COMPARATIVE STUDY ON MULTIPLE RESPONSE OPTIMIZATION USING RESPONSE SURFACE METHODOLOGY TECHNIQUE- CASE OF FRENCH BEANS AT KARIUA SUBLOCATION IN KANDARA, MURANG'A COUNTY.

BY

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN BIOSTATISTICS IN THE SCHOOL OF SCIENCE OF

THE UNIVERSITY OF ELDORET, KENYA

JULY, 2019

DECLARATION

Declaration by the Candidate

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DEDICATION

I dedicate this work to Kariua farmers for their industriousness, their hard-work in farming and zeal in earning their living.

ABSTRACT

In Kariua sub-location, the resources like land and man-power are extremely scarce and this has affected French beans production negatively. This research, conducted at Kariua, aimed to optimize and compare French beans output and plant health simultaneously using manures, water and crop-spacing as control parameters. The response variables of interest were average pods' mass, infected leaves and unharvested pods. Manures and seeds were obtained from the farmers while water was drawn from river Irera. A survey was conducted at the beginning of the experiments to assess the current situation in French beans production and to provide the factors' levels at which the experiments were to be conducted. All responses and control factors were measured per crop point. The survey results showed that farmers were experiencing low yields on average and poor plant health (harvest=13.4 g, infected leaves= 8 and immature pods= 15) which were attributed to scarce resources, pests, infections and poor farming techniques. Soil testing analysis was carried out and experiments were performed along the lines of untested and tested soils using response surface methodology and Hoke D2 design. For the untested and tested soils respectively, the diammonium phosphate and calcium ammonium nitrate applications were 5.65 dg and 2.65 dg, and 2.5 dg and 2.5 dg. Only one variety of the beans, Gregor, was tested since it was the variety cultivated that time. For both cases, 2nd order models were fitted and the two sets of models were compared using optimized responses' results when optimal levels of factors were applied in replicates. The optimizing factor levels for manure, water and spacing were found to be 26.1 g, 4.0 ℓ and 11.1 cm, and 24.5 g, 4.1 ℓ and 10.3 cm for untested and tested soils' cases respectively. The theoretical and practical optimal responses were found to be in agreement. The practical optimal responses on average were 24.2 g, 0 leaves and 21 pods, and 28.5 g, 0 leaves and 32 pods for untested and tested soils' cases respectively. These results were found to be statistically far much better than what the farmers are currently experiencing while those from tested soils' case were the best because of larger mean values and p-values less than 0.05 level of significance compared to the other cases. Therefore, Kariua farmers can apply the optimal factor levels for the tested soils' case for maximum benefit from the very limited resources in the region.

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

ANOVA	Analysis of Variance
BBD	Box-Behnken Design
C.A.N	Calcium Ammonium Nitrate
CCD	Central Composite Design
CCRD	Central Composite Rotatable Design
cm	centimetres
D-, A-, E-, T-	Determinant, Average variance, Eigen value, Trace
D.A.P	Diammonium Phosphate
dg	decigrams
FCC	Face Centred Cube
FO	First Order
g	grams
GenStat	General Statistics
HSD	Honestly Significant Difference
IFADATA	International Fertilizer Association DATA
km	kilometre
ℓ	litres
m	metre
mm	millimetre
Ms-Excel	Microsoft Excel
Ms-Word	Microsoft Word
N.P.K	Nitrate Phosphorous Potassium
OECD	Organisation for Economic Co-operation and Development
PQ	Pure Quadratic
PV	Prediction Variance
R	R Software
RBD	Randomized Block Design
RCBD	Randomized Complete Block Design
RSM	Response Surface Methodology
SAS	Statistical Analysis System
SPSS	Statistical Package for Social Sciences

TWI	Two-Way Interaction
U.A.N	Urea Ammonium Nitrate
N	Nitrogen
P	Phosphorous
K	Potassium

ACKNOWLEDGEMENT

I want to acknowledge the University of Eldoret and its entire fraternity for uplifting me financially to go beyond undergraduate level in the academic ladder, and the French beans companies in Kariua region for the information provided.

Secondly, I appreciate the Kariua farmers for their cooperation, Dr. Ayubu Anapapa and Dr. Julius Koech for their teaching and unwavering support that enabled me accomplish this work, and for their guidance throughout the project period. Together with these are my fellow students: Ms Miriam, Ms Kanyi, Mr Chirchir, Mr Omare and Ms Naomi for their efforts in developing the idea and the writing, Diana Ingado for her encouragements and moral supports as well as the soil analyst, Mr. Kuria, for the job well done.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Research indicates that there are two places of origin of the French beans, one in America (Southern Mexico, Guatemala, Costa Rica, Honduras) and the other in Andes (Becerra, Paredes & Debouck, 2011; https://doi.org/10.1787/9789264253421-7-en). The crop had spread to other parts of North America, Florida and Virginia by the year,1492 with the farmers starting to breed the crops by 1890 for cultivars of interest. The crops were brought to Europe and Africa by the voyagers from Spain and Portugal (www.producebluebook.com). The slim pods became well-known vegetables in France by the 19th century and they got the name 'French' beans. India is the leading producer of French beans while the leading nations in Latin America Caribbean is Brazil and Africa are DRC, Kenya, Tanzania and Uganda (Petry, Boy, Wirth & Hurrell, 2015). However, the largest consumers are citizens of Burundi, Kenya and Rwanda. Farmers as well as business people in this sector face both fortune and tragedy- there is good tidings if most of the produce is exported or huge loses in case most of the produce is counted as reject. The loses are attributed to pods that are unfit for consumption, infections as well as undesirable shapes and lengths of pods.

The small-scale farmers in Kenya comprise of about 80% of the French bean growers, which contributes about 60% by value of all horticultural products in most parts of Kenya for export (Dag, 2003), and thus, boosting the country economically and enhancing food security. By the year 2014, the counties in Kenya that were leading in French beans production were Kirinyaga, Murang'a and Meru (https://www.agricultureauthority.go.ke ; Odero, Mburu, Ogutu & Nderitu, 2013; Masiga et. al, 2014). These three counties contributed 81% of the total output in Kenya with majority being small-scale producers. Mostly, beans are produced by small-scale farmers in underdeveloped nations such as in Africa and Latin America. The world's estimation of the produce is a challenge due to intercropping methods. This type of farming technique has been shown to lower yields and increase area under farming but there is a challenge in over-approximation of area under the crop's farming and under-assessment of the total output. The technologies and knowledge developed in the plant's reproduction and propagation has helped achieve numerous varieties. The varieties, called cultivars in *Phaseolus vulgaris L.* have different characteristics both morphologically and agronomically. The cultivars have taproots extending up to about 15 cm into the ground (https://doi.org/10.1787/9789264253421-7-en) with the characteristics of the crop depending on the cultivar.

1.1.1 The French beans

The French beans/ common beans/ snap beans, *Phaseolus vulgaris L.*, (Broughton, Hernandez, Blair, Beebe, Gepts & Vanderleyden, 2003; Nestares, Barrionuevo, Urbano & Lopez-Frias, 2001) provide proteins, and particularly, they are fountains of amino acids, sources of lysine and suppliers of tryptophan. These beans belong to the Fabaceae family and are bred and cultivated for their pods and seeds. It is mostly known as "common bean" because it is the most generally eaten bean in the world or "snap bean" due to the sound produced when the pod is broken. The wellbeing and dietary significance of the French beans to people comprises of; source of vitamins A, B, D and K, contains flavonoids, antioxidants, phosphorous, calcium, copper, potassium, magnesium, protein, fat, starch and omega 3 fatty acids which are essential to body health It also contains little amounts of sodium, saturated fats and cholesterol making them the best natural aid for weight loss. They can be cooked in water as seeds, can be roasted or can be powdered into flour before cooking. They are actually vegetables that supply proteins, vitamins as well as minerals, the leaves are consumed as vegetables, mostly consumed when in tender form while straw serve as fodder for animals like cows, goats, sheep and other wild animals. In addition, they provide livelihood to many by boosting them economically not only in Kenya but in Africa (Speckhahn, Subramanian & Meyhöfer, 2001; https://www.agricultureauthority.go.ke).

The altitude for French beans ranges between 1000 m and 2100 m above sea level- averaging at about 1800 m. The best temperatures for the crops are at about 20^{o} C though it can do well at a range of temperatures with a minimum of about 12^{o} C and a maximum of about 34^{o} C. The overall outputs are negatively affected by too low and too high temperatures- especially those outside the specified range due to frost in low temperatures and drooping in high temperatures. Good soils are necessary for the crops and light sand to heavy clays that are well-draining and rich in organic manure/matter can be suitable for farming. However, the ideal soils for these crops are the loam soils that are plentiful of diverse nutrients- should be heavily loaded with manures and receiving good rainfalls that are well spread in the entire crops' season. During their season, they require rainfalls of about 750 up to 2000 mm per year that should be evenly-spread although measures such as irrigation are put in place to ensure the crops' demands are met in case the rainwaters are unreliable. The crops are very susceptible to water-supply especially at flowering phase and yields can be negatively affected. About 30 kg of seeds in an acre of land are required with spacing of about 30 cm and 50 cm between crops in a given furrow and between any two furrows respectively, though this varies with cultivars, local spacing routines and other factors (Orzolek, Greaser & Harper, 2002)

The crop is much susceptible to many types of pests such as bean flies as well as diseases like root rotting (Fusarium type). Harvesting, that involves green pods for export, in regular intervals is highly recommended to ensure uniformity in pods' sizes, shapes and lengths among other qualities. It takes about 2 ½ months to carry out this kind of reaping which start at 7th to 8th week from sowing of seeds (Orzolek, Greaser & Harper, 2002; Mutua, 2016; Agribusiness, 2018, https://www.Fbiznakenya.com%2Fbeans-farming-in-kenya; www.theorganicfarmer.org) and these beans are extremely human-labour-demanding; requiring workers from the initial stage till harvesting time. The numerous cultivars of snap beans can be grown in Kenya as vegetables for export while other new types are uncovered every day, and some are disease resistant (Kiptoo, Arunga and Kimno, 2018). These new types are of great help to farmers since they have ripening that is uniform and are high-yielding (Africa Research Bulletin, 2014, https://www.Fonlinelibrary.wiley.com%2Fjournal ; Meena, Chamola, Rana & Singh, 2018a). Such a move has advantages since harvesting can be done once instead of doing it in stages as the norm and generate satisfactory gains. The crop is quite good in giving farmers the chance to plant several seasons in a year- which is very advantageous.

1.1.2 The French beans' farming

The cultivation of the snap beans depends on a number of factors such as the size of the land available, the type/cultivar of the bean being cultivated, the cost of the beans, the climate of the region and the terrain of the land in the geographical region under question among other factors. These factors determine whether a farmer would engage in farming for food to consume locally or for commercial purposes through exports. It is the desire of every farmer to get maximum output, be it for food or for commercial purposes. The planting rate is about 60 to 160 thousand of seeds in an acre and this rate is lower when intercrops are involved. Although the spacing is about 30-90 cm by 15-30 cm for bush type cultivars and 30-120 cm with about 3-6 crops in a given hill for pole type cultivars (https://doi.org/10.1787/9789264253421-7-en; Becerra et. al, 2011)- the spacing depends on local practices. Large spacing of rows of the crops ease cultivation by facilitating the attendance to the crops. Close spacing of the rows leads to higher outputs due to larger crops and large number of pods formed but can lead to rise in disease incidences. The small-scale farmers usually utilize the services of manual labourers without use of machines in their fields.

D.A.P is applied before sowing seeds (about 80 kg per acre) although other types of fertilizers rich in phosphorous like triple super phosphate (T.S.P) can be used instead of D.A.P while C.A.N is applied twice (about 60 kg per acre)- first at three-leaf stage and secondly at onset of flowering although other fertilizers rich in nitrogen like urea can be used instead of C.A.N fertilizer. N.P.K fertilizer can be applied in small quantity before sowing in case the soils are in deficiency of the nutrients nitrogen and/or phosphorous and/or potassium. Weeding can be done twice; 2 to 3 weeks after germination of the seeds and about 2 and 3 weeks later in order to eliminate competition that may arise between the French bean crops and weeds in the field. This is done during dry times and not at flowering stages to avoid deflowering of the beans and spread of diseases and infections. Though the crops can rely on rainfall, this can be supplemented with irrigation where the crops require 50 mm (50 litres per m^2) of water weekly, but should be irrigated at 35 mm (35 litres per m^2) per week at early (less than 10 days old) and late (at podding) stages. If snap beans are of interest, then harvesting begins at 7-8 weeks after seeds are planted while dry seeds' harvest depends on the farmers' judgment on maturity of the pods. Output loses can be associated with pests and diseases, farming techniques, infertile soils and abiotic pressures. In developing nations such as Kenya, Uganda among others, majority of French bean farmers do not treat the beans as crops demanding high inputs in terms of labour, manures, fertilizers land among other inputs, but they channel the limited resources to other crops that can be cultivated alongside the beans resulting in very low yields compared to developed nations (https://doi.org/10.1787/9789264253421-7-en).

At moderate conditions, the seeds are buried at 0.5 to 1.0 inches deep into the soils but can be buried up to 1.5 inches when the soils are dry for adequate moisture (Orzolek, Greaser & Harper, 2002). The densities at which they are planted depends on several factors including soil types, French bean cultivars and pests control methods. The application of fertilizers should be done according to annual soil tests. At pH levels between 6.5 and 7.5 (Mutua, 2016), the snap beans do very well, and watering should be constant while controlling for weeds, diseases and pests like aphids, leafhoppers among others using herbicides, pesticides, disease-resistant cultivars and crop rotation. However, the land under cultivation of the crop has been wobbling over time (Dag, 2003) leading to alternation and non-observance to these specifications. Harvesting of pods after sowing of seeds may be done for about two months but the harvesting intervals should be regular to ensure unchanging shapes and sizes of the harvested pods that can attract the required market.

1.1.3 Inputs for the French beans' farming

As was mentioned earlier, French beans farming requires different inputs and labour. Labour in terms of preparing the land, tilling, planting, weeding, watering/irrigation and harvesting. Inputs include manure and fertilizers, pesticides, water among others.

a) Water and irrigation

Irrigation can be defined as application of water to crops in fields by man in order to sustain their growth and life. The technique is used where rainfall is in shortage or in dry areas. The snap bean crops can be watered at the rate of 50 mm per week (Mutua, 2016) and there are several ways of administering irrigation such as:

i. The channels/canals from main river to the land so that water wets the field, enabling crops to thrive.
ii. Raising water from rivers, dams, swamps, boreholes, etc. using buckets and cans and then pouring it on land- this is called manual irrigation.
iii. Another way is to use pumps and windmills to direct water from the source to the land.

Canals are used when irrigation is on large scales and on almost flatty lands. For example, it is canal irrigation that is practised in northern India (Moncrieff, 1905) where land sizes are large and almost flat. Some regions in India and of course in other countries have adopted the method of drip irrigation which is more effective and less costly in terms of water amount needed, manpower and others (Kumar, 2012). Water is a very important input parameter because the crop is very sensitive to water stresses and several investigations on effects of deficit irrigation water on French beans production have been done and reported (Saleh, Liu, Liu, Ji, He & Gruda, 2018; Lado, Onyando & Karanja, 2017).

b) Fertilizers and nutrients

Soil fertility is key in farming since the more fertile the soil is, the healthier the crops and the higher the yields. Extremely reduced fertility sharply affects productivity directly. Fertilizers are forms of inorganic manures that greatly improve crop production and yields. There is almost, in most cases, a linear relationship between fertilizers and crop production. Amongst factors of production, fertilizers help increase the soil fertility and improved output for sustaining the increasing populations, though it's very costly (Ramamurthy Naidu, Kumar, Srinivas & Hegde, 2009; Meena et. al, 2018a; Medellin, Apedaile & Pachico, 1994). But the excess of it makes soil saturated and leads to low crops' performance (Ascough, Fathelrahman & Hoag, 2013). In some instances, studies indicate declining crop outputs with increased usage of fertilizers in farms and this has been attributed to concentrations of the soil contents beyond the limit that is acceptable for crops' thriving (Sagar, 1995). Since this is the case, there is need to carry out soil testing (Gazey & Davies, 2009) to help determine the types of fertilizers and levels that are required because most farmers have been employing them for long though in small quantities. It is evident that it’s not easy to carry out farming for many types of crops without application of fertilizers (Rosser, 1953; www.ext.vt.edu) because huge productions are required every day to help meet the rising demands. Indeed, fertilizers are essential in today’s farming but the overuse of the same can cause negative effects like hardening soils, strengthening pesticides as well as pollution (Gazey & Davies, 2009).

It is possible to work with fertilizer levels below the recommended levels (micro-dosing) since a farmer cannot use amounts they cannot afford, and still record high outputs (https://www.jstor.org%2Fjournal%2Fspore). The fertilizers employed have nutrients including nitrogen (N), phosphorous (P) and potassium (K) (http://garden.org/learn/articles/view/453/; Douglas, 2018; Vishwakarma & Kumar, 2018; Zaman, Pramanick, & Mitra, 2014). Some research have been conducted in other areas to evaluate the optimal levels of various fertilizer components like nitrogen and phosphorus on different varieties of French beans (Wondimu & Tana, 2017). Increase in use of some nutrients such as N can result in better yields while soils saturated with other nutrients such as P can be productive even for 8 years without demanding for more application of those nutrients (Nawara *et al*., 2018). But it can be noted that too much nitrogen may lead to more vegetation at the expense of pods formation of the crops- and this calls for right knowledge in modern farming practices and in application of fertilizers. All these point to the fact that the services of soil analyst are needed before farmers engage in application of fertilizers in their fields. The usage of P globally rose up to four times worldwide (http://ifadata.fertilizer.org) in the bid to satisfy the growing human population and its balance is reverted to negative in some areas due to reduced use of it in fertile soils (Nawara *et al*., 2018). Potassium acts like an enzyme activator as well as playing a role in photosynthesis. Symptoms of lack of this nutrient can cause chlorosis and seeds and fruits that are of reduced quality (Uchida & Silva, 2000). Calcium in soil improves its structure, permeability and its infiltration while the organic substances advance soil productiveness as well as the water volume present (https://link.springer.com/chapter/10.1007/978-94-007-5663-2-5).

It is good to note that, the recommended fertilizers’ doses per crop point cannot be applied in Kariua due to the competition posed by the several planted crops in the same field. In the end, they subdivide the quantity supplied for other crops. There is a high possibility that, the various forms of nutrients have been accumulating for long and to high levels that can no longer support good yields. Although the amounts applied are at low levels, that is not a guarantee that accumulation has not been taking place.

c) Land size and crop-spacing

Land is a vital resource in farming and is becoming small and smaller through sub-divisions due to ever increasing population size that needs to be accommodated as well. The reduction of land size under cultivation is due to the housing required for the populations but another factor in Kandara area is due to terrain where the larger part of each piece is sloppy and unsuitable for irrigation. The sloppy parts of Kariua area have been left to tea/coffee bushes that were planted during the colonial periods, and that residents have been replanting with time. If farm size is large, then drip irrigation (as well as manual irrigation) cannot be practiced and cannot be recommended. In Central Kenya and other parts of the country, land sizes are as small as 0.15 hectares which is simply 0.375 acres (Otieno, Ogutu, Mburu & Nyikal, 2017). The farmers in Kariua/Kandara have to use land wisely and must develop techniques for maximum benefits. This makes them squeeze different types of crops into the available land and this leads to intercropping, leading to farms packed with a variety of crops. Any form of recommendations regarding to spacing, like increasing it (Vishwakarma et. al, 2018), of French bean crops and the avoidance of intercropping is misplaced since reality dictates otherwise. The crops that are planted together with French beans in the farm are maize, kales, arrowroots, potatoes etc. For this reason, investigating about the right and recommended spacing of these French beans would be of little help to these farmers. However, research into what spacing can give maximum output despite intercropping and other factors would be of great help.

d) Soils

In relation to farming, farmers can define soils as plant-life-supporting mixture of minerals and organic material and apart from supporting plant-life, soils are a habitat for micro-organisms. Soils in general are made up of components and the three components are; the minerals (about 45%), the organic matters (about 50%) and the pore spaces (about 5%). Any fluid, whether air or water, can fill up the pore spaces. Soil parameter/measure called pH is the concentration of H+(aq) in the soil solution. Some of the problems associated with reduced soil pH are nutrients deficiency, disease and herbicides interaction and reduced efficiency in the use of nutrients. There are a number of soil factors that influence acidity including organic matter and inorganic minerals among others. The factors that cause soil acidity include the organic acids, organic matter and acidic phosphate fertilizers among others. However, some of the ways of reducing soil acidity impact on agriculture include cultivation of crops and pastures that can tolerate acidity, guarding soils from becoming acidic by some ways like preventing soil erosion and minimizing the use of soil acidifying fertilizers, minimizing nitrate nitrogen leaching, application of limestone among other ways (Harsh, 2013; Naseri & Ulmer, 2015; Upjohn, Fenton & Conyers, 2005). Reduced plant health may imply low ability to protect itself from infections, hence the crops can easily be attacked by any form of disease and lower output.

