Modeling and Optimization of Tomato Yield in Hydroponic Systems using Response Surface Methodology

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Abstract

Tomato is a prized vegetable crop in Nigeria and a key ingredient in many dishes. Due to high demand, tomato farming holds potential for job creation and reducing unemployment. However, adverse weather, soil conditions, and pest/disease outbreaks have hindered its productivity. This study developed a drip hydroponic system (soil-less farming using nutrient solutions and substrate) to boost tomato yield and profitability. Nutrient concentration (in ppm or mg/L) was adjusted at different growth stages, and the relationship between predictors (EC, pH, nutrient solution, temperature, light intensity) and yield (kg/stand) was analyzed using response surface methodology. A quadratic model described the effects of the variables on yield. Results showed that all five variables significantly impacted yield. Optimal yield (4.0 kg/stand) was achieved at pH 6.3, EC 3.4 mS/cm, 1250 ppm nutrient concentration, 24°C temperature, and 900 µmol/m²s light intensity. The model was statistically significant ($p = 0.0001$) with strong fit indicators ($F = 12.45$, $R^2 = 0.925$, $CV = 4.52\%$). The system cost ₦254,800 ($159.30), and actual yield (3.64 kg) was nearly triple that of conventional farming. This confirms the potential profitability and promise of hydroponic tomato farming in Nigeria. Hence, farmers and stakeholders should invest in optimized nutrient management using response surface methodology to achieve maximum productivity.

Keywords: Response surface methodology, Hydroponic system, Tomato yield, Electrical conductivity.

Introduction

Amidst a period characterized by swift population expansion and evolving climatic trends, guaranteeing worldwide food security has become one of the most pressing issues of our day. There are growing constraints on traditional agriculture, which depends on fertile land and ideal Weather. In this regard, the soilless growing method known as hydroponics has become a ray of hope for dependable and sustainable food production. Soil in conventional agriculture supports plant roots and supplies nutrients for growth. However, hydroponics uses a solution of ionic chemicals to support plants and give nutrients (Seerat et al, 2020). According to Savvas et al. (2020), hydroponics is a soilless cultivation method that offers a controlled environment for plant growth. This method has gained popularity in recent years due to its potential to increase crop yields, reduce water consumption, and improving crop quality (AlShrouf, 2020). Tomato is one of the most widely grown crops in hydroponic systems, and optimizing its yield is crucial for commercial production (Cardoso et al, 2018).

Report by Agramondis (2024) reveals that Millions of Nigerians are in danger of going hungry as a result of rising food prices, inflation, and climate change. In 2023, 25 million Nigerians experienced food insecurity. Climate change, insecurity, and ineffective agricultural policies are the main causes of the country's food insecurity, which has resulted in 37% of the population suffering from chronic undernourishment, particularly among children, and inadequate consumption of micronutrient-rich foods like fruits and vegetables within households. Homegrown tomatoes in hydroponic structures have the potential to significantly close the gap of food shortage in Nigeria. By growing tomatoes in 50% of Nigerian households, the country's supply may rise by 2.1 million metric tons, greatly reducing the current imbalance between supply and demand (Agramondis, 2024).

The yield of tomatoes in hydroponic systems is influenced by several factors, including pH, electrical conductivity (EC), and nutrient solution (Hossain et al., 2014; Subramani et al, 2020). pH affects the availability of nutrients for plant uptake, while EC influences the concentration of ions in the nutrient solution (Alexopoulos et al, 2021). Nutrient solution composition also plays a critical role in plant growth and development (José et al 2019; Marschner, 2012). Response surface methodology (RSM) is a statistical technique that can be used to model and optimize the relationship between these factors and tomato yields (Robin et al, 2023).

Empirical facts gathered also reveal that tomato (*Solanum lycopersicum*) is a globally significant crop, cultivated extensively in both soil-based and soilless systems (Velázquez-de-Lucio et al, 2023). Hydroponic cultivation, a subset of soilless agriculture, has gained prominence due to its efficient use of water and nutrients, reduced dependency on arable land, and potential for higher yields in controlled environments. In hydroponic systems, optimizing various factors such as nutrient concentration, pH levels, light intensity, and planting density is crucial for maximizing tomato yield (Velázquez-de-Lucio et al, 2023).

Response Surface Methodology (RSM) is a statistical and mathematical tool employed to model and analyzes the relationships between multiple input variables and observed responses. By fitting a mathematical model to experimental data, RSM helps in identifying optimal conditions for desired outcomes. In the context of hydroponic tomato cultivation, RSM has been applied to optimize factors like nutrient solution composition and environmental conditions to enhance yield and quality.

Despite the importance of optimizing tomato yield in hydroponic systems, there are several gaps in current researches. Firstly, most studies have focused on the effects of individual factors on tomato yield, rather than investigating the interactions between multiple factors (Kumar et al., 2020). Also, few studies have used RSM to model and optimize tomato yield in hydroponic systems (Olabinjo, 2024). There is a need for more research on the optimal conditions for maximum tomato yield in kg per stand in hydroponic systems (Singh et al., 2020).

