treatment replication. On maize yield parameters, cob length (m) was determined on each of the five treatment replications by measuring 3 maize cobs sampled from the three middle plant rows at the harvesting stage, 110 days after planting, as presented in the formula below.

Cob length (m)=$\sum(L1 \dots L5)/5$ (4)

L is the mean length of three sampled maize cobs on the middle rows per treatment replication. The plant biomass (measured in tons per hectare) was collected from each of the five treatment replicates utilizing a digital scale. This was executed by weighing maize stalks harvested from the three central plant rows, excluding the two outer plant rows during harvesting, as depicted in the provided formula below.

Plant biomass (t/ha) =$\sum(B1 \dots B5)/5$ (5)

B is the biomass weight of plants harvested from the three middle rows per treatment replication. Finally, grain yield (t/ha) was determined on each of the five treatment replications by weighing maize grains from the three central plant rows during harvesting, excluding the two border rows. The formula below was employed, where Y represents the grain yield of maize collected from the three middle plant rows for each treatment replication.

Grain yield (t ha) =$\sum(Y1 \dots Y5)/5$ (6)

Statistical Analysis

The data collected in this study was analyzed with the support of JMP Statistical Analysis Software (SAS) version 14.0.0 utilizing one-way analysis of variance to test the null hypothesis, which posits no variance between site-specific and blanket fertilization methods on soil physicochemical properties and maize yield. Mean distinctions were computed using the Least Significant Difference (LSD) test at a 5 % level of significance in a procedure outlined by Gomez and Gomez in 1984.**RESULTS**

Soil Analysis Results of Samples Collected from the Site Before the Experiment

The results of the initial soil samples collected from the research site before setting up the experiment indicated that the site generally had a loam soil type which was characterized by low nutrient levels. Soil physicochemical properties, such as pH, were observed to fall between moderately and slightly acidic ranges (between 5.8 and 6.5), with Organic Carbon (%OC) measuring at a very low range (from 0.84% to 0.86%), and Organic Matter (%OM) also registering in a low range (from 1.45% to 1.48%). Additionally, total nitrogen (N) was detected at a very low range (0.07% to 0.08%), while phosphorus (P) was also identified as falling within a low range (between 3.0 and 5.20 ppm).

The study further revealed that other soil physicochemical characteristics, including potassium (K), exhibited medium to high levels ranging from 0.47 to 0.8 cmol/kg. Sulphur (S) was in very low levels ranging from 0.03 ppm to 0.05 ppm while magnesium (Mg) ranged from 2.83 to 20.5 cmol/kg falling within a high range. Calcium (Ca) levels were similarly high, ranging from 24.03 to 61.7 cmol/kg. Finally, the levels of Zinc (Z) and Copper (Cu) were extremely low, ranging from 0.02 to 0.08 ppm and 0.1 to 0.11 ppm, respectively, whereas the levels of Manganese and Iron (Fe) were extremely high, ranging from 1890.93 to 2234.61 ppm and 991.27 to 1089.22 ppm, respectively. Table 1 summarizes the study's findings regarding initial soil physicochemical properties at the research site before the experiment was set up.

Table 1: Soil physicochemical properties at Mikalango

Soil property	Mikalango		
	Critical Value	**Top**	**Sub**
Depth	>0.88	0-20 cm	20-40 cm
pH	1.5	5.81	6.5
% OC	>0.1	0.84	0.86
% OM	15	1.45	1.48
% N	0.2	0.07	0.08
P (ppm)	0.2	3	5.2
S (ppm)		0.03	0.05

Soil property	Mikalango		
	Critical Value	**Top**	**Sub**
K (cmol/kg)		0.47	0.8
Ca (cmol/kg)	0.5	24.03	61.7
Mg (cmol/kg)		2.83	20.5
Zn (ppm)		0.02	0.08
Mn (ppm)		1890.93	2234.61
Cu (ppm)		0.1	0.11
Fe (ppm)		991.27	1089.22
Sand		37	35
Silt		38	40
Clay		25	25
Textural class		Loam	Loam

