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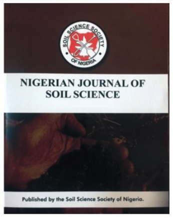

Zinc Estimation Needs for Improvement of *Vigna radiata* Productivity in Savannah Soils of South-eastern Ecological Zone, Nigeria.

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ABSTRACT

To identify the quantity of optimal rates of zinc fertilizer needed for maximizing *Vigna radiata* yield, a greenhouse and field studies were conducted in two cropping seasons. For the greenhouse, zinc sulphate was applied at five dosages (0, 5, 15, and 20 kg ha^{-1}) and at seven dosages (0, 3, 6, 9, 12, 15, and 18 kg ha^{-1}) for field study. The sandy loam (SL) soil samples had modest levels of OC (1.08 gkg^{-1}) and ECEC (4.38 cmol kg^{-1}) and were very strongly acidic (4.73). Using DTPA, EDTA, NH_4OAc, and HCl methods, the accessible zinc in the soils had mean values of 1.03, 1.65, 1.23, and 2.17 mgkg^{-1}, respectively. Using Cate-Nelson graphical and statistical models, the responses of the mungbean yield components to the Zn test values in the soil were established. In order to get the highest possible mungbean production in the Typic Paleudult, appropriate critical Zn levels were determined. Zn levels considerably raised the mungbean grain yields, Zn uptake, and Zn soil budget. Both the greenhouse and field studies, maximum utilization (1.27 mgplant^{-1}) and grain yields (9.93 kgha^{-1}) of mungbean were estimated at 13.01 and 12.53 kg Zn ha^{-1}, respectively.

1.0 Introduction

One of the most significant short-duration, drought-tolerant pulse crops that is frequently used as a protein supplement is mungbean (Vigna radiata (L.) R. Wilczek), which is a member of the Fabaceae family (previously known as Leguminosae (Jayne, 2010; Roy, 2014). It is a significant crop of legumes that was just added to Nigerian cuisine (Eteng, *et al*., 2024). Due to its outstanding characteristics in nitrogen fixation (Yakadri 2002; Asaduzzaman et al., 2008 and Sadeghipour et al., 2010) and nutritional significance in food diet (Nadeem et al., 2004; Jamal et al., 2018), it can meet the greater food needs of the developing countries. In terms of nutrition, Vigna radiata has 1-3 percent fat, 50.4% carbs, 3.5–4.5 percent fibers, and 4.5–5.5 percent ash. For every 100 grams of seed, there are 132 and 367 mg of calcium and phosphorus (Hossain, 2008; Kumar, 2014). As a result, per 100 grams of dried Vigna radiate seeds, Roy (2014) and Jamal et al. (2018) observed values of vitamin A (94 mg), iron (7.3 mg), calcium (124 mg), zinc (3 mg), and folate (549 mg).

Vigna radiata demands a good crop mineral nutrition for optimum growth (Marschner, 1995), and sustainable production (Nadeem, *et al*., 2004 and Jayne, 2010). Accordingly, Marschner (1995) and Kabata-Pendias, 2010) showed that, Zn is a micronutrient element with known essential functions for crops which, is readily absorbed by the crop roots and translocated to the above-ground plant parts. With this vital information at hand, it therefore suggests that, the low grain yield performance of mungbean in the farmer's fields of the study area could be an indication of possible deficiencies of Zn nutrient in the soil (Sillanpaa, 1990; Kabata-Pendias, 2010).

Zinc deficiency is the most widespread micronutrient deficiency in the world (Husain *et al.*, 2021). Zinc deficiency is ranked as the 5th leading risk factor for diseases (e.g. diarrhoea and pneumonia in children) in the developing countries (WHO 2002). It's deficiency in crop-plants has been one of the major concerns globally (Jamal *et al.*, 2018). Generally, the deficiency in soils does not support optimum crop yields because, plant growth becomes retarded by the deficiency leading to low yields (Sillanpaa, 1990; Chude *et al.,* 2004, Eteng, *et al*., 2024). The supplying of sufficient amount of appropriate plant nutrient could increase yield production (Nadeem, *et al*., 2004; Kaya *et al*., 2017). Biofortification of food crops with Zn by either breeding for higher uptake efficiency or by fertilization can be an effective strategy to address widespread dietary deficiencies in human populations (Graham et al. 2001, Eteng *et al*., 2024). The uptake of Zn nutrient elements by plant could increase proportionally to increasing soil micronutrients cations when, the soil contains substantial concentration in soil solution though, can be affected by the presence of major nutrients due to either negative (antagonistic) or positive (synergistic) interactions (Sillanpaa, 1990; Marschner, 1995; Kabata-Pendias, 2010).

One can establish a relationship between soil nutrient levels and plant response since the plant is able to absorb the micronutrient element from the soil (Cate and Nelson, 1965; 1971). The optimum concentration level is a helpful concept that is frequently used in agricultural production to relate soil -plant nutrient and crop output (Tariq et al., 2014). Accordingly, calibration functions using crop response data for every crop may be employed to determine an appropriate fertilizer prescription (Enwezor, et al., 1981, 1989 and 1990).

Therefore, one of the numerous elements that could be causing a substantial gap between the seed output of farmers (downstream) and that which could be produced under experimental (upstream) research circumstances is the limitation of Zn nutrients. The optimum Zn rate for different cropping systems is this ecological zone is not available. Also, not much information has been established about mungbeans' zinc needs in shale derived savannah soils of southeast Nigeria. Previous investigation has associated the lack of knowledge regarding mungbean's Zn requirements to their low demand for micronutrients for grain yields due to their relatively low yield potential. Therefore, the aim of this study was to ascertain the Zn needs for mungbean yield performances that are optimal in savannah soils generated from shale in southeast Nigeria.