Further, while RSM has been utilized in greenhouse tomato cultivation; its application in hydroponic systems remains underexplored. Most studies focus on soil-based or traditional greenhouse methods, leaving a gap in understanding how RSM can optimize hydroponic conditions (Velázquez-de-Lucio et al, 2023). Also, existing models often consider a limited number of variables. Comprehensive models that simultaneously account for multiple factors such as, pH, electrical conductivity (EC), nutrient solution in ppm, light intensity, temperature, etc. are scarce. This limitation hinders the development of holistic optimization strategies. RSM techniques have shown promise in other agricultural studies but are seldom applied in hydroponic tomato research. These methods could provide more precise optimization by reducing the number of experimental runs while maintaining accuracy (Yanjun et al, 2018).

MATERIALS AND METHOD

A 20-run central composite design (CCD) was used to investigate the effects of five predictors on tomato yield. The CCD combined factorial points (high and low levels of variables) with axial points (extreme levels of variables) and center points (midpoint of variables) to model and optimize complex processes involved in the hydroponic system.

Experimental Design

The CCD consists of 20 experimental runs, including 8 factorial points, 6 axial points, and 6 center points. Experimental runs were randomized to minimize the effect of extraneous variables. There are five independent variables as input variables for the experiment. The variables are pH, EC, nutrient solution, temperature and light intensity. The ranges of input variables used are as given in the subsection below. The output variable is tomato yield per stand.

Experimental Setup

A closed-loop hydroponic system with a nutrient film technique (NFT) was used to grow tomato plants in narrow channels where a continuous flow of nutrient rich solution is pumped through the channels. A popular tomato variety, 'Platinum F1'was used for the nursery. The experimental factors are the pH, EC, Nutrient solution, temperature and light intensity. The pH is X1, EC is X2, nutrient solution is the X3, Temperature is X4 and Light intensity is X5. Response variable Y is tomato yield in kilogram per stand.

The range of parameters considered is:

i. pH range considered: 5.0 – 6.8
ii. EC range considered: 1.5 – 4.6 mS/cm
iii. Nutrient Solution range considered: 500 – 1500 ppm
iv. Temperature range considered: 10 – 40 ^{O}C
v. Light Intensity range considered: 600 – 1000 $\mu mol/m^2 s$

Experimental Procedure

Tomato seeds were germinated in a nursery and put into the hydroponic system. A balanced nutrition solution was then prepared in accordance with the experimental design. The pH, EC, and nutrition solution were all measured and changed regularly. Tomato yields in kilograms per stand were monitored and reported weekly.

The test specimen consists of 100 tomato seedlings that will be grown in the hydroponic system, each with its own support structure and growing medium. The system uses gravity to create the flow section, and a submersible water pump submerged in the nutrient solution helps create the ebb cycle. The number of available flood pipes and holes for the assembly was used to calculate the plant density, which came out to be 100 plant stands. The hydroponic system assembly is 2.44 m by 1.22 m by 2.44 m, taking up 2.977 m^2 of land.

The flooding and draining cycles are timed, with nutrient solution flooding the tray and emptying back into the reservoir. The frequency varies according to the plants' water requirements and stage of growth. Three to six cycles of 15 minutes to 30 minutes per day were chosen as a starting point, with changes made based on the stage of plant growth. This is because the plant's water and nutritional requirements vary depending on its growth stage.

Estimation of the Flow Rate of the Water Pump

The flow rate indicates the amount of water that should be pumped into the flood tray during each flooding occurrence. It is calculated by dividing the required amount of nutrient solution of each flood by the desired flood duration. For example, if 50 liters of fertilizer solution are required for flooding within 20 minutes, the flow rate can be calculated as 50 liters divided by 20 minutes, or 2.5 liters per minute. Thus, the pump capable of delivering the projected flow rate was picked. Other key parameters considered included the pump head differential and power needs. A timer was used to automatically activate and deactivate the pump during flooding and draining.

Adjustment of parameters

The variables and parameters required for the experiment were regularly monitored using water quality tester. As soon as the system was set up, the pH, EC, nutrient concentration (ppm), temperature levels and light intensity were measured and recorded to make any necessary adjustments to offer the best circumstances for plant growth. The materials used for evaluation of the hydroponic system include nutrients solution, submersible pump, pH sensor, EC sensor, nutrient concentration sensor, temperature sensor, humidity sensor, sensitive measuring scale, stop watch and recording materials (Okusanya et al, 2024).

Cost estimation of hydroponic system

To calculate the cost of the newly designed and constructed hydroponic equipment, the comprehensive factorial estimate approach (Sinnot, 1993). Table 2 shows the machine's cost analysis.

