Analysis of Changes in Bioactive Compounds Profile in Onions Under Different Sulfur, Calcium and Magnesium Supplementation on Different Agri-Climates in Kenya

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ABSTRACT

This study investigated the effects of sulfur (S), calcium (Ca), and magnesium (Mg) supplementation on the bioactive compound profile of onions (Allium cepa) grown in two agri-climatic zones in Kenya. A Randomized Complete Block Design (RCBD) was employed across two sites (Kisaju-Kajiado and Koma-Machakos), with six treatment combinations including varying levels and combinations of S, Ca, and Mg. Bioactive compounds, including total flavonoid content (TFC), total phenolic content (TPC), anthocyanins, quercetin, and organosulfur compounds, were measured.

The treatment with S, Ca, and Mg at 60 kg/ha produced the highest bioactive compound concentrations, with TFC of 243.33 QE/kg in 'White Lisbon,' TPC of 1024 GAE/kg, anthocyanin of 9 mg, quercetin of 39 mg, and organosulfur of 3.9 S/kg DM in 'Red Creole.' The results suggest that application of S, Ca, and Mg at 60 kg/ha can significantly enhance onion nutritional quality. It is recommended that farmers apply this treatment to improve bioactive compound content and marketability.

Keywords*:* Bioactive compounds, Nutrition, Supplement, Enhance, Marketability.

INTRODUCTION

Onion production is faced with low bioactive compounds which end up affecting the nutrition of the crop leaving a huge gap for most farmers, given its health benefits (Soininen et al., 2014). There is also need to boost the onion bioactive compounds levels as well while ensuring sustainability in order to increase the health and nutrition value of the product due to its daily uses in most households (Muhammad et al., 2024).

With focus on sustainability and quality food for African nations, there is need to boos onion nutrition in order to achieve food security. Therefore, as was the objective of the research, supplementation of S, Ca and Mg aimed to address the challenges as other studies have also proven the method effective, for example (Baek et al., 2020).

Research Objective

To analyze changes in bioactive compounds profile in onions under different S, Ca and Mg supplementation when exposed to different agri-climates.

Research Hypothesis

$H_0 2$: Changes in bioactive compounds profile in onions are not significantly affected by S, Ca and Mg supplement as well as agri-climates.

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Delimitation

This research only confined itself to the main aim, "Analysis of Changes in Bioactive Compounds Profile in Onions Under Different Sulfur, Calcium and Magnesium Supplementation on Different Agri-Climates in Kenya", and did not seek to go beyond the subject.

Assumptions of the Study

This research assumed that all experimental plots were uniformly identical and any variations assumed to be random and natural. The variance of the errors was assumed to be constant across all treatment levels, as well as the independence of observation that all extraneous and external factors such as weeding, watering and other management factors were uniformly applied so that only the independent variables affected the outcome to ensure constant management.

LITERATURE REVIEW

A study was carried out by Andrzej et al. (2021) to determine the effect of using sulfur and organic bedding on the content of the macro, micro nutrients and the bioactive elements in garlic bulbs during winter and the results revealed that sulfur has a direct influence on the bulb development, the yield as well as the biological value of Allium sativa. 0 and 20 kg/ha of sulfur levels were used on five onion varieties and a control to measure the yield and the bioactive concentration of onion bulbs as well and the results were as follows: onion bulbs were also found to contain more dry weight as well as the bioactive concentration as compared to the control, where no treatment was applied.

Onions are also reported to contain more glutathione and total phenolic acid and the extracts with greater antioxidant activity compared to the whole dry bulb (Li et al., 2023). In a similar experiment, three different colour onion varieties planted with sulfur were assessed for their antioxidant activities as a result of sulfur applications and it was evident in the results that the maximum activity recorded in red onion as compared to the other coloured types; however, factors such as the incubation period of the mixed solutions or reagents and the solvent in use might also affect the reaction of the molecules ending up increasing the antioxidant activity (Idhan, 2022). In a study by Shreya et al. (2020) where seven doses of Sulphur, 0, 10, 20, 30, 40, 50, 60, 70kg/ha were administered in the form of magnesium sulphate to determine how graded levels of sulfur and magnesium sulphate affects the yield and quality of onions, sulfur was found to resulting to increased significant weights of up to 59.6kgs/ha at 40 and 50kg/ha: application of magnesium sulphate at 40kgs/ha was found to have the best quality effects of onions with increased bulb size.

According to a high-performance liquid chromatography (HPLC) analysis study by Guangmin et al. (2022), red onion had 0.20 µmol/g, yellow onion had 0.35 µmol/g, white onion had 0.14 µmol/g FW of flavonoid levels. Quercetin monoglycosides and diglycosides comprises 93% of the total flavonols produced during oxidative stress, with 5-10-folds flavonoids concentration, that is, 300 mg/kg as compared to other horticultural and fruit crops, such as broccoli with 100 mg/kg, apple with 50 mg/kg and blueberries with 40 mg/kg to name a few (Akira et al., 2015). Therefore, it is evident from a nutritional point of view that onion, due to its high quercetin content levels, is an important recommendation in the diet ingredient for humans.

In a study to investigate, purple, red, yellow and green onion cultivars total phenol contents, it was found that purple onion cultivar contained the highest flavonoid content as compared to the other onion cultivars with 47.3 mg/100g FW: red onions contain 44 mg/100g FW: yellow onions contain 34.7 mg/100g FW: and green cultivar contain 30 mg/100g FW (Nikola et al., 2022).

METHODOLOGY

Study Area

The research was conducted from December-May in two sites namely: Kisaju-Kajiado County, which is a which is a warm, dry, semi-arid climate (classification Cwb) with an annual optimum daily temperature of 15 – 25^{0}C and average annual precipitation of about 101.01 millimetres, which is about 3.98 inches of precipitation with a total of 188.92 rainy days with 51.76% probability of raining, while the second experiment in Koma-Machakos

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County, which is a Tropical wet and dry or savanna climate receiving average temperature of 18.9°C and about 912 millimetres, which is about 35.9 inches of precipitation with an average of 147 rainy days annually. Kisaju is located south of Isinya area approximately 1° 37’13” S latitude and 36° 49’32” S E longitude while Koma is located 63 km East of Nairobi along Kangundo road with primary coordinates of -1.29601, 37.21879. Kisaju site area is characterized by well-drained alluvial soils giving them a loose rich ash grey-brown colour while Koma area on the other hand is characterized by sticky heavy cracking black cotton soils giving them a dark colour, all suitable for onion production.

Experimental Design and Research Procedure

Field Experimental research due to treatments of Sulfur, Calcium and Magnesium administered to “Red Creole”, “Texas Grano” and “White Lisbon” onion varieties at different levels to measure the effects on the growth, yield and bulb development with a control (T1). RCBD was used with 18 random treatment combinations of the supplements replicated into three blocks, raised 15cm high and 30cm apart, making a total of 54 plots per site. The method was found appropriate according to Nchogu (2022).

Treatments, Combinations and Application Rates

- T1=S+Ca+Mg@0kg/ha
- T2=S+Ca+Mg@30kg/ha
- T3=S+Ca+Mg@40kg/ha
- T4=S+Ca+Mg@60kg/ha
- T5=S@40kg/ha
- T6=Ca+Mg@30kg/ha

This is on 1x 1 M plots size with 1 meter spacing between blocks and 30cm within plots in blocks with a total population of 810 individuals per site.

