Optimization of the Size Distribution of Potato (*Solanum-tuberosum*) Tuber Using a Second-Order Rotatable Design

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Abstract

Marketability of potato tubers due to its size has continued to remain big challenge among-smallholder famers in Kenya. Despite its importance, the recommended fertilizer levels for obtaining the maximum size distribution of the potato tuber have not been established in the rain-fed regions of Western Kenya. The main objective of this study was to optimize the size distribution of potato tuber using a second order rotatable design. The specific objective was to examine the effects of the factors potassium, nitrogen and phosphorous on the size distribution of potato tuber. This study presents an application of the RSM on the optimization of the size distribution of potato tuber using a three-factor central composite design (CCD). Ridge analysis method employed located the minimum levels of the factors K, N and P for size distribution of potato tuber as follows; $K = 44.82\,Kg\ K_2O\ ha^{-1}, N = 59.34\ Kg\,N\ ha^{-1}$ *and* $P = 180.94\ Kg\ P_2O_5\ ha^{-1}$ *respectively giving a minimum size distribution of 14.67 cm. Results revealed that potassium and nitrogen had a significant positive quadratic effect on the size distribution of potato tuber. Similarly, the interaction of the factors, potassium and nitrogen showed a significant positive effect on the size distribution of potato tuber. The findings obtained in this study have given the recommended fertilizer rates to be employed by both smallholder and large-scale farmers in Western Kenya.*

Keywords: Developing countries; Food security; Ridge analysis; CCD; Size distribution, RSM, Western Kenya.

Introduction

Potato (***solanum-tuberosum)*** is the second most important food crop in Kenya after maize, and the crop plays a major role in food security and alleviation of poverty through income generation. It is a source of livelihood for an estimated 500,000 small-scale farmers and employs approximately 2.5 million people (MOA, 2004). Fertilizer application has important effects on the quality and yield of potatoes (Westermann, 2005). Nitrogen supply also plays an important role in the balance between vegetative and reproductive growth for potato (Alva, 2004; White *et al.*, 2007). Fertilizer application for potato among the small-scale farmers has been low with only 10-15% of farmers using the recommended rates (Ogola *et al.*, 2011). Meeting the ever-growing demand for food remains a major challenge for world agriculture (Bhasin, 2002). Sub-Saharan Africa (SSA) is the only region of the world where per capita food production has steadily declined over the past two decades and where agricultural output has grown annually by an average of less than 1.5%, with food production increasing at a slower rate than the population growth (FAO, 2000). This greatly undermines the food security situation of the sub-region. However, current yield trends are not sufficient to meet the forecasted demand (Ray *et al.*, 2013). Response of potato to NPK varies with variety, soil characteristics and geographical escarpment (Naz *et al.*, 2011). (Sharma and Arora, 1987) have also reported that increased application of nitrogen and potassium fertilizers substantially increases the proportion of medium and large-sized tubers considerably.

Response surface methodology (RSM), is an experimental strategy first described by (Box and Wilson, 1951) for determining optimal conditions for multivariable systems, and is considered an efficient technique for process optimization (Kong *et al.*, 2004). In recent years, application and development of RSM has continued to be employed in many areas of research. (Myers, 2004) has exhaustively reviewed the literature in the sense, describing the developments and applications of this methodology. Response surface methodology has been applied in many different fields of research for optimization (Roberto *et al.*, 2003; DeFaveri *et al.*, 2004). When experiments are expensive, the number of experiments required for the optimization must be minimized to reduce the total cost of the optimization. Factorial designs using many factors (often of the 2^k series) have been widely used in the manufacturing industry as a means of maximizing output for a given input of resources (Montgomery, 1997). Optimization techniques used in response surface methodology usually depend on the nature of the fitted model. For first-degree models, the method of steepest ascent (or descent) is a viable technique for sequentially moving toward the point of optimum response. On the other hand, the second-degree model is used after a series of experiments have been sequentially carried out leading up to a region that is believed to contain the location of the optimum response (Andre and Khuri, 2010). However, there is limited information on the effects of potassium, nitrogen and phosphorus fertilizers on the size distribution of potato tuber. The aim of the present study was to investigate the effects of the factors potassium, nitrogen and phosphorus on the size distribution of potato tuber in the rain-fed areas of Western Kenya.