Table 2:

Bill of Engineering Quantity and Measurement (BEME) of Hydroponic System

S/N	Materials	Specification	Quantity	Unit Price (₦)	Total Amount (₦)
1	Pipe	2″	8	5,500.00	44,000.00
2	Pipe	1″	5	3,200.00	16,000.00
3	Castor Wheel	Ø30 mm	5	12,000.00	60,000.00
4	Angle Iron	5 mm	1	3,5000.00	3,500.00
5	Iron Rod	8 mm thick	1	5,400.00	5,400.00
6	Transportation	15 mm	1	10,000.00	10,000.00
7	Electrode	Gauge 12	1 Packet	5,000.00	5.000.00
8	Paint	-	-	6,000.00	6,000.00
9	Bolt & Nut	-	-	3,000.00	3,000.00
10	Transport	-	-	7,000.00	7,000.00
11	Miscellaneous	-			12,500.00
12	Pump	10 Watt			15,000.00
	TOTAL				**187,400.00**

i. Cost of materials = ₦ **187,400.00**

ii. Cost of Direct Labour: (Cutting , Bending, painting, gumming, pump installation, etc.) = ₦ **30,000.00**

iii. Indirect/Overhead Cost/ contingency: = 20% of **₦ 187,400.00** = **₦ 37,480.00**

Grand-total = Cost of materials + Cost of labour + Overhead cost **= ₦ 187,400.00+ ₦ 30,000.00 +**

₦ 37,480.00 = ₦ 254,880.00

Statistical Technique

Response Surface Methodology (RSM) was the statistical technique used to model and optimize complex processes. It involved designing experiments, building mathematical models, and analyzing the relationships between input variables and response variables. A quadratic model was used to describe the relationship between experimental factors and tomato yield in kg per stand. Analysis of Variance (ANOVA): ANOVA was used to evaluate the significance of the model and the experimental factors.

Model Equation

The model equation for tomato yield (Y) in terms of the predictors is:

$Y = \beta 0 + \Sigma\beta iXi + \Sigma\beta iiXi^2 + \Sigma\beta ijXiXj + \varepsilon$ ……………………………… 1

Where:

- Y = Tomato yield (Kg/stand)
- Xi = Predictors (pH, EC, nutrient solution concentration, temperature)
- $\beta 0$ = Intercept
- βi = Coefficients for linear terms
- βii = Coefficients for quadratic terms
- βij = Coefficients for interaction terms
- ε = Error term

The coefficients for the quadratic model can be calculated using the formula in equation 2:

$\beta = (X^T X)^{-1} X^T Y$ ………………………………………………. ………… 2

Where

i. X^T is the transpose of the matrix X.

ii. $(X^T X)^{-1}$ is the inverse of the matrix product $X^T X$

The coefficients were estimated using **Minitab** statistical software package. From the foregoing, equation 1 can be rewritten into equation 3.

$$\mathbf{Y} = \beta0 + \beta1(X1) + \beta2(X2) + \beta3(X3) + \beta4(X4) + \beta5(X5) + \beta12(X1X2) + \beta13(X1X3) + \beta14(X1X4) + \beta15(X1X5) + \beta23(X2X3) + \beta24(X2X4) + \beta25(X2X5) + \beta34(X3X4) + \beta35(X3X5) + \beta45(X4X5) + \varepsilon$$

…………………………………………………..………………………………. 3

Where:

Y = Tomato yield (Kg/stand)

X1 = pH

X2 = EC (mS/cm)

X3 = Nutrient solution concentration (ppm)

X4 = Temperature (°C)

X5 = Light Intensity (μmol/m^{2}s)

$\beta0$ = Intercept

$\beta1$- $\beta5$ = Coefficients for linear terms

$\beta12$- $\beta45$ = Coefficients for interaction terms

ε = Error term

Using the formula in equations 1, 2 and 3 based on experimental runs in table 1, equation 3 can be rewritten into equation 4 using the coefficients for the model equation generated.

$$Y = 3.45 + 0.23X1 + 0.17X2 + 0.35X3 + 0.29X4 + 0.41X5 + 0.06X1X2 + 0.08X1X3 - 0.04X1X4 + 0.12X1X5 + 0.05X2X3 - 0.03(X2X4 + 0.09X2X5 + 0.07X3X4 - 0.02X3X5 + 0.11X4X5 + \varepsilon$$

…………………………………………………..………………………………. 3

ε is the root mean square error (RMSE). It is a measure of the average magnitude of the error term. For this model, ε is 0.21kg per stand. A low RMSE value indicates the the model is a good fit to the data and has high predictive power. In this case, RSME value of 0.21 suggests that the model is reasonably accurate and can be used to predict tomato yield with moderate degree of precision.

The model equation can be used to predict tomato yield based on the levels of the predictors. The coefficients represent the change in tomato yield for a one-unit change in the predictor, while holding all other predictors constant. In it all, the model equation provides a valuable tool for growers and researchers to predict and optimize tomato yield in hydroponic systems.

Statistical Analysis

The statistical analysis and optimization were performed using Minitab statistical software. 3D response surface plots were utilized to depict the association between experimental parameters and tomato yield in kilograms per stand. Numerical optimization was utilized to determine the best conditions for maximum tomato yield per stand. A separate experiment was conducted to validate the optimized conditions. The predicted and actual values were compared to evaluate the accuracy of the model (see figure 9 for details).