Table 1 *Experimental Treatments, Levels and Treatment Combinations*

Treatments

Levels

	T_1	T_2	T_3	T_4	T_5	T_6
RC	RCT_1	RCT_2	RCT_3	RCT_4	RCT_5	RCT_6
TG	TGT_1	TGT_2	TGT_3	TGT_4	TGT_5	TGT_6
WL	*WLT_1*	*WLT_2*	*WLT_3*	*WLT_4*	*WLT_5*	*WLT_6*

Sulfur supplement was applied to the soil before planting in the form of sulphate fertilizers. A calculated measure of Ammonium Phosphate Sulphate (APS) fertilizer (0-0-50+ 18S) from “Unifert” fertilizers was applied seven days after transplanting when seedlings plants were stable in both sites during transplanting stage at a rate of 40 kg/ha, as was found appropriate by Nemtinov et al. (2021). This helped take advantage of the phosphate fertilizer element also required during planting as well and crucial in general onion planting. Also, 60 days later after transplanting, during bulb filling, “FALCON” Potassium Magnesium Sulphate fertilizer, (0-0-22+ 22) was applied as well, at a rate of 20 kg/ha respectively in both sites, as was recommended by Yeshiwas et al. (2023) to boost the bulbs formation. These fertilizers were available in solid state in the form of white crystal granule powders. Based on the nutrient application rate, the fertilizer grade/composition and the field area plots measurements, the application rates were calculated based on the following formula which was proposed by Gashaw (2021):

$$Ferlilizer\ applicationrate = \frac{(required\ nutrient\ application\ rate \times 100)}{(percentage\ nutrient\ in\ the\ fertilizer \times W)}$$

$$;\quad where\ W = fertiliser\ weight$$

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All supplements were applied as soil drenches in three split applications: at transplanting, at 30 days after transplanting, and at 60 days after transplanting. The first treatment of Calcium + Magnesium (MAGiCAL) supplementation was applied as fertilizers seven days after transplanting from the nursery when the transplanted seed plants were stable and before the bulb formation process was active, through foliar spraying to the leaves since the fertilizer elements are available to plants in liquid form, which was easy to apply (Kibebew et al., 2023). The second repeat of treatment administration was done 60 days after transplanting during bulbing stage on, both at equal rates of 3ml/20l of water. Figure 10 is a picture of the calcium and magnesium supplements used in the study

The foliar fertilizer was mixed with "AQUA STICK" sticker and spreader to prevent rain water washing off the *"MAGiCAL"* supplement especially during the rainy season for maximum effectiveness and accuracy of the data. This is due to the waxy upright nature of the onion leaves which make water wash off any foliar spray easily. The sticker also aided in ensuring an even coverage of the treatment and also improved its absorption as well. This fertilizer contained NPK in the form 8:2:2 with N-8%+Ca-18%, Mg-3%, Bo-1%+Stimulants. The fertilizer was applied at a rate of 30mls/20ls of water, which translated to about 100mls/70l/ha, and was applied two times during the growing season as stated and proposed by Hanna et al. (2024) in their report as found to be appropriate. As also proposed by the author, these fertilizers were applied based on the formula by Gashaw above on fertilizer application rates in liquid-state as foliar fertilizers directly to the leaves.

For the determination of bioactive compounds, bulb samples were freeze-dried and ground to a fine powder. Total phenolic content was determined using the Folin-Ciocalteu method and expressed as gallic acid equivalents (GAE). Total flavonoid content was determined using the aluminum chloride colorimetric method and expressed as quercetin equivalents (QE). Anthocyanin content was measured using the pH-differential method and expressed as mg of cyanidin-3-glucoside equivalents per 100g. Quercetin was quantified using high-performance liquid chromatography (HPLC) with UV detection at 370 nm. Organosulfur compounds were determined using a colorimetric method measuring total sulfur content and expressed as mg/kg dry matter. All analyses were conducted in triplicate.

Plot Layout

Table 2 *Plot Layout Displaying Random Treatments and Treatment Combinations*

Blocks

Treatment Levels

BLOCK A	**BLOCK B**	**BLOCK C**
WLT$_1$	RCT$_6$	WLT$_1$
WLT$_6$	WLT$_5$	RCT$_3$
TGT$_5$	RCT$_5$	TGT$_6$
RCT$_4$	TGT$_1$	WLT$_2$
WLT$_2$	RCT$_2$	RCT$_4$
RCT$_6$	WLT$_6$	RCT$_6$
TGT$_6$	TGT$_5$	RCT$_1$
TGT$_4$	TGT$_6$	RCT$_2$
RCT$_5$	RCT$_4$	TGT$_3$
TGT$_3$	TGT$_4$	TGT$_5$
RCT$_3$	TGT$_2$	WLT$_4$
WLT$_1$	WLT$_4$	TGT$_4$
RCT$_1$	RCT$_1$	WLT$_5$
WLT$_2$	WLT$_1$	WLT$_1$
WLT$_4$	RCT$_3$	WLT$_6$
RCT$_5$	TGT$_3$	TGT$_2$
TGT$_3$	WLT$_3$	TGT$_3$
TGT$_2$	TGT$_2$	RCT$_5$

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Field Activities

Soil samples, 12 inches deep, approximately 30cm deep and mixed to one heap, were randomly collected using zigzag method, well labelled and packed in small cartons and sent to the lab for analysis before planting (Xavier, 2023). Plots measuring 10x30m were identified and prepared for the experiment layout. Nursery preparation and seed sowing 1cm deep and row spacing of 20cm apart was done and nursery divided into 3 sections containing the trial varieties: "Red Creole (RC)", "Texas Grano (TG)" and "White Lisbon (WL)" respectively each containing 10 lines of seeds and a mulch installed. The seedlings were transplanted when they had fully emerged. The seeds were certified and of good quality with a germination percentage of almost 100% for all the varieties.

Figure 1 *Nursery Beds Preparation*

Before transplanting in the field, following the RCBD experimental design, the fields were partitioned into plots of 18 and replicated to form three blocks namely A, B and C in both sites as per the experimental design and layout. During blocks plots preparation, raised beds of 15cm high and 30cm apart trenches were created where transplanting was done on 1x1m square plots each containing a plant population of 15 heads per hill. Seedlings were planted approximately about 1cm deep into the soil in a spacing of 50x15cm apart and watering observed.

Figure 2 *RCBD Plots*

Onion bulbs were harvested by uprooting when 75% of the leaves were seen to be dry and bent. Protected curing was then initiated in the open sun for the bulb shoots to completely dry where sorting and grading were further done after all required data was taken, and samples from each plot sent to the lab for composition analysis.

During harvesting, data from plant samples were randomly selected from the entire population and used in the analysis and tests. Simple random probability sampling technique was used, where each member (n) of the population (N) was given an equal chance of selection by drawing numbers out of the 15 from each plot to act as a representation of the rest of the population. The selection put into consideration of the population integer per plot independently, that is, 10 plants from a scale of 1-15 plants, across all the 18 plots per block, translating to 540 individuals in the entire plot of 810 individuals. The formula below as proposed by Nikhil et al. (2024) was used in selection of the samples from the population:

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$$k = \frac{N}{n}$$

:

$$where, k = sampling\ interval, N = population\ size\ and\ n = sampling\ size.$$

Analytical Procedures

Each dependent variable in the study was analyzed independently against the treatments (supplements, variety and site) and effects were summarized into tables and graphs for easy interpretation and for order. Independent variables of the study included the Site, Supplements and Varieties and since they are qualitative, they were grouped as nominal or ordinal whereas the rest of the variable which presented the data were quantitative and were given a scale. The tables and figures were drawn after being summarized in SPSS and represent analysis drawn from the lab and SPSS. Analyzed data organized in custom tables and graphs and error bars where continuous values containing mean data was recorded are presented in the chapter. The grouped data was analyzed in relation to their measures of central tendency (mean, mode and median) depending on the variable nature.