2.0 MATERIALS AND METHODS

2.1 Description of study area

The study was conducted in a Shale derived savannah soils of Ebonyi State, Nigeria (Lat. $6^{o}04^{I}$ 59.99E – $8^{o}07^{I}$ 47.42E and Long. 6^{o} 15^{I} 0.00N – $6^{o}31^{I}$ 18.62N). The soil has been classified as a Typic Paleudult according to USDA system of classification (USDA, 2006). The soils have a high potential for dual seasons arable crop production was selected to represent shale derived soil of, Ebonyi State, Nigeria. The soil of the study area has been intensively and extensively put for the cultivation of many improved crop varieties (Table 1).

2.2 Soil sampling and sample collection

Six (6) composite surface (0-20 cm) shale derived savannah soil samples were collected from six different locations across Ebonyi State, Nigeria (Table 1) in areas where, the farmers have never applied any micronutrient fertilizers. The soils were air-dried and passed through 2.0 mm sieve. A portion of the sieved soil samples were bagged in plastic bags and taking to the NRCRI, Umudike Laboratory.

Table 1: Soil sample location and their coordinates used for the study

S/No	Location	Coordinates points		Cropping system
1	Abakalike	N 6^{o} 19^{l} 23.02	E8^{o} 06^{l} 43.24	Okra, rice, cassava
2	Afikpo	N 5^{o} 53^{l} 27.93	E7^{o} 55^{l} 50.46	Yam, cassava, sweet potato
3	Ikwo	N 6^{o} 7^{l} 54.39	E8^{o} 08^{l} 28.67	Cassava, rice, yam, maize
4	Ishiagu	N 5^{o} 57^{l} 18.78	E7^{o} 33^{l} 35.76	Rice, yam, maize
5	Ohaozara	N 5^{o} 59^{l} 30.21	E7^{o} 45^{l} 48.25	Sweet potato, yam, cassava
6	Uwana	N 5^{o} 51^{l} 57.67	E7^{o} 56^{l} 44.39	Rice, Yam, cassava

2.3 Laboratory Study

The soils samples collected were analyzed to determine the physical and chemical properties, status of available Zn and the critical Zn range (CNR) having been informed that Zn nutrient was a limiting micronutrients (Enwezor *et al*., 1990). 120g of each of the soil samples were subjected to determine the total and available forms of zinc by Aqua Regia Digestion method of extraction. The pH (H_2O) was analyzed as described by Thomas (1996), organic carbon was determined by wet oxidation (Nelson and Sommer, 1996), available P was determined by Bray I method (Kuo, 1996), and total N was determined by Kjeldahl procedure of Bremner (1996). Effective cation exchange capacity and exchangeable cations were determined by the method described by Sumner and Miller (1996). Zinc concentration in soil was extracted with DTPA, EDTA, NH_4OAc and HCl as described by Whitney (1988) and modified by Eteng *et al.* (2014) and determined with atomic adsorption spectrophotosmeter (AAS) (Unicam Solaar 32: Zn Astm D1691).

2.4 Greenhouse Study

The greenhouse study was set up to evaluate optimum Zn requirement rate from the mungbean shoots. Five levels of $ZnSO_4.7H_2O$ and six soil samples make up the treatments. The ZnSO4 treatments included five levels of Zn at 0, 5, 10, 15, and 20 kg ha^{-1}, whereas the soil treatments comprised of soils from the six locations (Table 1). Ten (10) kg of soil samples were collected from each of the six (6) locations, weighed, and then put on a flat plastic receiver with additional 15 L plastic containers. Mungbean (Vigna radiata (L.)) seeds were used as the test crop. Utilizing a completely randomized design (CRD) and four factorial arrangement replications, the study yielded 120 observations (containers) (6 soil locations x 5 levels of Zn x 4 reps.).

The soils were sieved to get rid of plant roots and rocks before weighing into 15-liter plastic containers, placed on a flat plastic receiver, and moistened with distilled water to the proper field level. Five mungbean seeds were planted in each container, and after seven days, the seeds were trimmed to three plants apiece. Seven days after sowing (7DAS), zinc sulfate in solution form was applied as soil to the pots in accordance with the experimental design. Single super phosphate, urea, and recommended baseline dosages of N, P2O5, and K2O at rates of 20, 10, and 10 kgha-1 were applied, together with potassium sulphate in solution (Ewerzor et al., 1981).

The mungbean plants (shoots and roots) were removed from each pot six weeks (6WAP; or 42 days) after emergence (DAE), rinsed with distilled water, pre-dried under shade to remove excess water, and then put in large envelopes and oven-dried at 70oC for 72 hours. The sections of the oven-dried plants were weighed and the dry matter yield was noted. In a stainless steel grinder, the dried plant samples from each container were independently ground into a powder that could fit through a 0.5 mm filter.

The triacid mixture (10:2:1 HNO3: HClO4: H2SO4) was used on a heated plate to digest the dry powdered plant samples. After that, Whatman No. 42 was used to filter the materials in order to determine the zinc content. An atomic absorption spectrophotometer (AAS) (Unicam Solaar 32: Zn ASTM D1688) was used to measure the zinc content of the digest. The zinc uptake in plant shoots (mg plant-1) was calculated by multiplying the dry matter yield (g plant-1) by the concentration (mg kg-1) in plant materials.

2.5 Field Study

Following the determination of the optimal zinc rate for mungbean in the greenhouse study, a field study was performed at Ishiagu, Ebonyi State, Nigeria (N 5^o 57l 18.78 and E7^o 33l 35.76), to ascertain the most suitable zinc levels for mungbean grain yield. The field was manually cleared and tilled. Four replications of a randomized complete blocks design (RCBD) were used to build up the experiment investigation. For a total of 28 observations, there were seven experimental plots in each block. Every subplot had 5.0 × 4.5 m (22.5 m^2) as its dimensions.

