Response Surface Methodology Approach to the Optimization of Potato (*Solanum tuberosum*) Tuber Yield Using Second-Order Rotatable Design

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Abstract

One of the major concerns among developing countries in recent decades is the effect of declining food security with ever-growing population. Hence, the importance of adopting cost effective farming methods has led to the development of various statistical methods to alleviate food insecurity. Among these methods, CCD has gained significant attention to its application in agriculture. In this paper, the response surface methodology (RSM) was applied in order to determine the effects of the factors potassium (K), nitrogen (N) and phosphorus (P) on the yield of potato tuber. The predicted values for the yield of potato tuber by the response functions were in a very close agreement with experimental data (R^2=90%). The second-order model was developed by solving the parameters of the regression equation using the method of least squares. The optimal combinations of the factors potassium (K), nitrogen (N) and phosphorus (P) with yield as the response of interest were determined by analyzing the 3D response surface plots and using the method of steepest ascent. Using ridge analysis method which corresponds to the method of steepest ascent, the optimal yield of potato tuber was estimated to be 29.26 t ha^{-1} which is much higher than the current national target of 14 t ha^{-1} with optimum factor levels being K=35.36 kg K_2o ha^{-1}, N=78.71 Kg N ha^{-1} and P=160.69 Kg P=160.69 kg $P_2o_5ha^{-1}$, respectively. Nitrogen and phosphorous had a significant positive linear effects on the potato tuber yield. Based on the results, it can be concluded that the response surface methodology is a suitable approach for determining the optimal conditions of the selected fertilizer types.

Keywords: Developing countries; Food security; Factors; CCD; Optimal yield; RSM; Steepest ascent

Introduction

Potato consumption has increased in the developing world, and over the last decade, world potato production has increased at an annual average rate of 4.5 percent. Furthermore; Kirkman [1] has estimated that global consumption in processed form will increase from 13% of total food use in 2002 to nearly 18% by 2020. Potato is a high nitrogen (N), phosphorus (P) and potassium (K)-demanding crop. Deficiency of any or combinations of these nutrients can result in retarded growth or complete crop failure under severe cases [2]. Fertilizer type and application rates for potato have not been extensively studied in the rain-fed areas of Western Kenya. The ever increasing demand for potato in the country is due to population growth, urbanization, tourism and export of processed products (MoA, 2005). Potato remains as an important food and cash crop in Eastern and Central Africa, playing a major role in national food security and nutrition, poverty alleviation and income generation, and; provides employment in the production, processing and marketing subsectors.

From a global perspective, its productivity is low in areas under rainfed farming systems [3,4]. Several factors have been attributed for the low yields which include low or inappropriate application of inputs like clean seeds, fertilizers and control of the major potato diseases [5]. RSM emerged in the 1950s [6] within the context of Chemical Engineering in an attempt to construct empirical models able to find useful statistical relationships between all the variables making up an industrial system. Response surface methodology (RSM) has been a useful statistical technique for modeling and analyzing situations in which the response of interest is influenced by several variables and the objective is to optimize this response [7].

In recent years, response surface methodology has been applied in many different fields of research for optimization [8]. Many agricultural experiments involve responses to the explanatory variables which are binary or counts in nature and which can thus be modelled within the generalized linear model framework [9]. Factorial designs have widely been used in experiments involving several factors where the interest is to investigate the joint effects of the factors on a response variable. Such an experiment allows the investigator to study the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable [10]. In this paper, the effects of the factors such as potassium (K), nitrogen (N) and phosphorus (P) on the yield of potato tuber was investigated with application of the second-order model.

Materials and Methods

Experimental design

2^3-factorial central composite designs (2^3-FCCD) were carried out in order to identify optimum parameter levels of fertilizer type for potato tuber yield. The parameters (or independent variables) that were investigated are: potassium (K), nitrogen (urea 46%) and phosphorus (TSP 46%). The FCCD had a total of 16 experimental trials that included eight trials for factorial points, six trials for axial points and two trials for the central points. The experiment was replicated three times to produce 48 experimental units.