Preliminary tests such as normality test were performed on the descriptives statistics and histograms graphs generated to check if the data followed a normal distribution before performing the analysis. Also, linear as well as multinominal regression analysis where collinearity, Durbin-Watson residual tests with histograms and normal probability plots were also performed on the data before analysis to check the strength of the relationships between the independent/treatment variables and the test/dependent variables, chi-square analysis was also performed on the same to check on the likelihood of the independent variables predicting the outcomes of the dependent variables and to check on the models suitability in relation to the tests.

Mean comparisons were done on the different test groups to relate the general effect as a result of the treatments administered and results summarized in tables. Analysis on Full factorial Univariate General Linear Model (ANOVA) test data is also presented to determine the differences in mean groups of each dependent variable as affected by the treatments with a significance difference level of 5% equivalent to p = .05 as tables. This test was also used to generate the Descriptive statistics of the data as well and attached in the appendices section in form of tables. LSD And Duncan Post Hoc Multiple Comparison for Observed Means test results are also presented in tables to check where the significant differences were or resulted from and to what extent. Homogeneity and F-Test heteroskedasticity analysis was also performed to ensure independence of observations within each group and that all groups had equal variance.

Discussions were done where the study findings were compared and linked to past studies from drawn from the literature so as to establish the context and credibility, to validate the methodologies, to resolve any contradictions as well as to broaden the significance of the work while advancing to existing knowledge also. These results were essential in drawing the conclusions and recommendations based on the findings of the study.

RESULTS AND DISCUSSIONS

The synergistic effect of combining S, Ca, and Mg at 60 kg/ha on bioactive compound levels can be explained by the complementary roles of these nutrients in plant metabolism. Sulfur is a critical component of cysteine and methionine, which are precursors of many secondary metabolites, including organosulfur compounds and flavonoids. Calcium plays a structural role in cell walls and membranes, influencing the transport of other nutrients and the accumulation of secondary metabolites. Magnesium is central to chlorophyll synthesis and acts as a cofactor for numerous enzymes involved in phenolic compound biosynthesis. When applied together, these nutrients may address multiple metabolic bottlenecks simultaneously, resulting in the enhanced accumulation of bioactive compounds. This synergistic effect suggests that integrated nutrient management, rather than single-nutrient supplementation, is the optimal strategy for enhancing onion nutritional quality. A detailed soil analysis report is also provided.

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Figure 3 *Lab Soil Analysis Report*

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National Agricultural Research Laboratories
P. O. Box 14733, 00800 NAIROBI
Email: soil.labs@kalro.org

SOIL TEST REPORT

Name	Briggx Nchogu Xavier
Address	0727478010
Location of farm	Kajiado
Crop(s) to be grown	Onions
Date sample received	31-10-2025
Date sample reported	15-11-25

	Soil Analytical Data							
Field	**Site 1**							
Sample designation	**Ongata Rongai**							
Lab. No/2025	17468							
Soil depth cm	Top							
Fertility results	value	class						
Soil pH	6.58	Slight acid						
Exch. Acidity meq%								
Total Nitrogen %	0.17	Deficient						
Total Org. Carbon %	1.68	Deficient						
Phosphorus (Mehlich) ppm	91.75	High						
Phosphorus (Olsen) ppm								
Potassium meq%	2.42	High						
Calcium meq%	34.60	High						
Magnesium meq%	4.31	High						
Manganese meq%	0.46	Adequate						
Copper ppm	0.09	Deficient						
Iron ppm	4.00	Deficient						
Zinc ppm	4.96	Deficient						
Sodium meq%	0.40	Adequate						
Electr. Conductivity mS/cm								

Interpretation and Fertilizer Recommendation

The soil reaction is **slightly acid. Nitrogen, Organic Carbon, Copper, Iron and Zinc** are deficient. **Onions:** Place **3 handfuls of well decomposed Farm Yard manure** per hole. During planting, apply **10g per hole of N:P:K Blended** fertilizer containing **Zinc.** At **30 and 45 days** after planting, apply **10g/plant and 20g/plant of CAN fertilizer respectively.**

NOTE: Test results are based on customer sampled sample(s).
Methods used: Information is given out on client's request.

Reporting officer (through Director NARL) F. WANDERA

The soil analysis lab results were performed before the experiment, and indicated that the soil was fit for onion production. However, several corrections were made as proposed in the report, along with the treatment levels proposed.

TFC Levels

Figure 4 *A Summary Graph on Onion Treatment Effects on TFC Levels*

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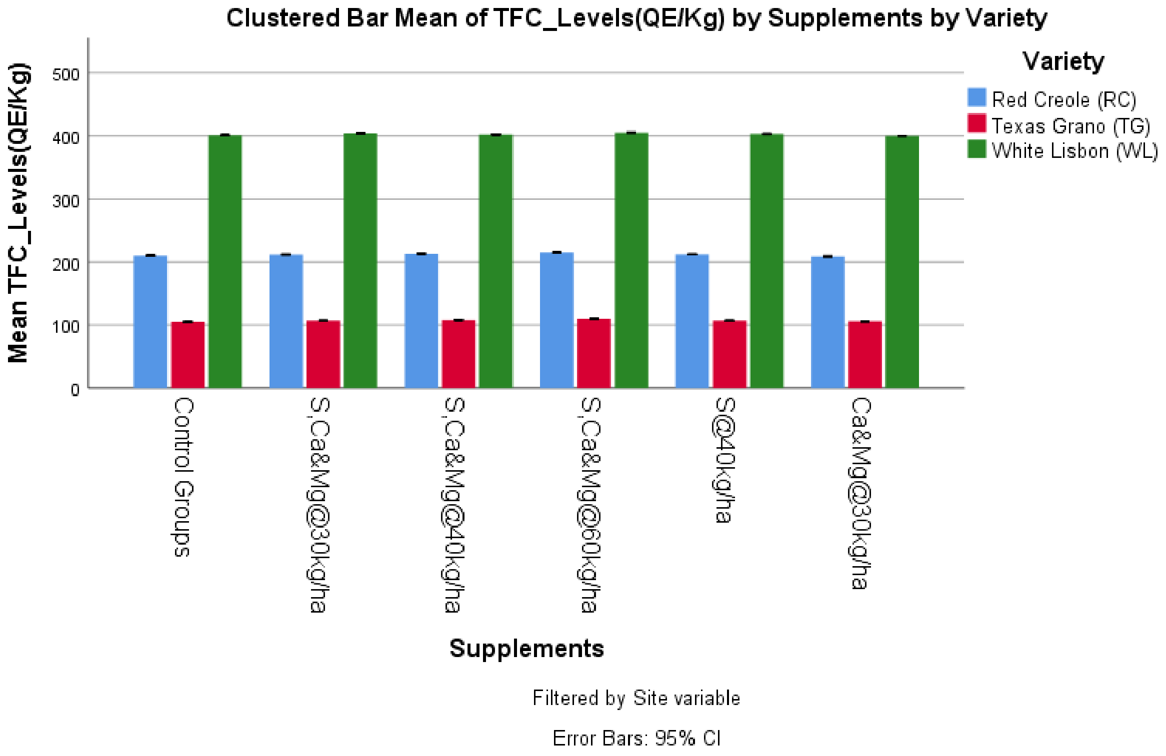

Figure 3 displays clustered bar means graph of the different supplementation treatments as well as the variety on the TFC levels of onions across the different study sites. The figure as well includes error bars to display the level of variances across the mean groups of the data.