There are various forms of soils- loam, sand and clay. The other forms of soils include mixtures of these three; the silty clays loam, the silty clays, the loamy sands among others (https://link.springer.com/chapter/10.1007/978-94-007-5663-2_5) and all the types of soils are categorized using the textural triangle (https://www.2Fclasses%2Fssc107%2FSSC107Syllabus%2Fchapter1). Clay soils are best for modelling of say pots, plates, decorating objects etc. It's not good for drainage since it retains most of the water on its surface. This is due to the fact that its particles are tightly packed together leaving almost no space for water to go through. Loam soil on the other hand is mainly used for farming. It's like an intermediary between sandy and clay soils. Its particles are moderately packed and allows water to pass through it slowly and this allows crops to get enough time to absorb water for growth. Sandy soils on the other hand are the best in drainage. They have large airspaces that drain water in the shortest time compared to the other types of soils. The type of soil in Kariua/Kandara region is mainly the loam soil. Tilling/ploughing is not a big deal since the land sizes are small and the soil is not too compacted. Therefore, hoes and *pangas* are usually the only necessary paraphernalia for tilling. Tilling is necessary, where the soil is thoroughly mixed up and holes/furrows for manure and seedlings/seeds are made, before the crops are placed for germination.

e) Manures

The manures which are usually applied during planting season are organic manures from animals' wastes, such as cows' and chicken's dung. It is the responsibility of the farmer to boost soils' fertility through manures and fertilizers when necessary. About 7 t to 10 t of manure (Agribusiness, 2018, https://www.Fbiznakenya.com%2Fbeans-farming-in-kenya) can be applied in a given acre of land in case the soils are in deficiency of the important nutrients to help boost the soil fertility. In Kariua, farmers prepare it very easily: they just cut the types of weeds and leaves that are not edible to the cows, as well as their leftovers from grass, and throw them in the cows' sheds. The cows sleep on them as well as trampling them under their feet until they are thoroughly mixed up with their wastes (excretions). After such preparation (of like 1 to 1 1/2 months), the sheds are cleaned where the un-rotten materials are placed in a heap for further decomposition. Finally, the manures are taken to the farm and placed (in small quantities) in holes/furrows dug for seeds or seedlings, depending on the type of crop being cultivated. However, rationing takes place because of its scantiness. The proposed amount of manure and its state of well decomposed/fully rotten or not cannot be applied because farmers have to work with what is available and not rely on what is not within their reach. Therefore, a study on the amount of manures that can bring out the highest yields in the presence of other constraints can be beneficial to the farmers.

f) Labour

A huge input in snap beans cultivation is labour. The common beans cultivation is extremely demanding in terms of labour. This input is required from land preparation to harvesting period. The Kariua farmers use human-labour provided by all ages of persons- children, teenagers and adults are involved in one way or the other.

1.1.4 The farming of common beans in Kariua/Murang'a

The adoption of French beans farming in Kariua sub-location by farmers, and Kandara constituency area in Murang'a at large has been at high levels in the recent years. The Kariua region falls within the right altitude for the common beans cultivation and with the temperatures required. There are many types of French beans grown in Kariua at different years; Allegria, Annabel, Masterpiece, Gregor, Prince, Purple Tepee, etc.

(http://www.gardenfocussed.co.uk), and almost all do well in the region. Cultivation of the crop in the area is increasing every day due to lack of other means of sustaining the families as well as failure of coffee, which is the main cash crop in Kariua region, to offer solutions as source of income and enhancing of food security. The payments made to farmers by the contracting French beans companies entices many more farmers to invest in French beans farming, because of the instant gains.

The farmers prepare their lands in advance before they get the seeds from the contracting company. The spacing of the crops, the amount of fertilizers applied, and the form of irrigation carried out are not done according to the instructions received from the company. Farmers are advised not to plant anything near the crops but that remains just as an advice and this has led to many farmers, producing no good results from year to year.

The population in the region has been increasing and constructions of buildings such as houses has reduced the land size meant for farming. Snap beans and other food crops such as maize, beans, arrowroots, potatoes (both sweet and Irish), different forms of kales, onions among others, are cultivated along the riverbanks where the land is flat and water for irrigation is available. The farming is carried out continuously throughout the year and that means irrigation has to be done till it rains, which is in low amounts and poorly distributed within one-year period (Masiga et. al, 2014). The type of irrigation is manual (involving cans/buckets) and such a method of irrigation has the following disadvantages: A lot of labour is required, dirty water can result in clogging/blocking of the watering equipment, training is required to help the user in using the method in the best way possible, time consuming and land surface hardening due to a lot of movement to and from the river and even crop destruction when stepped on. However, the method has some advantages such as: The efficiency of water usage is high in this method because of reduced water loss through evaporation, the water is directed well to the crops, one is able to water selected crops, it helps one to target specific points of the crops such as stems in the field and ensures constant water supply in all the stages of crop development.

The boosting of the nutrients in soils in the region is attained by adding of diverse fertilizer: inorganic fertilizers such as D.A.P, C.A.N, N.P.K, U.A.N among others; and organic fertilizers such as animal manure, compost, peat moss and mineral deposits. However, all these important and necessary ingredients are rare at Kariua since farmers rely on one cow or none for manure production and have little or no knowledge at all about other forms of organic manures.

Once the French beans are mature for harvesting, the produce is taken to selected collection centres (the centres' offices are in the region of interest such as in the village) where cleaning of unwanted materials, weighing and mass recording are done. Payments are made afterwards. Immediately after closing of harvesting, another farming activity/season is started, and the process is continued. This means that, the land is never at rest bearing in mind that, there are other crops cultivated alongside these beans such as maize.

The harvested immature green pods are the French beans called snap or green beans, but immaturity doesn't mean they are of no use. At that stage, no full development has taken place but can be useful for other purposes such as food before the seeds are fully mature. The half-formed seeds are consumed together with the pods that are still green and tender.

1.2 Statement of the problem

The level of French beans production is very low due to limited resources- mainly land, man-power and fertilizers- and the crop is prone to diseases, pests and various forms of infections leading to poor plant health. Generally, very small pieces of land, lack of enough organic fertilizers and other inorganic forms of manure, water shortage, inadequate man-power, pests, infections and diseases, intercropping, poor farming techniques as well as very steep landforms that are unsuitable for farming, are evident in the region, Kariua, which have affected the production negatively. Many researches have been done but none has focused specifically on the three factors (water, spacing and manures) of interest simultaneously with an aim of assisting farmers reap great from their overstretched efforts and resources. Many have focused on fertilizers alone and recommending that more fertilizers be used but a way of managing what is available without incurring more costs, that are usually unaffordable to farmers, is required. This research was optimizing the French beans production in Kariua region based on what farmers do and what they can afford, and comparing results to give the way forward in application of manures and water as well as land use.

1.3 Objectives

The objectives guiding this research were the main objective as well as four specific ones.

1.3.1 Main objective

The research aimed at comparing multiple response optimization of French beans using response surface methodology (RSM) technique based on soil testing analysis criterion at Kariua sub-location in Kandara, Murang'a county.

1.3.2 Specific objectives.

The specific objectives of the study were:

1. To carry out a sample survey to assess the current situation on French beans output of the beans on average, input levels of various resources and the general plant health (crop infection) in order to get the starting point for experiments.

2. To determine the appropriate 2^{nd} order models optimal design to employ based D-, A-, E- and T- optimality criteria on commonly used designs in order to obtain a design to employ in conjunction with the RSM technique.

3. To estimate 2^{nd} order models and factor levels that optimize the output and plant health simultaneously based on and without soil testing criterion and the identified optimal design from objective 2.

4. To select the better models by comparing optimal outputs using replicates as well as sample survey findings.

1.4 Research questions

In the end, this research was seeking to have answered the following questions:

1. What are the current levels of inputs, plant infections and production on average of French beans in the area?

2. Which is the most appropriate design among the commonly used designs for 2nd order models based on D-, A-, E- and T- optimality criteria?

3. On the basis of tested and untested soils, what models and factor levels would optimize yields and plant health simultaneously?

4. Which model is better in optimizing yields and crops' health, and is it actually pointing to better results than what is currently being experienced by the farmers?

1.5 Hypotheses

1. H_0: There's no starting point for the experiments and the current French bean farmers' situation is satisfactory.

   H_1: There's starting point for the experiments and the current French bean farmers' situation is unsatisfactory.

2. H_0: There's no appropriate 2nd order models optimal design to employ based D-, A-, E- and T- optimality criteria on commonly used designs.

   H_1: There's an appropriate 2nd order models optimal design to employ based D-, A-, E- and T- optimality criteria on commonly used designs.

3. H_0: Second order models and control factor levels for optimizing all responses simultaneously are not estimable.

   H_1: Second order models and control factor levels for optimizing all responses simultaneously are estimable.

4. H_0: All the models are the same and not different from farmers' experience.

   H_1: The models are not the same and they are different from farmers' experience.

1.6 Justification of the study

Kariua residents are extremely poor and the area is densely populated with very few residents who can be termed as rich. Continuous sub-division of the already small pieces of land has left only minute pieces of land for farming and this has led to over-farming. Buying of fertilizers is never their option when it comes to boosting soil fertility and the manure available is never enough, loans are not easily accessible due to exaggerated and unfriendly bureaucracies, most of the land is very sloppy and hence unsuitable for ‘good farming’ while manual irrigation- which is really labour-demanding- is the order of the day during the dry seasons. In general, factors affecting farmers such as EurepGap compliance are inability to purchase agro-chemicals and fertilizers, and the hiring of additional labour, socio-economic and farm attributes like land size under French beans, house-hold size among others (Muriithi, Mburu and Ngigi, 2011).

With the foregoing reasons, there is need to maximize the output of the French beans to ensure that the farmers benefit to the maximum from the limited resources as well as get to mitigate the effects of the challenges facing them. The findings will be disseminated to the farmers and can be applied to increase the production of the French beans and as well as control plant health. In general, this study would provide the way forward in managing the very limited resources for maximum benefits without incurring additional costs.

The companies involved should be able to receive increased supplies from the farmers for export and therefore, the country will earn increased foreign exchange. Indirectly, improved plant health means more leaves, branches and thick stems and since animals like cows feed on the plant, then their food security would also be secured too. The research would help bridge the gap that is existing in which researchers haven’t investigated the three factors of interest in the manner of this study.

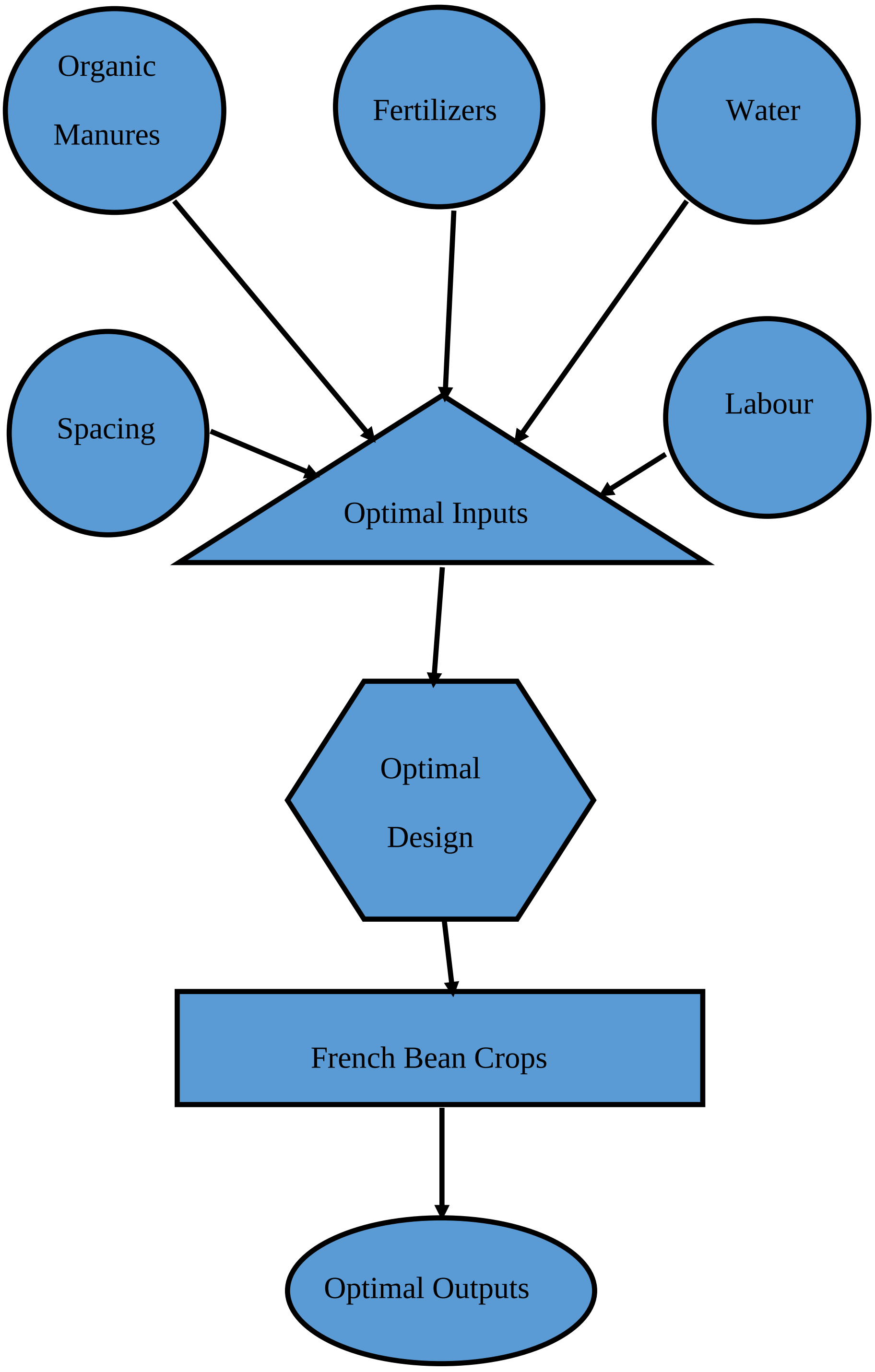
1.7 Scope of the research

The research was conducted at Githaiti village in Kariua sub-location. It involved only the farmers of French beans and the RSM was the main technique employed. French beans were the only crops experimented- Gregor variety because this was the only variety cultivated approved by the French bean companies for cultivation during that year. The fertilizers (D.A.P and C.A.N) were those used by farmers and organic manures applied were from cows' dung. The factors experimented on were the water for irrigation, organic/natural manures for increasing soil fertility and spacing among crops while the responses measured were the average yield for two weeks, average number of infected leaves and average number of immature pods, all measurements taken per crop point. Experiments were conducted along the lines of tested and untested soils only. As was deemed suitable, only the 1st and 2nd order models were fitted. The survey done aimed at obtaining only useful information for guiding the starting of the procedures in experiments and for comparison purposes in the end of the research. Only one design was chosen to be employed and consisted of complete replicate of factor levels.

1.8 Theoretical framework

In the objectives, optimization of the output is the key thing as well as the inputs in agricultural sense. Soil contents in terms of those nutrients provided by fertilizers and optimal design are key also. Bearing in mind of these key terms in the objectives, this part deals with a flowchart that shows the connection in all the processes. Figure 1 shows the flow chart of the processes involved in this research.

Labour was considered as a moderating variable. However, it was not measured directly but was done as farmers do. This ensured that its effect on experimental results was also felt by farmers hence it was a common factor for all. In this study, organic manures were measured in grams, water in litres, crop-spacing in centimetres and fertilizers in decigrams. All these measurements were done per crop point basis.



The Flow-Chart Representing the Processes

Figure 1: Theoretical framework in a flowchart form.

CHAPTER TWO

LITERATURE REVIEW

2.1 Definition and application of RSM

RSM is a set of techniques, both Mathematical and Statistical (Dette & Yuri, 2014; Johnson & Montgomery, 2009; Fu, 1994; Hill & Hunter, 1994; Myers, Montgomery & Cook, 2009), that helps study and realize the relationship between a given response(s) and some independent variables with the sole aim of optimizing the response. In other words, it is composed of techniques, for optimizing response(s) based on some control factor(s). The main objective in such cases is to optimize the response when the 'about right' levels of controlled factors are combined. 'Right' factor levels are estimates that are believed to bring about optimal outcome(s). If *Y* is taken to be the response of interest, then it becomes a function of control factor(s) such as

$$\Lambda = E(Y) = f(X_1, X_2, \ldots, X_k) \text{ for k factors} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Λ is called response surface. The error term in this case is taken to be normally-distributed with mean zero and variance σ^2.

The role of RSM in Agriculture and Biometric research was brought on the surface by Mead and Pike (Khuri, 2017) and has been applied intensively (Stamenkovska, Dimitrievski, Erjavec, Zgajnar & Stojcheskska, 2013; Quoc, Quang, Hoai, Duy, Tram & Ngoc, 2014; Muriithi, Koske & Gathungu, 2017; Mwaniki, Koske, Mutiso Mulinge, Kibunja & Eboi, 2017; Khuri, 2017) to see the way forward in managing limited resources in the presence of competing needs. It is now applied in many fields including those involving food and Biological applications. It has also been applied in the field of pharmacy (Shaji & Lodha ,2008) and in the field of Engineering (Pai, Rao, Shetty & Nayak, 2010)- in order to optimize the output and minimize production costs as well as other forms of resources (Pawan, Anish & Balinder, 2013).

2.2 Previous research on French beans

The importance of replication and reasons necessitating replicates when performing experiments in French beans and other crops has been explained by Gallagher (1966) in which potassium (K) fertilizers and farmyard manures were involved. The testing done was on soils and plant samples in which it was evident that the available K was low in Kinsealy soils while the yield in experiments involving K was higher than the experiments involving FNPK (fertilizer of type NPK together with farmyard manure). The winds played a big role in influencing the vigour of growth and the crops' growth is retarded when the winds damage the crops at seedling stage. This shows the need to have experiments in different locations (replicates) to cater for difference in climate, weather, soils, and other factors affecting French beans. According to the general knowledge, blocking is a technique that can be used to reduce the effect of nuisance factors. However, blocking requires replicating the runs. Furthermore, the need for replicates is not just necessitated by blocking but also by the desire to obtain larger data sets for better estimation of parameters of interest and for security purposes in case of threats of crops from wild animals and other threats.

Binnie and Clifford (1980) investigated the effects on French bean production due to application of treatments involving defoliation and decapitation to know whether the available assimilate supply is associated with limited harvestable sink yield. The results showed that the removal of subtending leaf has no effect on number of fruits, seeds at node 2 and fruit yield for both varieties. However, the removal of subtending leaf together with one primary leaf had negative effect on productivity at second node for variety Chicobel while there was no effect for variety Masterpiece.

The crops' populace concentration can affect the produce as well as quality. Field and Nkumbula (1986) investigated the effect of density of French bean population on quality and yield and showed that there was a substantial response to growing plant populace concentration of the pod output and the response was quadratic in nature. The research revealed that the plant arrangement is not a determining factor of yield but density is, while the pod size distribution was similar in all treatments statistically.

In the paper by Calvache, Reichardt, Baccchi and Neto (1997), the effects of irrigation and nitrogen fertilizers on French beans performance at different stages was investigated with the goal of identifying the French bean stages at which they are less sensitive to water stress and result in insignificant yield decrease. The research revealed that, the harvest from irrigation shortage factors was lower than those that had additional irrigation with flowering phase being the most affected when it comes to water stress. Nitrogen applied had a positive effect on crops since it increased the number of pods and yields in terms of grains. The effectiveness on water usage by the plants was lowermost with stress at the flowering phase while the factors with usual irrigation and stress at maturation had revealed higher water usage of the plants in relation to the old styles of farming techniques. It was noticed that reduced irrigation at different stages of plant development influences plants' water evaporation significantly as well as water balance. Water and fertilizer interaction were also significant in some experiments and it was observed that French beans require frequent irrigation.

Abdel-Mawgoud, El-Desuki, Salman and Abou-Hussein (2005) investigated how the NPK fertilizer affects yield of French beans as well as the pod quality determined by their length, thickness and fibre contents. The varieties that exhibited better response in vegetative growth compared to others were Royal Nel and Coby. Julia had the least effect. It was also noticed that, increase in levels of the fertilizer increased the vegetation growth. In terms of pod yields, Coby had the best results while Royal Nel had poorest response with a generalization that yield increased with increased levels of fertilizer. In terms of pod quality, there was no significant change with levels of fertilizers applied.

Maske, Kadam, Tidke and Pawar (2009) investigated diverse levels of fertility on genotypes' performance of four cultivars of snap beans using RBD. The HPR 35 variety was found superior over the other varieties: Contender, Waghya and Varun. It had better performance in terms of plant height, functional leaves, dry matter and branches. The differences among the various varieties of the experimented French beans were attributed to the genetic makeup of the varieties. The three levels of fertility were observed to have variation in yield and they were determined using different ratios for NPK fertilizers. The best results were obtained with level 150:75:75 NPK kg/ha while the worst results were found when 120:60:60 kg/ha level was applied. There was observation that at higher levels of the 150:75:75 NPK kg/ha application of fertilizers, there was significant increase in yield. The interaction between fertility levels and varieties showed significant improvement in number of functional leaves with every increase in fertility level with HPR 35 performing best in all levels of fertilizer.

2.3 Recent research

The study of the effects of germination conditions on many responses with mung bean, the effects of physical processes in crops by foliar fertilization on common beans, and French bean farmers' compliance with food safety standards in the use of pesticides were conducted and showed that the optimization time and temperature on germination are between 43.02 and 76.97 hour and 28.88^o C and 38.44^o C respectively. There was rise in iron matter in simple leaves because of the use of iron salts and urea can increase the rate of iron transport in French beans for the foliar fertilization case, while pesticides may be beneficial to farmers and crops but can lead to poisonous produce and loses to farmers (Hussain & Burhanddin, 2011; Borowski & Michalek, 2011; Okello, 2011).