For statistical calculations, the variables X_i was coded as x_i as shown in the equation (1) below

$$x_i = \frac{X_i - X_{0i}}{\Delta X_i}, i = 1, 2, 3, ..., k, \tag{1}$$

where x_i is the dimensionless value of an independent variable, X_i is the real value of an independent variable, X_{0i} is the real value of the independent variable at the centre point, and ΔX_i is the step change. In coded variables, the scale of the design variables are changed in such a way that the low and high value correspond to -1 and +1, respectively. The independent variables and their coded levels are shown in Table 1 below. The levels of each factor were established according to literature information by International Fertilizer Industry Association.

Experimental layout, treatments, design and procedures

Potatoes were planted in Western Kenya at one of the farms which is 15 km East of Eldoret Town between 15th March and 1st April 2016 after which seed potato tubers were left to grow for a period of three months (90 days). Fertilizer treatments applied at planting were broadcasted over the furrows.

The experiment was laid out using a randomized complete block design with three replicates for each treatment. Each experimental plot measured 4.0 m × 4.0 m and consisted of 5 rows of 18 tubers each. The plant spacing was 0.25 m × 0.75 m within and between the rows, respectively. The total number of experimental plots was 48. A distance of 1 m was maintained between the blocks and 50 cm within the replicates. At harvesting, tuber weight was recorded and this gave average total yield per plot. The treatments consisted of potassium (60% K_2o) with rates (32, 48.5 and 65 kg K_2o ha^{-1}) and nitrogen (N) supplied as Urea (46% N) at three rates (40, 60 and 80 kg N ha^{-1}), with all fertilizers being applied at planting season. Phosphorus (P) was also supplied at planting time as triple super phosphate (46% P_2o_5) at three rates namely (77, 116 and 155 Kg $P_2o_5 ha^{-1}$), respectively. The experimental range and level of the above variables are given in Table 2 below.

Transformation of coded variable/factor (x_i) levels to uncoded/original variables were obtained using the following equations

$$X_1 = 16.5x_1 + 48.5; X_2 = 20x_2 + 60; X_3 = 39x_3 + 116 \tag{2}$$

The second order equation to predict the optimal condition can be expressed as shown below;

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} \sum_{j=2}^{k} b_j x_i x_j + \sum_{i=1}^{k} b_i x_i^2 + \varepsilon, i \neq j \tag{3}$$

Where Y is the response variable, whereas x_i is representing the explanatory or the independent variables and ε is the random error. The β coefficients, which should be determined in the second-order model, are obtained by the least square method. In general, equation (3) can be written in matrix form as

$$Y = bX + \varepsilon \tag{4}$$

where Y is defined to be a matrix of measured response values, X to be a matrix of independent variables and ε consist of the error term,

respectively. The solution of equation (4) can be obtained by the matrix approach as shown in equation (5) below,

$$b = (X^T X)^{-1} X^T Y \tag{5}$$

Where X^T is the transpose of the matrix X and $(X^T X)^{-1}$ is the inverse of the matrix $X^T X$. The experimental data were analyzed using R and SAS version 9.2 statistical software. The validity of the predicted model was verified by use analysis of variance (ANOVA). The second-order model quality was also assessed by using the correlation factor (R^2). Finally, the optimal combinations of the factors were obtained by analyzing the 3D response surface curves and with application of ridge analysis method.

Results and Discussion

Table 1 below shows that the highest yield of potato tuber attained was 29.79 t ha^{-1} when the combination of the components potassium, nitrogen, and phosphorous were at 32, 80, and 155 Kg ha^{-1}, respectively (**Run 2**). This yield is particularly higher than what has been obtained recently in the selected countries of Eastern Africa, Central Africa and Southern Africa where average potato tuber yield was found to be below 13 t ha^{-1} while in Kenya was approximately 23 t ha^{-1} [11]. Also, the lowest yield was at 18.96 t ha^{-1}, which was achieved when potassium, nitrogen, and phosphorus components were at 32, 40, and 77 Kg ha^{-1}, respectively (Table 2).

Effect of the type and level of fertilizer applied on the yield of potato tuber

This section presents exploratory analysis of factors that are known to influence yield of potato tuber. This is illustrated using correlation analysis, box plots and regression analysis with application of the second-order model.