As presented, “White Lisbon” yellow onion variety had a spectacular higher significant level as compared to the other onion varieties, that is, the white and yellow. This is with an average of 400QE/Kg. This was followed by the red bulb onion with an average close to 200QE/Kg, then yellow onion with an average of around 100QE/Kg. These differences were observed uniformly across all onion supplement treatments. However, between the varieties themselves, there was no significant differences observed. The results displayed confirm and indicate that S, Ca and Mg treatment variations did bring elevated significant differences in onions TFC levels. Supplement treatment 4 had the highest average of the means while supplement treatments 1 significantly had the lowest in comparison across the varieties. According to researches by Andrzej et al. (2021), Calcium and Magnesium compounds were found to increase the flavonoids which are responsible for the green sprouts colour increasing the chlorophyll levels in the plants due to the processes of photosynthesis. In line with this study, this was investigated and found true where increase in treatment levels where calcium and magnesium were present was significantly found to increase the TFC levels, more especially as reported in the scallion onion variety where the levels were highest reported on the shoots. In a study to investigate, purple, red, yellow and green onion cultivars total phenol contents in the bulbs, Nikola et al. (2022) found out that purple onion cultivar contained the highest flavonoid content as compared to the other onion cultivars with 47.3 mg/100g FW: red onions contained 44 mg/100g FW: yellow onions contained 34.7 mg/100g FW: and green cultivar contained 30 mg/100g FW. This research also strongly agrees with the authors’ report.

All the onion supplements are recommended for use across any of the onion varieties as they all significantly showed higher levels of TFC concentrations as compared to the control treatment. However, planting “White Lisbon” white scallion onion variety significantly yields the highest concentration of TFC levels under S, Ca and Mg at 60 kg/ha with a mean of 243.33 QE/kg. These levels are essential in increasing the onion nutrition quality by increasing the flavour compounds in onions as well as quality produce for the market.

Table 3 *ANOVA Analysis on Treatment Effects on TFC Levels in Onion*

Tests of Between-Subjects Effects					
Dependent Variable: TFC Levels					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.

Corrected Model	16539782.436[a]	35	472565.212	931580.168	.000
Intercept	57196095.523	1	57196095.523	112752159.632	.000
Site	12.214	1	12.214	24.077	.000
Supplements	2989.753	5	597.951	1178.756	.000
Variety	14061559.428	2	7030779.714	13859960.010	.000
Site * Supplements	36.056	5	7.211	14.215	.000
Site * Variety	25.686	2	12.843	25.318	.000
Supplements * Variety	344.499	10	34.450	67.912	.000
Site * Supplements * Variety	78.238	10	7.824	15.423	.000
Error	558.000	1100	.507		
Total	16540340.436	1135			
a. R Squared = 1.000 (Adjusted R Squared = 1.000)					

Table 4 indicates the univariate analysis tests of between-subjects effects on the group mean variance of the different independent variables of site, supplements and variety done on the onion TFC levels, and their significant p value levels, testing if there were significant differences in variances or not. As displayed, these significant differences in onion TFC levels were present in all treatments and their combinations as well as they all had significant values of 0.00 in their mean differences $p < .05$.

Table 4 *Post Hoc Analysis on Supplements Effects on TFC Levels in onions*

Homogeneous Subsets									
TFC Levels (QE/Kg)									
				Subset					
	Supplements	Means	N	1	2	3	4	5	6
Duncan[a,b,c]	S, Ca& Mg at 40 kg/ha	241	207	208.84					
	S at 40 kg/ha	240.67	180		224.96				
	S, Ca& Mg at 30 kg/ha	241	189			226.48			
	S, Ca& Mg at 60 kg/ha	243.33	188				237.66		
	Ca& Mg at 30 kg/ha	238.67	192					245.59	
	Control Groups	238.67	180						265.72
	Sig.			1.000	1.000	1.000	1.000	1.000	1.000
Means for groups in homogeneous subsets are displayed. Based on observed means. The error term is Mean Square (Error) = .507.									
a. Uses Harmonic Mean Sample Size = 188.914.									
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.									
c. Alpha = .05.									

Table 5 represents Duncan Post Hoc analysis test performed on the onion TFC levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the supplements. The differences in means of onion TFC levels as a result of supplements treatment were present within all six levels of treatments across all six subsets without any overlap as all values fell on different subset groups as presented.

Table 5 *Post Hoc Analysis on Variety Effects on TFC Levels in onions*

Multiple Comparisons									
								95% Confidence Interval	95% Confidence Interval
	Means	N	(I) Variety	(J) Variety	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound

LSD	212	387	Red Creole	Texas Grano	104.38*	.051	.000	104.28	104.48
				White Lisbon	-190.62*	.052	.000	-190.72	-190.52
	107	397	Texas Grano	Red Creole	-104.38*	.051	.000	-104.48	-104.28
				White Lisbon	-295.00*	.052	.000	-295.10	-294.90
	402	352	White Lisbon	Red Creole	190.62*	.052	.000	190.52	190.72
				Texas Grano	295.00*	.052	.000	294.90	295.10

Based on observed means.
The error term is Mean Square (Error) = .507.
*. The mean difference is significant at the .05 level.

Table 6 represents LSD Post Hoc analysis test performed on the onion TFC levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the varieties.

According to the table, differences in TFC levels were also brought about by the varieties whose means had an effect. All the varieties according to Least Significance Difference (LSD) had a significance difference on the subject, and this was indicated by the presence of the asterisks in the mean difference groups of the onion varieties.

TPC Levels

Figure 5 *A Summary Graph on Treatment Effects on TPC Levels in Onions*

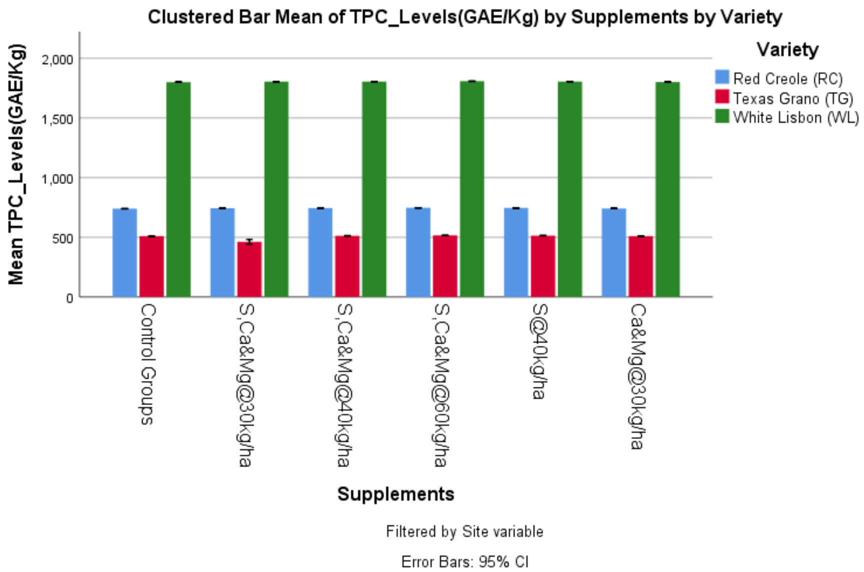

Figure 4 displays clustered bar means graph of the different supplementation treatments as well as the variety on the TPC levels of onions across the different study sites. The figure as well includes error bars to display the level of variances across the mean groups of the data.