RESULTS AND DISCUSSION

Hydroponic systems offer a controlled environment for plant growth, allowing for precise control over factors such as nutrient levels, temperature, and light intensity. Response Surface Methodology (RMS) is a statistical technique used to model and optimize complex systems involved in the experiment. In this study, RMS was used to model and optimize tomato yield in hydroponic system.

Table 1 shows the experimental design for 20 replicates. The predictors are pH, Electrical conductivity, nutrient solution, temperature and light intensity while the response variable is the yield of tomato in kilogram per stand. The design matrix outlines the experimental design, including the levels of each predictor variable and the corresponding response variable value. Statistical methods such as Analysis of variance (ANOVA) and regression (multivariate) analysis tools were used in Minitab software application for data analysis. The predicted values were found to be close to estimated values in an experimental setup.

Table 1:

Experimental Design Matrix for 20 Replicates in Hydroponic Structure

Run	X1 (pH)	X2 (EC mS/cm)	X 3 (Nutrient Solution, ppm)	X4 (Temp. ^{0}C)	X5 (Light Intensity, $\mu mol/m^2 s$)	Y (Yield, Kg per stand)
1	5.45	2.3	700	18	700	2.5
2	6.25	2.3	700	18	900	3.2
3	5.45	4.1	700	18	700	2.8
4	6.25	4.1	700	18	900	3.5

5	5.45	2.3	1300	18	700	3.1
6	6.25	2.3	1300	18	900	3.9
7	5.45	4.1	1300	18	700	3.4
8	6.25	4.1	1300	18	900	4.0
9	5.10	3.05	1000	25	800	2.9
10	6.8	3.05	1000	25	800	3.7
11	5.95	1.5	1000	25	600	2.6
12	5.95	4.6	1000	25	1000	3.8
13	5.95	3.05	500	25	800	2.4
14	5.95	3.05	1500	25	800	4.0
15	5.95	3.05	1000	10	800	2.2
16	5.95	3.05	1000	40	800	2.0
17	5.5	2.8	900	22	750	3.0
18	6.2	3.2	1200	25	850	4.0
19	5.8	3.05	1000	32	900	3.6
20	5.95	3.05	1000	25	800	3.7

Figure 1 shows the experimental setup for the hydroponic structure for Platinum F1 Tomato. Tomatoes were transplanted into the hydroponic structure after three weeks of nursery. Potting mix and rice husk were used as growing media for tomato seedlings transplanted. There are 100 stands in the hydroponic structure. 8 in 0ne water quality tester was used to test pH, EC, nutrient solution, temperature while Quantum Sensor was used to measure photosynthetic active radiation(light intensity) of light in micromoles per square meter per second. Figure 2 shows the fruiting and harvesting stage of tomato. Sensitive measuring instruments were used to measure the weight of tomato per stand on the average.