Figure 1 below show that there was a weak negative correlation between yield of potato tuber and potassium as a factor ($r = -0.061_{rs}$, *p*-value=0.821). This finding is in disagreement with other studies conducted elsewhere which have shown potassium to increase yield of potato tuber [12]. However, a slight positive association was observed for the effect of nitrogen on the yield ($r = 0.261_{rs}$, *p*-value=0.321), with higher levels of the factor having increased yield of potato tuber. It is also evident that there was a strong significant positive correlation between yield and the factor phosphorus ($r = -0.749_s$, *p*-value=0.0008).

The present study is in agreement with the findings of Rosen and Bierman [13], who reported that the interaction effect of nitrogen and phosphorus affected average tuber number per hill of potato plants. The increase in tuber numbers per hill for potato in response to increased application of nitrogen and phosphorus is also consistent with the results of Jenkins and Ali [14]. Similarly, other researchers have reported increased rates of phosphorous to cause improved yield of potato tuber [15]. The reason for this is that phosphorus contributes to early development of the crop, early tuberization and thus increasing the number of tubers per plant.

From Figure 2 below, it is clear that application of 48.5 kg of potassium results in better yield than application of 65 kg per hectare.

Factor		Coded factor level (x_i)				
	Symbol (X_i)	-1.68(α)	-1	0	1	1.68(α)
Potassium(K)	X_1	20.8	32	48.5	65	76.2
Nitrogen (N)	X_2	26.4	40	60	80	93.6
Phosphorus (P)	X_3	50.5	77	116	155	181.5

Table 1: Assigned levels of fertilizer to be used in CCD for *k*=3.

Run	x_1	X_2	X_3	Mean yield(t/ha)		Deviation of Experiment and Predicted %
				Observed	Predicted	
1	1	1	1	25.42	24.897	2.06
2	-1	1	1	29.79	29.408	1.28
3	1	-1	1	20.83	21.650	-3.94
4	-1	-1	1	24.79	24.916	-0.51
5	1	1	-1	21.46	21.923	-2.16
6	-1	1	-1	20.42	20.190	1.13
7	1	-1	-1	22.08	23.052	-4.40
8	-1	-1	-1	18.96	20.073	-5.87
9	-1.68	0	0	23.96	23.871	0.37
10	1.68	0	0	23.33	22.583	3.20
11	0	-1.68	0	24.17	22.650	6.29
12	0	1.68	0	24.79	25.475	-2.76
13	0	0	-1.68	20.21	19.114	5.42
14	0	0	1.68	25.42	25.680	-1.03
15	0	0	0	23.75	22.674	4.53
16	0	0	0	21.45	22.674	-5.71