Introduction to response surface modelling

The study focused on developing a linear model that relates the response and the independent variables. In general, the relationship is given by equation (1) below;

$$Y_i = f\left(x_1, x_2, ..., x_k\right) + \varepsilon \qquad (1)$$

Where Y_i in equation (1) above is the response, $x_1, x_2, ...x_k$ are the independent variables being investigated and ε is a term that represents other sources of variability not accounted for in the model. It is treated as a statistical error that is normally distributed with mean 0 and variance σ^2 i.e. N $(0; \sigma^2)$. The two most common models used in response surface methodology are first degree and second degree models.

First-order model

For first-order model, the response variable is usually defined by a linear function of independent variables. This is appropriate when one is interested in estimating the true response from a small region of an independent variable space where there is little curvature in the response function f. Therefore, a first-order model with three explanatory variables in coded form can be expressed using equation (2)

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \qquad (2)$$

Where β_0 is the intercept, and β_1, β_2 and β_3 are the regression coefficients for the independent variables x_1, x_2 and x_3, respectively. The form of the first-order model in is also referred to as the main effects model, because it includes only the main effects of the three independent variables x_1, x_2 and x_3. If there is an interaction between these variables, the model takes the form;

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon \qquad (3)$$

In general, a first-order model with *N* experimental runs and having *q* design variables can be expressed as follows;

$$y = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + ... + \beta_q x_{iq} + \varepsilon_i, \left(i = 1,2,...,N\right) \qquad (4)$$

Where the response variable Y is a function of the design variables $x_1, x_2, x_3, ..., x_N$ and the experimental error ε.

Second-Order model

If there is a curvature in the response surface, then first-order model is not appropriate and therefore, a second-order model is then considered. For the case of three input variables x_1, x_2 and x_3, the second-order model is given by equation (5) below;

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{11} x_1^{\ 2} + \beta_{22} x_2^{\ 2} + \beta_{33} x_3^{\ 2} + \varepsilon$$

(5)

hence, a second-order model with $k-input$ variables and which involves all the possible terms i.e.

Main effects, interaction of the main effects and quadratic terms, is represented by the polynomial equation (6) below.

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k}\sum_{j=2}^{k} b_{ij} x_i x_j + \sum_{i=1}^{k} b_{ii} x_i^{\,2} + \varepsilon, i \neq j \tag{6}$$

Where Y is the response variable, whereas x_i represents 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 (6) can be written in matrix form as

$$Y = bX + \varepsilon \tag{7}$$

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 (7) can also be obtained by the matrix approach using equation (8) below,

$$b = \left(X^T X\right)^{-1} X^T Y \tag{8}$$

Where X^T is the transpose of the matrix X and $\left(X^T X\right)^{-1}$ is the inverse of the matrix $X^T X$. Details of experimental designs for fitting response surfaces are found in (Montgomery, 2001) and (Khuri and Cornell, 1987).

Experimental treatments

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 fertilisers being applied at planting season. Phosphorus was also supplied at planting time as triple super phosphate (46% $P_2 0_5$) at three rates namely (77, 116 and 155 Kg $P_2 0_5\ ha^{-1}$) respectively. At harvesting, tuber weight was recorded and this gave average yield per plot

Experimental design and layout.

The experiment was laid out in a randomized complete block design with three replications each. 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 blocks. The land for use in this experiment was prepared in March 2016, using a tractor followed by manual harrowing, leveling and making of furrows. Fertilizer treatments potassium, nitrogen and phosphorus were applied at planting where broadcasting was done over the furrows. A three-factor central composite design was employed out in order to obtain optimum parameter levels of fertilizer type for potato tuber yield. The parameters (or independent variables) that were investigated are: potassium nitrogen (Urea 46%) and phosphorus (TSP 46%). The experiment had a total of 16 trials that included eight trials for factorial points, six trials for axial points and two for the central points. The experiment was replicated three times to produce a total of 48 experimental units.