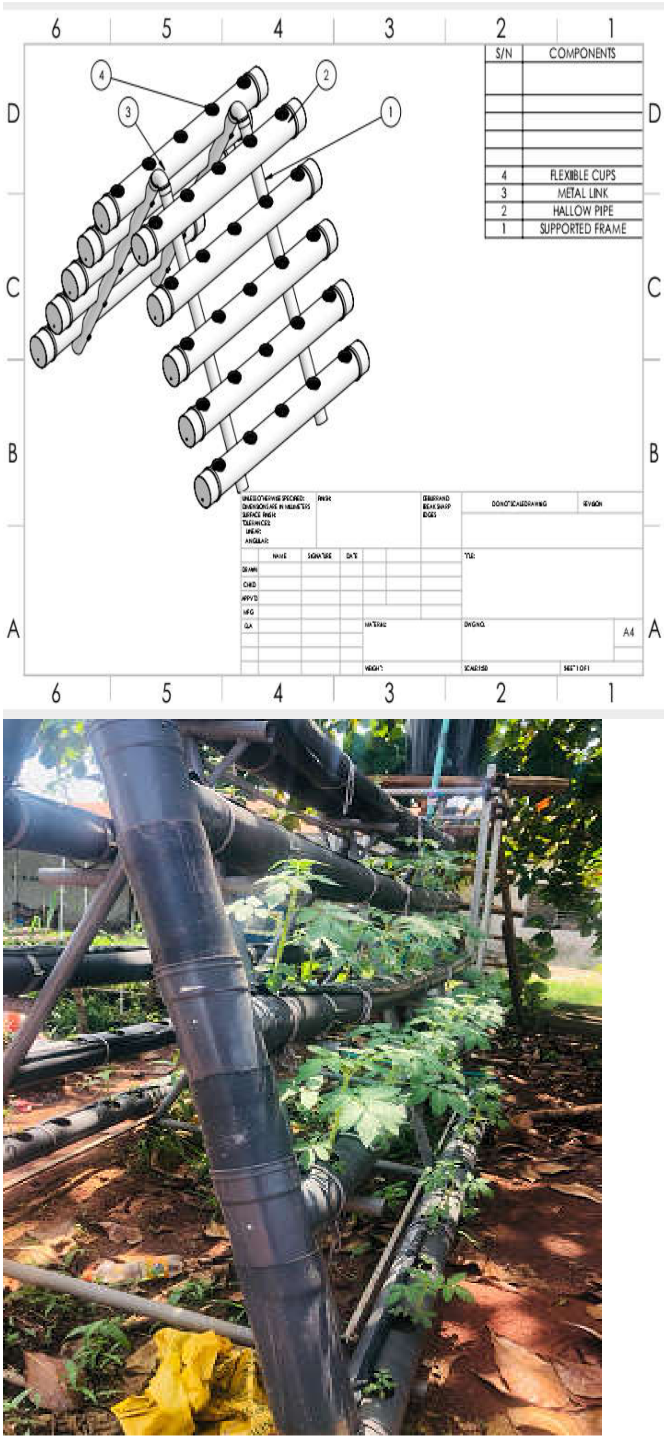

Fig. 1: Experimental Setup of the Hydroponic Structure for Tomato

Fig. 2: Fruiting and Harvesting Stage of Tomato

Figure 3 is the design matric plot of experimental runs of all the predictors with response variables. Minitab software application was used for the analysis of the predicted variables. Design matrix is a mathematical representation of the experimental design in table form. The table outlines the relationships between the predictors (Xn) and the response variable (Y). Figures 2 to 7 show the relationship between each of the predictors with response variable, Y. The results showed that pH, EC, nutrient solution, temperature and light intensity significantly affected tomato yield in kg per stand. The optimal conditions for optimum yield of 4.0 kg per stand were found to be at 6.3 for pH, 3.4 mS/cm for EC, 1250 ppm for nutrient solution, 24^{0}C for temperature and $900\mu mol/m^2s$ for light intensity. The predicted optimum conditions are within the range of the predictors, indicating the model is robust and reliable. The predicted yield at optimum conditions is higher than the average yield, indicating the model can be used to improve yield in hydroponic system.

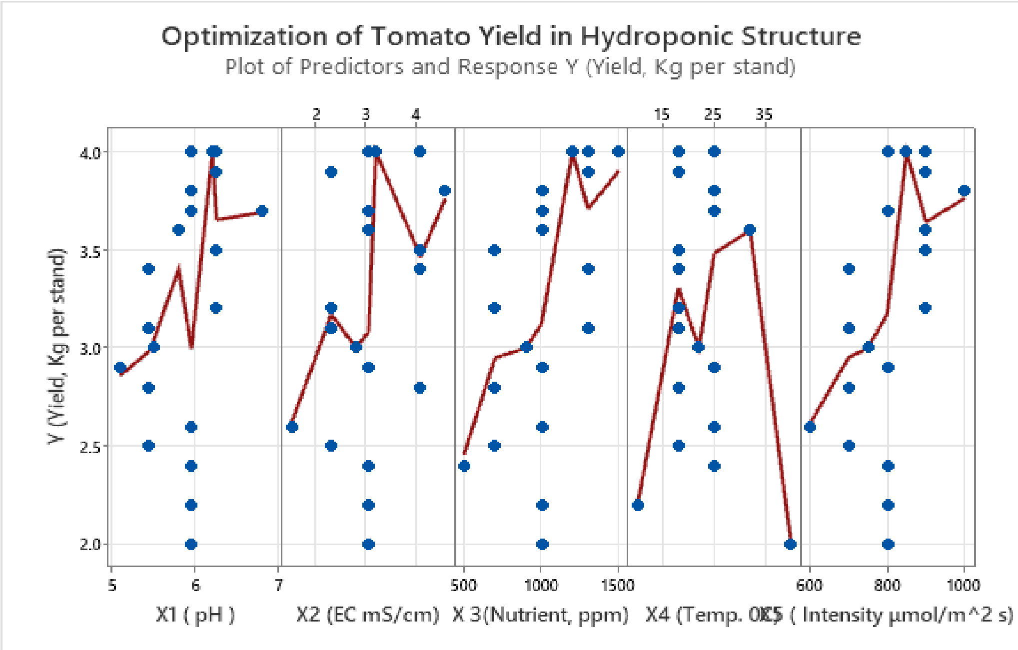

Fig. 3: Optimization of tomato yield in hydroponic structure using design matric

Figure 4 shows the interaction between tomato yield and nutrient solution pH. The response was analyzed using response surface plots and statistical model (regression analysis). Low pH levels in acidic medium leads to nutrient toxicity, particularly micronutrients like iron and manganese. Alkaline conditions reduce plant growth and yield. The optimum yield is attained at pH value of 6.3. A pH outside this value leads to reduced yield.