Nyasani, Meyhöfer, Subramaniana and Poehling (2012) investigated thrips species composition as well as their population density, at KARI- Embu, and results indicated that, the thrips population was increasing over time and was at peak at flowering stage. On the intercrops, the species were available too. The sole French bean crop hosted more species compared to when intercropped. The maximum outputs were gotten from sole common bean crops while French beans intercropped with diverse crops produced less outputs. In conclusion, more species of thrips are hosted when French bean is not intercropped while intercropping helps reduce the species and their effects. Petrova, Matev, Kuomanov and Petrova (2013) studied the productivity of the snap beans while varying irrigation in Bulgaria and the results showed that the unirrigated areas have improved production during medium wet times of the year from dry times. When the pre-irrigation moisture in soils is maintained between 80-90% of FC (FC is a measure of moisture in soils and was not defined), the yield is not only stabilized but also increased. The findings did not recommend the other pre-irrigation soil moistures' levels.

Ogendo, Ogweno, Nyaanga, Wagara, Ogayo and Ochola (2014) carried out survey on farmers to examine the common beans production restraints, the maladies and pests attacking them and the management approaches in Nakuru using the sample surveys. The results showed that French beans were among the main grown crops and bacterial blight was among the main disease attacking them. Nazrul and Shaheb (2016) tested the performance of French bean genotypes in an experiment that involved evaluation of the best variety for maximum yield for farmers using CRBD and 8 bean genotypes. It was found that there was significant variation among the genotypes in terms of yield, with the 5 local genotypes performing better than the 3 developed ones. The Local-4 and Local-5 yielded the maximum output.

The work by Ngelenzi, Mwanarusi and Otieno (2017) on increasing the French bean pods' output and their quality, by application of diverse painted agronet covers, was done aiming to assess the effects of the covers on Source cultivar. There was a difference in growth and crop performance based on different net covers. The results were positive since there were more pods on crops and better marketable yields than the open field experiments. The bright-painted nets enhanced the rate of pod maturing leading to better French beans harvests and better quality- which means that, netting can help improve French bean production and more so, light-coloured nets.

In the paper by Meena, Ram and Meena (2018b), on yield and quality of French bean traits under Lucknow (capital city of Uttar Pradesh) conditions, these researchers found that the effect of varieties on response was statistically different from one variety to another. The variety PDR-14 was found to be better in terms of duration from sowing to first flowering. The rhizobium bio-fertilizer was found to be better than the rest since it had better results for yield and quality traits. The association between varieties and bio-fertilizers was significant with the best results being gotten when rhizobium and PDR-14 interact.

2.4 Pests, pesticides and spraying chemicals for French beans

French beans are attacked by pests, just like any other crop of vegetable type. Certain pests like Western-flower-*thrips*, the whiteflies, the aphids and the bean fly among others destroy the common beans' pods whereas others devour the leaves. Pesticides and other spraying chemicals such as predatory mites, entomopathogenic fungus and others have been manufactured with the sole aim of eliminating any pest posing threat to the crops (Nyasani, Subramanian, Poehling, Maniania, Ekesi & Meyhöfer, 2015), and researchers elsewhere have studied some of these pesticides in relation to some diseases (Kasina et. al, 2009; Otim et. al, 2016; Kiptoo et. al, 2018). There is also rust infection that lowers the photosynthesis, leading to low yields (Murray & Walters, 1992). Most of the farmers in Kenya, Kariua area included, depend on application of chemical pesticides in order to keep the crops healthy. However, spraying has not guaranteed the crops' health since one can still find crops that are unhealthy with leaves' colours that are far from green, thin stems and "dwarf" pods among defects. Frequent sprayings not only result in pollution and high costs but also makes the edible pods unfit for human consumption (Mujuka, Affognon, Muriithi, Subramanian, Irungu & Mburu, 2017). The bacteriological infections/maladies include the common bacterial blight with its variations, the fuscous and halo blight, as well as the bacterial brown spots (https://www.2Fipm.illinois.edu%2Fdiseases), that have destructive consequences on the beans in overall. It has been assessed that about 10-20 percent of production can be lost from these diseases only, especially in rainy and windy seasons. They also lower the quality of beans and affect mostly the leaves and bean pods. The use of pesticides has been attributed to stringent measures that require marketing yields that are free from blemishes caused by pests that attack the crops. Though the pesticides are beneficial in some ways, they also have limitations in farming since they can lead to residual (Okello, Narrod & Roy, 2007) (accumulation when used wrongly as well as their costs reducing income).

In general, diseases, pests and others form of infections, lower yields of beans and other plants. This is not different from what the Kariua French beans farmers experience. Although there is regular spraying at three stages of the crops, this has not helped farmers to fully escape the loses.

Many scholars and researchers have investigated the issues to do with French beans production worldwide, in Kenya and in Central region in particular- even the post-harvest life of the beans (Thenmozhi, Kumaravel and Vimakarani, 2016; Ambuko Emong'or, Shibairo and Cheminingw'a, 2003) and diseases (Kiptoo et. al, 2018). They have identified the problems facing farmers and the crop itself, areas that need to be improved such as increasing soil nutrients like ammonium, phosphorous, etc. as well as organic manures and changing methods of farming by application of new technologies. They have also recommended to the farmers to increase the land size under use, the best time of the day to irrigate the crops, to acquire loans and other extension services among other things. However, most have done and relied on surveys to conduct the researches and haven't performed experiments. Furthermore, optimization using RSM technique that is based on soil testing knowledge has not been exploited in that region and no multiple responses optimization has been done especially, to minimize infections (improving plant health) and improve production without application of more chemicals. This research would come in to find the best way to use what French bean farmers have for better outputs that are not jeopardizing good plant health without incurring additional costs and it would be based on soil testing knowledge and exploitation of the RSM technique that haven't been applied in the area. It would be the first experiment to use a combination of the three specific factors of interest, the three responses of interest, the RSM technique and soil testing analysis knowledge simultaneously.

CHAPTER THREE

METHODOLOGY

3.1 Materials and labour

3.1.1 Materials

The materials necessary for the experiments were:

i) French bean seeds	ii) Fertilizers (D.A.P and C.A.N)
iii) Hoes and p*angas*	vi) Water,
v) Spraying chemicals and equipment	vi) Animal manures
vii) Land.	viii) Buckets/cans
ix) Water and weight measuring instruments	x) Tape measure
xi) Books, pens and calculator	xii) Questionnaires

All these materials were obtained from the farmers except study questionnaires and writing materials while water was always drawn from river Irera where the experimental land was located.

3.1.2 Labour provision

French beans farming requires rigorous and quality labour throughout the entire period, from land preparation and planting to harvesting time. Labour was provided regularly as per the experimental procedures and requirements. Specialists in tilling the land, sowing seeds, weeding, watering of crops as well as harvesting and collecting data on factors and responses of interest were hired from the region to ensure they benefited from the project, reduce cost and had the knowledge about the area and were supervised by the researcher to ensure strict observance of the experimental requirements. One Soil analyst, one French beans company staff and three Guards were hired too.

3.2 Response surface methodology and designs

For the sample survey, simple random sampling method was used to select subjects for interview where sample size was predetermined. For the rest of objectives, the appropriate design employed was determined using the analysis of D-, A-, E- and T-optimality criteria on the most commonly employed designs for fitting second order models in optimization process. The D-, A-, E- and T- optimality are the most commonly used optimality criteria according to most researchers, scientists and experimenters because they are easy to compute and reliable in minimizing variances (Pukelsheim, 1993). The most extensively employed designs for fitting 2^{nd} order functions in processes of optimization include:

i)The central composite designs (CCD) ii) The Hoke (D1 to D7) designs

iii) The Box-Behnken designs (BBD) iv) The 3^k factorials designs

According to literature, the most widely employed types of CCD are the face-centred CCD, spherical CCD and rotatable CCD only. For the case of small composite design, Myers et. al (2009) noted that they should not be used because it's estimation and performance in prediction are very low. In general, there are seven designs (face-centred CCD, spherical CCD and rotatable CCD, Hoke D2, Hoke D6, Box-Behnken designs and 3^k factorial designs) widely used and one was selected out of these based on D-, A-, E- and T- optimality criteria for application. The number of runs was determined by the design selected. The RSM technique was used in the whole process to estimate the desired results because it was the only practical technique found that could help the researcher arrive at the desired results and it is now used extensively in cases of optimization as a standard tool in the analysis of data from experiments. Since both spherical and cuboidal regions are important in providing useful information, then the experiments' region of concern was not specified by the researcher.

3.2.1 The response surface methodology (RSM)

RSM is now the standard tool used in the analysis (Dette et. al, 2014) of data obtained from experiments meant to optimize responses of interest. One of the effective ways to solve problems is to conduct experiments. They are used to obtain useful characteristic information about a subject under investigation with an aim of justifying or dismissing a hypothesis/claim. RSM is now being used extensively in cases of optimization, designing of products, developing processes, and partly in modern framework for robust parameter design (Johnson et. al, 2009). The method has been applied in a wide range of experiments in different fields and areas in life and has been proven reliable. The factors are allowed to interact hence the model has interaction terms. For each parameter of interest, the lower and upper bounds are coded as -1 and +1 respectively (Gunawan & Chuin, 2014) for easier fitting of desired models.

The model that describes the relationship is of the form

$$\mathrm{Y} = \mathrm{f}\,(X_1, X_2, X_3, X_4, \ldots) + \varepsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

where Y is the response of interest, $X_1, X_2, \mathrm{X}_3, X_4, \ldots$ are the independent/explanatory variables or the treatments in the experiment and ε is the error in response y, and in this case, it's assumed that $\varepsilon \sim \mathrm{N}\,(0, \sigma^2)$. The model generated to optimize the response is

$$\mathrm{E(Y)} = \mathrm{f}\,(X_1, X_2, \mathrm{X}_3, X_4, \ldots)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

In general, the response is a function of the controllable variables where a second order model is adequate in achieving the objective of maximization or minimization and the model is given by

$$\hat{y} = b_0 + \sum_i b_i X_i + \sum_i b_{ii} X_i^2 + \sum_i \sum_j b_{ij}\, X_i\, X_{j(i<j)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

In these forms of functions/models, the parameters b's are to be approximated as the regression constants. In terms of the factors involved in this research, the model is given by:

$$\hat{y} = b_0 + b_1X_1 + b_1X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \ldots \text{(5)}$$

3.2.2 RSM second order model designs

i) The Central Composite designs (CCD)

These 2nd order models' designs are the widely employed in practices (Myers & Montgomery, 1995; Myer et. al, 2009). Its variations include rotatable and the spherical CCDs, the small composite designs as well as the face-centred cube. There are other forms of CCD but cannot be exhausted. Note that, replication of star points lowers the optimality of *D* and *G* in CCDs (Oyejola & Nwanya, 2015). CCD for k = 2, each at 2 levels (2^k design) is given by Gunawan et. al (2014):

Set of Points	Factor Combinations
Factorials= $2^2 = 4$	(-1, -1), (1, -1), (-1, 1), (1, 1)
Axial= 2*2 = 4	$(-\alpha, 0), (+\alpha, 0), (0, -\alpha), (0, +\alpha)$, where $\alpha = 1.4142 = (2^2)^{¼}$
Centre points	0, 0, …, 0

ii) Box-Behnken designs (BBD)

These can be rotatable or can be almost rotatable designs involving three level incomplete factorials designs (Ferreira et. al, 2007). They are a set of designs with high efficiency and can be likened to most of CCD's points and can replace CCD. They have spherical region. Nevertheless, the designs have need for each factor to have at least three levels. Experimentalists are very familiar with these designs together with the CCDs as noted by Myers et. al (2009).

iii) Hybrid family of designs

These designs are constructed without the aim to satisfy any optimality criteria though they are economical and very efficient. They are designed in such a way that the same degree of orthogonality in CCD and regular polyhedron designs is exhibited in them too: they are near rotatable as well as near minimum point in size as well as enable easy coding (Roquemore, 1976; Myers *et al*., 2009). They haven't been in much application and involve levels that are awkward/messy.

iv) Hoke designs

These are economical designs since they require fewer experiments compared to CCD and BBD. They require 3 or more factors. They are based on partially balanced designs of irregular fractions of 3^k factorial designs (Neifar, Kamoun, Jaouani, Ghorbel & Chaabouni, 2011). In case the region of interest is cuboidal, then these designs are appropriate and they are made from subsets of factor levels -1, 0, and +1. The Hoke D2 and D6 are formed as a result of combinations of factor levels from the following sets: (-1, -1, -1), (1, 1, -1), (1, -1, -1) and (-1, 0, 0) for D2 when there are 3 factors and (-1, -1, -1, -1), 1, 1, 1, -1), (1, 1, -1, -1) and (-1, 0, 0, 0) for D2 when there are 4 factors. They are the most known among the seven of Hoke designs due to their good performance in predicting observations as well as their small variance (Myers et. al, 2009). Hoke D6 is similar to Hoke D2 with the addition of the set of levels (1, 1, 0) for 3 factors and (1, 1, 1, 0) for 4 factors.

v) 3^k factorials designs

These designs have *k* treatments where each treatment has 3 levels. The factorial designs are used when one wants to investigate the effects of factors and their interactions simultaneously on some responses of interest. The types of factorial designs vary depending on the number of factors and the levels of each factor (https://www.2Fnewonlinecourses.science.psu.edu%2Fstat503 ; Myers et. al, 2009). Examples are 2^k, 3^k, …, S^k in which there are k factors at 2 levels, 3 levels up to S levels each respectively. The 3-levels factorial designs are rivals with CCD when the design region is a cube. Design of the study has been identified as a 3-level with 3 factors factorial design. i.e. $3^3 = 27$ design points.

All these are classified as standard designs. In case of non-standard situations, these designs are not applicable. Such situations include: unusual sample size requirements, non-standard blocking conditions, variations from standard models and non-normal distribution of the responses, among others (Johnson et. al, 2009). Note that, exact designs are actually the designs for a specified number of runs (Jacob & Boon, 2007) and all designs are exact designs in practice (XiangFeng, 2007).

vi) Other designs

The other designs are not widely employed such as the equiradial designs, Notz designs, San Cristobal Designs and Koshal designs among others- including hybrid/ Roquemore designs.

Factor combinations for the seven chosen designs are displayed in the appendices 3 and 4.

3.2.3 The optimal designs and the D-, A-, E-, T- optimality criteria

Optimal designs are experimental designs that can be generated on the basis of a specific optimality criterion such as minimum variance, smallest Eigen-value among other criteria. Optimal designs have some advantages over non-optimal/sub-optimal experimental designs such as reduced costs of experimentation due to use of fewer experimental runs, accommodation of multiple types of factors, mixture, and discrete factors and can be used when the design-space is constrained. Optimality is the aspect of minimizing or maximizing something of interest. In the design of experiments, optimality has to do with minimization of variance and/or cost as well as maximizing the precision of estimates. In this case, the optimal design is selected based on D-, A-, E-, T- Optimality criteria. This is because, given some factors and their levels, there are many designs that can be formed out of that. Other criteria used in optimization include: the I-optimality and G-optimality among others (Das, 2002). According to Frank & Todeschint (1994), the design chosen becomes more suitable with increase in D- but with decrease in A- and E-. Let $\boldsymbol{X}$ be the design matrix (n*p model matrix constructed by expanding the design matrix to model form) and $\boldsymbol{X'}\mathbf{X}$ be the information matrix. The matrix M = $(\frac{X'X}{N})$ is called the moment matrix, N is the total number of runs. The N penalizes the designs for the number of runs and ensures that each design is to provide information per run and not as a group of runs. So, it ensures that the information given by each matrix is an average. The moment matrix determines the estimated response surface statistical properties.

According to Pukelsheim (1993),

D-optimal, ϕ_0(C) refers to determinant criterion = (det (C))$^{1/p}$ …………………... (6)

A-optimal, ϕ_{-1}(C) refers to average-variance criterion = $(\frac{1}{p}$*trace $(C)^{-1})^{-1}$……… (7)

E-optimal, $\phi_{-\infty}$(C) refers to smallest-eigenvalue criterion = $\lambda_{\min}(C)$…………… (8)

T-optimal, ϕ_1(C) refers to trace criterion = $\frac{1}{p}$*trace (C)…………….………… (9)

In all these cases, p is the number of parameters, C is the information matrix of the optimal design of interest defined as C = $(K'M^{-}K)^{-1}$; M is the moment matrix and K is the submatrix of parameters of interest while M^{-} is the generalized inverse of moment matrix M.

Note that, some optimizing criteria aim at estimating good parameters of the model while some bring about good prediction in the region of the design (Myers et. al, 2009).

3.2.4 Multiple responses optimizations

In many cases in life and in practice, the researcher is usually interested in several responses and not just one (Myers et. al, 2009). For example, one may be fitting a model that is maximizing crop (say maize) output while interested in investigating the plant height and base diameter based on some factors. In another case, the researcher may want to maximize the weight of an animal as well as the milk it produces while minimizing the time taken to achieve all this based on some inputs. These kinds of investigation require that one builds necessary response surface models for each response separately and then searching for the set of conditions that optimizes all the responses simultaneously or the set of conditions that maintain all the responses within a range of interest (Myers et. al, 2009). One of the techniques for optimizing many responses simultaneously is overlapping the contour plots for each model for the cases where few process factors are involved. The region at which all the responses are seen to be optimized is determined by the parts in which all the responses hover around in the overlaid contour plots. Therefore, the researcher determines the necessary operating conditions that optimizes all the responses concurrently from the plot of overlaid contour plots. However, for more than three factors, the method of overlaying contour plots doesn’t yield the desired results because of the awkwardness of the plotting- the contour plots have two dimensions only.

There are many techniques that can be used in optimizing multiple responses simultaneously. A formal way to achieve this involves formulating as well as solving a problem as a constrained optimization problem such as: minimize y1 subject to 20<y2 and 45>y3 where y2>0 and y3>0 (Myers et. al, 2009). After formulating the inequalities, the non-linear programming methods (numerical techniques) can be applied to find the solution. Note that, the direct search procedure is used by some software such as the Design-Expert in solving these kinds of problems.

3.2.5 The prediction variance

From Myers et. al (2009), the prediction variance (PV) is given by

$$PV(x) = Var[\hat{y}(x)] = \sigma^2 X^{(m)\prime} (X'X)^{-1} X^{(m)} \quad (10)$$

In this case, $X^{(m)}$ is a function of the location in the design variables at which one predicts. Again, it's a function of the model and (m) reflects the model- (m) = 1 for 1st order model. In a case where the number of factors is j, the we have $X^{(1)\prime} = (1, X_1, X_2, \ldots, X_j)$- for first order model, and for three factors with interaction, then

$X^{(1)\prime} = (1, X_1, X_2, X_3, X_1X_2, X_1X_3, X_2X_3, X_1X_2X_3)$. When one wants to compare designs, the scaled prediction variance can be used and is abbreviated as SPV. It's given by the formula:

$SPV(x) = NVar[\hat{y}(x)]/\sigma^2 = N\, X^{(m)\prime}(X'X)^{-1}X^{(m)}$ where the division helps achieve a quantity that's scale free while the reflection of variance based on each observation is achieved through the multiplication by N. For other models of higher orders, m is replaced by the appropriate value.

3.3 Study area

Murang'a is located in the upper midland parts of agro-climate belt. Kandara division/ constituency is located in Murang'a county as an administrative division. Kariua in Kandara is located at an elevation of 1755 m above sea-level. The location's co-ordinates are $0^0$49'60" S and $36^0$58'60" E. The soil type is generally loam (but in particular, andosols, formed from recent volcanic materials) and is suitable for farming/agriculture (Muchena & Gachene, 1988). The climate is also suitable for crops. The soils are suitable not only for horticultural crops, but also for coffee, tea and maize. The form of employment is self, where people rely on their land for food and money to cater for other needs. Figure 2 is the map of Kenya showing the Murang'a county as well as the Kandara sub-county that hosts Kariua sub-location.

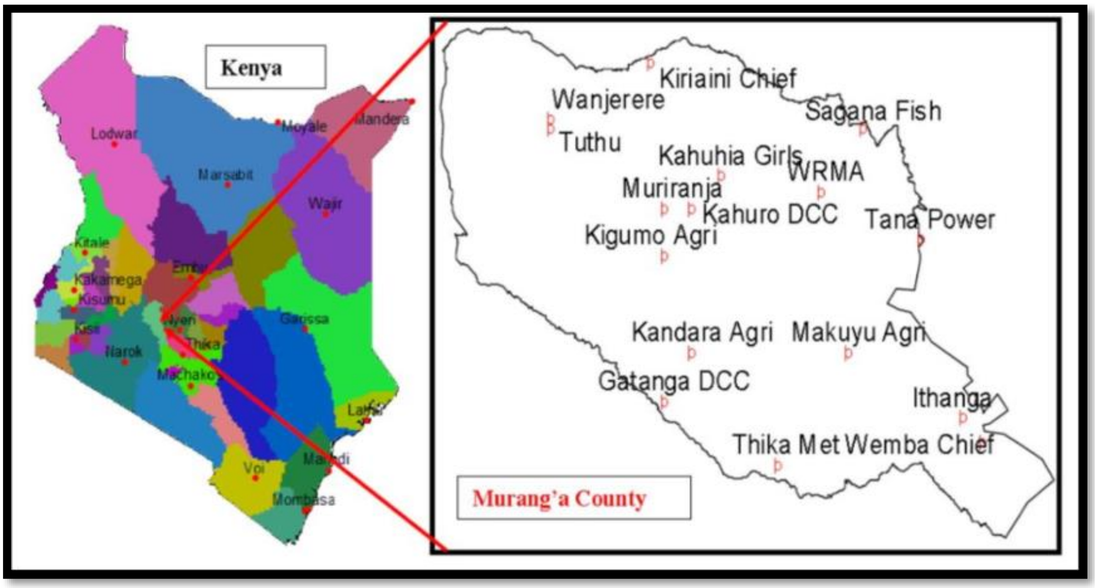


Figure 2: Map of Kenya showing the Kandara area in Murang'a county.