Table 2: Design matrix of centered central composite design (CCD) for yield of potato tuber.
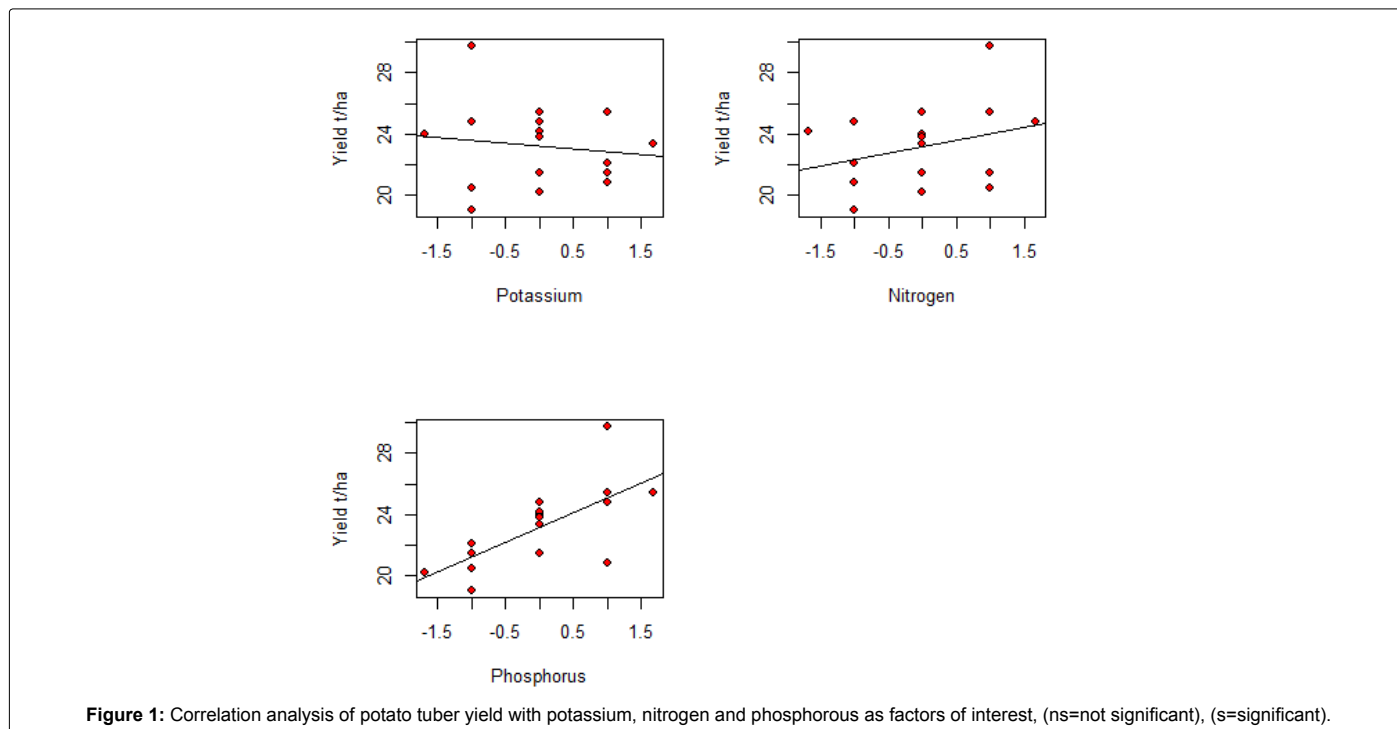

Figure 1: Correlation analysis of potato tuber yield with potassium, nitrogen and phosphorous as factors of interest, (ns=not significant), (s=significant).

However, there is no clear trend on the effects of different levels of potassium on the yield of potato tuber. On the other hand, potassium fertilizer application may not necessarily increase yield but can be useful as it makes potato plants adapt to the environmental stresses which leads to increased resistance of potato to some pests [16].

In Figure 3, increasing application of nitrogen fertilizer resulted in higher yield up to a certain level when compared to lower factor levels of nitrogen [17]. However, over-use of Nitrogen fertilizer has been established by other researchers elsewhere to cause a reduction in the yield of potato tuber [18] and this is consistent with the results of this study.