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

$$x_i = \frac{X_i - X_{0i}}{\Delta X_i},\ i = 1,2,3,...,k \tag{9}$$

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 displayed in (Table 1) below. The levels of each factor were established according to literature information by International Fertilizer Industry Association (IFA, 1992).

Table 1: Assigned levels of fertilizer type to be used in a three-factor CCD.

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

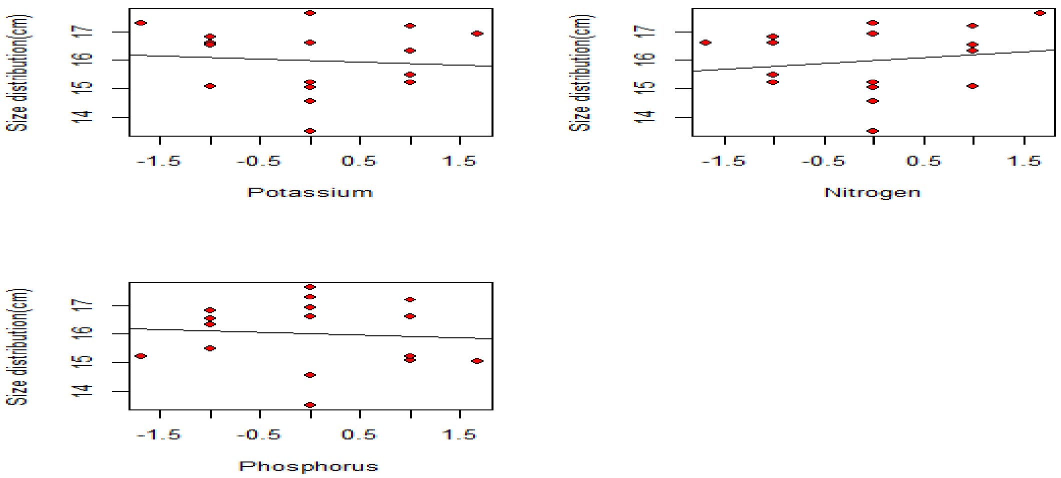
Transformation of coded variable (x_i) levels to original variables can be obtained using the following equations

$$X_1 = 16.5x_1 + 48.5; X_2 = 20x_2 + 60; X_3 = 39x_3 + 116 \qquad (10)$$

Results and discussions

This section presents exploratory analysis of factors suspected to influence the size distribution of the potato tuber using both correlation analysis and box plots. Estimation of the coefficients for the second-order model was performed using the method of least squares as earlier discussed. A weak negative correlation between potassium and size distribution of potato tuber $(r = -0.061_{ns}, p-value = 0.821)$ is shown (Figure 1). Similar trend was also observed for the effect of phosphorus on the size distribution of potato tuber $(r = -0.088_{ns}, p-value = 0.745)$. The results of this study are contrary to what other researchers elsewhere have established where potassium was identified to increase the size distribution of potato tubers (Trehan *et al.*, 2001). Furthermore, literature shows that there is no much information that exists on the effect of phosphorous on the size distribution of potato tuber and this interesting finding can be investigated in a different study. Conversely, (Figure 1) illustrates a weak positive correlation between nitrogen and the size distribution of potato tuber although the association remained insignificant $(r = 0.126_{ns}, p-value = 0.640)$.