(Source: http://www.information cradle.com)

3.4 Performing the experiments and sample survey

The specific objectives were investigated in the order in which they have been listed in chapter one.

3.4.1 Objective 1- Sample survey

A sample survey was carried out in Kariua region. The Cochran's formula (Cochran, 1963)

$$n = \frac{Z^2{}_{\alpha/2} * P * Q}{d^2} \quad \ldots\ldots\ldots\ldots (11)$$

was employed in computing the sample size. In this research,

α =5% is the level of significance, P = proportion of farmers cultivating French bean crops, Q = 1- P (proportion of farmers not involved in cultivating French bean crops), Z is the value from standard normal distribution statistical table that corresponds to the specified α- value, d = the margin error and n is the sample size or the number of the farmers sampled. The P value was taken to be 0.5 since the actual number of French beans farmers couldn't be determined precisely. The *d* value was fixed to be 0.15 due to unavailability of the farmers in the fields at the time of data collection (from pilot survey experience) and the formula yielded

$$n = \frac{1.96*1.96*0.5*0.5}{0.15^2} = 42.6844 \cong 43 \text{ farmers.}$$

Based on simple random sampling, data were collected from 43 farmers using questionnaires on the input levels (fertilizers, manures, water and spacing of crops), land size under French beans cultivation, the output, the levels of infections of crops and other important information, including the demographic information. Farmers were observed when at work in their fields as well as questioning them on how they carry out the whole process. The exercise took place from the time of land preparation up to harvesting time. At land preparation time, farmers were observed as they dug the land, created furrows and applied manures and D.A.P fertilizers. They were observed at seeds sowing time and during irrigation as well as at C.A.N application and harvesting times.

The fertilizers, manures and water application levels were determined from the amounts applied per furrow and the number of crop points in it. Spacings of the crops were determined from the length of each furrow and the number of crop points in it. These were averaged for several furrows for each farmer. For the responses, each farmer was observed harvesting. For the first two weeks, each harvest from each furrow was measured and averaged for the crop points in that furrow. The average of several furrows for the two weeks was the 1st response. The furrows of choice were determined using the lottery method when harvesting time came, and the same were observed till the end of the exercise and were considered for all responses. The number of infected leaves and the number of unharvested pods were determined immediately after the 2-week harvesting. The average number of infected leaves and number of immature pods for each crop point were the 2nd and 3rd responses respectively from each farmer when averaged for several furrows. The two extreme ends of each factor were used as starting point in objective 3.

3.4.2 Objective 2- Selection of design

There are many 2^{nd} order model designs for optimization, they are based on different criteria and it is good to note that, a design may be optimal in one criterion but fails in another criterion. In this case, appropriate optimal design for second order models was determined based on the D-, A-, E- and T- optimality criteria on the commonly employed designs. This is the most commonly used criteria in optimization for minimizing the variance of prediction. The commonly used designs considered in this experiment were Face-Centred CCD, Spherical CCD, Rotatable CCD, Hoke D2, Hoke D6, Box-Behnken design and 3^k Factorial design and they are presented in table form in the appendices 3 and 4.

The optimal design employed was chosen accordingly with the help of a computer software (R). Design matrices were generated and were fed into Ms-Excel and imported to R. For each design, the design matrix **X** involving all the factors and interactions as well as augmented with additional factor denoted as X_0 for estimating the intercept was created. The design matrix **X** for each of the seven designs was constructed using the standard way of listing the factor levels. The 5 centre points used to augment the designs were chosen based on the lottery method employed in simple random sampling. According to Myers et. al (2009), number of centre points should be between 3 and 5, and hence through lottery, 5 was chosen. The **X** matrix was of the form

$$\mathbf{X} = (X_0, X_1, X_2, X_3, X_1^2, X_2^2, X_3^2, X_1X_2, X_1X_3, X_2X_3) \ldots\ldots (12)$$

where X_0 is a column of units while the rest of X_i's and X_iX_j's are factor levels, and X_1X_2, X_1X_3, X_2X_3 are represented as X_{12}, X_{13}, X_{23} (as interaction terms) respectively in the matrices. From this matrix, the information matrix of the design was constructed as $X'X$, which makes it become a square matrix. The moment matrix M of the design and the information matrix C for the optimal design were obtained, in which, K was the identity matrix representing the sub-system matrix of the parameters of interest. This means that the matrix $C = M$.

Each of the seven designs mentioned here, in form of C, was subjected to all the criteria, one criterion at a time. That's to say, determinant, trace, average variance and Eigen-value were computed for each matrix C according to Pukelsheim (1993). The value and score of every design in each criterion was noted- meaning that, the scores were ranked for all the designs. Then the smallest value for each criterion was ranked 1 while the largest was ranked 7. Then, the ranks for each design were averaged. In the end, the design with the least average rank-score was the design employed. This ensured that the design chosen averaged the optimality of all criteria.

3.4.3 Objective 3- Performing the experiments

This objective was achieved in a procedural manner. The factor levels from objective 1 were the starting point for this objective. The soil analyst performed the soil testing analysis and provided the judgement on applications of fertilizers (D.A.P and C.A.N) to be between 2 dg and 3 dg per crop point for both types. Standard pieces of land (each measuring 6m*5m = 30 m^2) were thoroughly prepared by digging, weeding, mixing up the soils, creating crop-points in form of furrows and applying the manures. Manure was buried in soil for one week and watered once before the seeds could be sown to facilitate decomposition. D.A.P fertilizer was then applied and two seeds of Gregor variety were sown per crop point. Then, two experiments were run concurrently using (i) fertilizers were applied according to what farmers do for untested soils' case and according to soil analyst's recommendations for tested soils' case. D.A.P amount was $\frac{(3+8.3)}{2} = 5.65$ dg per crop point while C.A.N amount was $\frac{(2.1+3.2)}{2} = 2.65$ dg per crop point for the untested soils' case. (ii) This research applied the average of the two levels, $\frac{(2+3)}{2} = 2.5$ dg, for both D.A.P and C.A.N per crop point for the tested soils' case as was recommended by the soil analyst.

For both untested and tested soils, the following coding was used: $\frac{Factor-(High+Low)/2}{(High-Low)/2}$ and this yielded: $\frac{Manure-24.4}{6.4}$, $\frac{Water-4.4}{1.3}$, $\frac{Spacing-10.2}{3.4}$

The factor combinations were allotted at random. For both tested and untested soils, the experiment for each factor combination levels was replicated thirty (30) times in its own row at each stage for reliable results to be obtained. In turn, each set of experiments was replicated three (3) times in different pieces of land.

Watering/irrigating the seeds and plants was done as the farmers do- once in two days and in the evenings. Spraying was done as recommended by the companies to protect the crops from pests and diseases as was done to other farmers' crops. C.A.N was applied twice- once at three-leaf stage of the plant and once at the onset of flowering as topdressing for both cases. After 54 days from planting, harvesting was done once in three days for 2 weeks. The unwanted pods were separated from the acceptable pods by an expert from the French beans company before the mass of the pods could be determined. Yield or output (y_1) was the average of the four harvestings per crop point for each level combination of factors for the three replicates. The number of immature/unharvested pods (y_2) that remained after the 2-week harvestings were recorded too, together with the number of the infected leaves (y_3). The total mass of all the pods per crop point was determined as an average of all the replicates after the two weeks of harvesting in order to use the data in fitting first models for construction of paths of steepest ascent. After the first set of experiments, the quadratic models of the form $\hat{y} = b_0 + \sum_i b_i X_i + \sum_i b_{ii} X_i^2 + \sum_i \sum_j b_{ij} X_i X_{j(i<j)}$ were significant at (5%) level of significance for both tested and untested soils' cases- curvatures were significant and this means that the researcher was already in the region of interest. Data analysis for the responses of interest was then performed, second order models fitted and optimal factor levels determined- for both tested and untested soils' cases.

3.4.4 Objective 4- Comparison of results

The optimal levels of factors obtained in objective 3 were applied to more experiments using replicates to provide optimal outputs and crop infection levels. New pieces of land were prepared as was described in objective 3. Each furrow had 43 crop points, and each was replicated 3 times. After harvesting and collecting all the necessary data, the optimal outputs for the two sets of models were compared using t-test as well as the infections to help determine the better set of models. Again, t-test was used to confirm whether the theoretical and optimal responses would be in agreement. Then, the two sets of results were in turn compared, using ANOVA, with that of sample survey to determine whether or not the farmers should employ the new knowledge. Finally, investigation of the performance of each response at each factor level was done at optimal levels of the rest of the factors. In this case, each factor was fixed at levels -1, 0 and +1 while the rest of factors were optimal and the responses investigated to see how they behave at different levels of factors. This was done for all the factors for the two cases.

3.5 Assumptions

In the whole process of the research, the following assumptions were necessary:

1. Farmers provided accurate and reliable information during sample survey exercise.
2. Soils are homogeneous in the entire region and hence no need for blocking.
3. The sunshine and weather in general remained constant or ever occurred as a pattern.
4. All the data were normally distributed with insignificant errors in measurements.
5. Factors of interest were applied in accuracy throughout as per the experimental requirements.
6. Infected leaves were enough in determining the crops' health.
7. All the pods considered were suitable for export and consumption purposes.
8. The crops' output is directly proportional to the crops' health (output is inversely proportional to levels of infection).

3.6 Data analysis

Both statistical and computer software were used in the whole process of data management: starting from data entry, cleaning, coding, analysis and report writing. The descriptive as well as the inferential statistics were generated in R and Ms-Excel and modified accordingly. The RSM package was installed from R and used in generating response surface and contour plots, fitting of models and locating the optimal points while Design Expert was used in developing overlay contours for objective 3. In objective 1, Descriptive analysis was done using contingency tables, bar charts and graphs like normal curves and histograms while the inferential statistics was achieved using t-tests, Wilcoxon tests, ANOVA, Kruskal- Wallis tests, proportion tests and regressions. In objective 2, analysis was done in R by computing information and moment matrices, determinants, Eigen-values, traces and average variances and then in Ms-Excel for comparisons. For objective 4, R was used to perform t-tests and ANOVA as well as the further tests.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Objective 1- Sample survey

The sample survey data was coded where necessary and entered in Ms-Excel. The data was cleaned and imported to R for analysis.

4.1.1 Descriptive summaries

In descriptive statistics, most of the analysis made use of histograms because most of the data was quantitative or numerical in nature.

Table 1 gives the summaries of categorical variables for the demographic information. From Table 1, most of the farmers sampled were males (56%), while female farmers were 44%. Cows provide manure to almost all the farmers in the region (95.3%). Most of the farmers irrigate their crops thrice in a week (79.1%) while only 20.9% of the sampled farmers water crops four times per week. A higher proportion, 93%, of the crops in farmers' fields are infected with diseases. Families with eight members have the highest percentage, 18.6%, while those with 9 members have the least percentage, 4.7%. No family was found to have a single member.

Table 2 shows the summaries of the numerical variables studied during the sample survey exercise. From Table 2, the mean and median values of all the variables are close to each other. The standard deviations for the D.A.P, C.A.N and water are very small and hence there is no big variation in their data while the rest of the variables have large standard deviations indicating big variations in their data. The C.A.N applied and land size under French beans farming have the smallest and largest deviations respectively.

Table 1: Summary of the demographic variables.

Variable, n=43	Categories	Frequency	Percent (%)
Gender	Male	24	56.0
	Female	19	44.0
Manure Source	Cows	41	95.3
	Goats/Sheep	2	4.7
Watered Times	Three	34	79.1
	Four	9	20.9
Infected Leaves	No	3	7.0
	Yes	40	93.0

Family Size	Two	Three	Four	Five	Six	Seven	Eight	Nine
Percent (%)	16.3	9.3	16.3	14.0	9.3	11.6	18.6	4.7

Table 2: Summary on the study numerical variables.

Variable, n=43	Min	Q_1	Median	Mean	Q_3	Max	Std. Dev.
Manure (g)	18	21.75	24.7	24.690	27.6	30.8	3.6210
Spacing (cm)	6.8	8.55	9.2	9.809	11.4	13.6	1.9930
Yield (g)	7.3	9.20	9.9	9.960	10.85	13.4	1.2236
Pods (counts)	8	10	12	11.580	13	15	1.8288
D.A.P (dg)	3.0	4.10	4.7	4.747	5.2	8.3	0.9838
C.A.N (dg)	2.1	2.3	2.5	2.491	2.7	3.2	0.2486
Water (ℓ)	3.1	3.75	4.4	4.381	5.05	5.7	0.8293
Age (years)	19	24	29	29.370	34.5	44	6.8800
Land Size (m^2)	43.3	61.4	81.8	79.8	91.4	116	19.6743

Figure 3 shows that majority of French bean farmers in the area have families of 8 members in total- about 18%. This is closely followed by the families with 2 and 4 members- about 16% for each. No family was found to have a single member. It can be concluded that, families get involved in this kind of farming; probably for sustaining the families.

Table 3 shows the levels of crop infection in the region studied. From Table 3, most of the crops in the field, 23%, have 6 leaves that have infections on average. Those without any blemish are 7%, which is the case with those having 3, 4 and 5 blemished leaves. No crops on average were found having more than 8 abnormal leaves.

Table 3: Level of crop infection.

No. of leaves	0	1	2	3	4	5	6	7	8
Frequency	(7%)	(16%)	(2%)	(7%)	(7%)	(7%)	(23%)	(12%)	(19%)

Figure 3 shows the histogram of the farmers' yields on average.

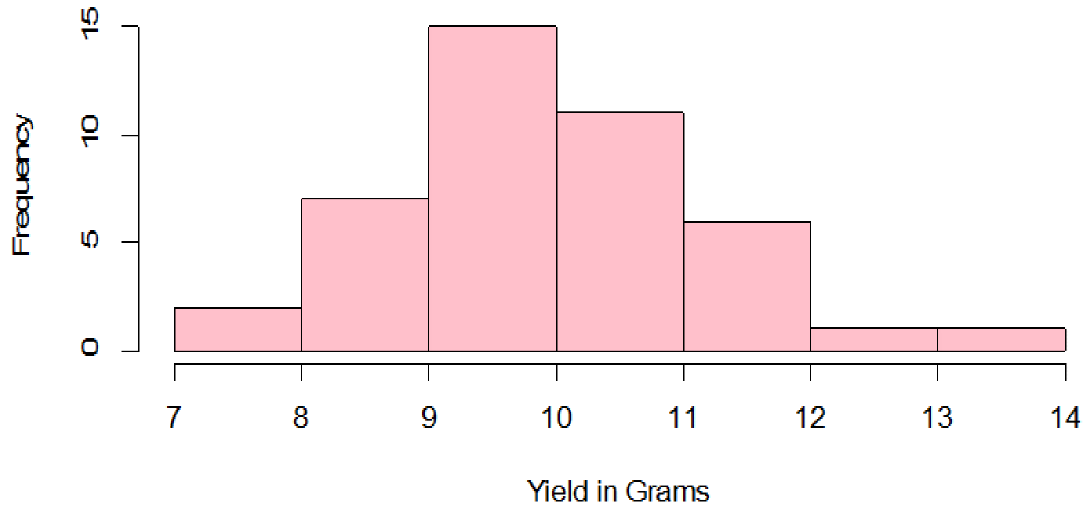


Figure 3: Mass of French beans harvested by farmers on average.

The histogram in Figure 3, assumes the shape of Gaussian distribution. It suggests that our yield data can be assumed to be normally distributed. The figure also shows that the mode lies between 9 g and 10 g. But from Table 2, it had been observed that the mean and median are 9.96 g and 9.9 g respectively. These three figures show that the three determinants of central tendency are nearly the same and hence the data can be assumed to be normally distributed. The same histogram also indicates that, those farmers who harvest less than 8 g and more than 12 g are very few, while no one obtains less than 7 or more than 14 g per crop point. In short, most French bean farmers in Kariua region harvest approximately between 8 and 12 g.

Figure 4 shows the normal curve of the unharvested pods from the farmers' farms. From Figure 4, the pods data is normally distributed and hence, the parametric methods can be used in the analysis.

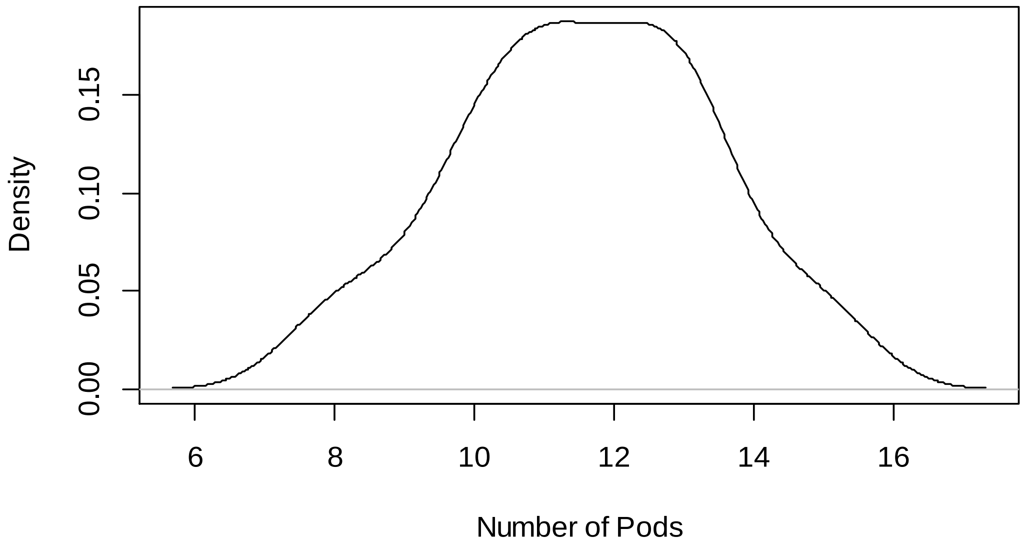


Figure 4: Immature pods' normal curve.

Table 4 gives the distribution of gender in percentage across the family sizes. From Table 4, one can observe that most of the female French bean farmers have families of 4 members, which is actually 21.1% of the total female farmers from the sample. No female farmer has family of size 9 members. On the other hand, majority of the male French beans farmers have 8 members, 20.8%. Only 8.3% of the male farmers have families of sizes 9 members while 4.2% have 3 family members. No farmer in general has a family with more than 9 members.

Table 4: Distribution of family size across gender.

	Family Size							
Gender	2	3	4	5	6	7	8	9
Female	(15.8%)	(15.8%)	(21.1%)	(15.8%)	(10.5%)	(5.3%)	(15.8%)	(0.0%)
Male	(16.7%)	(4.2%)	(12.5%)	(12.5%)	(8.30%)	(16.7%)	(20.8%)	(8.3%)

4.1.2 Inferential Statistics

In this part of statistics, most of the testing were based on regressions to help determine if there is any relationship among qualitative data variables. All the tests in this research were carried out using α =5% as level of significance.

(a) Tests on Proportions

Table 5 shows the output of tests on equality of proportions of the binary variables. From Table 5, the p-value= 0.5419 is greater than α= 0.05 level of significance and hence the male and female farmers' proportions are equal in the region statistically. The rest of the variables have p-values less than the level of significance and hence their proportions are different. Conclusion is that cows provide manures to most of the farmers, those irrigating crops thrice are more than those irrigating four times in a week while most of crops are unhealthy in the fields.

Table 5: Test on equality of proportions.

Variable	Chi-Square	df	p-value	95% C. I
Gender	0.3721	1	0.5419	[0.2941, 0.5999]
Manure Source	33.5810	1	0.0000	[0.8294, 0.9919]
Times Watered	13.3950	1	0.0003	[0.6352, 0.8942]
Presence of Infection	30.1400	1	0.0000	[0.0182, 0.2012]

(b) Tests on relationships (Regressions)

Table 6 is a summary of the multiple linear regression model between yield and selected variables.

Table 6: Table showing the multiple regressions on yield.

	Estimates	Std. Errors	t-values	p-values
Intercept	5.4799	3.5757	1.5330	0.1350
Age (years)	0.0160	0.0307	0.5220	0.6050
Family Size	0.0069	0.0932	0.0740	0.9420
Land Size (m^2)	-0.0093	0.0110	-0.8410	0.4060
D.A.P (dg)	0.1953	0.2145	0.9100	0.3690
C.A.N(dg)	0.8178	0.8188	0.9990	0.3250
Manure Amount (g)	0.0847	0.0570	1.4870	0.1460
Water Amount (ℓ)	-0.0664	0.2458	-0.2700	0.7890
Spacing (cm)	-0.0050	0.1123	-0.0450	0.9650
Multiple R^2= 0.1255		**Adj. R^2** = 0.0803		
F-value= 0.6097,		**DF**= (8,34),	**p-value**= 0.7633	

From Table 6, all the variables influence the yield insignificantly because there is no p-value in the last column that is less than the 5% level of significance. Therefore, there is no significant relationship between the yield and selected variables. The multiple R^2 and adjusted R^2 are too small to explain the yield. The overall p-value= 0.7633 is greater than the 5% level of significance and hence the model doesn't fit the data well; there is no goodness of fit.

For the case of regression between the number of unharvested pods and selected variables, Poisson log-linear model (multiple regression) was fitted since the pods are just counts that are assumed to follow Poisson distribution. Table 7 shows the output from the multiple regression for the Poisson log-linear model.