Onion Total Phenolic Content (TPC) also had an interesting display on the analysis results as affected by the supplement treatments on different onion varieties. As per the graph analysis, “White Lisbon” scallion variety had the highest phenolic content as compared to their counterparts, the bulb varieties. “Red Creole” red bulb onion had the highest content as compared to “Texas Grano” yellow bulb onion. The results also present that there was close to no significance differences within the varieties themselves at all supplement treatment levels. Generally, treatment 4 of variety 3 had the highest average phenolic content whereas the least was observed in treatment 2 of variety 2. 0 and 20 kg/ha of sulfur levels were used on five onion varieties and a control to measure the yield and the bioactive concentration of onion bulbs as well and the results were as follows: Those planted with sulfur were also found to contain more total phenolic acid and the extracts were found to contain a greater antioxidant activity compared to the whole dry bulb according to Li et al. (2023). This is a strong justification in this research which fully supports the authors as similarly, increasing levels of the same were significantly found on analysis on the onion bulbs where the red bulb onions had the highest TPC levels as compared to the yellow bulb onion varieties. This was in relation to treatment 1 which acted as the control where the results were

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compared to on normal conditions. Other studies too, support that phenolic acid concentration is greatly correlated and determined by the colour of the onion cultivar used, this is on top of other factors such as temperature as well, which may also affect the level of these compounds, as was reported by the author. This research also found this to be true as higher levels of phenolics were reported in red skinned onion as compared to the yellow skinned onion.

All the onion supplements are recommended for use across any of the onion varieties as they all significantly showed higher levels of TPC concentrations as compared to the control treatment. However, planting “White Lisbon” white scallion onion variety yields the highest concentration of TPC levels under S, Ca and Mg at 60 kg/ha with a mean of 1024 GAE/kg. These levels are essential in increasing the onion nutrition quality by increasing the flavour compounds in onions as well as quality produce for the market.

Table 6 *ANOVA Analysis on Treatment Effects on TPC Levels in onions*

Univariate Analysis of Variance

Tests of Between-Subjects Effects					
Dependent Variable: TPC Levels					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	350812082.235[a]	35	10023202.350	24878.448	.000
Intercept	1024803867.849	1	1024803867.849	2543651.144	.000
Site	5657.266	1	5657.266	14.042	.000
Supplements	34818.122	5	6963.624	17.284	.000
Variety	300447049.559	2	150223524.780	372867.680	.000
Site * Supplements	29440.099	5	5888.020	14.615	.000
Site * Variety	11246.096	2	5623.048	13.957	.000
Supplements * Variety	64369.190	10	6436.919	15.977	.000
Site * Supplements * Variety	65573.107	10	6557.311	16.276	.000
Error	443175.652	1100	402.887		
Total	351255257.887	1135			
a. R Squared = .999 (Adjusted R Squared = .999)					

Table 7 indicates the univariate analysis tests of between-subjects effects on the group mean variance of the different independent variables of site, supplements and variety done on the onion TPC levels, and their significant p value levels, testing if there were significant differences in variances or not.

As indicated in the table, strong significant differences were recorded within all treatment groups of site, supplements and variety as well as their combinations. These differences were indicated by significance values of 0.00 in their means, which is $p < .05$.

Table 7 *Post Hoc Analysis on Supplement Effects on TPC Levels in onions*

Homogeneous Subsets									
TPC Levels									
				Subset					
	Supplements	Means	N	1	2	3	4	5	6
Duncan[a,b,c]	S, Ca& Mg at 40 kg/ha	1021	207	878.57					
	S at 40 kg/ha	1022	180		926.81				
	S, Ca& Mg at 30 kg/ha	1020	189			947.40			

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	S, Ca& Mg at 60 kg/ha	1024	188				1002.06		
	Ca& Mg at 30 kg/ha	1018	192					1040.78	
	Control Groups	1017	180						1147.22
	Sig.			1.000	1.000	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 402.887.

a. Uses Harmonic Mean Sample Size = 188.914.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

c. Alpha = .05.

Table 8 represents Duncan Post Hoc analysis test performed on the onion TPC levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the supplements.

These significant differences in the means in the supplement treatments were brought about by all the supplementation applied at all levels within all the six subsets as indicated in the table. No values fell within any of the same subset group thus the strong significant differences within the supplement treatments.

Table 8 *Post Hoc Analysis on Variety Effects on TPC Levels in onions*

Multiple Comparisons									
	Means	N	(I) Variety	(J) Variety	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
LSD	744	387	Red Creole	Texas Grano	241.28*	1.434	.000	238.47	244.09
				White Lisbon	-1059.29*	1.478	.000	-1062.19	-1056.39
	503	397	Texas Grano	Red Creole	-241.28*	1.434	.000	-244.09	-238.47
				White Lisbon	-1300.57*	1.469	.000	-1303.45	-1297.69
	1803	352	White Lisbon	Red Creole	1059.29*	1.478	.000	1056.39	1062.19
				Texas Grano	1300.57*	1.469	.000	1297.69	1303.45

Based on observed means.
The error term is Mean Square (Error) = 402.887.

*. The mean difference is significant at the .05 level.

Table 9 represents LSD Post Hoc analysis test performed on the onion TPC levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the varieties.

The Post Hoc test conducted to determine the result of the differences within the varieties themselves indicated significant differences in TPC levels in onions as a result of differences in the three varieties' mean indicated by the asterisks in their mean difference values.

Anthocyanin Levels

Figure 6 *A Summary Graph on Treatment Effects on Anthocyanin Levels in Onions*

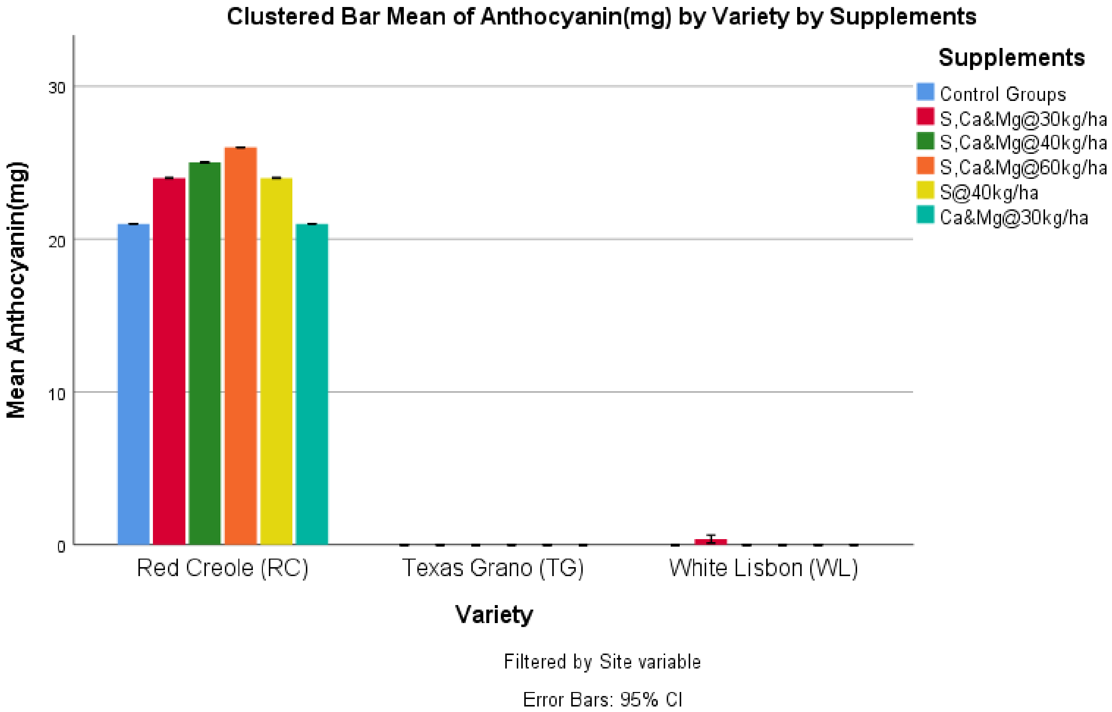

Figure 5 displays clustered bar means graph of the different supplementation treatments as well as the variety on the anthocyanin levels of onions across the different study sites. The figure as well includes error bars to display the level of variances across the mean groups of the data.