Four mungbean seeds, spaced at 65 cm x 35 cm, were manually planted per hole. Three plants per hole were thinned 14 days after emergence to guarantee an even number of plants in each plot. During sowing, a base dose of N.P.K., 15:15:15 fertilizer was applied to each plot at a rate of 150 kg/ha. According to the treatment plan, zinc fertilizer was given out at the following rates one week after germination: 0, 3, 6, 9, 12, 15, and 18 kg Zn ha^{-1} as $ZnSO_4.7H_2O$. All agronomic and cultural practices, such as pest management, weeding, tilling, and so forth, were executed. When the plants were fully grown, they were harvested so that the grain and biological yields could be determined. Measurements for growth include plant height (cm), stem girth (mm), number of branches/plant, number of leaves/plant, and leaf area (cm^2). For yielding, measurements include number of pods/plant, number of seeds/plant, pod weight (g), and grain yield (kgha-1).

2.6 Statistical Analysis

The data collected from the field studies and greenhouse were subjected to the analysis of variance (ANOVA) method using the general linear model of GenStat. At the 5% probability level, significant means were differentiated using Fisher's least significant difference (F-LSD). Basic regression and correlation analysis were used to find the relationships between soil Zn and yield variables using PASW Statistics 18 for Window 7.0. Excel Window 13 was used to construct the graphs, which show the mungbean yield performance as well as the key constraints and ideal zinc concentrations. The zinc uptake in plant shoots (mg.plant-1) was determined by multiplying the dry matter accumulation (gplant-1) by the concentration (mg kg-1) in plant materials. With Microsoft Excel Windows 2013, the responses to the curve graphs were generated. The coefficient of determination (r2) was used to select the model that best suited the data. The best extraction method for soils was identified by comparing the zinc extracted from each extraction solution with the zinc available for mungbean absorption, given as mg per kg of soil.

The critical limits of zinc were analyzed using the statistical (R2-technique) and graphical approaches of Eteng and Asawalam (2016) and Cate and Nelson (1965). As part of the graphical technique, Zn uptake levels were plotted as the Y-axis and soil test data as the X-axis in a scatter diagram. The critical value differentiates soils into highly and non-responsive categories when $ZnSO_4$ is used as a soil treatment. In this study, $P<0.05$% was utilized to categorize mungbean to sufficient and insufficient levels according to their reaction to Zn fertilizer—or lack thereof.

The most significant zinc extractable values (mg kg-1) and the maximum amount of zinc that mungbean can absorb (mg plant-1) are equal, indicating that mungbean crops are expected to respond strongly to additional zinc. The highest predictability (R2) value, or the theoretical critical level, can be used to simply partition a population (Fig. 1).

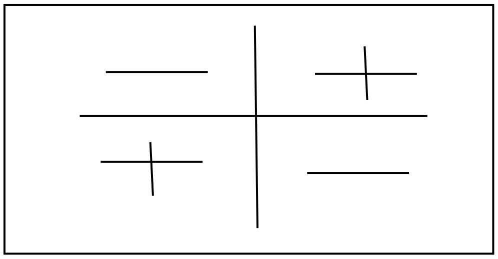

Figure 1: Format of clear plastic overlay which is used for

3.0 RESULTS AND DISCUSSION

3.1 Laboratory study

3.1.1Soil physical and chemical characteristics of the study area

Table 2 shows the wide variations in the characteristics of the soil samples used in this investigation.The most noticeably acidic soil in each of the six locations had an average pH of 4.78, with the range ranging from 4.30 to 5.08. Based on the results of the soil test, the average amount of organic carbon in each soil sample was moderate, ranging from 0.91 to 1.24 gkg^{-1}. The surface (0–20 cm) soils' average ECEC, aside from the previously indicated traits, ranged from 2.91 to 6.14 cmol kg^{-1}. N, P, K, Ca, Mg, Na, and other soil nutrients had average levels of 0.79 gkg^{-1}, 12.77 mg.kg^{-1}, 0.09 cmol.kg^{-1}, 1.52 cmol.kg^{-1}, 1.37 cmol.kg^{-1}, 0.09 cmol.kg^{-1}, and 0.63 mg.kg^{-1}, in that order. As can be seen from Table 3, the mean soil samples are sandy loam (SL).

Based on several extraction procedures, the mean extractable zinc values from the soil for DTPA, EDTA, NH_4OAc, and HCl were 0.88, 1.19, 0.63, and 1.49 mg/kg, respectively. These were somewhat low, indicating a widespread shortage in zinc in the soils (Table 4). On the other hand, the higher mean Zn value in the Ishiagu soil was attributed to the lower pH. The soil characteristics generated were typically equivalent to the physiochemical parameters of the soils reported in Southeastern Nigeria (Enwezor *et al.*, 1981; Chude *et al.*, 2004; Eteng and Asawalam, 2017).