Analysis of 3D response surfaces

The 3D response surface plots were employed to evaluate the effect of independent variables on the yield of potato tuber. This was done by varying two variables within the experimental range under investigation and holding the other variable at its central level (0 level). The relationship between independent and dependent variables was graphically represented by 3D response surfaces as shown in Figures 4-7, respectively. Figure 5 show the 3D response surface plot for the effect of potassium (x_1) and nitrogen(x_2) on the yield of the potato tuber. It can be observed that increasing nitrogen similarly raised the yield of potato tuber while on the other hand increasing potassium decreased yield significantly. The increase of potato tuber yield due to nitrogen may be favored by the fact that nitrogen application increases potato plant density, hence resulting in higher potato tuber yield [19]. Similar findings were also reported by Arap Koskei [20] who revealed that potato tuber yield per unit area was increased with increasing nitrogen fertilizer up to a suitable level.
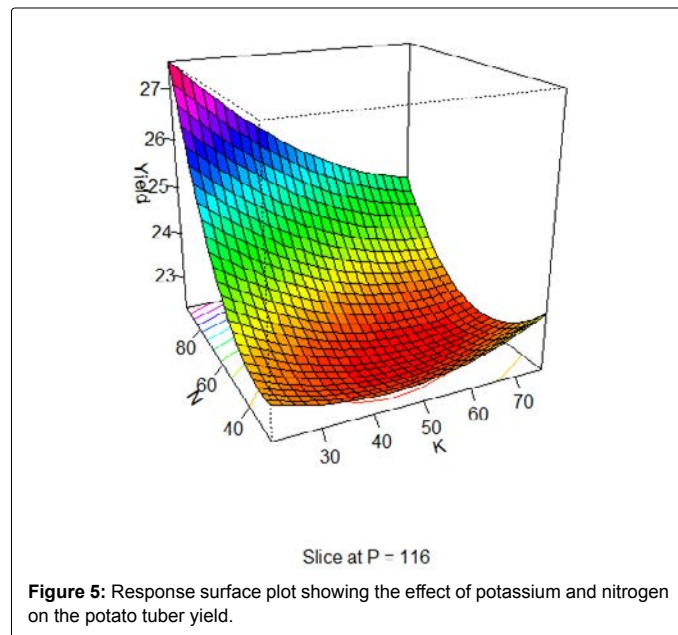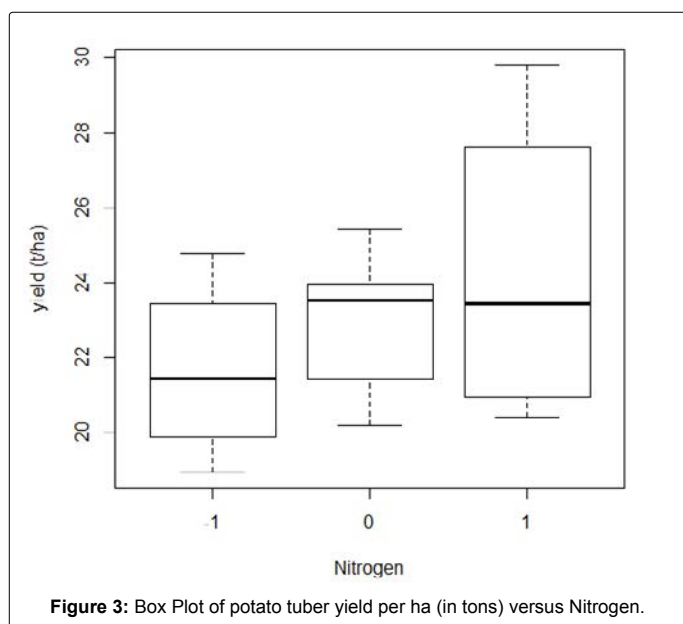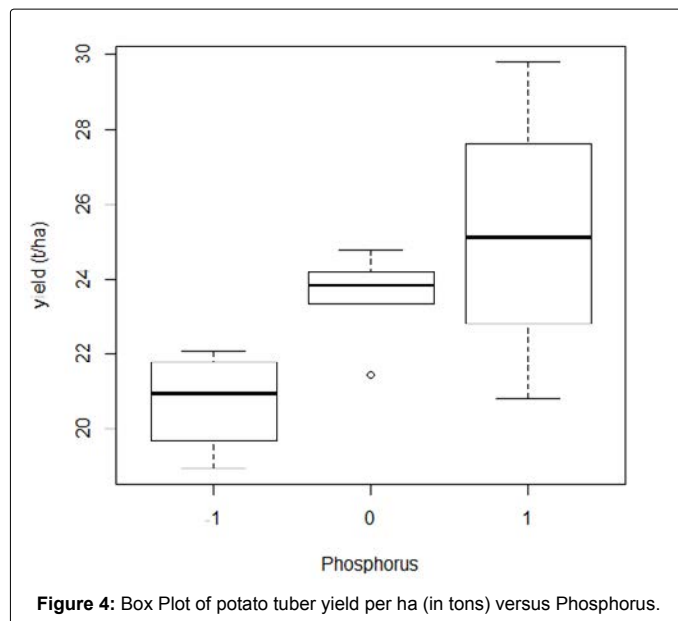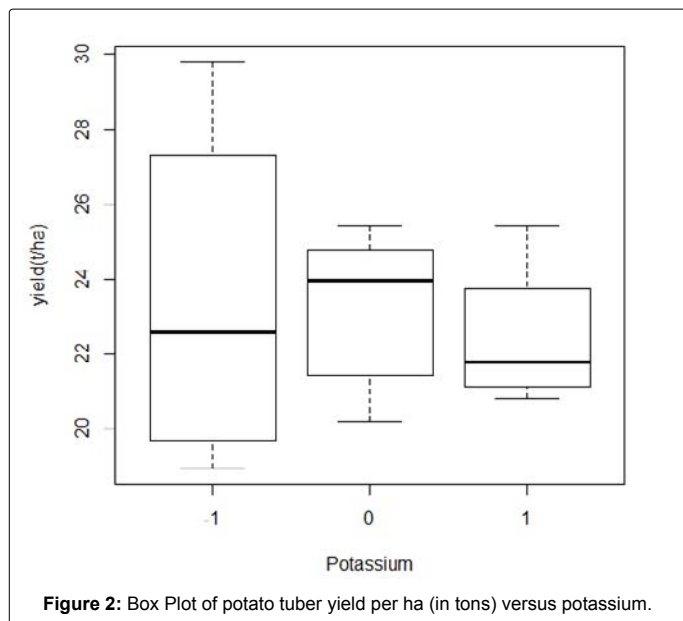
Figure 2: Box Plot of potato tuber yield per ha (in tons) versus potassium.