As per the results, only the red onion variety was recorded to possess the highest average levels of the bioactive compound in them with high values close to over 25 mg. The highest levels were recorded across all treatments with treatment 4 having the highest levels of anthocyanin in them with slightly over 25 mg on average. The lowest level was recorded in red onion in treatment 1 which had slightly over 20 mg concentration. The rest of the onion varieties, that is, the yellow and white scallion onions had no anthocyanin compound present in them with a 0 mg on them, except for the "White Lisbon" white scallion onion where traces of the compound were found, however with only around 1 mg concentration. The supplement treatments however had higher significant difference on the average TPC levels within the red bulb onion indicated by the graph bars. According to Shreya et al. (2020), Magnesium compound had been found to increase the anthocyanins levels in onions which are responsible for the green sprouts colour increasing the chlorophyll levels in the plants due to the processes of photosynthesis. This was found true especially on red bulb onions where the levels were found to be the highest of all the onion varieties. This research as well strongly agrees with Idhan et al. (2022), who stated that anthocyanin compounds in onions are responsible for the pigmentation, which is red and purple, colours. As per this study's result analysis, red onion was found to contain quite a significant amount of anthocyanin levels, probably a huge contribution resulting from the pigmentation, and significant traces reported as well on the scallion onion shoots although very minimal; close to zero.

All the onion supplements are recommended for use across any of the onion varieties as they all significantly proved higher levels of anthocyanin concentrations as compared to the control treatment. However, this compound is only reported to be found in red/purple onion varieties, giving them color, especially on S, Ca and Mg at 60 kg/ha with which showed the highest concentration levels with a mean of 9 mg. These levels are essential in increasing the onion nutrition quality by increasing the flavour compounds in onions as well as quality produce for the market.

Table 9 *ANOVA Analysis on Treatment Effects on Anthocyanin Levels in onions*

Tests of Between-Subjects Effects
Dependent Variable: Anthocyanin

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Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	142459.581[a]	35	4070.274	90202.037	.000
Intercept	60980.076	1	60980.076	1351389.962	.000
Site	.309	1	.309	6.851	.009
Supplements	403.066	5	80.613	1786.483	.000
Variety	127387.229	2	63693.614	1411525.152	.000
Site * Supplements	1.609	5	.322	7.130	.000
Site * Variety	.595	2	.298	6.595	.001
Supplements * Variety	835.194	10	83.519	1850.888	.000
Site * Supplements * Variety	3.185	10	.318	7.058	.000
Error	49.636	1100	.045		
Total	215935.000	1136			
Corrected Total	142509.217	1135			
a. R Squared = 1.000 (Adjusted R Squared = 1.000)					

Table 10 indicates the univariate analysis tests of between-subjects effects on the group mean variance of the different independent variables of site, supplements and variety done on the onion anthocyanin levels, and their significant p value levels, testing if there were significant differences in variances or not.

As illustrated by the table, these significant differences in the anthocyanin levels in the onion brought about by the supplement treatments and their combinations with p values of $p < .05$.

Table 10 *Post Hoc Analysis on Treatment Effects on Anthocyanin Levels in onions*

Homogeneous Subsets

				Subset					
	Supplements	Means	N	1	2	3	4	5	6
Duncan[a,b,c]	Control Groups	7	180	5.83					
	S, Ca& Mg at 30 kg/ha	8	189		6.97				
	Ca& Mg at 30 kg/ha	7	192			7.87			
	S, Ca& Mg at 60 kg/ha	9	188				8.30		
	S, Ca& Mg at 40 kg/ha	8	207					8.45	
	S at 40 kg/ha	8	180						10.80
	Sig.			1.000	1.000	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = .045.
a. Uses Harmonic Mean Sample Size = 188.914.
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c. Alpha = .05.

Table 11 represents Duncan Post Hoc analysis test performed on the onion anthocyanin levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the supplements.

It was found that the differences in means in all of the supplement treatments resulted to the anthocyanin levels variances because all the mean values within the supplement treatment levels fell on different subsets with no case of overlap.

Table 11 *Post Hoc Analysis on Variety Effects on Anthocyanin Levels in onions*

Multiple Comparisons	
Dependent Variable: Anthocyanin	

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	Means	N	(I) Variety	(J) Variety	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
LSD	23.55	387	Red Creole	Texas Grano	23.55*	.015	.000	23.52	23.57
				White Lisbon	23.49*	.016	.000	23.45	23.52
	0.00	397	Texas Grano	Red Creole	-23.55*	.015	.000	-23.57	-23.52
				White Lisbon	-.06*	.016	.000	-.09	-.03
	0.06	352	White Lisbon	Red Creole	-23.49*	.016	.000	-23.52	-23.45
				Texas Grano	.06*	.016	.000	.03	.09

Based on observed means.
The error term is Mean Square (Error) = .045.
*. The mean difference is significant at the .05 level.

Table 12 represents LSD Post Hoc analysis test performed on the onion anthocyanin levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the varieties.

On analysis and interpretation of the results, all the varieties were found to have contributed to the variations in means. This was indicated by asterisks in their mean difference values as displayed in the table.