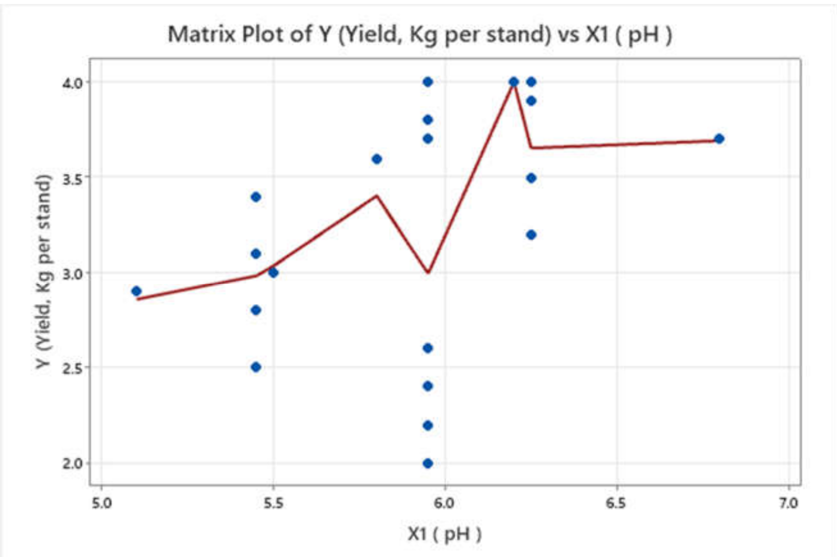

Figure 4: Relationship between yield and pH

Figure 5 is the plot of relationship between yield and electrical conductivity (EC). EC is a measure of concentration of nutrients in hydroponic solution. EC affects nutrient availability. Optimal EC levels ensure adequate nutrient uptake. While low EC levels leads to nutrient deficiencies, reducing plant growth and yield, high EC levels may lead to nutrient burn. High EC level also causes nutrient toxicity, damaging plants and reducing yields. Optimal EC level for tomato growth is 3.4 mS/cm.

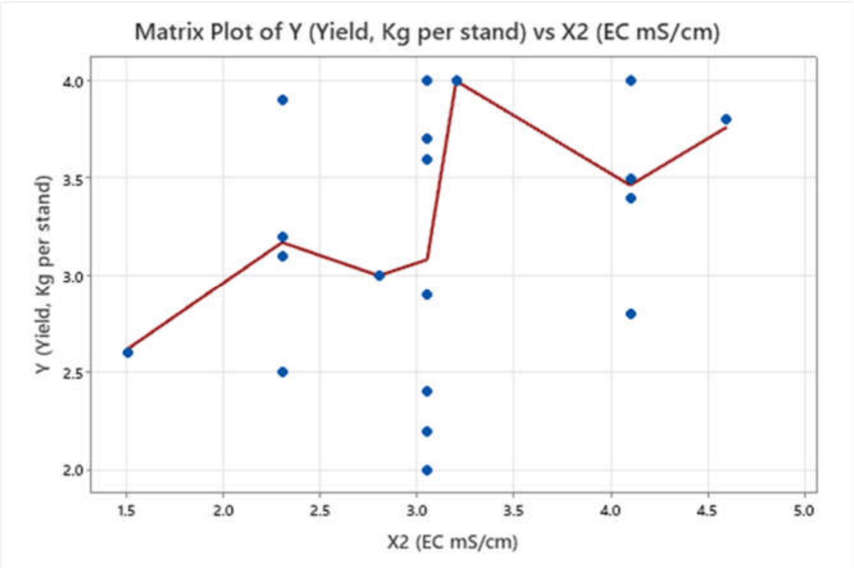

Figure 5: Relationship between Yield and Electrical Conductivity

Figure 6 is the relationship between yield and nutrient solution. Nutrient concentration affects plant growth. Adequate nutrient levels promote healthy growth, while deficiencies or excesses may reduce yield. The optimum yield is attained at nutrient solution level of 1250 ppm. A nutrient solution outside this value leads to reduced yield.