Figure 4: Box Plot of potato tuber yield per ha (in tons) versus Phosphorus.

Figure 3: Box Plot of potato tuber yield per ha (in tons) versus Nitrogen.

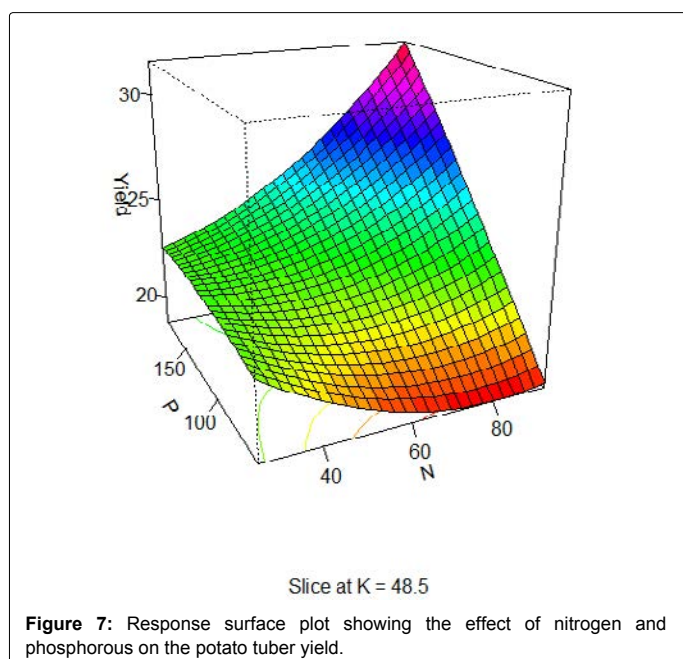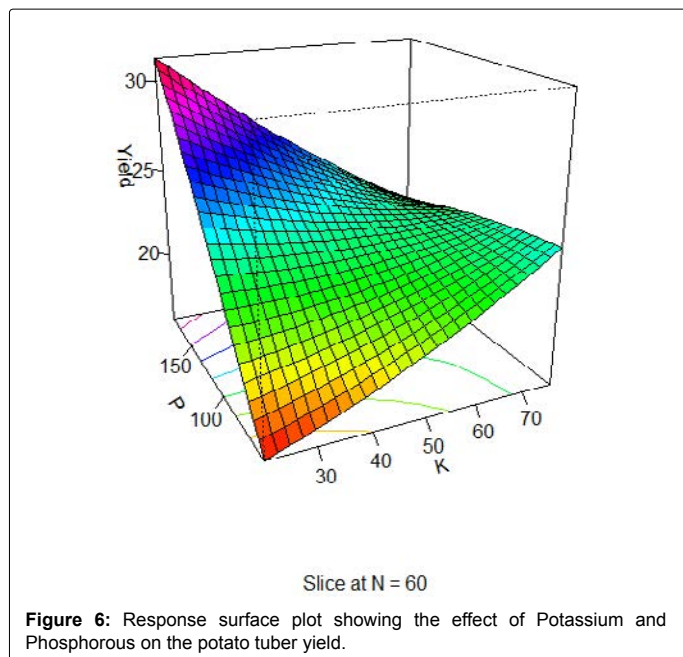**Figure 5:** Response surface plot showing the effect of potassium and nitrogen on the potato tuber yield.