Effects on Soil Physicochemical Properties after the Experiment

The physical property results on soil texture indicated no significant difference ($p>0.05$) due to the different fertilization treatments. The elements of sand (36.2%), silt (38.8%), and clay (25.8%) corresponded to a range for a loam soil textural class in each treatment plot after the experiment. On chemical properties, the results revealed notable variations in macronutrients. Nitrogen (N) and Phosphorus (P) exhibited highly significant differences ($p<0.05$), while Potassium (K) exhibited a slightly significant difference ($p<0.05$) as a result of the different treatments. Site-specific fertilizer (0.81%) and national fertilizer (0.80%) treatments resulted in significantly higher N compared to mixed fertilizer (0.20%), manure (0.15%), and control (0.12%) treatments while significantly higher P was as a result of the site-specific fertilizer (0.31 ppm) treatment compared to national fertilizer (0.28 ppm), mixed fertilizer (0.27 ppm), manure (0.26 ppm), and control (0.25 ppm) treatments. On the other hand, significantly higher K was a result of national fertilizer (0.63 cmol/kg) compared to site-specific fertilizer (0.52 cmol/kg), mixed fertilizer (0.55 cmol/kg), manure (0.53 cmol/kg), and control (0.52 cmol/kg) treatments.

The results of micronutrients revealed that sulphur (S), and zinc (Zn) exhibited highly significant differences due to the different treatments. Sulphur (S) significantly increased as a result of site-specific fertilizer application (24.2 ppm) compared to the application of national fertilizer (14.4 ppm), mixed fertilizer (12.8 ppm), manure (12.4 ppm), and control (0.10 ppm). Similarly, Zn levels also significantly increased with site-specific fertilizer application (1.92 ppm) compared to the application of national fertilizer (1.30 ppm), mixed fertilizer (1.14), manure (0.52 ppm), and the control treatment (0.02 ppm). Meanwhile, the power of hydrogen (pH), organic carbon (OC), and organic matter (OM) did not exhibit significant differences due to the different treatments. The pH levels were recorded at 6.5 in plots with site-specific fertilizer treatment, 5.5 in national fertilizer treatment, 6.2 in mixed fertilizer treatment, 5.8 in manure treatment, and 5.7 in the control treatment. The OC levels were recorded at 0.77% in plots with site-specific fertilizer treatment, 0.74% in national fertilizer treatment, 0.82% in mixed fertilizer and control treatments, and 0.86% in manure treatment. Further, the OM levels were recorded at 1.32% in plots with site-specific fertilizer treatment, 1.27% in national fertilizer treatment, 1.40% in mixed fertilizer treatment, 1.48% in manure treatment, and 1.41% in control treatment.

Furthermore, the results on other trace elements indicated no significant differences ($p>0.05$). Magnesium (Mg) levels were identical at 0.28 cmol/kg in plots treated with site-specific, national, and mixed fertilizers. Similarly, the Mg levels were consistent at 0.29 cmol/kg in plots treated with manure and the control treatments. Calcium (Ca) levels were at 24.0 cmol/kg in plots treated with site-specific fertilizer treatment, 22.2 cmol/kg in plots with national fertilizer, 22.4 cmol/kg in plots with mixed fertilizer, 21.6 cmol/kg in plots with manure, and 23.1 cmol/kg in plots with the control treatment which did not posit significant differences. Iron (Fe) levels were at 160 ppm in plots treated with site-specific fertilizer, 152 ppm in plots treated with national and mixed fertilizers, 150 ppm in plots treated by manure, and 148 ppm in plots with the control treatment which did not posit significant differences as well. Copper (Cu) levels were at 5.30 ppm in plots treated with site-specific fertilizer, 5.22 ppm in plots treated with national fertilizer, 5.24 ppm in plots treated with mixed fertilizer, 5.06 ppm in plots treated with manure, and 5.16 ppm in plots with the control treatment. Manganese (Mn) levels were identical at 300 ppm in plots treated with site-specific fertilizer and manure, 290 ppm in plots treated with national fertilizer, 282 ppm in plots treated with mixed fertilizer, and 292 ppm in plots with the manure treatment. Table 2 summarizes the study's findings regarding soil physicochemical properties at the research site after the experiment.