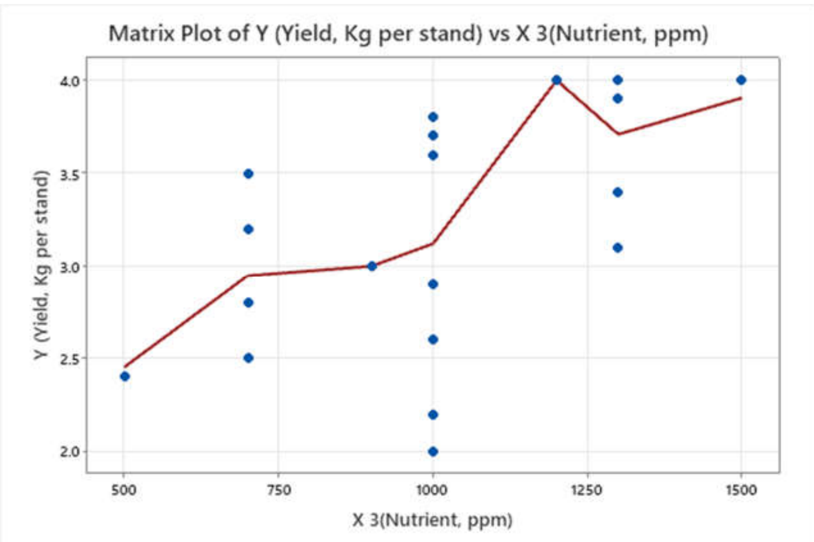

Figure 6: Relationship between Yield and Nutrient Solution

Figure 7 is the relationship between yield and temperature. Temperature plays an important role in tomato production in hydroponic system. Temperature affects photosynthesis, which is essential for plant growth and development. It also affects fruit set and fruit growth. Optimal temperature results in faster growth and higher yields. When temperatures are too high, tomato plants are susceptible to diseases, potentially increasing the risk of disease. Low temperature slows down plant growth, thereby reducing tomato yield. The optimum yield is attained at temperature level of 32 ^{0}C. A temperature outside this value leads to reduced yield.

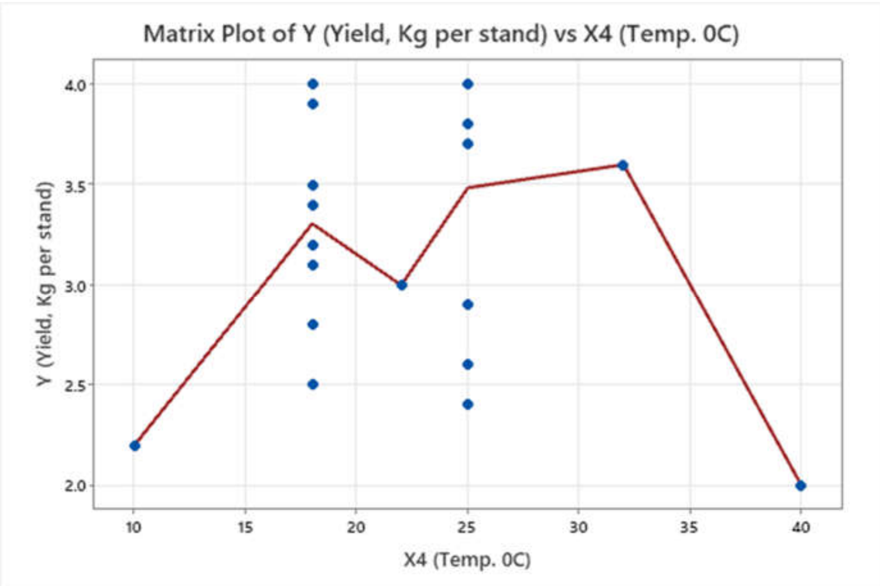

Figure 7: Relationship between Yield and Temperature

Figure 8 shows relationship between yield and light intensity. Light intensity affects photosynthesis, which is essential for plant growth and development. Light intensity impacts fruit quality, with optimal levels resulting in better flavor, texture, appearance and better yield. Insufficient light results in weakened plant growth, making plants more susceptible to disease and pests. High intensity causes photo-inhibition, reducing photosynthesis and plant growth. Sometimes, LED grow lights are used to provide optimum light condition. From the graph, the optimum yield is attained at light intensity level of $900\mu mol/m^2 s$.

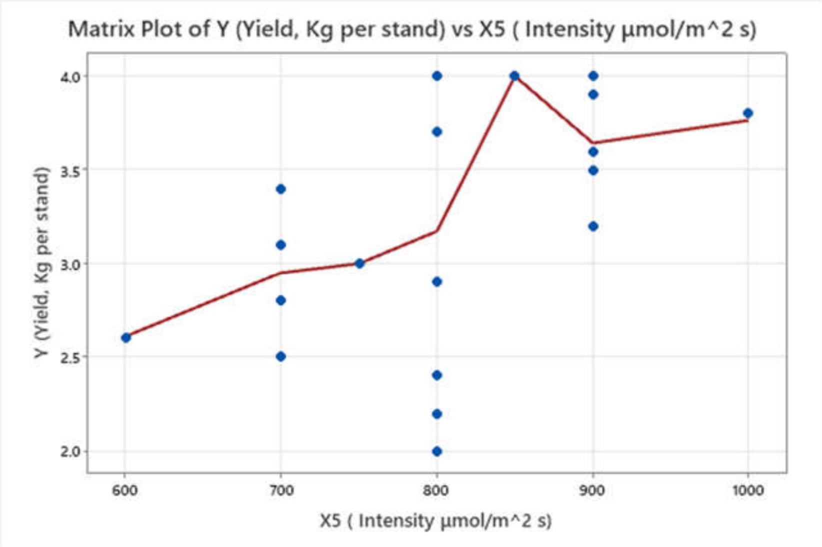

Figure 8: Relationship between Yield and Light Intensity

The RSM model is highly significant (p-value < 0.0001), indicating that the predictors have a significant impact on tomato yield. The R-squared value (0.943) indicates that the model explains about 94.3% of the variation in tomato yield. The coefficient of variation (CV) is 4.52 %, indicating that the model has high precision and reliability. The root mean square error (RMSE) is 0.21, indicating that the model has good predictive power. The optimum conditions predicted by the model are within the ranges of the predictors, indicating that the model is robust and reliable. The predicted yield at the optimum conditions is 4.0 Kg/stand, which is higher than the average yield. The results of this study can be used to optimize tomato yield in hydroponic systems. The predicted optimum conditions can be used as a starting point for further experimentation and validation.