Quercetin Levels

Figure 7 *A Summary Graph on Treatment Effects on Quercetin Levels in Onions*

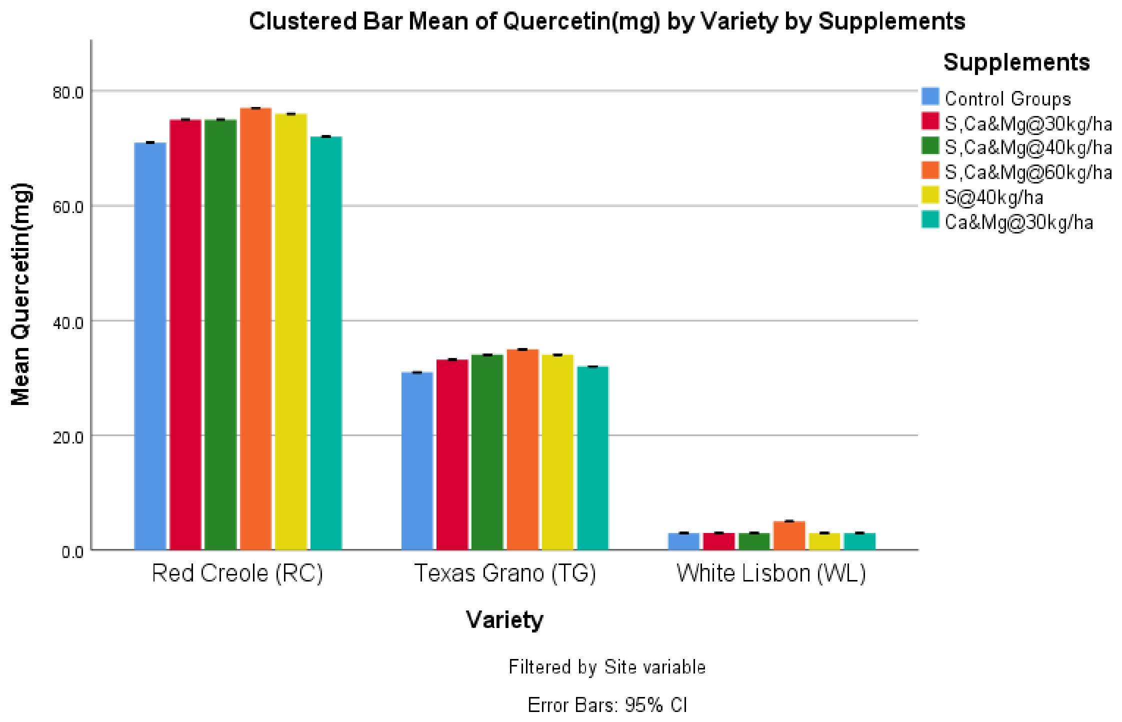

Figure 6 displays clustered bar means graph of the different supplementation treatments as well as the variety on the quercetin levels of onions across the different study sites. The figure as well includes error bars to display the level of variances across the mean groups of the data.

The supplement treatments did not prove any huge significant differences withing the varieties, however, there were huge significant differences recorded between the different varieties at all levels. Treatment 4 was recorded to contribute the highest average quercetin concentration across all the varieties, with a lead in the red onion variety with a value close to 80 mg. The lowest concentrations were recorded on the “White Lisbon” white

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scallion onions, with most supplement treatments contributing almost 0 levels. This report indicated that when administering S, Ca and Mg supplement treatments in onions, no much significant disparity is observed within the same variety. This experiment results agree to research by Akira et al. (2015) who found out that quercetin, a nutrient element in onion bulbs to ranging from 54 to 286 mg/kg FW as is displayed in the graph were a range of 60 to 80 mg/kg. for the red bulb onion. Both sites in this experiment were dyer climates accompanied by very high day temperatures, and the results significantly proved true to the authors" findings as the quercetin levels were found to be high in all the varieties and across the treatments increasingly.

All the onion supplements are recommended for use across any of the onion varieties as they all significantly led to higher levels of quercetin concentrations as compared to the control treatment. However, planting "Red Creole" onion variety significantly yields the highest concentration of quercetin levels as compared to yellow or white scallion varieties, especially under S, Ca and Mg at 60 kg/ha with a mean of 39 mg. These levels are essential in increasing the onion nutrition quality by increasing the flavor compounds in onions as well as quality produce for the market.

Table 12 *ANOVA Analysis on Treatment Effects on Quercetin Levels in onions*

Univariate Analysis of Variance

Tests of Between-Subjects Effects					
Dependent Variable: Quercetin					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	947782.306[a]	35	27079.494	3120184.533	.000
Intercept	1350975.316	1	1350975.316	155663625.597	.000
Site	.044	1	.044	5.074	.024
Supplements	1686.838	5	337.368	38872.554	.000
Variety	855423.520	2	427711.760	49282294.444	.000
Site * Supplements	.229	5	.046	5.281	.000
Site * Variety	.140	2	.070	8.089	.000
Supplements * Variety	610.659	10	61.066	7036.200	.000
Site * Supplements * Variety	.831	10	.083	9.578	.000
Error	9.547	1100	.009		
Total	947791.852	1135			
a. R Squared = 1.000 (Adjusted R Squared = 1.000)					

Table 13 indicates the univariate analysis tests of between-subjects effects on the group mean variance of the different independent variables of site, supplements and variety done on the onion quercetin levels, and their significant p value levels, testing if there were significant differences in variances or not.

On the analysis of the difference in onion quercetin levels means brought about by the treatments, all the

treatments played a role in the results, withal having strong significant differences, with significant levels of 0.00, $p < .05$. the site also played a significant difference with a significant level of 0.02, which is also $p < .05$.

Table 13 *Post Hoc Analysis on Supplements Effects on Quercetin Levels in onions*

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Homogeneous Subsets

	Supplements	Means	N	Subset 1	2	3	4	5	6
Duncan[a,b,c]	Control Groups	35	180	29.667					
	S, Ca& Mg at 30 kg/ha	37	189		36.029				
	Ca& Mg at 30 kg/ha	36	192			37.031			
	S, Ca& Mg at 60 kg/ha	39	188				38.830		
	S, Ca& Mg at 40 kg/ha	37	207					40.976	
	S at 40 kg/ha	38	180						45.494
	Sig.			1.000	1.000	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = .009.
a. Uses Harmonic Mean Sample Size = 188.914.
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c. Alpha = .05.

Table 14 represents Duncan Post Hoc analysis test performed on the onion quercetin levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the supplements.

All the supplements were recorded to have resulted in the significant differences as all the values were reported to fall on different subsets with no overlap across all the subset groupings.

Table 14 *Post Hoc Analysis on Variety Effects on Quercetin Levels in onions*

Multiple Comparisons
Dependent Variable: Quercetin

	Means	N	(I) Variety	(J) Variety	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
LSD	74.44	387	Red Creole	Texas Grano	41.087*	.0067	.000	41.074	41.100
				White Lisbon	71.100*	.0069	.000	71.086	71.113
	33.36	397	Texas Grano	Red Creole	-41.087*	.0067	.000	-41.100	-41.074
				White Lisbon	30.013*	.0068	.000	29.999	30.026
	3.35	352	White Lisbon	Red Creole	-71.100*	.0069	.000	-71.113	-71.086
				Texas Grano	-30.013*	.0068	.000	-30.026	-29.999

Based on observed means.
The error term is Mean Square (Error) = .009.
*. The mean difference is significant at the .05 level.

Table 15 represents LSD Post Hoc analysis test performed on the onion quercetin levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the varieties.

As was found and shown in the table, all the varieties were found to have significant differences in their mean groups, with all the varieties values having asterisks in their mean difference values.

Organosulfur Levels

Figure 8 *A Summary Graph on Treatment Effects on Organosulfur Levels in Onions*

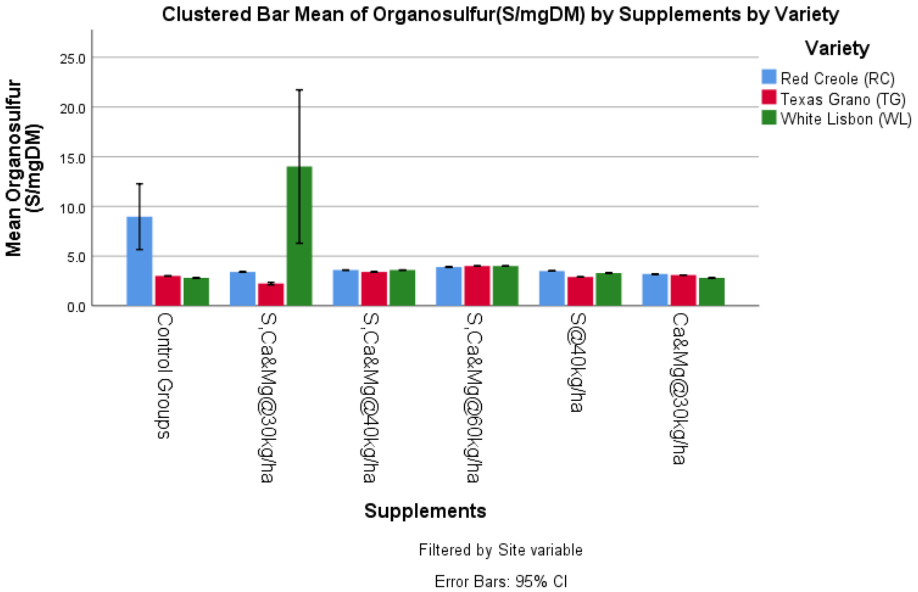

Figure 7 displays clustered bar means graph of the different supplementation treatments as well as the variety on the organosulfur levels of onions across the different study sites. The figure as well includes error bars to display the level of variances across the mean groups of the data.