Table 2: Characterization of physical and chemical properties of the shale derived soils used for the Greenhouse study (N=30)

Sample location	**Sand**	**Silt**	**Clay**	**Soil textural class**	**pH (H_2O)**	**Org carbon**	**Total Exch. Base**	**Total Exch. Acidity**	**ECEC**	**BS**
	g/kg					g/kg	Cmol.kg^{-1}			%
Abakaliki	710.11	109.55	180.34	Sandy loam	5.04	1.19	2.86	1.12	3.98	71.86
Amasiri	656.04	123.61	220.35	Sandy clay loam	4.64	0.91	3.91	2.23	6.14	63.68
Ikwo	720.23	104.21	175.56	Sandy loam	5.60	0.83	2.28	2.06	4.34	52.53
Ishiagu	535.16	340.62	124.22	Loam	4.00	1.12	1.73	1.18	2.91	59.45
Ohoazara	655.44	104.44	240.12	Sandy clay loam	4.65	1.21	3.16	1.44	4.60	68.70
Uwana	707.22	83.59	209.19	Sandy clay loam	5.08	1.24	2.68	1.64	4.32	62.04
Mean	664.03	144.34	191.63	Sandy loam	4.84	1.08	2.77	1.61	4.38	63.04
CV (%)	6.43	14.22	12.65		4.05	5.23	7.14	4.45	8.52	9.11

Table 3: Nutrient properties of the shale derived soils used for the Greenhouse study (N=30)

Sample location	**Total Nitrogen (N)**	**Avail. Phosphorus (P)**	**Calcium (Ca^{+2})**	**Magnesium (Mg^{+2})**	**Sodium (Na^{+})**	**Potassium (K^{+})**
	gkg^{-1}	mg.kg^{-1}	cmol.kg^{-1}			
Abakaliki	0.12	24.50	3.00	1.50	0.15	0.16
Amasiri	1.12	7.46	1.60	1.30	0.24	0.27
Ikwo	0.80	10.40	1.00	0.97	0.09	0.12
Ishiagu	0.90	12.60	0.90	0.76	0.03	0.04
Ohoazara	1.31	26.06	2.12	1.15	0.44	0.21
Uwana	1.00	8.90	1.10	1.43	0.05	0.06
Mean	0.91	15.00	1.61	1.19	0.17	0.14
CV (%)	8.15	18.06	6.24	8.52	12.31	8.33

3.2 Extractable Zn in soils by different extractants

The zinc availability in the soil for the cultivation of mungbean is clearly depicted by the extractable zinc values in Table 4. The extractable zinc content varied greatly depending on the extraction solution used and the different characteristics of the soil (Kabata-Pendias, 2010; Eteng et al., 2014; Sillanpaa, 1990). DTPA recovered the least amount of extractable zinc (1.03 mgkg-1) since the soil was acidic; on the other hand, Ishiagu's soil produced the highest concentration of zinc (3.62 mgkg^{-1}), which is greater than the average value obtained using the HCl technique (2.17 mgkg^{-1}). The result is similar to the research reported by Alam and Islam (2016) and Schnug *et al.* (2001).

Table 4: Extractable Zn properties of the shale derived soils used for the Greenhouse study (N=30)

Sample location	**Extractable Zn (mg.kg^{-1})**				**Mean**
	DTPA-Zn	EDTA-Zn	NH_4OAc-Zn	HCl-Zn	
Abakaliki	1.25	1.09	0.82	2.52	1.42
Amasiri	1.05	1.67	1.12	1.58	1.36
Ikwo	0.55	1.20	0.80	1.32	0.97
Ishiagu	2.45	2.95	2.65	3.62	2.92
Ohoazara	0.19	1.75	1.06	1.87	1.22
Uwana	0.70	1.22	0.90	2.13	1.24
Mean	1.03	1.65	1.23	2.17	1.54
CV (%)	12.5	8.6	10.1	10.5	

3.3 Greenhouse experiment

3.3.1 Determination of optimum Zn uptake as influenced by Zn levels on mungbean

Applying zinc to mungbean shoots resulted in a significant (P<0.05) increase in zinc uptake when compared to the control, suggesting that zinc may be one of the soil's limiting minerals (Fig. 1). The assessment of the efficiency of zinc feeding in mungbean production has frequently been done using zinc uptake. A differential yield response curve was established when different levels of ZnSO4 were applied as fertilizer to shale soils in different locations. This yielded the optimal Zn level needed to induce maximal Zn uptake in mungbean shoots grown six weeks after planting (WAP).

Consequently, Fig. 2 provided the polynomial regression analysis together with the related R2 values. The findings indicated that the maximum accumulation of Zn uptakes in mungbean plant shoots for shale-derived soils of Abakaliki, Amasiri, Ikwo, Ishiagu, Ohaozara, and Uwana were 4.12, 3.86, 4.04, 3.93, 4.18, and 4.20 mg plant^{-1}. These optimal levels for Zn uptake in mungbean shoots were influenced by Zn levels and determined by the quadratic regression method. Table 5 presents the ideal locations in kgha-1 along with their corresponding R^2 values, which are determined by the Zn values obtained from the quadratic regression curves. As per the graphs presented here, mungbean yields have the potential to rise with additional Zn increases until they reach turning points that are marginally above the optimal level (Feiziasl *et al*., 2009; Hussain et al., 2021). Hussain *et al*. (2021) and Malakouti and Gheybi (1997) found that soil zinc enhanced the amount of zinc absorbed and stored by plants, and these results are consistent with their findings.