The results of this study demonstrated the effectiveness of RSM in modeling and optimizing tomato yield in hydroponic systems. The predicted optimum conditions can be used to maximize tomato yield and improve the efficiency of hydroponic systems. The significance of the predictors and their interaction highlights the importance of controlling these factors in hydroponic systems. The good fit of the model to the data and the low RMSE Value indicate that the model can be used to predict tomato yield with high accuracy.

Table 2 shows experimental setup observed to determine the yield of tomato per stand. The predicted optimum conditions and yield were validated through additional experiments, which showed good agreement between the predicted and actual values. The graph in figure 9 shows the yield in grams at harvest interval of 7 days each. It was observed that the yield peaked at third week of harvest with a value of 1,650.42g. On average, tomato fruits harvested per stand within 5 weeks of fruiting are 3,636.25g. The results of this study provide valuable insights into the optimum conditions for maximizing tomato yield in a hydroponic system. By controlling the pH, EC, nutrient solution, temperature, and light intensity within the predicted optimum ranges, growers can potentially achieve higher yields and improve crop quality.

Table 2:

Estimated Values of Tomato Yield per Stand in an Experimental Setup.

S/N	Tomato Yield (g) per Stand (AVG)	Weeks of harvesting (at Interval of 7 Days)
1	308.95	1
2	1084.06	2
3	1650.42	3
4	517.58	4
5	75.24	5

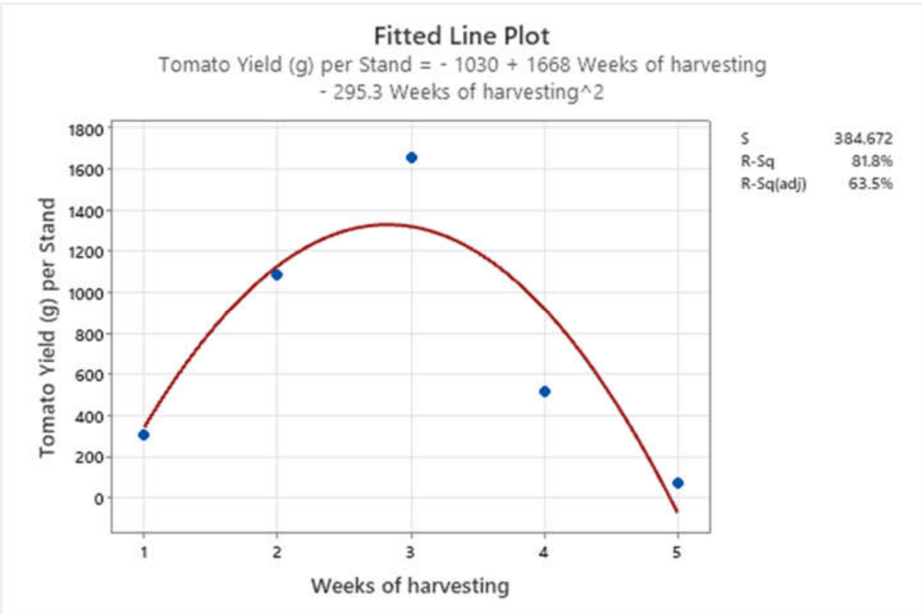

Figure 9: Relationship between Yield and Weeks of Harvesting

CONCLUSION

This study successfully demonstrated the application of response surface methodology for modeling and optimizing tomato yield in a hydroponic system. The results provide valuable insights into the effects of key predictors, including pH, EC, nutrient solution concentration, temperature, and light intensity, on tomato yield. The predicted optimum conditions and yield provide valuable insights for growers and researchers, and the methodology can be applied to other crops and growing systems. By optimizing growing conditions and improving crop yields, hydroponics can play an increasingly important role in meeting the world's food production needs.

Homegrown hydroponic systems for tomatoes represent a viable solution to Nigeria's food security crisis. By empowering households to cultivate their produce, Nigeria can significantly reduce its dependence on imports, lower post-harvest losses, and improve nutrition across the country. This approach not only addresses the immediate demand-supply gap but also paves the way for a more resilient and self-sufficient food system. Given the pressing concerns of food inflation and food insecurity in Nigeria, hydroponic farming of tomatoes offers a promising solution.

DECLARATION OF COMPETING INTEREST

The authors (Muyiwa Abiodun OKUSANYA; Adedamola O. OKE and Josiah Ibukun OYEKALE) hereby declare that there is no conflict of interest whatsoever on this work.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Muyiwa Abiodun Okusanya: Conceptualization, investigation, methodology, writing

Adedamola O. OKE: Formal analysis, data creation, validation, and fabrication.

Josiah Ibukun OYEKALE: Visualization, fabrication and Review,

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