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



From (Figure 2) below, it is apparent that application of 32 Kg ha^{-1} of potassium results in better size distribution of potato tuber than application of either 48.5 Kg or 65 Kg ha^{-1} of the same fertilizer. This demonstrates that application of higher levels of potassium seems not to increase the size distribution of potato tuber. This analysis also reveals that application of 80 Kg ha^{-1} of nitrogen improves the size distribution of potato tuber than application of either 40 Kg or 60 Kg ha^{-1} of the same fertilizer type (Figure 3). This result explains that using higher quantities of the nitrogen fertilizer increases the size distribution of potato tuber and therefore increasing the marketability of the potato tuber. This finding is similar to results previously demonstrated by other researchers elsewhere (Saeidi *et al.*, 2009).

Conversely with this result, (Rosen and Bierman, 2008) reported that increased rates of phosphorus application significantly decreased the proportion of large and medium-sized tubers while on the other hand increasing the proportion of small-sized tubers (Figure 4).

Figure 2: Box Plot of potato tuber size distribution (in cm) versus Potassium.

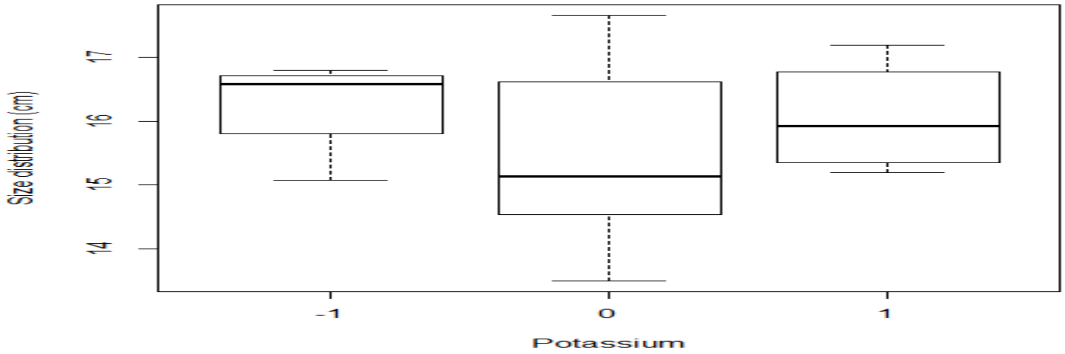


Figure 3: Box Plot of potato tuber size distribution (in cm) versus Nitrogen.

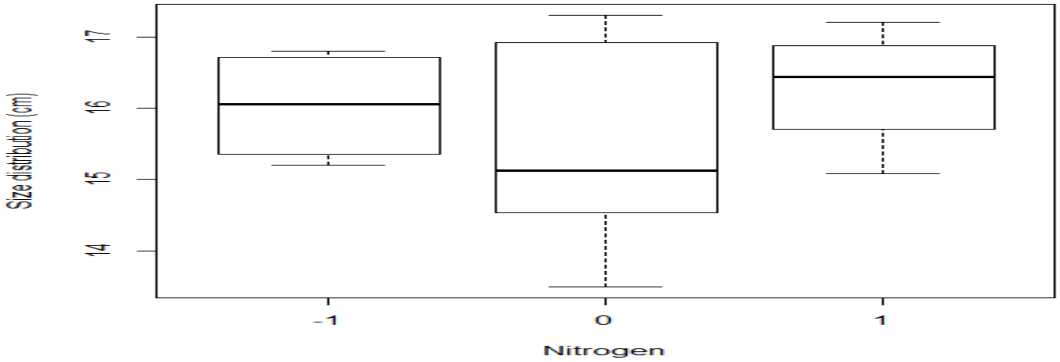
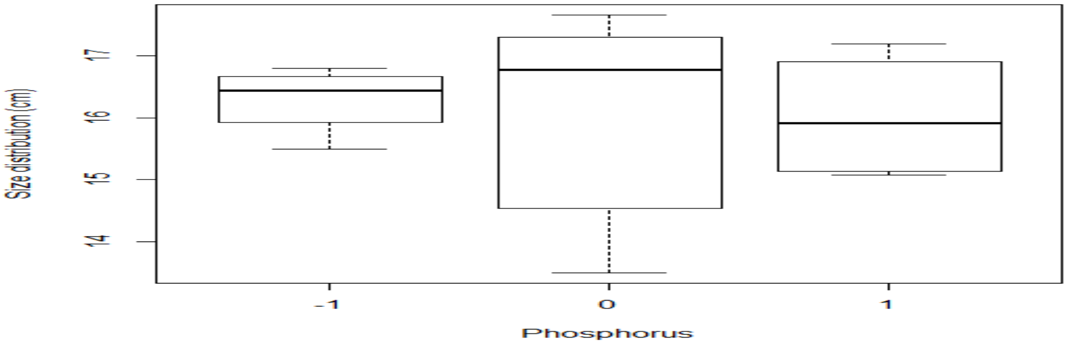