No major differences in the treatments were recorded as a result of the supplementation within the different varieties except in treatment 1 and treatment 2 where some varieties recorded a spike. Treatment 2 was recorded to have the highest level of organosulfur concentration in the white scallion onion variety, whereas the lest levels were recorded in treatment 2 of the yellow bulb onion variety. According to a high-performance liquid chromatography (HPLC) analysis study by Guangmin et al. (2022), the authors found out that upon application of sulfur, red onion had 0.20 µmol/g, yellow onion had 0.35 µmol/g where as white onion had 0.14 µmol/g FW. The findings of this study however fail to fully agree with the report as red onions were significantly recorded to have most higher organosulfur levels as a result of the supplementation as compared to the other onion varieties, although with slight margin differences.

All the onion supplements are recommended for use across any of the onion varieties as they all significantly led to higher levels of organosulfur concentrations as compared to the control treatment as presented in figure 30. However, planting "White Lisbon" white scallion onion variety significantly yields the highest concentration of organosulfur levels under S, Ca and Mg at 60 kg/ha with a mean of 3.9 S/mg DM. These levels are essential in increasing the onion nutrition quality by increasing the flavor compounds in onions as well as quality produce for the market, not forgetting the diverse health benefits accompanied as well.

Table 15 *ANOVA Analysis on Treatment Effects on Organosulfur Levels in onions*

Univariate Analysis of Variance

Tests of Between-Subjects Effects

Dependent Variable: Organosulfur

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	14082.501[a]	35	402.357	9.301	.000
Intercept	16707.007	1	16707.007	386.201	.000
Site	39.508	1	39.508	.913	.339
Supplements	1114.764	5	222.953	5.154	.000
Variety	521.689	2	260.844	6.030	.002
Site * Supplements	1975.428	5	395.086	9.133	.000
Site * Variety	1034.338	2	517.169	11.955	.000

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Supplements * Variety	4413.171	10	441.317	10.202	.000
Site * Supplements * Variety	3314.303	10	331.430	7.661	.000
Error	47585.879	1100	43.260		
Total	61668.379	1135			
a. R Squared = .228 (Adjusted R Squared = .204)					

Table 16 indicates the univariate analysis tests of between-subjects effects on the group mean variance of the different independent variables of site, supplements and variety done on the onion organosulfur levels, and their significant p value levels, testing if there were significant differences in variances or not.

The differences in concentration levels were analyzed and significant differences in means were found in almost all the treatment groups and their combinations with p value significant levels of $p < .05$, except for the site difference which proved to have no significant differences at all with a p value significance of $p > .05$. This indicated that when planting different varieties of onions under different supplementation of S, Ca and Mg, the site of selection does not have a significant difference in the organosulfur concentration levels.

Table 16 *Post Hoc Analysis on Supplements Effects on Organosulfur Levels in onions*

Homogeneous Subsets

	Supplements	Means	N	Subset		
				1	2	3
Duncan[a,b,c]	Ca& Mg at 30 kg/ha	3.0	192	3.034		
	Control Groups	3	180		4.567	
	S, Ca& Mg at 30 kg/ha	2.9	189			6.117
	Sig.			.213	.079	1.000
Means for groups in homogeneous subsets are displayed. Based on observed means. The error term is Mean Square (Error) = 43.260.						
a. Uses Harmonic Mean Sample Size = 188.914.						
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.						
c. Alpha = .05.						

Table 17 represents Duncan Post Hoc analysis test performed on the onion organosulfur levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the supplements.

On analysis of the differences in the supplementation treatment means in relation to the organosulfur levels concentration, significant differences were found present across all the subset groups within the control treatment 1, as well as treatments 2 and 6 with no case of overlap in the means across.

Table 17 *Post Hoc Analysis on Variety Effects on Organosulfur Levels in onions*

Multiple Comparisons	
Dependent Variable: Organosulfur	

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	Means	N	(I) Variety	(J) Variety	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
LSD	4.2	387	Red Creole	Texas Grano	1.104*	.4698	.019	.182	2.026
	3.1	397	Texas Grano	Red Creole	-1.104*	.4698	.019	-2.026	-.182
				White Lisbon	-1.873*	.4815	.000	-2.818	-.928
	5.0	352	White Lisbon						
				Texas Grano	1.873*	.4815	.000	.928	2.818

Based on observed means.
The error term is Mean Square (Error) = 43.260.

*. The mean difference is significant at the .05 level.

Table 18 represents LSD Post Hoc analysis test performed on the onion organosulfur levels where significant differences were recorded to determine which specific treatments caused the variances and at what levels on the varieties.

Between “Red Creole” red bulb and “Texas Grano” yellow bulb onion varieties and between “Texas Grano” and “White Lisbon” white scallion onion varieties, there were significant differences in their mean groups indicated by the asterisks in their mean difference values.

CONCLUSION

Significant differences were found on analyzing the bioactive compounds and therefore the null hypothesis was rejected to state that varying rates of nutrient supplementation significantly affected the bioactive compounds profile in onions under different agri-climates. S, Ca and Mg at 60 kg/ha significantly proved the highest bioactive compounds with means of 243.33QE/kg TFC levels, 1024GAE/kg TPC levels, 44 mg/100g calcium levels, 18.33 mg/100g magnesium levels on “White Lisbon” and 9% anthocyanin levels, 39 mg quercetin levels and 3.9 S/kg DM organosulfur levels on “Red Creole” variety.

S, Ca and Mg at 60 kg/ha significantly proved the highest bioactive compounds with “White Lisbon” recording highest TFC, TPC, calcium as well as magnesium levels and “Red Creole” had the highest anthocyanin, quercetin and organosulfur levels.

For farmers intending to produce onions with high bioactive compounds, S, Ca and Mg at 60 kg/ha is highly recommended on “White Lisbon” or “Red Creole”.

However, several limitations of this study should be acknowledged. First, the research was conducted over a single growing season, and the results may be influenced by seasonal variation in weather conditions. Second, the study included only two sites, limiting the generalizability of the findings to other agri-climatic zones in Kenya. Third, the study focused on three onion varieties; the responses of other commercially important varieties may differ. Fourth, the economic analysis was not conducted, limiting the practical applicability of the findings for farmers. Fifth, the bioavailability of the enhanced bioactive compounds to consumers was not assessed. Future research should address these limitations by: (1) conducting multi-season trials to assess the consistency of treatment effects; (2) expanding the study to include additional agro-ecological zones; (3) evaluating a wider range of onion varieties; (4) conducting cost-benefit analysis to guide farmer adoption; and (5) assessing the bioavailability of the enhanced bioactive compounds through human intervention studies. Such research would provide a more comprehensive understanding of the potential for mineral supplementation to improve the nutritional quality of onions and contribute to food security and public health.

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