Effects on Maize Growth and Yield Components

Maize growth components such as plant height (m), leaf area index, and leaf colour index exhibited significant differences ($p<0.05$) due to the different fertilization treatments. The height of maize plants significantly increased in maize plots that were treated with site-specific fertilizer (2.29 m), surpassing those treated with national fertilizer (2.13 m), mixed fertilizer (2.07 m), manure (1.90 m), and control (1.82 m) treatments. The leaf area index significantly increased in maize plots that were treated with site-specific fertilizer (3.92), national fertilizer (3.58), and mixed fertilizer (3.41) compared to those treated with manure (2.98) and control (2.22) treatments. Similarly, the leaf color index also significantly increased in maize plots that were treated with site-specific fertilizer (3.0), national fertilizer (3.0), and mixed fertilizer (2.80) surpassing manure (2.0) and control (1.0) treatments.

Meanwhile, maize yield components such as cob length (m), plant biomass (t/ha), and grain yield (t/ha) exhibited significant differences ($p<0.05$) due to the different fertilization treatments (Table 3). Cob length (m) significantly increased in maize plots treated with site-specific fertilizer (0.40 m), national fertilizer (0.38 m), and mixed fertilizer (0.38 m) surpassing the plots treated with manure (0.36 m), and control (0.33 m) treatments. Plant biomass (t/ha) significantly increased in maize plots treated with site-specific fertilizer (3.41 t/ha) compared to the plots treated with national fertilizer (2.77 t/ha), mixed fertilizer (2.64 t/ha), manure (2.05 t/ha), and control (1.52 t/ha) treatments. Similarly, grain yield (t/ha) significantly increased in maize plots that were treated with site-specific fertilizer (7.03 t/ha) compared to the plots that were treated with national fertilizer (5.75 t/ha), mixed fertilizer (5.43 t/ha), manure (3.80 t/ha), and control (2.40 t/ha) treatments.

DISCUSSION

The study showed that site-specific fertilizer application significantly improved essential soil physicochemical properties, maize growth, and yield components at the research site. Maize farming is predominant in Malawian farming systems. The crop occupies at least 60% of cultivated land and is farmed by 97% of farming households (White, 2019). However, the productivity of maize is hindered by the limited uptake of advanced technologies, inadequate soil fertility, unpredictable rainfall patterns, and the prevalence of pests and diseases (MOA, 2020). Results of previous studies showed a variability in most soil parameters across the agricultural development divisions implying that no single fertilizer recommendation can work for all the regions (Mutegi et al., 2015).

Prior soil fertility status assessment in this study at the Mikalango research site revealed that the essential physicochemical properties were observed to be at insufficient levels. This indicates that the research site had a deficient

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fertility status and lacked the necessary primary nutrients for achieving optimal maize yields. These findings are collaborated by multiple other studies, which indicated that most soils in Malawi are experiencing a significant decline in essential nutrients. Therefore, it is necessary to restore these nutrients using appropriate fertilizers (Snapp, 2016; Waddington et al., 2015; Saka et al., 2006).