Figure 4: Box Plot of potato tuber size distribution (in cm) versus Phosphorus.



The average size distribution of potato tuber for each individual run along with the predicted responses is given in (Table 2). From Table 2, it is clear that the highest size of 17.62 cm was achieved when the combinations of the factors potassium, nitrogen, and phosphorus were 48.5, 93.6, and 116 Kg ha^{-1} , respectively (**Run 12**).
However, the lowest size was at 13.5 cm, which was attained when the combination of the factors were at the levels 48.5, 60, and 116 Kg ha^{-1}, respectively (**Run 16**).

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

Run	x_1	x_2	x_3	Mean Size distribution (cm)		
				Observed	Predicted	Deviation of Experiment and Predicted %
1	1	1	1	17.2	17.182	0.47
2	-1	1	1	15.08	15.683	-3.99
3	1	-1	1	15.2	15.644	-2.92
4	-1	-1	1	16.62	16.465	0.93
5	1	1	-1	16.34	16.855	-3.18
6	-1	1	-1	16.54	16.456	0.48
7	1	-1	-1	15.5	15.257	1.55
8	-1	-1	-1	16.8	17.177	-2.26
9	-1.68	0	0	17.3	17.032	1.56
10	1.68	0	0	16.92	16.678	1.42
11	0	-1.68	0	16.62	16.542	0.48
12	0	1.68	0	**17.62**	17.228	2.21
13	0	0	-1.68	15.2	15.037	1.05
14	0	0	1.68	15.06	14.713	2.32
15	0	0	0	**14.54**	14.065	3.23
16	0	0	0	**13.5**	14.065	-4.22

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

Interpreting coefficients of the second-order model

The regression coefficients and significance levels of the second-order model representing the size distribution of potato tuber is shown in (Table 3) below. It is evident that all the model linear effects remained insignificant while potassium and nitrogen had significant positive quadratic effects on the size distribution. On the other hand, potassium was found to have the highest quadratic effect on the size distribution of potato tuber ($\beta_{11} = 0.988$, p= 0.0022) when compared to nitrogen ($\beta_{22} = 0.580$, P = 0.3327). Interaction of the factors, potassium and nitrogen also showed a significant positive effect on the size distribution of potato tuber indicating that the size of potato tuber increased as the levels of these factors increased to certain levels. The reason for this is that other studies have shown that potassium and nitrogen have a positive effect on the size distribution of potato tuber. In line to this result, (Sharma and Arora, 1987) also noted increased application of nitrogen and potassium fertilizers to substantially affect the proportion of medium and large-sized tubers considerably. Additionally it has been indicated that the interaction terms between all the other factors remained insignificant.