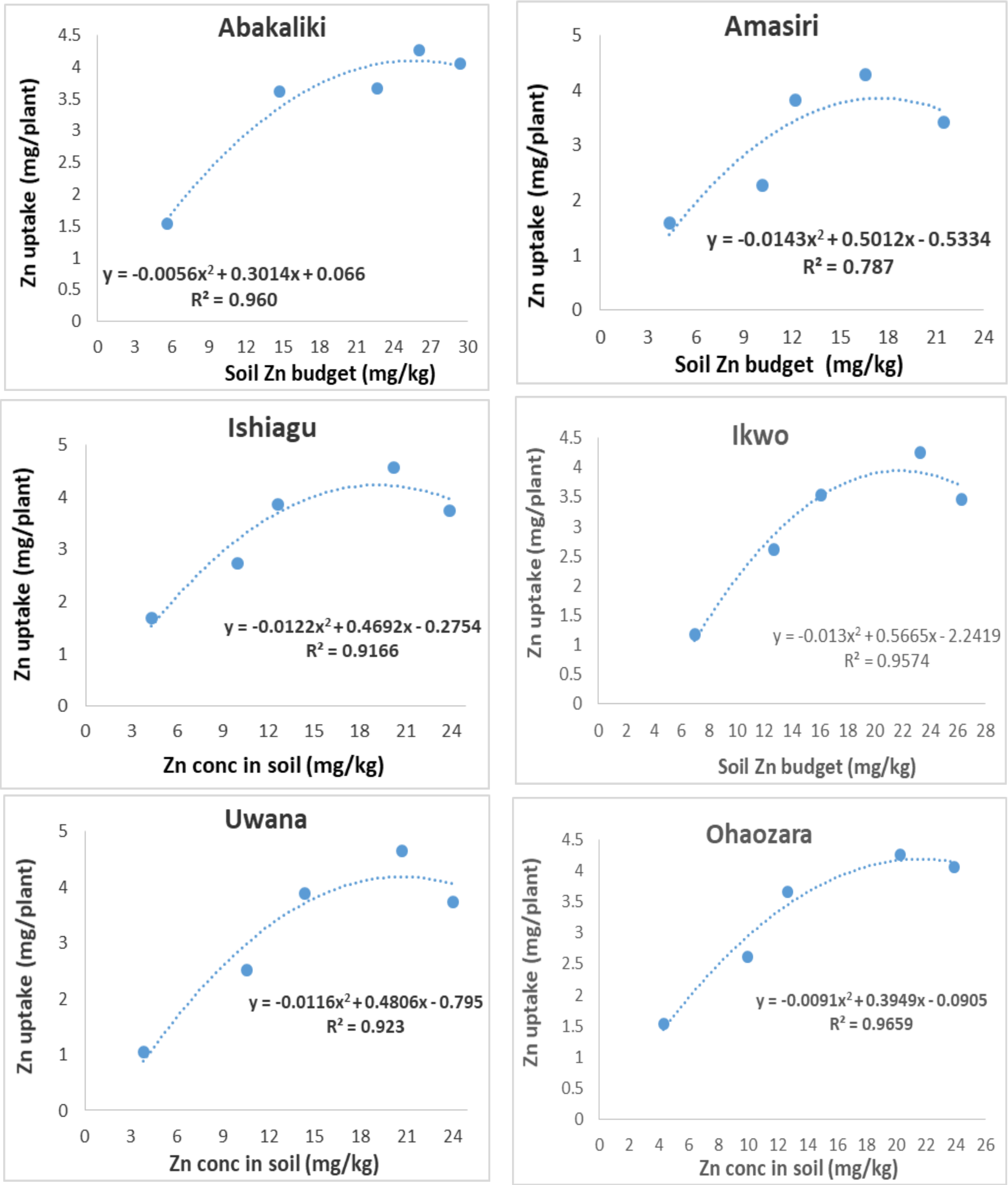

Figure 2: Scatter diagrams showing the relationship between extractable Zn and Zn uptake to determine the critical level of Zn in the different shale soil locations

Table 5: Coefficients of determination (R^2) between extractable Zn in different Shale soils and Zn uptake by mungbean plants (N=120)

S/No	Sample location	Zn Coefficients of determination (R^2)
1	Abakaliki	0.960**
2	Amasiri	0.787*
3	Ikwo	0.966**
4	Ishiagu	0.917**
5	Ohaozara	0.966**
6	Uwana	0.923**

3.3.2 Critical limits of soil Zn as influenced by Zn levels on mungbean

The critical levels of EDTA-extractable zinc estimated for mungbean production at different locations for shale-derived soils in Abakaliki, Amasiri, Ikwo, Ishiagu, Ohaozara, and Uwana were found to be 11.95–26.91, 11.45–17.52, 14.00–21.80, 11.15–19.23, 11.35–21.70, and 12.65–20.72 mg Zn kg -1, respectively. The boundaries were found using the Cate-Nelson graphical technique (Fig.1). The essential levels of mungbean reported using other extractants were found to be nearly equal to the findings of this study when these research findings were compared with the findings of the current investigation (Table 6). Similar findings have been reported on Zn by Kaya *et al*. (2017) and Eteng and Asawalam (2017).

Based on the mungbean crop's considerable reaction and lack of response to Zn application, the amount was calculated using the plant response column order technique. The results can be compared to those reported by Hafeez *et al*. (2013) and Gahlot et al. (2020). In contrast, soils with values above the critical levels rated high were sufficient (non-responsive) or may exhibit toxicity, according to Malakouti and Gheybi (1997). All of the soils in the area with available zinc values below the corresponding critical value rated low were deficient (responsive) in their levels of mungbean uptake. The study backs up these conclusions. In similar studies, Srinivasan *et al*. (2009) revealed comparable critical Zn concentrations in soil and plant for increased ginger productivity.