Effects of the different fertilization treatments on soil physicochemical properties were observed due to changes in certain physicochemical qualities on the research site following the experiment. The soil texture remained consistent across the various fertilizer treatments on the site, indicating that the treatments did not affect the soil classification, which was predominantly loam. This outcome is likely due to the higher proportion of chemical elements compared to organic elements present in the different fertilizer treatments. The findings are further supported by the observation by Jaja (2016) that soil texture is rarely affected by fertilizer application, as it directly relates to nutrient retention and drainage capabilities of the soil. Similarly, the pH of the research site did not significantly vary across the different fertilization treatments and was in a good range for maize production (5.7 to 6.5), indicating that each fertilizer treatment created an environment that was equally favourable for the majority of nutrients to be absorbed by plants. Brady and Weil (1996) stated that soil pH values below 5.0 are considered acidic and unfavourable for the growth and development of most crops, including maize. In very acidic soils ($pH<5.0$), several macro and micronutrients such as calcium, magnesium, nitrate-nitrogen, phosphorus, boron, and molybdenum are deficient. In contrast, elements like aluminum, iron, and manganese are abundant, sometimes reaching toxic levels for certain plants (Belachew and Abera, 2010). Therefore, soil pH significantly influences the mobility of trace elements in the soil and is a crucial factor influencing the absorption of nutrients by plants.

Additionally, Organic carbon (OC) and Organic matter (OM) did also not significantly vary across the different fertilization treatments and were at low levels (<2), which can most likely be explained by the previous conventional tillage farming practices used on the site. Organic carbon (OC) plays a critical role in decomposing organic matter within the soil, whereas organic matter (OM) fosters optimal conditions for plant growth. It aids in moisture retention, temperature, and pH regulation, enhances aeration, and serves as a continuous food source for decomposers. The findings correlated with the results of a related study by Snapp (2016) conducted in the northern and southern regions of Malawi where the lowest OC levels averaging 1.2% were recorded. Wolf and Snyder (2003) also noted that soil fertility will continue to decline with conventional tillage if organic matter loss and decomposition are not prevented, rendering the system unsustainable.

On the other hand, significant differences observed in macronutrients (N, P, K) could be attributed to the influence of the different fertilization treatments. Total N fixed was notably higher in soils where maize plants were treated with site-specific and national fertilizer treatments due to the high %N in these fertilizer blends compared to the other treatments: mixed fertilizer, manure, and control while available P fixed was notably higher in soils treated with site-specific fertilizer due to high P content in the site-specific fertilizer blend compared to the other fertilizer treatments: national fertilizer, mixed fertilizer, and manure whereas exchangeable K fixed was slightly higher in soils where plants were treated with the national fertilizer blend due to high K content in the national fertilizer blend but also due to the readily available K in the soils at the research site as observed by the availability of K in plots that were treated by site-specific fertilizer and control treatments which did not contain any K. Therefore, the high increase in N and P means that the site had low levels of these nutrients, while K was adequate, making site-specific blend the most ideal and cost-effective fertilizer in supplying both N and P in optimum levels on the site. These results are supported by Chilimba and

Nkosi (2014), who reported an average of low to medium thresholds of N and P, while a high threshold of K was observed in Mikalango, southern Malawi.

Similarly, some micronutrients or trace elements such as sulphur (S) and zinc (Zn) also indicated significant differences due to the different fertilization treatments. Plots treated with site-specific fertilizer had significantly higher S and Zn than those treated with the other fertilizer treatments: national fertilizer, mixed fertilizer, manure, and control in their respective order, most likely because the site-specific fertilizer had slightly higher S and Zn content than the other treatments making it the ideal fertilizer for the site given the significance of these micronutrients in plant nutrient retention. These findings are reinforced by earlier fertilizer trials, which demonstrated that micronutrients like sulfur (S) and zinc (Zn) are essential for improving crop response to nitrogen (N) and phosphorus (P) fertilizers (Mutegi et al., 2015).

Meanwhile, other micronutrients, including magnesium (Mg), calcium (Ca), iron (Fe), copper (Cu), and manganese (Mn), showed no significant differences due to the various fertilizer treatments. This indicates that the fertilizer treatments did not impact the levels of these micronutrients. This is likely due to the low levels or absence of these trace elements in the composition of the fertilizer treatment blends. The trace elements were not included in the site-specific fertilizer because plants only need them in small quantities, and the soil at the research site already had enough of these elements, as indicated by the initial soil fertility results for the Mikalango area. The results align with Snapp's (2016) findings, which showed that nearly all soils in Malawi contain adequate trace elements like Ca. Previous research has also highlighted a low cation exchange capacity in Malawi, a parameter not examined in this study. However, low cation exchange capacity is likely to affect the availability of Ca (Mwandemere and Robertson, 1975).