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

Parameter	Coefficients	Standard Error	t Value	Pr > |t|
Intercept	14.065259	0.414373	33.94	<.0001***
x_1	-0.105417	0.159144	-0.66	0.5323
x_2	0.204268	0.159144	1.28	0.2466
x_3	-0.096388	0.159144	-0.61	0.5669
x_1^2	0.988485	0.193375	5.11	0.0022***
x_1x_2	0.580000	0.207840	2.79	0.0316**
x_2^2	0.999115	0.193375	5.17	0.0021***
x_1x_3	0.275000	0.207840	1.32	0.2340
x_2x_3	-0.015000	0.207840	-0.07	0.9448
x_3^2	0.286955	0.193375	1.48	0.1884

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

*Significance at 10% level;
** Significance at 5% level;
*** Significance at 1% level.
Multiple R-squared: 0.8973, Adjusted R-squared: 0.7432
F-statistic: 5.825 on 9 and 6 DF, p-value: 0.02199

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 size distribution of potato tuber. The Analysis of Variance (ANOVA) results indicated a good model fit with the correlation coefficient (R^2) value of 0.897 for the size distribution of potato tuber. This explains 89.7% of the variability in the calculated model. This finding is similar to what other researchers elsewhere have established (Chen, 2011).

Table 4: Analysis of variance for the fitted quadratic polynomial model for optimization of potato size distribution

Regression	DF	SS	MS	F Value	Pr > F
Linear	3	0.847739	0.0420	0.82	0.5295
Quadratic	3	13.969979	0.6920	13.47	**0.0045**
Cross-product	3	3.298000	0.1634	3.18	0.1059
Residuals	6	2.0735	0.3456		
Lack of fit	5	1.532682	0.306536	0.57	0.7585
Pure error	1	0.540800	0.540800		
Total error	6	2.073482	0.345580		

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

2D contour plots and 3D response surface plots

In this study, use of 2D and 3D response surface plots were investigated for the effects of potassium, nitrogen and phosphorus on the size distribution of potato tuber and the results are presented in figures 5(a)-(c) and 6(a)-(c) below respectively.

Effect of potassium, nitrogen and phosphorus on the size distribution of potato tuber.

Figure 5(a) describes the effect of potassium (x_1) and nitrogen (x_2) on the size distribution of potato tuber. It was observed that when phosphorus (x_1) was fixed at 0 level, the interaction of potassium (x_1) and nitrogen (x_2) had a quadratic effect on the size distribution of potato tuber. It showed that the minimum size distribution of potato tuber that could be achieved was 15 cm when using near 60 Kg ha^{-1} of nitrogen (x_2) while.

The maximum size of potato tuber reached was 19 cm. Figure 5(b) shows the effect of potassium (x_1) and phosphorus (x_3) on the size distribution of potato tuber. Interaction of potassium and phosphorus gave the minimum and the maximum size of potato tuber as 15 cm and 18 cm respectively when nitrogen was fixed at 0 level. As shown in figure 5(c), when potassium (x_1) was fixed at 0 level, the interaction of nitrogen (x_2) and phosphorus (x_3) gave the minimum size distribution of potato tuber as 15 cm and the maximum size as 17 cm respectively. However, this was achieved when using close to 180 Kg ha^{-1} of phosphorus (x_3).

Figure 5: Contour plots showing the effects of (a) potassium and nitrogen, (b) potassium and phosphorus, and (c) nitrogen and phosphorus on the size distribution of potato tuber respectively.