Table 6: Critical limits of Zn in soils from the different locations (N=120)

S/No	Sample location	Rating of critical limits of Zn ($mgkg^{-1}$)		
		Low	Moderate	High
1	Abakaliki	≤11.95	11.95 – 26.91	≥26.91
2	Amasiri	≤11.45	11.45 – 17.52	≥17.52
3	Ikwo	≤14.00	14.00 – 21.79	≥21.79
4	Ishiagu	≤11.15	11.15 – 19.23	≥19.23
5	Ohaozara	≤11.35	11.35 – 21.70	≥21.70
6	Uwana	≤12.65	12.65 – 20.72	≥20.72

3.3.3 Optimal Zn levels for DMY, Zn content and Zn uptake in mungbean plants.

All of the soils in the region with available zinc levels below the corresponding critical value rated low were deficient (responsive) in their levels of mungbean uptake, while those with values above the critical levels rated high were sufficient (non-responsive) or might exhibit toxicity, according to Malakouti and Gheybi (1997). The study lends credence to these conclusions. According to relevant experiments, Srinivasan *et al*. (2009) revealed similar critical Zn concentrations in soil and plant for better ginger productivity. A differential growth response curve for zinc absorption, concentration, and dry matter yield at various zinc treatment doses is shown in Figure 3. This curve shows how much zinc is optimally needed to produce the maximum number of mungbean shoots when cultivated at 6 WAP. Applying 15 kg Zn ha^{-1} to mungbean shoots increased the dry matter yield (5.29 g $plant^{-1}$), Zn concentration (31.83 mg kg^{-1}), and Zn absorption (1.27 mg $plant^{-1}$) significantly ($P<0.05$). Similarly, following the application of 15 kg Zn ha^{-1}, a greater Zn concentration of 44.54 $mgkg^{-1}$ was found in the soil.

On the other hand, the quadratic regression curves in Figure 3 and Critical limits in Table 6 were utilized to determine the optimal zinc values. For the highest accumulation of DMY, Zn intake, Zn in plants, and Zn budget in soil, respectively, these curves indicate that the ideal point for ZnSO4 is at 14.23 kg ha^{-1} ($R^2 = 0.990$), 13.01 kg ha^{-1} ($R^2 = 0.935$), 14.49 kg ha^{-1} ($R^2 = 0.993$), and 15.49 kg ha^{-1} ($R^2 = 0.975$). These graphs showed that mungbean yields will rise until they reach turning points, which are slightly over the ideal level, with more Zn inputs. These results supported the findings of Furlani *et al*. (2005), Haider *et al*. (2018), and Kanwal et al. (2010), who found that plant zinc content and absorption were enhanced by soil zinc. The differences found in DMY, Zn content, and mungbean shoot uptake across different types of soil could be caused by variations in the soils' ability to supply Zn to the plants. The uneven responses of mungbean plants to Zn fertilizers in terms of DMY, Zn concentration, and absorption could be attributed to variations in soil and ambient circumstances. This could also be due to the diluting impact caused by the increase in DMY (Kanwal *et al*., 2009). The findings align with previous studies conducted by Potarzycki and Grzebisz (2009) on maize production and Srinivasan et al. (2009) on critical Zn limitations in ginger soil.

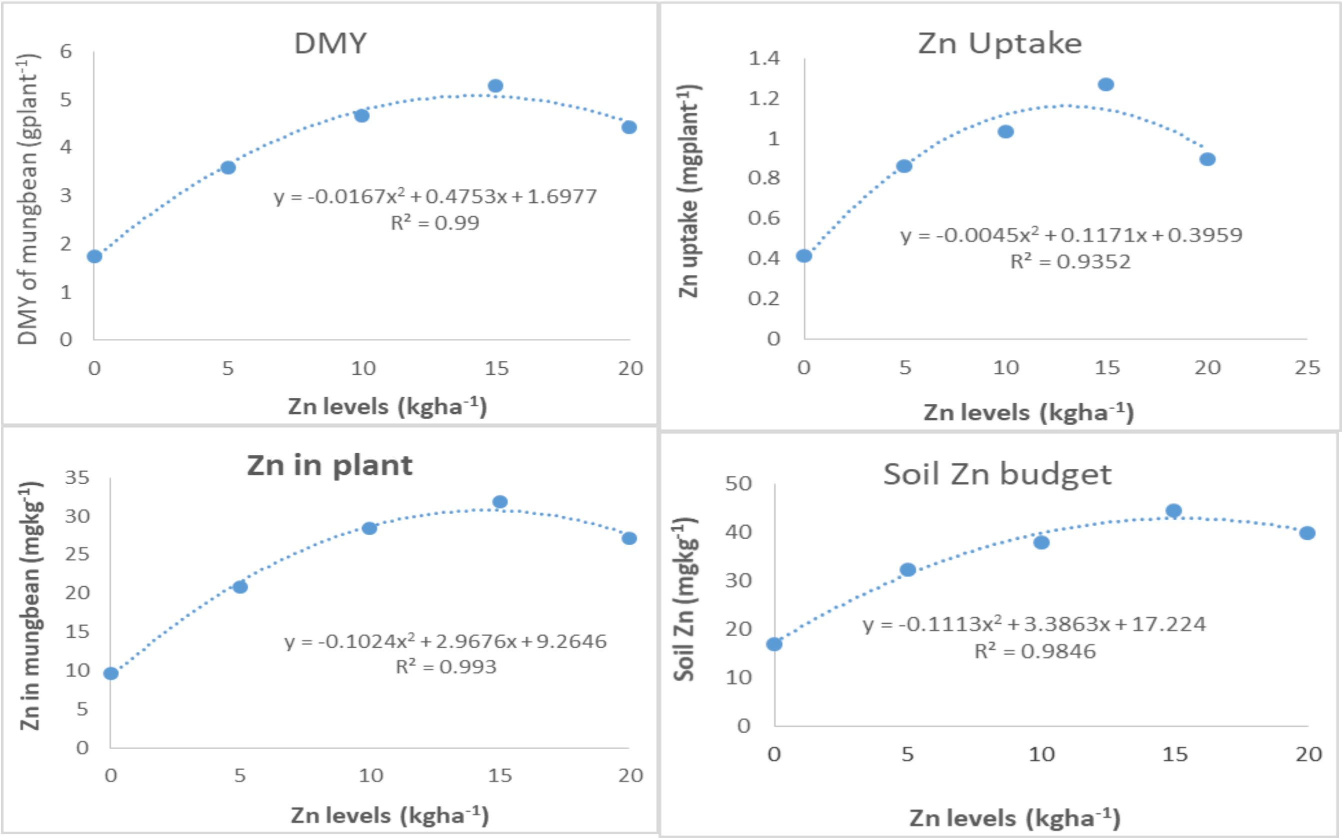

Fig. 3: Polynomial graphs showing optimum Zn levels for mungbean DMY (gplant^{-1}), Zn uptake (mg plant^{-1}), Zn in plant (mg kg^{-1}) and Soil Zn budget (mg kg^{-1}) of the greenhouse study.