From the output in Table 7, it can be seen that all the p-values, except for intercepts, are greater than the 5% level of significance and hence, the independent variables in the model (age, family size, land size, D.A.P, C.A.N, manure, water and spacing applied) are not significant in predicting the number of immature pods from the crops. This means that, the relationship between the number of pods and the selected variables is not significant. From the corresponding fitted model, it can be noted that, the log of the mean number of pods decreases with increase in all the variables except with family size, land size, spacing and C.A.N amounts.

Table 7: Table showing Poisson log-linear model on number of pods.

Variable	Estimate	Std. Error	z value	p-value
Intercept	2.6823	0.8180	3.2790	0.0010
Age (years)	-0.0054	0.0072	-0.7490	0.4541
Family Size	0.0139	0.0215	0.6450	0.5187
Land Size (m^2)	0.0002	0.0025	0.0970	0.9225
D.A.P (dg)	-0.0281	0.0502	-0.5600	0.5754
C.A.N (dg)	0.0721	0.1863	0.3870	0.6987
Manure (g)	-0.0048	0.0131	-0.3640	0.7158
Water (ℓ)	-0.0390	0.0568	-0.6860	0.4926
Spacing (cm)	0.0074	0.0257	0.2900	0.7718

$\log(\mu)$ = 2.6823- 0.0054*Age+ 0.0139*FamilySize+ 0.0002*LandSize- 0.0281*D.A.P+ 0.0721*C.A.N- 0.0048*ManureAmount- 0.0390*WaterAmount+ 0.0074*Spacing

(c) T-tests on means of responses and factors

In this section of t-tests, yield and spacing variables have been analysed since the data for the two variables are approximately normally distributed. Table 8 gives the results of t-tests on yield and pods across gender and number of times crops are watered. From Table 8, all the p-values are greater than 0.05 level of significance except for the case of the number of times of watering the beans in yield response (p-value= 0.0017 < α = 0.05). This means that the mean yield for the farmers who irrigate their crops thrice in a week (10.2324) is higher than that of farmers who irrigate four times in a week (8.9333). Therefore, the two categories of the selected variables produce the same output of French beans (whether in form of yield or unharvested pods) except for the number of times the crops are watered for the response yield.

Table 8: T-tests on mean responses across categories of selected variables.

Responses	Categorical Variables	t-values	p-values	95% C. I
Yield (g)	Gender	0.8192	0.4175	[-0.4356, 1.0299]
	Watered Times	3.7226	0.0017	[-2.0359, -0.5621]
Unharvested Pods(count)	Gender	0.3264	0.7458	[-0.9567, 1.3251]
	Watered Times	0.7584	0.4624	[-0.9866, 2.0454]

(d) The Wilcoxon-Rank-Sum tests

This section of tests deals with variables that are not approximately normally distributed. The variables include age of farmers, D.A.P, C.A.N, Manure, Spacing, Land size and Water applications. The Wilcoxon-Rank-Sum tests have been used since the samples are not paired but independent. Table 9 has the output from Wilcoxon Rank Sum tests.

Table 9: Table showing non-parametric test Wilcoxon on variables across gender.

Variables Vs Gender	w-value	p-value
Age (years)	189.0	0.3453
Land Size (m^2)	221.0	0.8750
D.A.P (dg)	204.0	0.5649
C.A.N (dg)	281.0	0.1946
Manure (g)	238.0	0.8163
Crop Spacing (cm)	242.0	0.7411
Watered (ℓ)	208.5	0.6417

Table 10: Output of the non-parametric tests, Kruskal Wallis.

Numerical Variable	Categorical Variable	Chi-Squared Value	df	p-value
Land Size (m^2)	Family Size	4.4517	7	0.7265
	Infected Leaves	10.983	8	0.2027
D.A.P (dg)	Family Size	13.084	7	0.0701
	Infected Leaves	10.463	8	0.2340
C.A.N(dg)	Family Size	4.3296	7	0.7411
	Infected Leaves	4.8649	8	0.7719
Manure (g)	Family Size	9.0936	7	0.2460
	Infected Leaves	12.126	8	0.1457
Spacing (cm)	Family Size	12.507	7	0.0851
	Infected Leaves	4.909	8	0.7673
Water (ℓ)	Family Size	13.011	7	0.0719
	Infected Leaves	9.602	8	0.2941

From Table 9, all the p-values are greater than 0.05 level of significance. This indicates that, age of farmers is the same across gender, land size under French beans cultivation is the same across gender, D.A.P, C.A.N, Manure and Water amount for irrigation applied as well as crop spacing are the same for both male and female farmers.

Table 10 shows the Kruskal Wallis tests on non-normal variables. From table 10, it can be seen that, performing the Kruskal-Wallis tests on Land size, D.A.P, C.A.N, Manure, Spacing and Water across the categories of family size and infected leaves yields the same results that all are the same across the categories.

(e) The analysis of variances (ANOVA)

In this section, the Analysis of Variances (ANOVA) was performed on approximately normally distributed variables. These are Yield and Crop Spacing variables. Table 11 gives the ANOVA results.

Table 11: The ANOVA tables in summary.

Response	**Categorical Variables**	**df**	**Sum of Squares**	**F-value**	**p-value**
Yield (g)	Family Size	(1,41)	0.30	0.1930	0.6620
	Infected Leaves	(1,41)	5.53	3.9570	0.0534
Unharvested	Family Size	(1,41)	5.52	1.6770	0.2030
Pods(cpunt)	Infected Leaves	(1,41)	7.87	2.4320	0.1270

From Table 11, it is clear that all the p-values are greater than the level of significance and hence, the means of yield and number of unharvested pods are the same across all the categories of the selected variables.

4.1.3 Discussion of sample survey data analysis and exercise

From the analysis, it is clear that in all tests, the mean yield is different across the number-of-times the farmers irrigate their crops per week. Those who irrigate their beans four times in a week had lower mean yield compared to those who irrigate thrice per week. That means, increase in water for irrigation lowers yield probably due to water logging. Also, the proportion of crops infected is greater than that of uninfected crops, based on presence or absence of abnormal leaves, hence more crops are infected in the area. Moreover, cows provide manure to most of the farmers at Kariua area. It is evident that no input can be used to predict yield in Kariua area as was seen from the regression analysis. Even spacing, that affects the crops' yield, has no relationship with yields and infections.

During the data collection exercise, a large number of intercrops was evident in the region as well as very small pieces of land, as shown in the photographs in the appendices taken during the exercise. This is supported by the statistics on spacing of the crops in which the average spacing is 9.809 cm. This spacing is far below the recommended spacing of 15 cm. Although this can be termed as poor farming techniques due to poor spacing and intercropping, the reality at the ground level cannot accept anything contrary. Therefore, the results from the sample survey indicate that, there is poor spacing of crops, presence of diseases/infections, intercropping, too much water for crops and limited resources like land. It was observed that, the minimum and maximum levels of water, manure, spacing, D.A.P and C.A.N fertilizers applied levels are as shown in Table 2. The pods were subjected to strict selection of unwanted ones from the suitable ones to ensure that only the best was considered for mass recording. This revealed that most of the output from the farmers was rejected due to unsuitability for export. The current levels of responses on yields and infections can also be found in Table 2.

It can be noted that, the recommended input levels of the factors depend on some factors such as fertility of the soils, varieties of the French beans involved, climatic conditions and so on (https://www.2Fipm.illinois.edu%2Fdiseases). This means that, soil analysis is required before application of the commercial fertilizers and organic manures.

The data from the sample survey is attached in this report as appendix 2 for reference. The current situation that farmers are experiencing in their fields can be seen in the images displayed in appendix 7.

4.2 Objective 2- Selection of design

The arrangements of the seven designs considered in this research are shown in the appendices 3 and 4.

4.2.1 Information matrices for the designs of interest

The following are the information matrices for each of the seven designs after rounding off each value to 4 decimal places and each design has been augmented with the centre points. The interaction factors given by X_{12}, X_{13}, X_{23} represent the interactions X_1X_2, X_1X_3, X_2X_3 respectively in all the matrices below.

Information Matrix for Box-Behnken Design

$$\begin{bmatrix} & X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \\ X_0 & 17 & 0 & 0 & 0 & 8 & 8 & 8 & 0 & 0 & 0 \\ X_1 & 0 & 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_2 & 0 & 0 & 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_3 & 0 & 0 & 0 & 8 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_1^2 & 8 & 0 & 0 & 0 & 8 & 4 & 4 & 0 & 0 & 0 \\ X_2^2 & 8 & 0 & 0 & 0 & 4 & 8 & 4 & 0 & 0 & 0 \\ X_3^2 & 8 & 0 & 0 & 0 & 4 & 4 & 8 & 0 & 0 & 0 \\ X_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 \\ X_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4 & 0 \\ X_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4 \end{bmatrix}$$

Information Matrix for CCD- Face Centred Design

	X_0	X_1	X_2	X_3	X_1^2	X_2^2	X_3^2	X_{12}	X_{13}	X_{23}
X_0	19	0	0	0	10	10	10	0	0	0
X_1	0	10	0	0	0	0	0	0	0	0
X_2	0	0	10	0	0	0	0	0	0	0
X_3	0	0	0	10	0	0	0	0	0	0
X_1^2	10	0	0	0	10	8	8	0	0	0
X_2^2	10	0	0	0	8	10	8	0	0	0
X_3^2	10	0	0	0	8	8	10	0	0	0
X_{12}	0	0	0	0	0	0	0	8	0	0
X_{13}	0	0	0	0	0	0	0	0	8	0
X_{23}	0	0	0	0	0	0	0	0	0	8

Information Matrix for CCD- Rotatable Design

	X_0	X_1	X_2	X_3	X_1^2	X_2^2	X_3^2	X_{12}	X_{13}	X_{23}
X_0	19	0	0	0	13.6448	13.6448	13.6448	0	0	0
X_1	0	13.6448	0	0	0	0	0	0	0	0
X_2	0	0	13.6448	0	0	0	0	0	0	0
X_3	0	0	0	13.64480	0	0	0	0	0	0
X_1^2	13.6448	0	0	0	23.9319	8	8	0	0	0
X_2^2	13.6448	0	0	0	8	23.9319	8	0	0	0
X_3^2	13.6448	0	0	0	8	8	23.9319	0	0	0
X_{12}	0	0	0	0	0	0	0	8	0	0
X_{13}	0	0	0	0	0	0	0	0	8	0
X_{23}	0	0	0	0	0	0	0	0	0	8

Information Matrix for CCD- Spherical Design

	X_0	X_1	X_2	X_3	X_1^2	X_2^2	X_3^2	X_{12}	X_{13}	X_{23}
X_0	19	0	0	0	13.9858	13.9858	13.9858	0	0	0
X_1	0	13.9858	0	0	0	0	0	0	0	0
X_2	0	0	13.9858	0	0	0	0	0	0	0
X_3	0	0	0	13.9858	0	0	0	0	0	0
X_1^2	13.9858	0	0	0	25.9149	8	8	0	0	0
X_2^2	13.9858	0	0	0	8	25.9149	8	0	0	0
X_3^2	13.9858	0	0	0	8	8	25.9149	0	0	0
X_{12}	0	0	0	0	0	0	0	8	0	0
X_{13}	0	0	0	0	0	0	0	0	8	0
X_{23}	0	0	0	0	0	0	0	0	0	8

Information Matrix for 3^K Factorial Design

	X_0	X_1	X_2	X_3	X_1^2	X_2^2	X_3^2	X_{12}	X_{13}	X_{23}
X_0	32	0	0	0	18	18	18	0	0	0
X_1	0	18	0	0	0	0	0	0	0	0
X_2	0	0	18	0	0	0	0	0	0	0
X_3	0	0	0	18	0	0	0	0	0	0
X_1^2	18	0	0	0	18	12	12	0	0	0
X_2^2	18	0	0	0	12	18	12	0	0	0
X_3^2	18	0	0	0	12	12	18	0	0	0
X_{12}	0	0	0	0	0	0	0	12	0	0
X_{13}	0	0	0	0	0	0	0	0	12	0
X_{23}	0	0	0	0	0	0	0	0	0	12

Information Matrix for Hoke D2 Design

$$\begin{array}{cc} & \begin{matrix} X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \end{matrix} \\ \begin{matrix} X_0 \\ X_1 \\ X_2 \\ X_3 \\ X_1^2 \\ X_2^2 \\ X_3^2 \\ X_{12} \\ X_{13} \\ X_{23} \end{matrix} & \begin{bmatrix} 15 & -2 & -2 & -2 & 8 & 8 & 8 & -1 & -1 & -1 \\ -2 & 8 & -1 & -1 & -2 & -1 & -1 & -1 & -1 & -1 \\ -2 & -1 & 8 & -1 & -1 & -2 & -1 & -1 & -1 & -1 \\ -2 & -1 & -1 & 8 & -1 & -1 & -2 & -1 & -1 & -1 \\ 8 & -2 & -1 & -1 & 8 & 7 & 7 & -1 & -1 & -1 \\ 8 & -1 & -2 & -1 & 7 & 8 & 7 & -1 & -1 & -1 \\ 8 & -1 & -1 & -2 & 7 & 7 & 8 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 & -1 & -1 & 7 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 7 & -1 \\ -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 7 \end{bmatrix} \end{array}$$

Information Matrix for Hoke D6 Design

$$\begin{array}{cc} & \begin{matrix} X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \end{matrix} \\ \begin{matrix} X_0 \\ X_1 \\ X_2 \\ X_3 \\ X_1^2 \\ X_2^2 \\ X_3^2 \\ X_{12} \\ X_{13} \\ X_{23} \end{matrix} & \begin{bmatrix} 18 & 0 & 0 & 0 & 10 & 10 & 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 & 0 & -1 & 0 & 0 \\ 10 & 0 & 0 & 0 & 10 & 8 & 8 & 0 & 0 & -1 \\ 10 & 0 & 0 & 0 & 8 & 10 & 8 & 0 & -1 & 0 \\ 10 & 0 & 0 & 0 & 8 & 8 & 10 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & -1 & 8 & -1 & -1 \\ 0 & 0 & -1 & 0 & 0 & -1 & 0 & -1 & 8 & -1 \\ 0 & -1 & 0 & 0 & -1 & 0 & 0 & -1 & -1 & 8 \end{bmatrix} \end{array}$$

The information matrices for the optimal designs were computed according to Pukelsheim (1993) definitions where C = $(K'M^{-}K)^{-1}$, M = $(\frac{X'X}{N})$. M^{-} is the generalized inverse of the moment matrix *M*. *K* is the sub-system matrix containing only the parameters of interest. In this research, all of the 10 parameters in the second order model are of interest and therefore, $K = Ip$, which means K becomes identity matrix.

$$K = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Substituting K and M in C = $(K'M^{-}K)^{-1}$ yields the $C = M$ hence our information matrix C of the optimal design is the same as the moment matrix M. Alternatively, C can be computed as follows: $C = LM^{-}L'$ where L is the left inverse of matrix K. Since K is an identity matrix for this case, then L is identity matrix too. The two cases yield $C = M$.

4.2.2 Information matrices for the optimal designs of interest

The information matrices, C's, for the seven designs (optimal designs) are shown below, after rounding each matrix off to 4 decimal places.

Information Matrix for Optimal Box-Behnken Design

$$\frac{1}{17}\begin{bmatrix} & X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \\ X_0 & 17 & 0 & 0 & 0 & 8 & 8 & 8 & 0 & 0 & 0 \\ X_1 & 0 & 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_2 & 0 & 0 & 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_3 & 0 & 0 & 0 & 8 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_1^2 & 8 & 0 & 0 & 0 & 8 & 4 & 4 & 0 & 0 & 0 \\ X_2^2 & 8 & 0 & 0 & 0 & 4 & 8 & 4 & 0 & 0 & 0 \\ X_3^2 & 8 & 0 & 0 & 0 & 4 & 4 & 8 & 0 & 0 & 0 \\ X_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 \\ X_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4 & 0 \\ X_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4 \end{bmatrix}$$

Information Matrix for Optimal CCD- Face Centred Design

$$\frac{1}{19}\begin{array}{cc}
 & \begin{matrix} X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \end{matrix} \\
\begin{matrix} X_0 \\ X_1 \\ X_2 \\ X_3 \\ X_1^2 \\ X_2^2 \\ X_3^2 \\ X_{12} \\ X_{13} \\ X_{23} \end{matrix} &
\begin{bmatrix}
19 & 0 & 0 & 0 & 10 & 10 & 10 & 0 & 0 & 0 \\
0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 \\
10 & 0 & 0 & 0 & 10 & 8 & 8 & 0 & 0 & 0 \\
10 & 0 & 0 & 0 & 8 & 10 & 8 & 0 & 0 & 0 \\
10 & 0 & 0 & 0 & 8 & 8 & 10 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8
\end{bmatrix}
\end{array}$$

Information Matrix for Optimal CCD- Rotatable Design

$$\frac{1}{19}\begin{array}{cc}
 & \begin{matrix} X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \end{matrix} \\
\begin{matrix} X_0 \\ X_1 \\ X_2 \\ X_3 \\ X_1^2 \\ X_2^2 \\ X_3^2 \\ X_{12} \\ X_{13} \\ X_{23} \end{matrix} &
\begin{bmatrix}
19 & 0 & 0 & 0 & 13.6448 & 13.6448 & 13.6448 & 0 & 0 & 0 \\
0 & 13.6448 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 13.6448 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 13.64480 & 0 & 0 & 0 & 0 & 0 & 0 \\
13.6448 & 0 & 0 & 0 & 23.9319 & 8 & 8 & 0 & 0 & 0 \\
13.6448 & 0 & 0 & 0 & 8 & 23.9319 & 8 & 0 & 0 & 0 \\
13.6448 & 0 & 0 & 0 & 8 & 8 & 23.9319 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8
\end{bmatrix}
\end{array}$$

Information Matrix for Optimal CCD- Spherical Design

$$
\begin{array}{c|cccccccccc}
 & X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \\
\hline
X_0 & 19 & 0 & 0 & 0 & 13.9858 & 13.9858 & 13.9858 & 0 & 0 & 0 \\
X_1 & 0 & 13.9858 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
X_2 & 0 & 0 & 13.9858 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
X_3 & 0 & 0 & 0 & 13.9858 & 0 & 0 & 0 & 0 & 0 & 0 \\
X_1^2 & 13.9858 & 0 & 0 & 0 & 25.9149 & 8 & 8 & 0 & 0 & 0 \\
X_2^2 & 13.9858 & 0 & 0 & 0 & 8 & 25.9149 & 8 & 0 & 0 & 0 \\
X_3^2 & 13.9858 & 0 & 0 & 0 & 8 & 8 & 25.9149 & 0 & 0 & 0 \\
X_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & 0 & 0 \\
X_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & 0 \\
X_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8
\end{array}
\times \frac{1}{19}
$$

Information Matrix for Optimal 3^K Factorial Design

$$
\begin{array}{c|cccccccccc}
 & X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \\
\hline
X_0 & 32 & 0 & 0 & 0 & 18 & 18 & 18 & 0 & 0 & 0 \\
X_1 & 0 & 18 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
X_2 & 0 & 0 & 18 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
X_3 & 0 & 0 & 0 & 18 & 0 & 0 & 0 & 0 & 0 & 0 \\
X_1^2 & 18 & 0 & 0 & 0 & 18 & 12 & 12 & 0 & 0 & 0 \\
X_2^2 & 18 & 0 & 0 & 0 & 12 & 18 & 12 & 0 & 0 & 0 \\
X_3^2 & 18 & 0 & 0 & 0 & 12 & 12 & 18 & 0 & 0 & 0 \\
X_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12 & 0 & 0 \\
X_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12 & 0 \\
X_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12
\end{array}
\times \frac{1}{32}
$$

Information Matrix for Optimal Hoke D2 Design

$$\frac{1}{15}\;\begin{array}{cc} & \begin{array}{cccccccccc} X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \end{array} \\ \begin{array}{c} X_0 \\ X_1 \\ X_2 \\ X_3 \\ X_1^2 \\ X_2^2 \\ X_3^2 \\ X_{12} \\ X_{13} \\ X_{23} \end{array} & \begin{bmatrix} 15 & -2 & -2 & -2 & 8 & 8 & 8 & -1 & -1 & -1 \\ -2 & 8 & -1 & -1 & -2 & -1 & -1 & -1 & -1 & -1 \\ -2 & -1 & 8 & -1 & -1 & -2 & -1 & -1 & -1 & -1 \\ -2 & -1 & -1 & 8 & -1 & -1 & -2 & -1 & -1 & -1 \\ 8 & -2 & -1 & -1 & 8 & 7 & 7 & -1 & -1 & -1 \\ 8 & -1 & -2 & -1 & 7 & 8 & 7 & -1 & -1 & -1 \\ 8 & -1 & -1 & -2 & 7 & 7 & 8 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 & -1 & -1 & 7 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 7 & -1 \\ -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 7 \end{bmatrix} \end{array}$$

Information Matrix for Optimal Hoke D6 Design

$$\frac{1}{18}\;\begin{array}{cc} & \begin{array}{cccccccccc} X_0 & X_1 & X_2 & X_3 & X_1^2 & X_2^2 & X_3^2 & X_{12} & X_{13} & X_{23} \end{array} \\ \begin{array}{c} X_0 \\ X_1 \\ X_2 \\ X_3 \\ X_1^2 \\ X_2^2 \\ X_3^2 \\ X_{12} \\ X_{13} \\ X_{23} \end{array} & \begin{bmatrix} 18 & 0 & 0 & 0 & 10 & 10 & 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 & 0 & -1 & 0 & 0 \\ 10 & 0 & 0 & 0 & 10 & 8 & 8 & 0 & 0 & -1 \\ 10 & 0 & 0 & 0 & 8 & 10 & 8 & 0 & -1 & 0 \\ 10 & 0 & 0 & 0 & 8 & 8 & 10 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & -1 & 8 & -1 & -1 \\ 0 & 0 & -1 & 0 & 0 & -1 & 0 & -1 & 8 & -1 \\ 0 & -1 & 0 & 0 & -1 & 0 & 0 & -1 & -1 & 8 \end{bmatrix} \end{array}$$

4.2.3 Analysis of D-, A-, E-, and T- optimality criteria

From the information matrices, C's, the optimality criteria D-, A-, E-, and T- were applied.