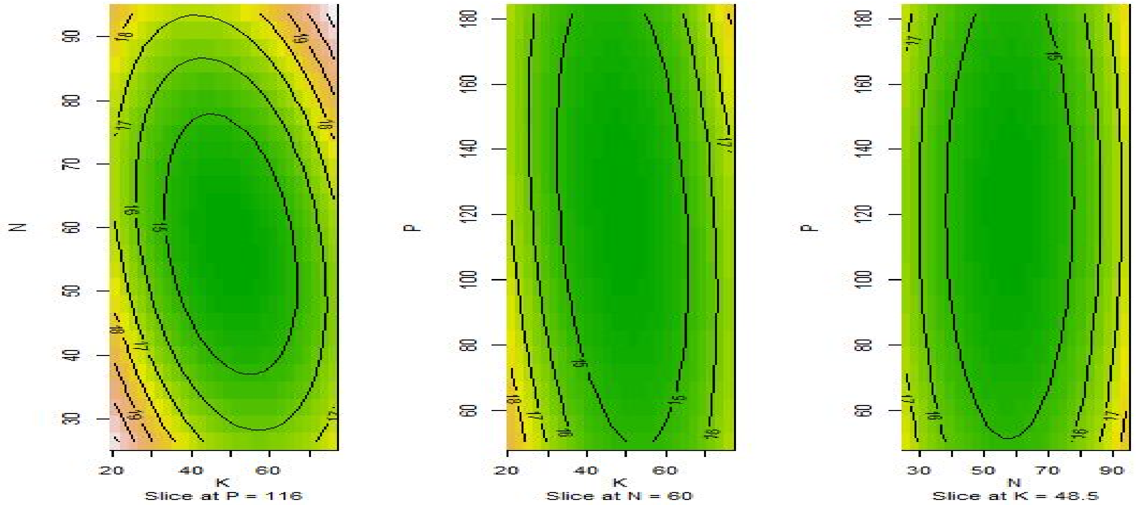


Figure 6 presents the interaction effect of potassium and nitrogen on the size distribution of potato tuber. It is evident that the size distribution of potato tuber decreased to a minimum value as the level of potassium (x_1) dropped and nitrogen (x_2) increased to a certain value. This phenomenon can be explained as a result of positive effect of nitrogen on the size distribution of potato tuber. On the other hand, the effect of potassium (x_1) and phosphorous (x_3) on the size distribution of potato tuber is shown in figure 7. It is obvious that decreasing levels of both potassium and phosphorous fertilizers had a positive effect on the size distribution of potato tuber. However, in figure 8, it is clear that increasing levels of nitrogen and having lower levels of phosphorous as a factor had a positive effect on the size distribution of potato tuber.

Figure 6: Response surface plot showing the effect of potassium and nitrogen on the potato tuber size distribution.

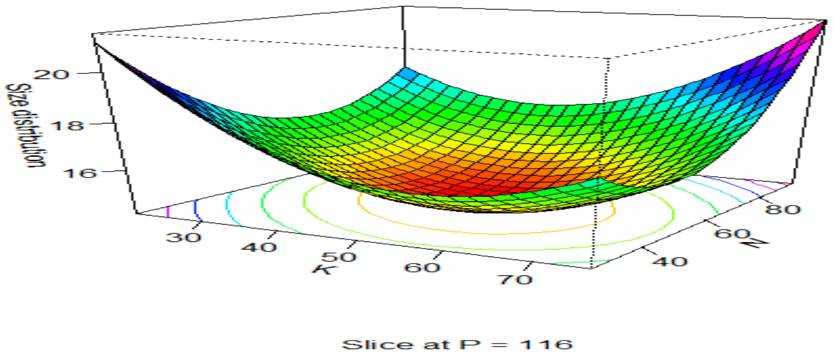


Figure 7: Response surface plot showing the effect of potassium and phosphorus on the potato tuber size distribution.

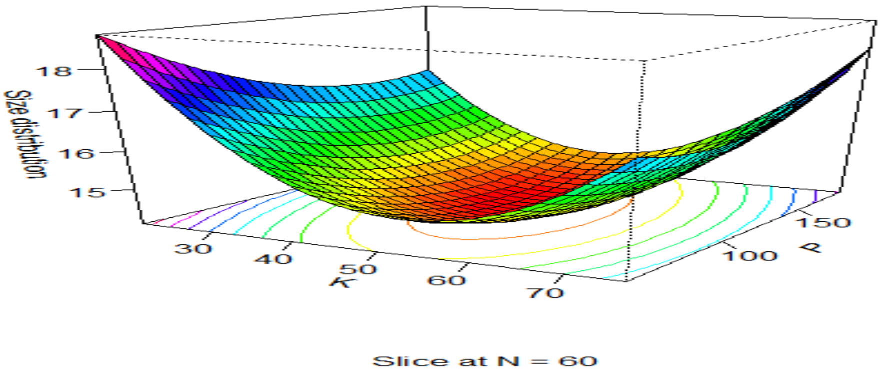
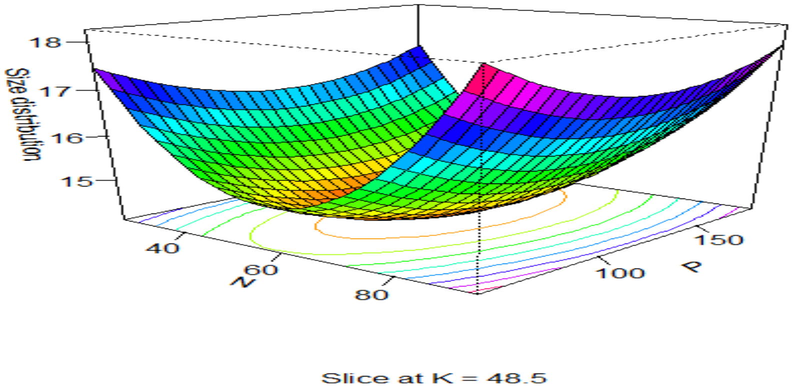