3.4 Field Experiment

3.4.1 Effects of Zn levels on growth components of mungbean plants

There were substantial ($P<0.05$) differences among the Zn levels, according to the analysis of variance performed on the growth parameters of the mungbean plants in the field study (Table 7). The productivity of the plant in terms of grain yield and fodder is directly correlated with the mungbean's growth attribute. The increased growth of mungbean plants was caused by the varying Zn levels. Applying 15 kg of zinc fertilizer per hectare resulted in a maximum plant height of 52.75 cm, whereas 12 kg of zinc fertilizer per hectare produced maximum numbers of branches, leaves, stem girth, and leaf area per plant, which were 3.34, 14.67, 3.49 cm, and 334.07 mm, respectively. Table 6 shows that the control consistently produced lower results.

According to Table 7, the optimal zinc application rates for mungbean growth attributes fall between 12 and 14 kg Zn/ha, which is the range of fertilizer rates assessed for mungbean yield components. Increased zinc fertilizer levels were associated with higher mungbean production and grain zinc content, according to similar findings by Roy (2014), Kaya et al. (2017), Jamal et al. (2018), and Husain et al. (2021). Haider et al. (2018), Husain et al. (2021), Gahlot et al. (2020), and Van Biljon et al. (2010) all state that low zinc concentration in the soil was the cause of the notable reaction of the mmungbean growth attributes to $ZnSO_4$ application.

Table 7: Effect of Zn levels on growth attributes of mungbean plants (N=28)

Zn levels (kg/ha)	Plant height (cm)	Number of branches/plant	Number of leaves/ plant	Stem girth (cm)	Leaf area (mm)/ plant
0	36.82	1.67	7.12	1.86	155.34
3	40.01	2.12	8.56	2.69	199.82
6	45.44	2.26	9.44	2.95	201.38
9	49.81	2.46	12.35	3.22	304.81
12	51.48	3.34	14.67	3.49	334.07
15	52.75	3.18	12.78	3.32	312.29
18	48.77	2.64	9.44	3.14	266.23
Mean	46.01	2.52	11.62	3.02	281.99
LSD	0.983	0.119	7.21	1.98	34.17
CV (%)	1.22	2.98	12.6	11.7	15.6

3.4.2 Zinc calibration study

The yield components of mungbean were significantly (P<0.05) increased by ZnSO4 application above control, according to the data displayed in Fig. 4. When Zn fertilizer was applied, the maximum number of pods/plant, number of seeds/pod, pod weight/plant, and grain yield were produced, with values of 16.87, 228.35, 12.27 g, and 9.93 kg ha^{-1}. These results were obtained from the optimal Zn levels of 14.05, 12.75, 13.97, and 12.46 kg Zn ha^{-1} (Fig. 4), and their corresponding R2 predictability was 0.98 (98 %), 0.99 (99 %), 0.96 (96 %), and 0.98 (97 %) (Table 7), respectively. According to the findings presented in Figure 4, the yields decreased when zinc levels were raised above optimal levels. This is most likely because applied zinc in soil has a high toxicity level (Rashid and Fox, 1992).

However, the control continuously achieved the minimum mungbean yield components, suggesting that the shale soil's zinc deficiency may be the cause of the poor yields. These results are consistent with those of Roy (2014), Jamal *et al.* (2018), and Husain *et al.* (2021), who found that between 12 and 20 kg Zn ha-1, mungbean achieved its greatest seed yields and yield qualities. In a similar vein, Haider *et al.* (2018) and Jamal *et al.* (2018) observed that higher Zn fertilizer levels were associated with an increase in mungbean production and grain zinc content.

In related research, Farhan *et al.* (2019) found that applying P and Zn greatly enhanced the mungbean's test weight, dry matter accumulation, number of pods per plant, number of seeds per pod, and seed production. These scientists also noted that the application of P (60 kg/ha) and Zn (20 kg/ha) led to notable variations in leaf area ratios, which suggested improved dry matter partitioning, more pods, and higher seed output. The low zinc concentration in the shale soil (Table 3) was the cause of the notable reaction of the mungbean yield attributes to ZnSO4 application, according to Husain et al. (2021), Gahlot *et al.* (2020), and Van Biljon *et al.* (2010).

However, the increased availability of Zn in the soil due to the enhanced budgeted soil Zn from the Zn treatment may have increased Zn uptake and efficient use of the applied Zn fertilizer for grain output (Hossain, 2008; Ahmad, 2012; Husain *et al.*, 2021). Since micronutrient applications to the soil have never occurred before, the notable increase in grain yield and relatively stable yield despite fluctuations in rainfall in the study area could be attributed to zinc's capacity to benefit the crop. This could have a significant knock-on effect for mungbean cultivation in the future.

According to the study, adding zinc fertilizer to mungbean in field experiments and greenhouse settings increased the plant's tissue content and improved soil production, which may help address the issue of micronutrient deficiencies in human nutrition (Ahmad, 2012, Eteng *et al*., 2014). Furthermore, the field tests' findings on the response of mungbean yield components to Zn fertilizer levels validated the Zn uptake findings from the greenhouse studies conducted in various shale soils (Hossain, 2008; Haider et al., 2018, Eteng *et al*., 2024).