Figure 6 demonstrates the interaction between potassium (x_1) and phosphorous (x_3) on the potato tuber yield. It was found out that increasing potassium to near 60 kg ha^{-1} improved the yield of potato tuber considerably. However, when the potassium level reached over 60 kg ha^{-1}, there was a gradual decline in the yield of potato tuber, while an increase in phosphorus showed a significant positive effect on the yield of potato tuber. The possible explanation for this result is that rising levels of phosphorous equally increases the number of potato tubers hence improving overall yield [15].

Figure 7 illustrates the effect of nitrogen (x_2) and phosphorous (x_3) on the yield of potato tuber. It was observed that when potassium (x_1) was fixed at 0 level, yield of potato tuber increased to maximum when nitrogen was increased to a value of approximately 60 kg ha^{-1}, while equally an increase in the level of phosphorous raised the yield of potato tuber.

Estimating regression parameters by method of least squares using second-order.model

This section presents experimental estimation of the parameters in the model for purposes of fitting our second-order model using equation (3) where data on the yield of potato tuber was considered as the response variable of interest and the factors potassium(x_1), nitrogen(x_2) and phosphorous(x_3) were the independent variables [21-23]. Response surface methodology (RSM) was adopted for developing model for yield of potato tuber. The regression coefficients and significance levels of the model representing potato tuber yield is shown in Table 3 below. It is evident from Table 3 that the model terms x_3 and x_1x_3 were significant at ($P<0.05$) while the terms x_2 and x_2x_3 remained significant at ($P<0.10$). Regression analysis of the experimental data (Table 3) showed that nitrogen(x_2) and phosphorous(x_3) had significant positive linear effects on the potato tuber yield. Out of the three parameters,

Figure 6: Response surface plot showing the effect of Potassium and Phosphorous on the potato tuber yield.

Figure 7: Response surface plot showing the effect of nitrogen and phosphorous on the potato tuber yield.

phosphorous was found to have the highest contribution on the potato tuber yield with the highest linear positive effect (β_3=1.954, p=0.0017), followed by nitrogen and potassium (β_2=0.841, p=0.0601) indicated a negative linear effect. Interaction of the factors, potassium and phosphorous x_1x_3 showed a strong significant negative effect on the potato tuber yield indicating that yield decreased as the levels of these factors decreased, while the interaction of the factors nitrogen and phosphorous (x_2x_3) showed a positive significant effect at 10% level of significance indicating that potato tuber yield was higher as the levels of the factors also increased above certain values [24,25]. This finding is consistent with the study conducted by other researchers using second-order polynomial model elsewhere where the interaction between nitrogen and phosphorous(x_2x_3) was shown to be significantly

associated with increased potato tuber yield. Table 3 also indicates that the quadratic terms between all factors were not significant when yield was considered as the response of interest.

In Table 4, results of the analysis of variance was performed to evaluate the lack of fit and the significance of the linear, quadratic and interaction effects of the factors influencing the yield of potato tuber. The ANOVA results indicated a good model fit with the correlation coefficient (R^2) value of 0.90 for yield of potato tuber [26]. These can explain 90% of the variability in the calculated models. The statistical analysis gave high significant level, attesting the goodness of fit of the model in case of the yield (p=0.02199). The results obtained showed that the models could work well for the prediction of the three factors studied while using yield of the potato tuber as response variable of interest. It is clear from Table 5 below that using ridge analysis the optimal yield for potato tuber was 29.26 $t\ ha^{-1}$.