On the other hand, maize growth and yield components showed significant differences, underscoring the impact of the different fertilization treatments on both aspects of maize cultivation. On maize growth components, height (m) was by average significantly higher in plots treated with site-specific fertilizer compared to the other fertilizer treatments due to a combination of sufficient N and P in site-specific fertilizer blend, leaf area index (LAI) was by average significantly higher in plots treated with site-specific fertilizer, national fertilizer, and mixed fertilizer compared to the rest of the treatments due to comparatively high N in the three fertilizer blends and leaf colour was also by average significantly better in plots treated with site-specific fertilizer, national fertilizer, and mixed fertilizer compared to the rest of the treatments due to comparatively higher N and S in the three fertilizer blends. These findings agree with other studies in which nitrogen (N) is generally the most crop-limiting nutrient (Mutegi et al., 2015). Maize plant growth is slow, resulting in stunted plants that will mature early without sufficient nitrogen (Baijukya et al., 2020).

Table 2: Effects on Soil physicochemical properties on the research site after the experiment

Treatment	Mean soil physicochemical properties															
	pH	**OC (%)**	**OM (%)**	**N (%)**	**P (ppm)**	**K (cmol/ kg)**	**S (ppm)**	**Mg (cmol/ kg)**	**Zn (ppm)**	**Ca (cmol/ kg)**	**Fe (ppm)**	**Cu (ppm)**	**Mn (ppm)**	**Sand (%)**	**Silt (%)**	**Clay (%)**
Site-specific	6.5	0.77	1.32	0.81^{a}	0.31^{a}	0.52^{b}	24.2^{a}	0.28	1.92^{a}	24.0	160	5.30	300	36.2	38.0	25.0
National fertilizer	5.5	0.74	1.27	0.80^{a}	0.28^{b}	0.63^{a}	14.4^{b}	0.28	1.30^{b}	22.2	152	5.22	290	35.2	38.8	25.4
Mixed fertilizer	6.2	0.82	1.4	0.20^{b}	0.27^{b}	0.55^{b}	12.8^{b}	0.28	1.14^{b}	22.4	152	5.24	282	33.2	38.8	25.8
Manure	5.8	0.86	1.48	0.15^{b}	0.26^{b}	0.53^{b}	12.4^{b}	0.29	0.52^{c}	21.6	150	5.06	300	33.8	38.8	25.8
Control	5.7	0.82	1.41	0.12^{b}	0.25^{c}	0.52^{b}	0.1^{c}	0.29	0.02^{d}	23.1	148	5.16	292	36.2	38.8	25.8
LSD (5%)	0.28^{ns}	0.10^{ns}	0.17^{ns}	0.41	0.02	0.10	3.20	0.01^{ns}	0.12	2.6^{ns}	18.66^{ns}	0.38^{ns}	38.88^{ns}	4.44^{ns}	1.67^{ns}	1.37^{ns}
SE	0.09	0.03	0.06	0.14	0.01	0.03	1.07	0.003	0.04	0.87	6.23	0.13	12.97	1.48	0.55	0.46
CV%	6.95	1.87	1.8	14.3	0.97	2.62	3.74	0.50	1.84	1.71	1.83	1.10	1.98	1.89	0.64	0.80

Means with different letters in the same column are significantly different at p<0.05; LSD = least significant difference at 5% significant level; ns = non-significant difference; S.E. = standard error and CV = coefficient of variation