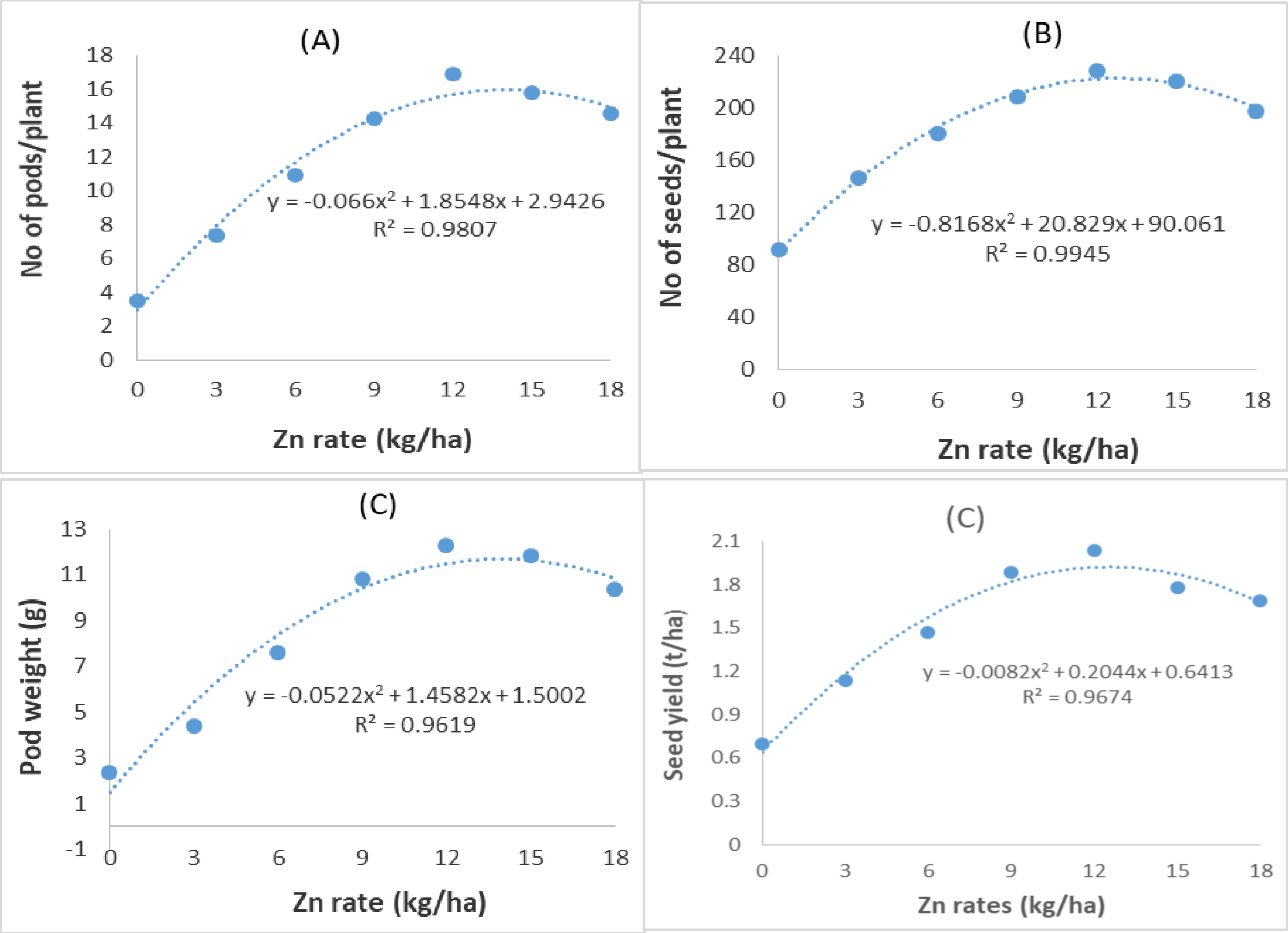

Fig. 4: Polynomial graphs showing the field optimum Zn levels on maximum yield components (A-C) of mungbean

Table 8: Optimum Zn levels for Mungbean yield parameters in the study soils (N=28)

Yield components of mungbean	Optimum Zn levels ($kgha^{-1}$)	Prediction value (R^2)
No of pods/plant	14.05	0.981
No of seeds/plant	12.75	0.995
Pod weight	13.97	0.962
Grain yield	12.46	0.967

4.0 CONCLUSION

According to the study, the soil formed from shale exhibited a severe zinc shortage because of poor OC, ECEC, and zinc availability. It has been determined how zinc fertilizers may enhance mungbean yield performance in soils. The critical limits of zinc available by various extraction techniques for the production of mungbean at various locations were determined to be 11.95–26.91, 11.45–17.52, 14.00–21.80, 11.15–19.23, 11.35–21.70, and 12.65–20.72 mg Zn kg-1 for the shale-derived soils of Abakaliki, Amasiri, Ikwo, Ishiagu, Ohaozara, and Uwana, respectively.

Significant ($P<0.05$) differences were observed between the different Zn treatment levels with regard to the number of pods plant-1, number of seeds pod-1, pod weight, grain yield, Zn uptake of mungbean, and soil nutrient budget content. For both greenhouse and field studies, the maximum zinc uptake (1.27 mgplant-1) and grain yields (9.93 kgha-1) of mungbean were determined to be at their optimal rates of 13.01 kg Zn ha-1 and 12.53 kg Zn ha-1, respectively. Owing to the significant zinc deficit, it is advised that soils in the same agroecological zone that are formed from shale should apply 12.5 kg Zn ha-1 of zinc sulphate.

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