Determinant = $(\det(C))^{1/p}$, Average-variance = $(\frac{1}{p}*\text{trace}\,(C)^{-1})^{-1}$, Eigen-value = $\lambda_{\min}\,(C)$ and Trace = $\frac{1}{p}*\text{trace}\,(C)$. Table 14 shows the optimal criteria values to 4 decimal places. Table 12 shows the optimal values, their ranks and averages for the selected designs. From Table 12, the values in brackets are the ranks and these ranks were averaged as shown in the last column. The smallest value in each column is ranked 1 while the largest one is ranked 7. The design with the minimum average is the best design compared to the other six. In this case, Hoke D2 with an average of 1.75 was chosen as the optimal design. This design was applied in the field experiments throughout the entire period of the research. It is the design with the minimum variance and has the least number of runs among the seven designs.

Table 12: The optimality values, ranks & averages for the seven optimal designs.

Design	D-Opt.	A-Opt.	E-Opt.	T-Opt.	AVERAGE
Box-Behnken	0.3403 (2)	0.2887 (4)	0.1550 (4)	0.4529 (1)	2.75
CCD Face Centred	0.3812 (3)	0.2760 (3)	0.1053 (3)	0.5421 (2)	2.75
CCD Rotatable	0.6357 (6)	0.5186 (6)	0.1905 (6)	0.8196 (6)	6.00
CCD Spherical	0.6587 (7)	0.5307 (7)	0.1927 (7)	0.8563 (7)	7.00
3K Factorial	0.4054 (5)	0.3293 (5)	0.1695 (5)	0.5500 (3)	4.50
Hoke D2	***0.3190 (1)***	***0.1700 (1)***	***0.0585 (1)***	***0.5600 (4)***	***1.75***
Hoke D6	0.3878 (4)	0.2723 (2)	0.1032 (2)	0.5667 (5)	3.25

4.3 Objective 3- Performing experiments

4.3.1 Experimental data for the responses of interest

Table 13 and 14 display the data obtained from the untested and tested soils experiments respectively. From Table 13 and 14, there are three responses of interest in both data sets and a fourth response for fitting the models to be used in locating the path of steepest ascent. The aim was to use the total pods mass output (grams) to construct a model that would help move away from the centre of the design towards the region of optimization through the path of steepest ascent.

Table 13: Measured untested soils experimental data.

Manure (g)	Water (l)	Spacing (cm)	X_1	X_2	X_3	Yield (g)	Infected Leaves (count)	No. of Unharvested Pods(count)	Total Pods Mass (g)
18.0	3.1	6.8	-1	-1	-1	18.3	6	15	95.1
30.8	5.7	6.8	1	1	-1	18.2	5	14	94.3
30.8	3.1	13.6	1	-1	1	22.1	1	17	98.5
18.0	5.7	13.6	-1	1	1	19.8	5	16	108.2
30.8	3.1	6.8	1	-1	-1	22.3	6	18	106.5
18.0	5.7	6.8	-1	1	-1	18.1	6	13	85.8
18.0	3.1	13.6	-1	-1	1	20.1	3	17	101.8
18.0	4.4	10.2	-1	0	0	21.8	1	20	120.8
24.4	3.1	10.2	0	-1	0	22.9	1	20	123.2
24.4	4.4	6.8	0	0	-1	22.7	3	19	126.3
24.4	4.4	10.2	0	0	0	23.9	1	21	135.9
24.4	4.4	10.2	0	0	0	24.2	1	21	135.2
24.4	4.4	10.2	0	0	0	23.7	0	21	135.3
24.4	4.4	10.2	0	0	0	24.3	0	21	135.1
24.4	4.4	10.2	0	0	0	23.5	1	20	134.7

4.3.2 Preliminary analysis- path of steepest ascent

In the analysis of the total pods mass, models were fitted for the data obtained. The following are the results of analysis done on total pods mass.

(a) Untested soils' case

In this case, the general hypothesis tested take the form:

H_0: A given factor/factor interaction contributes insignificantly to the fitted model. Verses

H_1: A given factor/factor interaction contributes significantly to the fitted model.

Table 14: Measured tested soils experimental data.

Manure (g)	Water (l)	Spacing (cm)	X_1	X_2	X_3	Yield (g)	Infected Leaves (count)	No. of Unharvested Pods(count)	Total Pods Mass (g)
18	3.1	6.8	-1	-1	-1	23.4	3	20	108.7
30.8	5.7	6.8	1	1	-1	23.2	2	20	106.3
30.8	3.1	13.6	1	-1	1	24.7	1	19	111.3
18	5.7	13.6	-1	1	1	24.5	2	22	118.5
30.8	3.1	6.8	1	-1	-1	25.3	1	25	115.1
18	5.7	6.8	-1	1	-1	24.8	3	18	102.8
18	3.1	13.6	-1	-1	1	25.6	2	26	117.4
18	4.4	10.2	-1	0	0	26.9	1	28	129.1
24.4	3.1	10.2	0	-1	0	27.9	1	30	135.3
24.4	4.4	6.8	0	0	-1	27.4	1	29	137.2
24.4	4.4	10.2	0	0	0	28.1	0	30	146.5
24.4	4.4	10.2	0	0	0	28.3	1	33	146.9
24.4	4.4	10.2	0	0	0	28.6	0	33	146.1
24.4	4.4	10.2	0	0	0	28.6	0	32	146.8
24.4	4.4	10.2	0	0	0	28.4	0	31	146.1

Table 15 shows the output for fitted total pods mass model from untested soils experiment. From Table 15 and its accompanying quadratic model fitted, all the factors are significant on response except manure and interaction between manure and water-all the p-values are less than the level of significance except for the interaction between manure and water.

Table 16 shows the ANOVA output for the fitted pods model. From Table 16, the first order and two-way interaction terms as well as the pure quadratic term are all significant because their p-values are less than 0.05. Therefore, the first order, two-way interaction and pure quadratic terms contribute significantly to the fitted model. It also shows that, although there is lack of fit that is significant (the lack of fit has a p-value = 0.0111 that is less than the 5% level of significance and hence the lack of fit is significant), the second order model fitted is appropriate and significant (overall p-value= 5.861e-07 is less than 5% level of significance). The model is a good fit to the data.

Table 15: Table showing the total pods mass model for untested soils.

	Estimate	Std. Error	t-value	p-value
Intercept	135.5938	0.3876	349.8617	0.0000
X_1	0.9684	0.4460	2.1713	0.0820
X_2	-1.7816	0.4460	-3.9948	0.0104
X_3	3.2684	0.4460	7.3284	0.0007
X_1:X_2	-0.9461	0.4621	-2.0472	0.0960
X_1:X_3	-3.8961	0.4621	-8.4305	0.0004
X_2:X_3	3.7039	0.4621	8.0147	0.0005
X_1^2	-14.7098	0.8457	-17.3932	0.0000
X_2^2	-15.0598	0.8457	-17.8071	0.0000
X_3^2	-6.9098	0.8457	-8.1703	0.0004

$$y = 135.5938 + 0.9684X_1 - 1.7816X_2 + 3.2684X_3 - 0.9461X_1X_2 - 3.8961X_1X_3 + 3.7039X_2X_3 - 14.7098X_1^2 - 15.0598X_2^2 - 6.9098X_3^2$$

Table 16: ANOVA for total pods mass model for untested soils.

	Df	Sum Sq	Mean Sq	F-value	p-value
FO(X_1, X_2, X_3)	3	215.3	71.76	79.619	0.0001
TWI(X_1, X_2, X_3)	3	826.1	275.36	305.534	0.0000
PQ(X_1, X_2, X_3)	3	3464.8	1154.92	1281.486	0.0000
Residuals	5	4.5	0.90		
Lack of fit	1	3.8	3.75	19.969	0.0111
Pure error	4	0.8	0.19		
Multiple R^2 = 0.9990,			**Adjusted R^2** = 0.9972		
F-Statistic= 555.5,		**df**= (9,5),		**p-value**= 5.861e-07	

The Eigen-values associated with the response surface are -6.0452, -15.1653 and -15.4689 and all are negative values. This means that the response surface is a maximizing response surface. This is a confirmation that the process is already at the optimal region and hence the data on outputs and infection can be analysed to locate the optimal points. The stationary points for the model are $X_1 = 0.0039$, $X_2 = 0.0039$ and $X_3 = 0.2270$.

Figure 5 shows the response surface plot on total mass of pods from untested soils data. The response surface plot in Figure 5 is dome-shaped as an indication that the response surface is maximizing. The optimal point is near the centre of the factors' levels.
Figure 6 shows the contour plot on total mass of pods from untested soils data. The contour plot in Figure 6 is increasing towards the centre of the contours and hence confirms that the response is maximizing response surface. The best mass of pods obtained was 135 g.

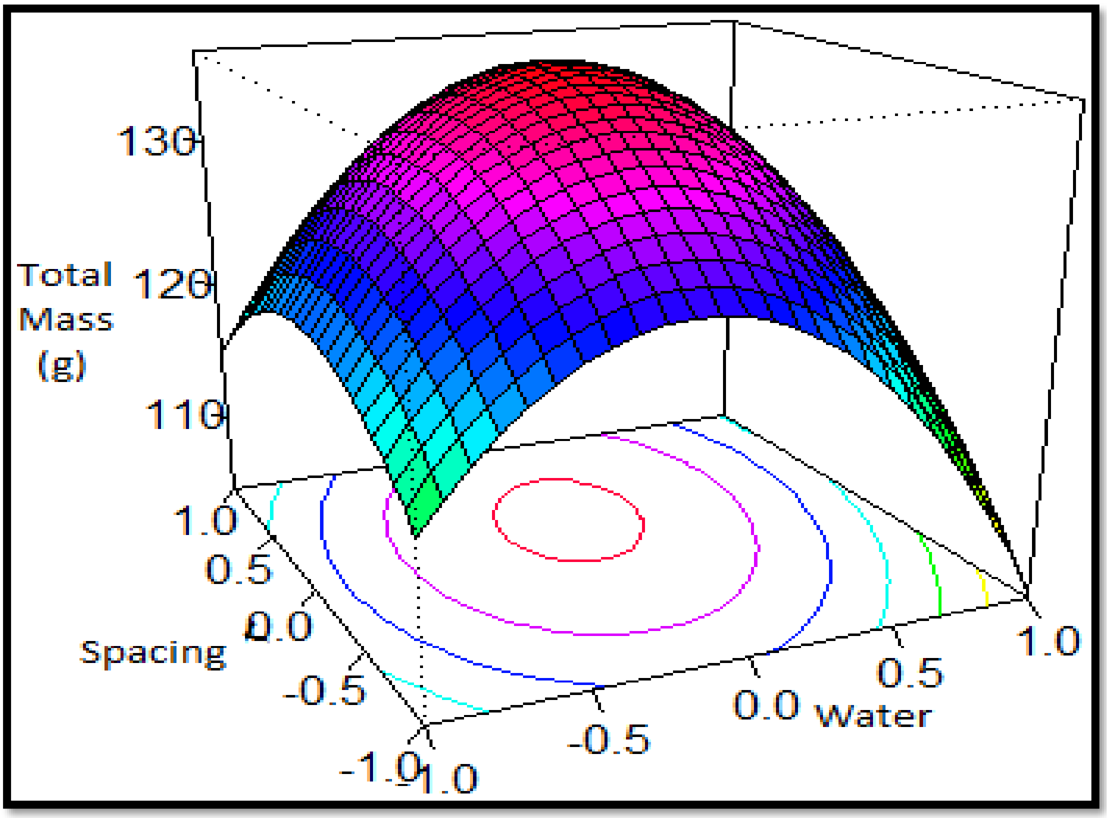


Figure 5: Response surface plot on total pods' mass for untested soils.

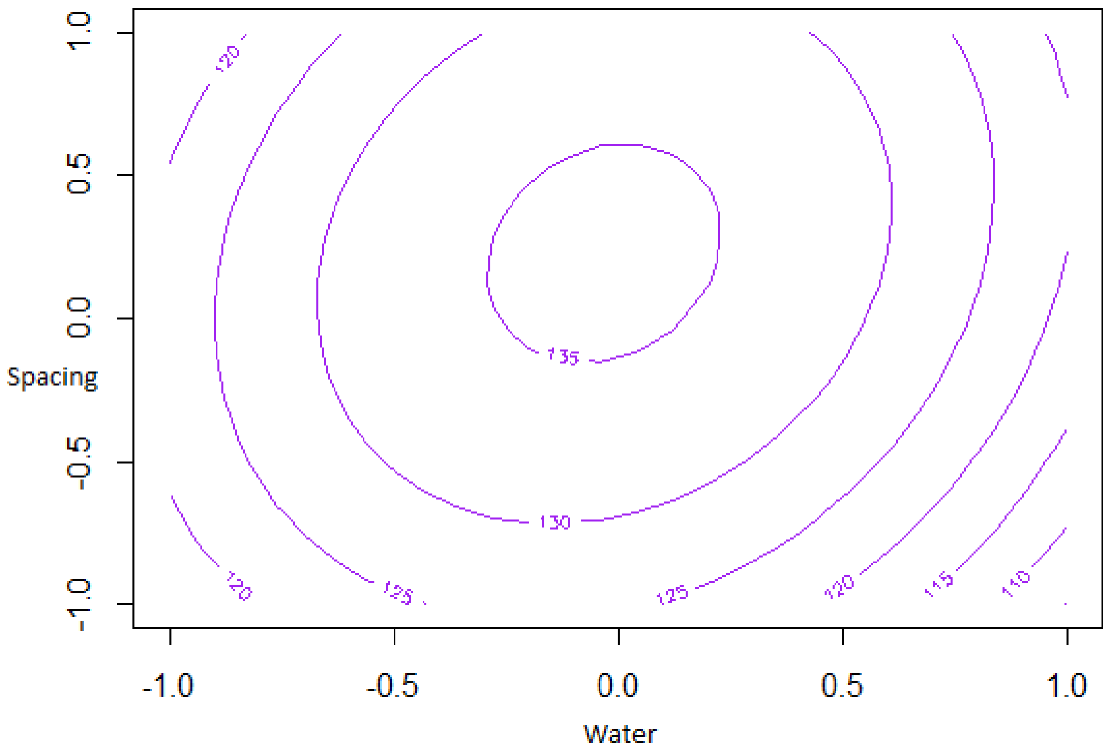


Figure 6: Contour plot on total pods' mass for untested soils.

Table 17 shows the path of steepest ascent from the centre of the design. The path of steepest ascent from ridge analysis was constructed with the help of a software (R) and was not done practically in the field. This is because the curvature in the data was significant and hence had confirmed that the results were from the region of interest.

From Table 17, the results show that the estimated total pods mass would reduce as one would move farther away from the centre of the design. The highest masses were 135.594 and 135.523 g and are obtained around the centre of the design. This confirms that the researcher cannot move away from the centre of the design for better results.

Table 17: The path of steepest ascent from ridge analysis for untested soils.

Steps	Distance	X_1	X_2	X_3	Estimated Pods Mass
1	0	0	0	0	135.594
2	0.5	-0.043	0.004	0.498	135.523
3	1.0	-0.149	0.097	0.984	132.272
4	1.5	-0.259	0.197	1.464	125.990
5	2.0	-0.370	0.299	1.943	116.664
6	2.5	-0.482	0.401	2.420	104.338
7	3.0	-0.594	0.504	2.897	88.9780

Table 18 gives the analysis of the canonical path for defining the linear path through any canonical variable beginning from the stationary point.

From Table 18, it can be seen that the estimated optimal pods mass is at the stationary point. This mass is given by 135.995 g and is at 0 distance. The canonical path analysis is evidence enough that there is no other region of better results that can be found.

Testing for normality of the total pods mass, for the untested soils' case, the normal probability plot is shown in Figure 6. In this case, the residuals follow approximately a normal distribution since the points almost follow a straight line.

Testing for the response values that are not predicted well by the fitted second order model, the plot for actual response values verses the model's predicted response values yields the graph shown in Figure 7.

Table 18: The analysis of the canonical path from the stationary point for untested soils.

Distance	X_1	X_2	X_3	Estimated Pods Mass
-2.5	-0.560	0.487	2.607	98.2060
-2.0	-0.447	0.383	2.131	111.813
-1.5	-0.334	0.280	1.655	122.391
-1.0	-0.221	0.176	1.179	129.950
-0.5	-0.109	0.072	0.703	134.483
0	**0.004**	**-0.031**	**0.227**	**135.995**
0.5	0.117	-0.135	-0.249	134.482
1.0	0.229	-0.239	-0.725	129.949
1.5	0.342	-0.342	-1.201	122.393
2.0	0.455	-0.446	-1.677	111.810
2.5	0.567	-0.550	-2.153	98.2090

Figure 8 shows the plot of predicted values against the actual values of the total mass of pods from untested soils data. Looking at graph in Figure 8, one can see that all the data points are split evenly by the 45^0 line (the straight line in the graph). In fact, all the data points are on the straight line as an indication that there's no value that's not predicted well by the model. Therefore, the model fits the data well and hence it is appropriate as was indicated by the model's p-value, the multiple R^2 and the adjusted R^2.

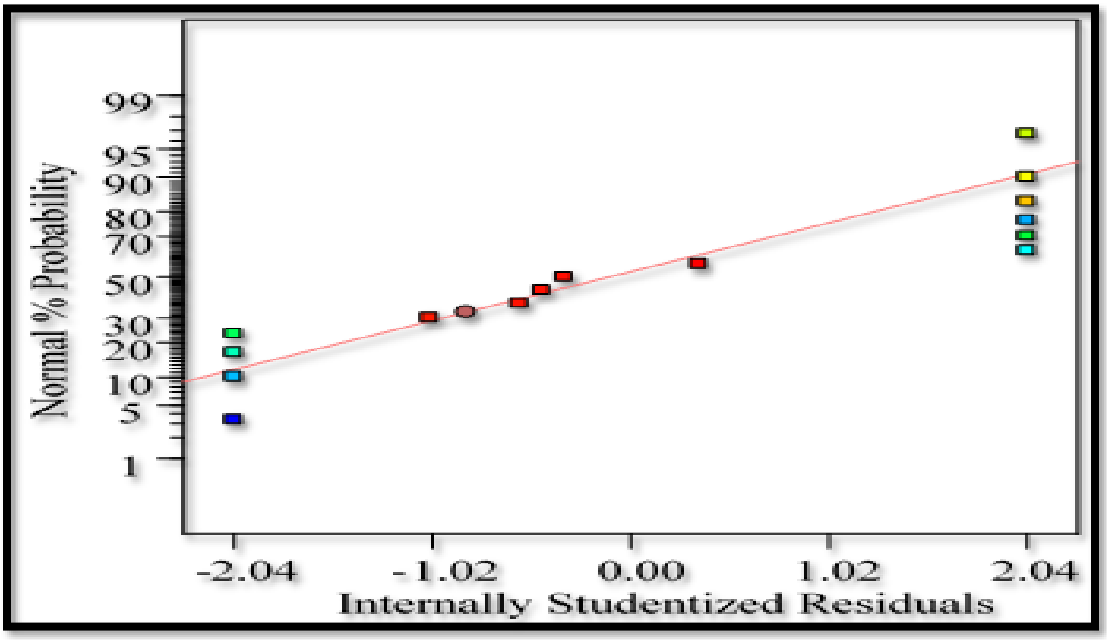


Figure 7: Normal plot of the residuals testing normality of data for untested soils.

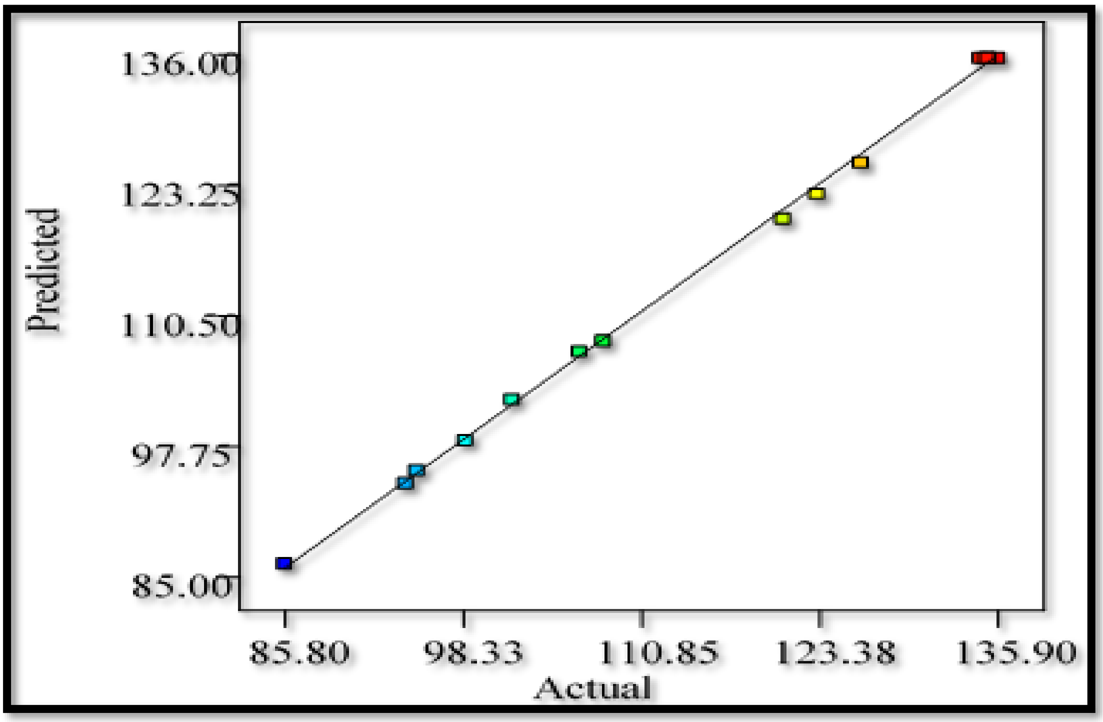


Figure 8: Figure showing a plot on fitted model's predicted values verses the actual values for untested soils.