Parameters	Coefficients	Standard Error	t Value	Pr > |t|
Intercept	22.674223	0.947011	23.94	<.0001***
x_1	-0.383179	0.363709	-1.05	0.3327
x_2	0.840731	0.363709	2.31	0.0601*
x_3	1.954063	0.363709	5.37	0.0017***
x_1^2	0.195881	0.441940	0.44	0.6731
x_1x_2	-0.311250	0.474999	-0.66	0.5366
x_2^2	0.491728	0.441940	1.11	0.3084
x_1x_3	-1.561250	0.474999	-3.29	0.0167**
x_2x_3	1.093750	0.474999	2.30	0.0609*
x_3^2	-0.098195	0.441940	-0.22	0.8315

Table 3: Estimated regression model of relationship between response variable (yield of Potato tuber) and independent variables (x_1, x_2, x_3).

Regression	DF	SS	MS	F Value	Pr > F
Linear	3	63.748730	0.5915	11.77	**0.0063**
Quadratic	3	3.353914	0.0311	0.62	0.6276
Cross-product	3	29.845338	0.2769	5.51	**0.0369**
Residuals	6	10.830	1.805		
Lack of fit	5	8.185	1.637	0.6189	0.7404
Pure error	1	2.645	2.645		
Total error	6	10.830	1.8050		

Notes: DF, degree of freedom; SS, sum of squares; MS, mean square.

Table 4: Analysis of variance for the fitted quadratic polynomial model for optimization of potato tuber yield.

Estimated Ridge of Maximum Response for Yield					
Coded Radius	Estimated Response	Standard Error	Uncoded Factor Values		
			x_1	x_2	x_3
0.0	22.674223	0.947011	0	0	0
0.1	23.058842	0.939904	-0.044770	0.074973	0.143523
0.2	23.494885	0.919270	-0.109712	0.161933	0.273198
0.3	23.989748	0.887317	-0.185185	0.254385	0.393714
0.4	24.546929	0.848272	-0.266428	0.349489	0.508387
0.5	25.168209	0.809201	-0.351084	0.445983	0.619224
0.6	25.854568	0.780916	-0.437903	0.543261	0.727443
0.7	26.606588	0.777907	-0.526171	0.641008	0.833804
0.8	27.424633	0.815455	-0.615457	0.739052	0.938803
0.9	28.308944	0.904030	-0.705484	0.837291	1.042775
1.0	**29.259685**	1.045819	**-0.796066**	**0.935662**	**1.145956**

x_1: Potassium; x_2: Nitrogen; x_3: Phosphorous.

Table 5: Optimal yield of potato tuber using Ridge analysis.

Conclusion

This study used RSM and CCD to evaluate the effects of potassium, nitrogen and phosphorus on the yield of potato tuber. Based on the developed models, it was found that increased application of nitrogen and phosphorous was accompanied by an increase in the yield of potato tuber. However, the effect of potassium showed a negative effect on the yield of potato tuber and this maybe as a result of potassium being identified as a water retention factor. The yield of potato tuber showed both a positive linear and cross-product behaviour by nitrogen and phosphorus respectively. The application of response surface methodology combined with the CCD can be used as effective methods for investigating the effects of potassium, nitrogen and phosphorus on the yield of potato tuber. The factors considered in this study are important in influencing yield of potato tuber and can be adopted by both small and large-scale farmers in the rain-fed regions of Western Kenya.

The optimization process identified the optimum point for the yield of potato tuber to be a saddle point. Ridge analysis method which corresponds to the method of steepest ascent showed that the predicted optimum levels of the factors on the yield of potato tuber were as follows; K=35.36 kg ha^{-1} of potassium, 78.71 kg ha^{-1} of nitrogen supplied as Urea and 160.69 kg ha^{-1} phosphorus supplied as triple super phosphate (TSP). At this optimum level for the response, one can achieve a potato tuber yield of 29.26 t ha^{-1}. The current study recommends other researchers to adopt this method since the yield obtained was significantly higher than the current national target which stands at 14.2 t ha^{-1}. Finally, the approach applied in this research has been shown to be effective in saving farmers the cost of farm inputs.

Acknowledgements

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