Figure 8: Response surface plot showing the nitrogen and Phosphorous on the potato tuber size distribution.



However, when the size distribution of potato tuber was optimized using ridge analysis method, the minimum estimated response for potato tuber size distribution was 14.67 cm with uncoded values being obtained as follows; $x_1 = -0.223, x_2 = -0.033$ and $x_3 = 1.665$ respectively (table 5). Using equation (10), the variables in their uncoded form can be transformed into their original form and the values are given as follows; $K = 44.82$ Kg $K_2O\ ha^{-1}$, $N = 59.34$ Kg $N\ ha^{-1}$ and $P = 180.94$ Kg $P_2O_5\ ha^{-1}$ respectively.

Table 5: Minimum tuber size distribution for potato tuber using Ridge analysis

Estimated Ridge of Minimum Response for size distribution					
Coded Radius	**Estimated Response**	**Standard Error**	**Uncoded Factor Values**		
			x_1	x_2	x_3
0.0	14.065259	0.414373	0	0	0
0.1	14.043077	0.411264	0.066571	-0.112370	0.105665
0.2	14.051041	0.402235	0.063122	-0.140553	0.298591
0.3	14.076935	0.388257	0.031761	-0.134552	0.484668
0.4	14.118025	0.371182	-0.003315	-0.122664	0.660702
0.5	14.173818	0.354109	-0.039347	-0.108926	0.831978
0.6	14.244160	0.341778	-0.075750	-0.094363	1.000711
0.7	14.328987	0.340534	-0.112332	-0.079357	1.167930
0.8	14.428266	0.357062	-0.149015	-0.064083	1.334175
0.9	14.541981	0.395933	-0.185759	-0.048636	1.499757
1.0	**14.670120**	0.458091	**-0.222544**	**-0.033068**	**1.664867**

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

Conclusions

The study used response surface methodology with application of a three-factor CCD to evaluate the effects of potassium, nitrogen and phosphorus on the size distribution of potato tuber. Results indicated that increased application of potassium and nitrogen showed a positive quadratic behavior. Similarly, the interaction of the factors, potassium and nitrogen showed a significant positive effect on the size distribution of potato tuber. However, potassium had a negative effect on the size distribution of potato tuber although the association was not significant and this maybe as a result of potassium being identified as water retention factor. The optimization process identified the optimum point for the size distribution of potato tuber as a minimum point. The predicted values at the minimum levels of the factors were as follows; 44.82 Kg ha^{-1} of potassium, 59.34 Kg ha^{-1} of nitrogen supplied as Urea and 180.94 Kg ha^{-1} phosphorus which was also supplied as triple super phosphate (TSP). At this minimum level, one can obtain a potato tuber size distribution of 14.67 cm. The factors considered in this study are important in influencing the size distribution of potato tuber. The current study recommends other researchers to adopt this method so as to improve on the marketability of potato tubers with minimal cost.

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