(b) Tested soils' case

Total pods' mass analysis

Table 19 gives the output for fitted total pods mass model from tested soils experiment.

Table 19: Total pods mass model for tested soils.

	Estimate	Std. Error	t-value	p-value
Intercept	146.3000	0.2266	645.7210	0.0000
X_1	-0.4813	0.2607	-1.8458	0.1242
X_2	-1.7563	0.2607	-6.7361	0.0011
X_3	3.1438	0.2607	12.0578	0.0000
X_1:X_2	-0.6125	0.2702	-2.2671	0.0727
X_1:X_3	-3.0125	0.2702	-11.1510	0.0001
X_2:X_3	1.8625	0.2702	6.8939	0.0010
X_1^2	-17.2310	0.4944	-34.8530	0.0000
X_2^2	-12.3060	0.4944	-24.8910	0.0000
X_3^2	-5.5063	0.4944	-11.1370	0.0001

$$y = 146.3000 - 0.4813X_1 - 1.7563X_2 + 3.1438X_3 - 0.6125X_1X_2 - 3.0125X_1X_3 + 1.8625X_2X_3 - 17.2313X_1^2 - 12.3063X_2^2 - 5.5063X_3^2$$

From Table 19, the quadratic model fitted shows that all the factors investigated are significant on the response except manure and interaction between manure and water. This is because all the p-values are less than the 0.05 level of significance except for the case of manure and interaction between manure and water. This is similar to what was observed for the case of untested soils.

Table 20 gives the ANOVA results from the fitted total pods mass model for the tested soils case.

Table 20: ANOVA for total pods mass model for tested soils.

	Df	Sum Sq	Mean Sq	F-value	p-value
FO(X_1, X_2, X_3)	3	173.9	57.96	188.1745	0.0000
TWI(X_1, X_2, X_3)	3	606.0	202.01	655.8778	0.0000
PQ(X_1, X_2, X_3)	3	3189.8	1063.27	3452.1920	0.0000
Residuals	5	1.5	0.31		
Lack of fit	1	1.0	0.97	6.8451	0.0590
Pure error	4	0.6	0.14		
Multiple R^2= 0.9996,			**Adjusted R^2**= 0.9989		
F-Statistic= 1432,		df= (9,5),		**p-value**= 5.51e-08	

From Table 20, the first order and two-way interaction terms as well as the pure quadratic term are all significant. Therefore, the first order, two-way interaction and pure quadratic terms contribute significantly to the fitted model. Results also shows that, the second order model fitted is appropriate and significant (overall p-value= 5.51e-08 is less than 5% level of significance). Both multiple R^2 and adjusted R^2 are greater than 0.8 and hence there is a good model fit. The lack of fit has a p-value = 0.0590 that is greater than the level of significance and hence the lack of fit is not significant. Therefore, the 2nd order model fitted is significant and there is no lack of fit.

The Eigen-values associated with the response surface are -5.1857, -12.4294 and -17.4286 and all are negative values. This means that the response surface is a maximizing response surface. This is a confirmation that the process is already at the optimal region and hence the data on outputs and infection can be analysed to locate the optimal points. The stationary points for the model are X_1 = -0.0382, X_2 = -0.0486 and X_3 = 0.2877.

Figure 9 shows the response surface plot for the total mass of pods from tested soils data. The response surface plot in Figure 8 is dome-shaped as an indication that the response surface is maximizing. The optimal point is near the centre of the factor levels.

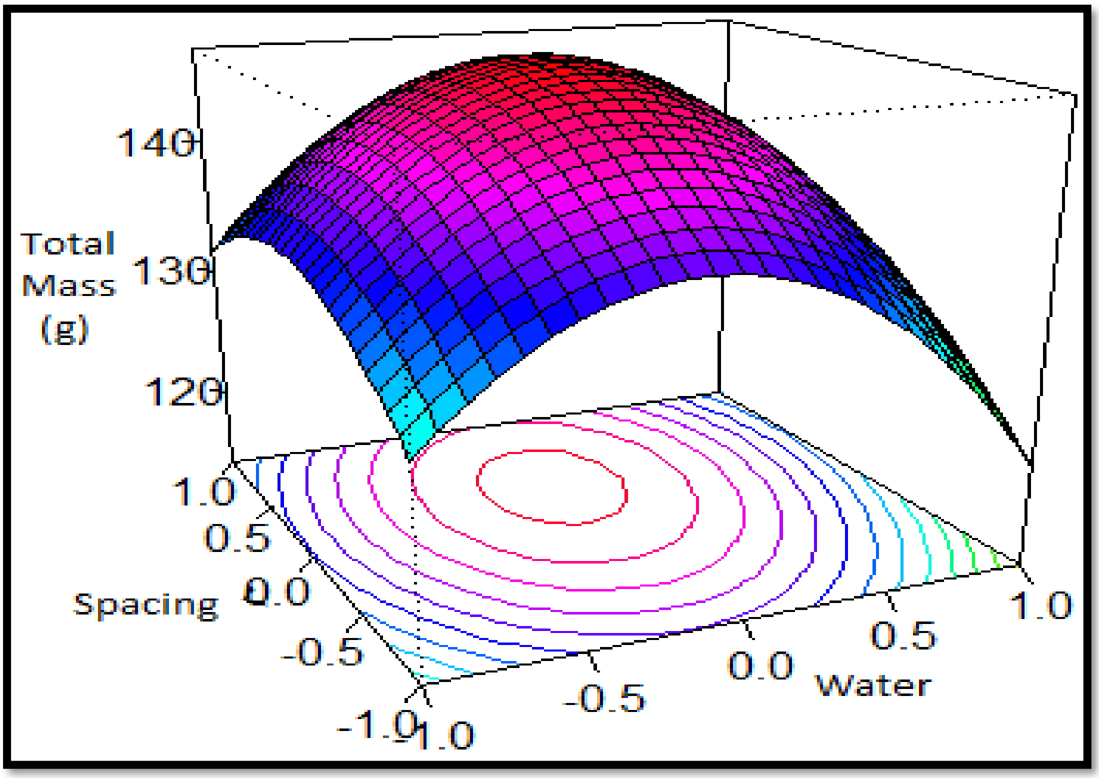


Figure 9: Response surface plot on total pods' mass for tested soils.

Figure 10 shows the contour plot for the total mass of pods from tested soils data. The contour plot in Figure 10 has contours increasing towards the centre of the plot and hence confirms that the response is maximizing response surface. The highest total mass of the pods obtained is 145 g.

Attempting to create a path of steepest ascent from the centre of the design yields unsatisfactory results as shown in table 21. The path of steepest ascent from ridge analysis was constructed with the help of a software (R) and was not done practically in the field. This is because the curvature in the data was significant and hence had confirmed that the results were from the region of interest.

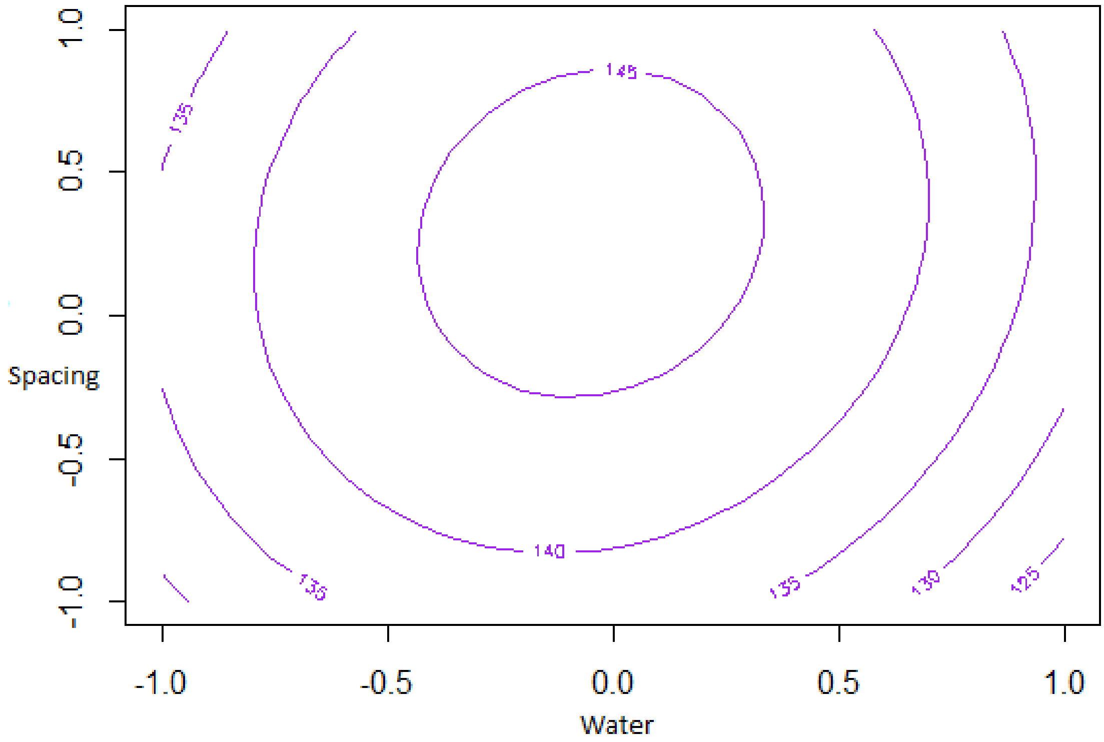


Figure 10: Contour plot on total pods' mass for tested soils.

Table 21 shows the path of steepest ascent constructed from the origin for the tested soils case. From Table 21, the results show that the estimated total pods mass would reduce as one would move farther away from the centre of the design. The highest masses (146.3 and 146.577 g) are obtained near the centre of the design. This confirms that the researcher cannot move very far away from the centre of the design for better results.

Table 21:The path of steepest ascent constructed from the origin for tested soils.

Steps	Distance	X_1	X_2	X_3	Estimated Pods Mass
1	0	0	0	0	146.300
2	0.5	-0.065	-0.039	0.494	146.577
3	1.0	-0.129	0.010	0.992	144.161
4	1.5	-0.192	0.070	1.486	139.148
5	2.0	-0.255	0.133	1.979	131.539
6	2.5	-0.319	0.197	2.472	121.321
7	3.0	-0.382	0.263	2.964	108.525

Table 22 gives the analysis of the canonical path for defining the linear path through any canonical variable beginning from the stationary point. From Table 22 output, it can be seen that the estimated optimal pods mass is at the stationary point. This mass is given by 146.804 g and is at 0 distance. This canonical path analysis is evidence enough that there is no other region of better results that can be found.

Table 22: The analysis of the canonical path from the stationary point for tested soils.

Distance	**X_1**	**X_2**	**X_3**	**Estimated Pods Mass**
-3.0	-0.417	0.353	3.236	100.147
-2.5	-0.354	0.286	2.745	114.394
-2.0	-0.291	0.219	2.254	126.052
-1.5	-0.228	0.152	1.762	135.137
-1.0	-0.165	0.085	1.271	141.614
-0.5	-0.101	0.018	0.779	145.509
0	**-0.038**	**-0.049**	**0.288**	**146.804**
0.5	0.025	-0.116	-0.204	145.506
1.0	0.088	-0.183	-0.695	141.62
1.5	0.151	-0.25	-1.187	135.130
2.0	0.214	-0.317	-1.678	126.063
2.5	0.278	-0.384	-2.17	114.379
3.0	0.341	-0.451	-2.661	100.129

Testing for the normality of the total pods mass, for the tested soils' case, the normal probability plot is shown in Figure 11. From Figure 11, the plot indicates that the residuals follow approximately a normal distribution since the points almost follow a straight line.

Testing for the response values that are not predicted well by the fitted second order model, the plot for actual response values verses the model's predicted response values yields the graph shown in Figure 12.

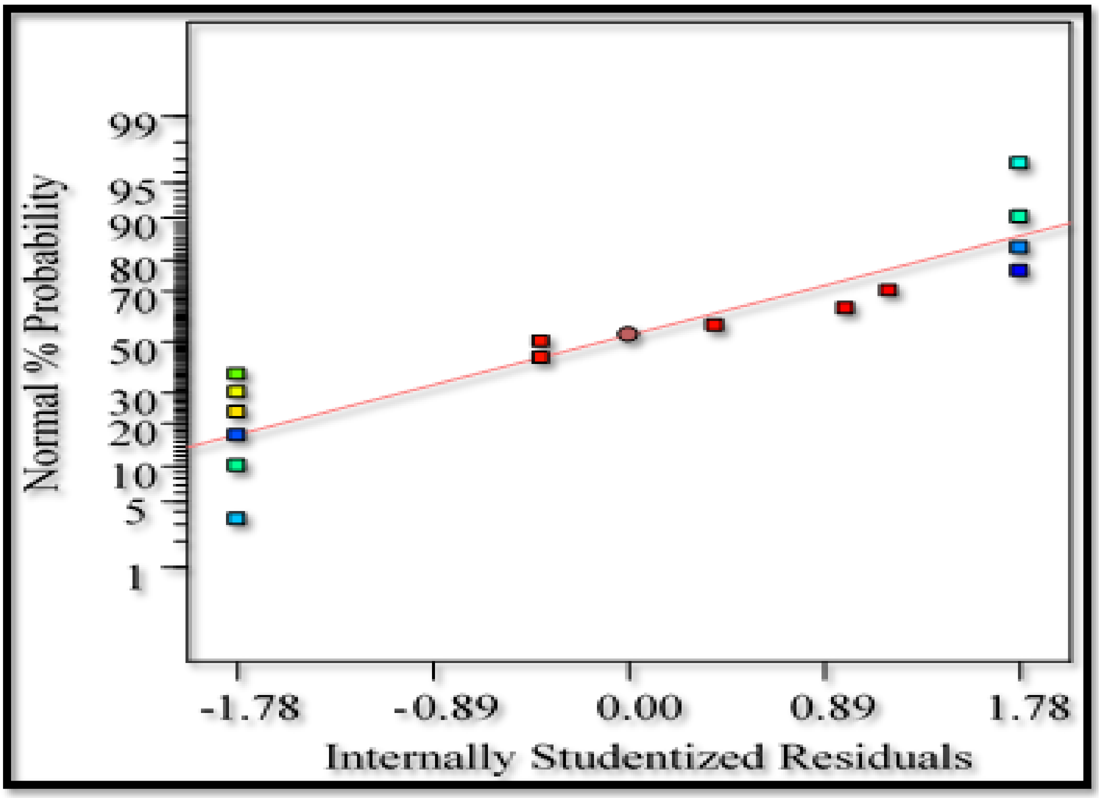


Figure 11: Figure showing the normal plot of the residuals- tested soils' case.

Looking at Figure 12, one can see that all the data points are split evenly by the 45^0 line (the straight line in the graph). In fact, all the data points are on the straight line as an indication that there's no value that's not predicted well by the model. Therefore, the model fits the data well and hence it is appropriate as was indicated by the good model's fit with high values of the multiple R^2 and the adjusted R^2.

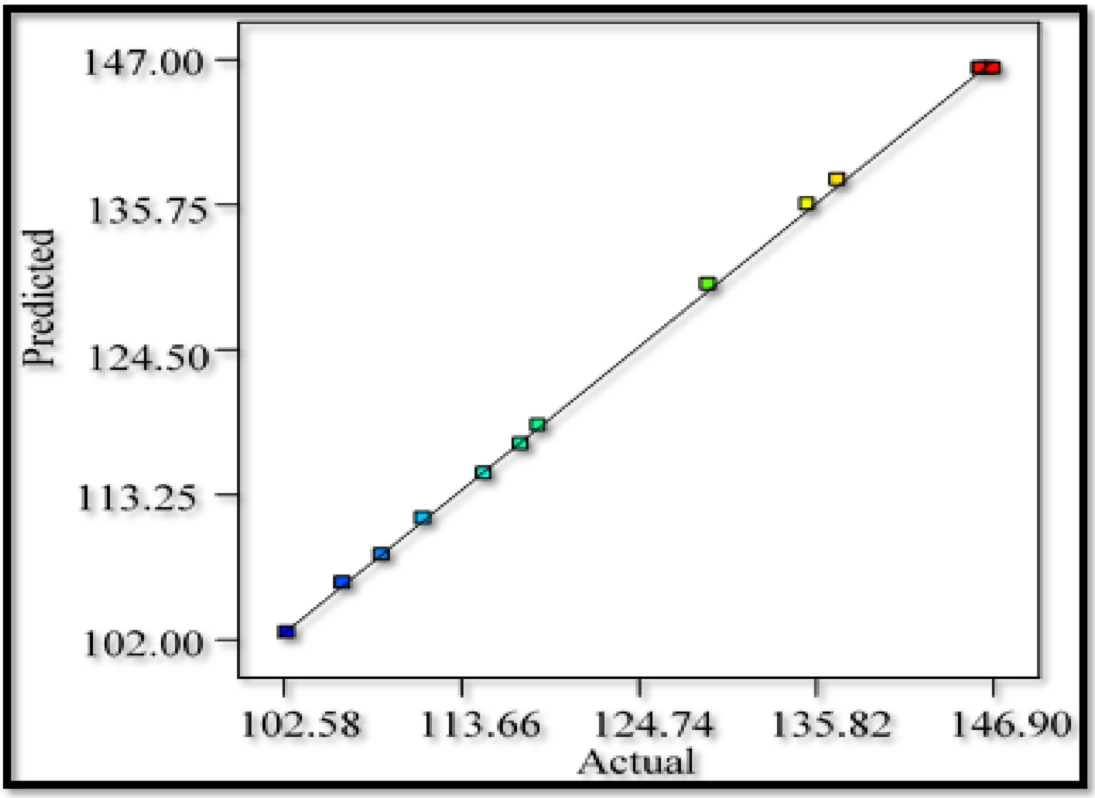


Figure 12: Figure showing the plot of the fitted model's predicted values verses the actual values for tested soils.

4.3.3 Data analysis for the responses of interest

Having studied the output on total mass of the pods, it became evident that no further steps could be taken to move away from the centre of the design to some other regions. This paved way for the researcher to investigate the rest of the outputs (yields, infections and unharvested pods) as the responses of interest in this study.

From the two sets of data (untested and tested soils' data sets), models were fitted, one for yield, one for number of infected leaves and one for immature pods. Let y1, y2 and y3 be the responses for yield, infected leaves and number of unharvested/ immature pods respectively for both untested and tested soils' cases.

a) Untested soils' case

(i) Yield

Table 23 gives the output from the fitted yields model from untested soils data.

Table 23: Yield's model for untested soils.

	Estimate	Std. Error	t-value	p-value
Intercept	23.9000	0.1238	193.0100	0.0000
X_1	0.5438	0.1425	3.8159	0.0124
X_2	-1.0813	0.1425	-7.5880	0.0006
X_3	0.3938	0.1425	2.7633	0.0397
X_1:X_2	-0.9625	0.1477	-6.5186	0.0013
X_1:X_3	-0.4875	0.1477	-3.3016	0.0214
X_2:X_3	-0.0125	0.1477	-0.0847	0.9358
X_1^2	-1.5063	0.2702	-5.5744	0.0026
X_2^2	-2.0313	0.2702	-7.5173	0.0007
X_3^2	-0.7563	0.2702	-2.7988	0.0381

$$y_1 = 23.9000 + 0.5434X_1 - 1.0813X_2 + 0.3938X_3 - 0.9625X_1X_2 - 0.4875X_1X_3 - 0.0125X_2X_3 - 1.5063X_1^2 - 2.0313X_2^2 - 0.7563X_3^2$$

From Table 23 output and accompanying model, only manure (X_1) and spacing (X_3) factors had a positive effect on the yield. Thus, addition of the amount of manure and increase in spacing among crops leads to increased yield. All the interactions of the factors have negative effects on yield as is indicated by the negative signs of the coefficients. All the main and interaction effects are significant in predicting yield except the interaction effect between water and spacing (X_2 and X_3). In terms of the actual factors, the model from the computer software is given by:

$$Yield = -45.7864 + 2.6171 * manure + 12.5968 * water + 2.0095 * spacing - 0.1157 * manure * water - 0.0224 * manure * spacing - 0.0028 * water * spacing - 0.0368 * manure^2 - 1.2019 * water^2 - 0.0654 * spacing^2$$

Table 24 presents the ANOVA results for the fitted yields model from untested soils data.

Table 24: Table showing the ANOVA for yield's model for untested soils.