Table 3: Effects on Maize growth and yield components on the research site

Treatment	Mean maize growth and yield components					
	Plant height (m)	**Leaf area index (LAI)**	**Leaf color index (1-3)**	**Cob length (m)**	**Plant biomass (t/ha)**	**Grain yield (t/ha)**
Site-specific fertilizer	2.29^{a}	3.92^{a}	3.0^{a}	0.40^{a}	3.41^{a}	7.03^{a}
National fertilizer	2.13^{b}	3.58^{a}	3.0^{a}	0.38^{a}	2.77^{b}	5.75^{b}
Mixed fertilizer	2.07^{b}	3.41^{a}	2.80^{a}	0.38^{a}	2.64^{bc}	5.43^{b}
Manure	1.90^{c}	2.98^{b}	2.0^{b}	0.36^{ab}	2.05^{cd}	3.80^{c}
Control	1.82^{c}	2.22^{b}	1.0^{c}	0.33^{b}	1.52^{d}	2.40^{d}
LSD (5%)	0.21	0.78	0.27	0.02	0.31	0.45
SE	0.07	0.26	0.09	0.007	0.1	0.15
CV%	1.54	3.59	1.69	0.85	2.46	1.85

Means with different letters in the same column are significantly different at p<0.05; LSD = least significant difference at 5% significant level; SE = standard error and CV = coefficient of variation

Regarding maize yield components, the cob length (measured in meters) was significantly greater on average in maize harvested from plots treated with site-specific fertilizer, national fertilizer, and mixed fertilizer compared to the other treatments. This was due to the comparatively high N in these three fertilizer treatments. Additionally, the plant biomass (measured in tons per hectare) was significantly higher on average in maize harvested from plots treated with site-specific fertilizer compared to the other treatments. This was due to sufficient N and P in the site-specific fertilizer, unlike the rest of the fertilizer treatments. Furthermore, the highest average grain yield was attained in maize plots with the site-specific fertilizer treatment. The observed effects can be attributed to the site-specific fertilizer, which contained elevated levels of N, P, and Zn. Previous studies have also documented similar results, indicating that higher nitrogen levels resulted in superior maize cobs. Mthambala et al. (2022) observed that P is used for grain filling which affected maize yield in their study. Additionally, a study conducted by Kumari (2017), found that the application of N and P fertilizers significantly increased the biomass of harvested plants. Similarly, researchers conducting related studies on maize have also discovered that increased levels of N, P, K, and Zn result in higher grain yield, plant biomass, and seed weight (Bashan et al., 2013; Mwafulirwa, 2023).

CONCLUSION

The research concluded that site-specific fertilizer application had the greatest influence on soil physicochemical properties, maize growth, and yield components at Mikalango, surpassing the application of the current blanket fertilizer recommendations. Initial soil test results before setting up the experiment revealed notably deficient levels of essential physicochemical properties at the site. Nevertheless, the post-experiment analysis revealed that applying fertilizer tailored to the specific site led to a substantial enhancement in most soil properties. The maize growth and yield results similarly showed a significant increase in most components due to the site-specific fertilizer application. This enabled the realization of the maize variety's potential yield ranging from 6 to 10 tons per hectare, as opposed to the current yields of 2 to 5 tons per hectare achieved with blanket fertilizer application.

Hence, it is imperative to promote the practice of soil testing and site-specific fertilizer blending in all agroecological zones, as it represents the most efficient method for enhancing soil fertility and boosting crop yields. In addition, site-specific fertilizers, tailored to the specific soil conditions, can contribute to climate change mitigation in agriculture. They achieve this by preventing excessive application of N and P fertilizers, which can lead to greenhouse gas emissions and leaching of nutrients from heavily fertilized agricultural soils. These practices ultimately contribute to the alteration of the climate.

CONFLICT OF INTERESTS

No conflicts of interest have been disclosed by the authors.

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Abbreviations

AIP, Affordable Inputs Program; **DARS**, Department of Agricultural Research Services; **FAM,** Fertilizer Association of Malawi; **FAO,** Food and Agriculture Organization; **FISP,** Farm Input Subsidy Program; **GOM,** Government of Malawi; **MOA,** Ministry of Agriculture.

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