	Df	Sum Sq.	Mean Sq.	F-value	p-value
FO(X_1, X_2, X_3)	3	16.621	5.5404	60.2219	0.0002
TWI(X_1, X_2, X_3)	3	6.216	2.072	22.5217	0.0025
PQ(X_1, X_2, X_3)	3	47.692	15.8974	172.7974	0.0000
Residuals	5	0.460	0.092		
Lack of fit	1	0.012	0.012	0.1071	0.7598
Pure error	4	0.448	0.112		
Multiple R^2= 0.9935,			**Adjusted R^2**= 0.9819		
F-Statistic= 85.18,		df= (9,5),		**p-value**= 6.194e-05	

From Table 24, the 1st order, the 2-way interactions and the pure quadratic terms really contribute to the fitted model significantly. The p-value= 0.7598 for lack of fit from the same table is greater than 5% level of significance. Therefore, lack of fit is not significant. So, statistically there is no lack of fit. Considering the overall p-value = 6.194e-05, the conclusion is made that the model fits the data well because that value is extremely smaller than the α =5% level of significance. The multiple R^2= 0.9935 and adjusted R^2= 0.9819 in the same table help support the fitting of the model. The two are above 0.8 and hence there is goodness of fit to the data. Thus, the fitted model fits the obtained data well and there's no lack of fit.

The Eigen-values associated with the response surface are -0.6688, -1.2970 and -2.3279 and all are negative values. This means that the response surface is a maximizing response surface. The stationary points for the model are $X_1 = 0.2559$, $X_2 = -0.3273$ and $X_3 = 0.1806$. The stationary points can be converted to the original/non-coded/natural variables using the formula corresponding to each factor as follows:

$\frac{Manure - 24.4}{6.4} = 0.2559 \Rightarrow$ Manure = 26.0375 ≅ 26.0 g.

$\frac{Water - 4.4}{1.3} = -0.3273 \Rightarrow$ Waters = 3.9745 ≅ 4.0 ℓ.

$\frac{Spacing - 10.2}{3.4} = 0.1806 \Rightarrow$ Spacing = 10.8139 ≅ 10.8 cm.

Figure 13 shows the response surface plot for the yields from untested soils data. From the response surface plot in Figure 13, it can be seen that it is a maximizing response surface since it's dome-shaped. Maximum yield is at low levels of water and middle levels of spacing. It shows that the maximum yield is about 24 g.

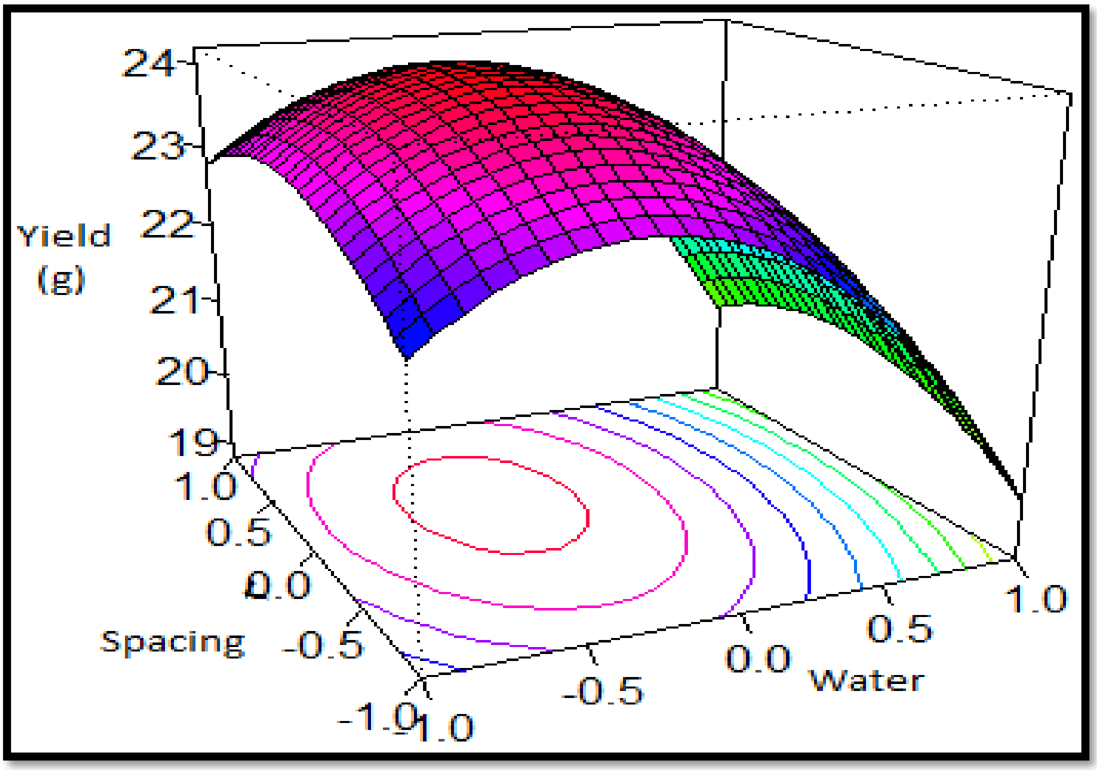


Figure 13: Response surface plot on yield's data for untested soils.

Figure 14 shows the contour plot for the yields from untested soils data. The contour plot in Figure 14 indicates a maximizing response since yield is increasing towards the centre of the contours. This confirms the information provided by the Eigen-values and the response surface plot discussed. It shows that the maximum yield obtained is approximately 24 g.

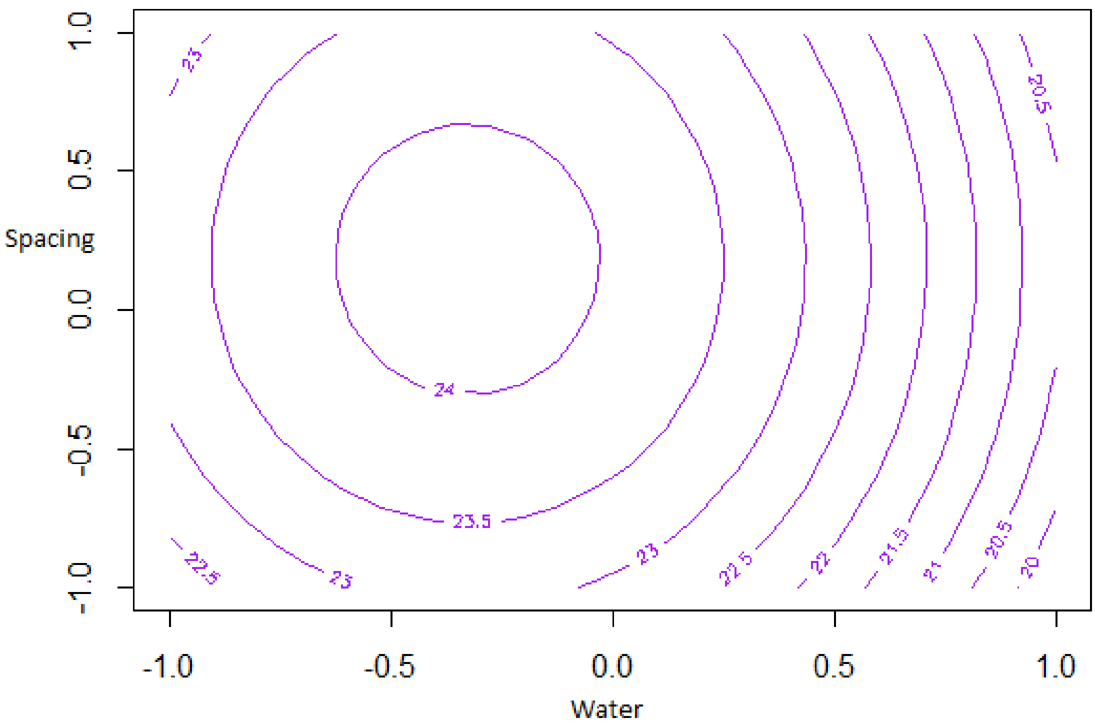


Figure 14: Contour plot on yield's data for untested soils.

Testing for the response values that are not predicted well by the fitted second order model, the plot for actual response values verses the model's predicted response values yields the graph shown in Figure 15. From the graph in Figure 15, one can see that all the data points are split evenly by the 45^0 line (the straight line in the graph). This is an indication that there's no value that's not predicted well by the model. Therefore, the model fits the data well and hence it is appropriate as was indicated by the model's p-value, the multiple R^2 and the adjusted R^2.

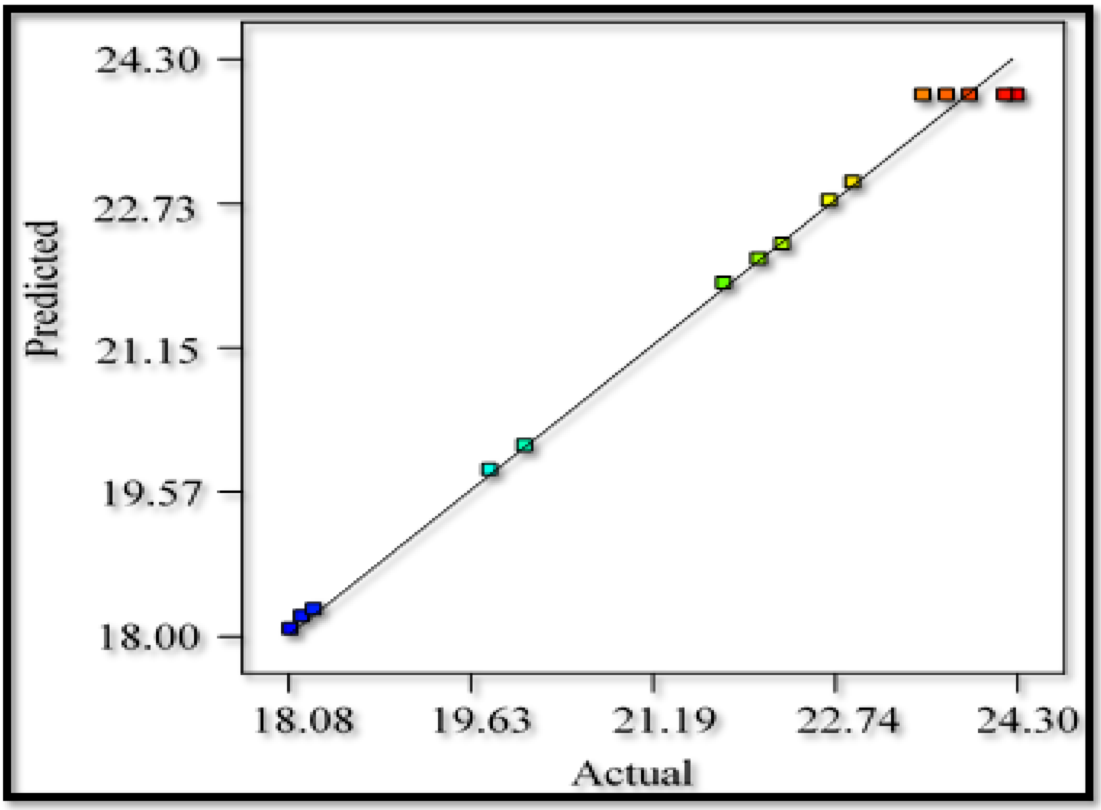


Figure 15: Plot on fitted model's yield's predicted values verses actual values for untested soils.

(ii) Infection rate

Analysis of crop infection data

Table 25 gives the output for the fitted infection model from untested soils data. From Table 25 and the accompanying model, manure and spacing had a negative effect on infection. This means that, they have a positive effect on plant health. The interaction between manure and water as well as manure and spacing had a positive effect on plant health. However, it's only spacing factor that has a significant effect on plant health for both main and quadratic effects as it can be seen from the p-values that are less than the 5% level of significance.

Table 25: Table showing infection's model for untested soils.

	Estimate	Std. Error	t-value	p-value
Intercept	0.3958	0.2858	1.3850	0.2247
X_1	-0.5586	0.3289	-1.6984	0.1502
X_2	0.4414	0.3289	1.3421	0.2373
X_3	-1.3086	0.3289	-3.9788	0.0105
X_1:X_2	-0.1224	0.3408	-0.3591	0.7342
X_1:X_3	-0.3724	0.3408	-1.0927	0.3244
X_2:X_3	0.6276	0.3408	1.8416	0.1249
X_1^2	0.5560	0.6237	0.8915	0.4135
X_2^2	1.5560	0.6237	2.4949	0.0548
X_3^2	1.8060	0.6237	2.8958	0.0340

$$y_2 = 0.3958 - 0.5586X_1 + 0.4414X_2 - 1.3086X_3 - 0.1224X_1X_2 - 0.3724X_1X_3 + 0.6276X_2X_3 + 0.5560X_1^2 + 1.5560X_2^2 + 1.8060X_3^2$$

In terms of the actual factors, the model from the computer software is given by:

$$Infection = 47.6513 - 0.5104 * manure - 8.8520 * water - 3.7791 * spacing - 0.0147 * manure * water - 0.0171 * manure * spacing + 0.1420 * water * spacing + 0.0136 * manure^2 + 0.9207 * water^2 + 0.1562 * spacing^2$$

Table 26 gives the ANOVA output for the fitted infection model from untested soils data. From Table 26, the 1st order, the 2-way interactions and the pure quadratic terms really contribute to the fitted model significantly. The lack of fit is not significant. So, statistically there is no lack of fit. Considering the overall p-value= 0.0033, the conclusion is made that the model fits the data well since value is less than the 5% level of significance. The multiple $R^2 = 0.9675$ and adjusted $R^2 = 0.9089$ in the same table help support the overall fitting of the model. The two are above 0.8 and hence there is goodness of fit to the data. Thus, the fitted model fits the obtained data well and there's no lack of fit.

Table 26: ANOVA for infection's model for untested soils.

	Df	Sum Sq	Mean Sq	F-value	p-value
FO(X_1, X_2, X_3)	3	21.979	7.3262	14.9483	0.0063
TWI(X_1, X_2, X_3)	3	11.025	3.6749	7.4982	0.0268
PQ(X_1, X_2, X_3)	3	39.879	13.2932	27.1231	0.0016
Residuals	5	2.451	0.4901		
Lack of fit	1	1.251	1.2505	4.1684	0.1107
Pure error	4	1.200	0.3000		
Multiple R^2= 0.9675,			**Adjusted R^2**= 0.9089		
F-Statistic= 16.52,		df= (9,5),		**p-value**= 0.0033	

The Eigen-values associated with the response surface are 2.0427, 1.3466 and 0.5286 and all are positive values. This means that the response surface is a minimizing response surface. The stationary points for the model are $X_1 = 0.6347$, $X_2 = -0.2105$ and $X_3 = 0.4643$. The stationary points can be converted to the original/non-coded/natural variables using the formula corresponding to each factor as follows:

$\frac{Manure-24.4}{6.4} = 0.6347 \Rightarrow$ Manure = 28.4618 ≅ 28.5 g.

$\frac{Water-4.4}{1.3} = -0.2105 \Rightarrow$ Waters = 4.1263 ≅ 4.1 ℓ.

$\frac{Spacing-10.2}{3.4} = 0.4643 \Rightarrow$ Spacing = 11.7786 ≅ 11.8 cm.

Figure 16 shows the response surface plot for the infection from untested soils data. The response surface plot in Figure 16 shows that the minimum number of infected leaves is about zero. The plot shows that the surface is minimum response surface because it assumes the shape of a down-set dome. The maximum plant health is achieved at low levels of water and at high levels of spacing.

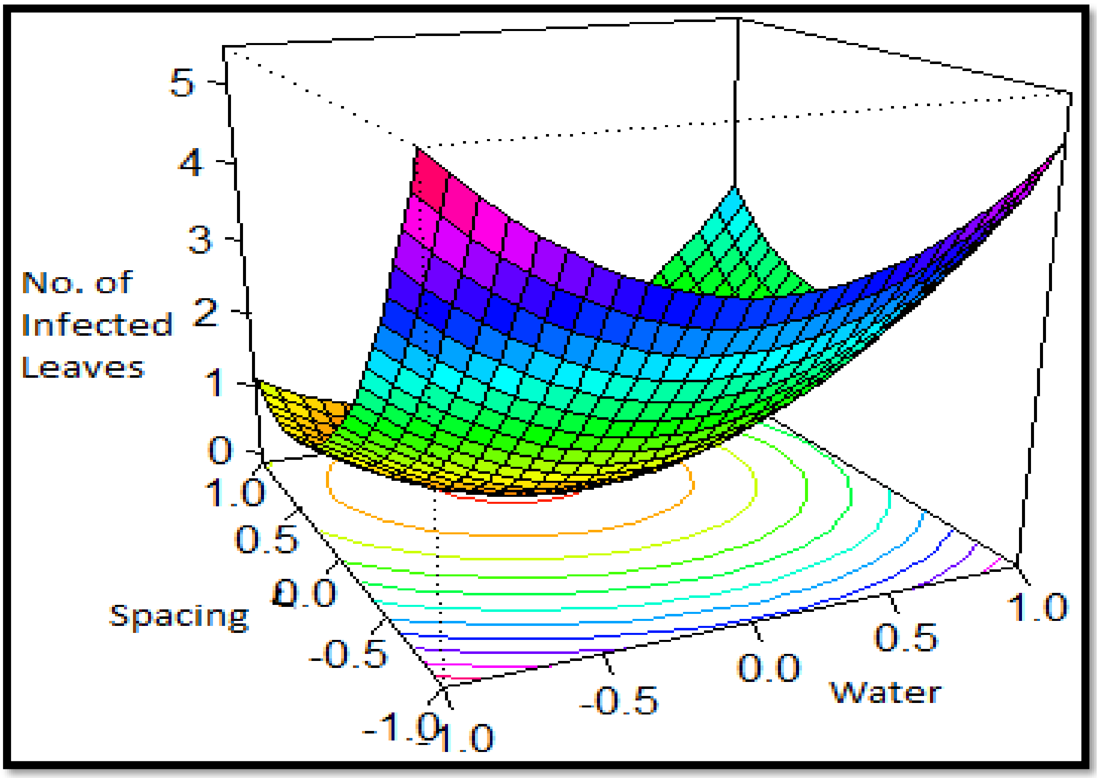


Figure 16: Response surface plot on crop infection's data for untested soils.

Figure 17 shows the contour plot for the infection from untested soils data. The contour plot in Figure 17 is an indication of a minimum response surface since the values increase outwards. The minimum number of infected leaves is zero and this plot confirms the information obtained from the Eigen-values and the response surface plot. The minimum value is obtained at low levels of water and at higher levels of spacing.

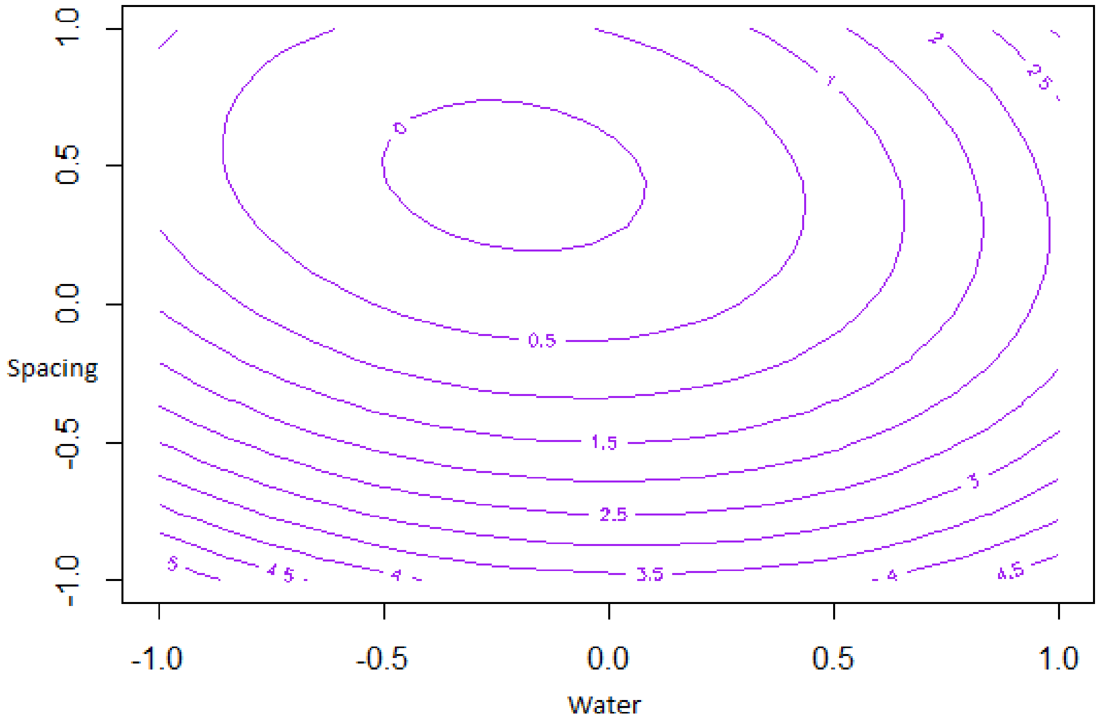


Figure 17: Contour plot on crop infection's data for untested soils.

Testing for the response values that are not predicted well by the fitted second order model, the plot for actual response values verses the model's predicted response values yields the graph shown in Figure 18.

Looking at Figure 18, one can see that all the data points are almost split evenly by the 45^0 line (the straight line in the graph). This is an indication that almost all values are predicted well by the model. Therefore, the model fits the data well and hence it is appropriate since it fits the model with R^2 of at least 80%.

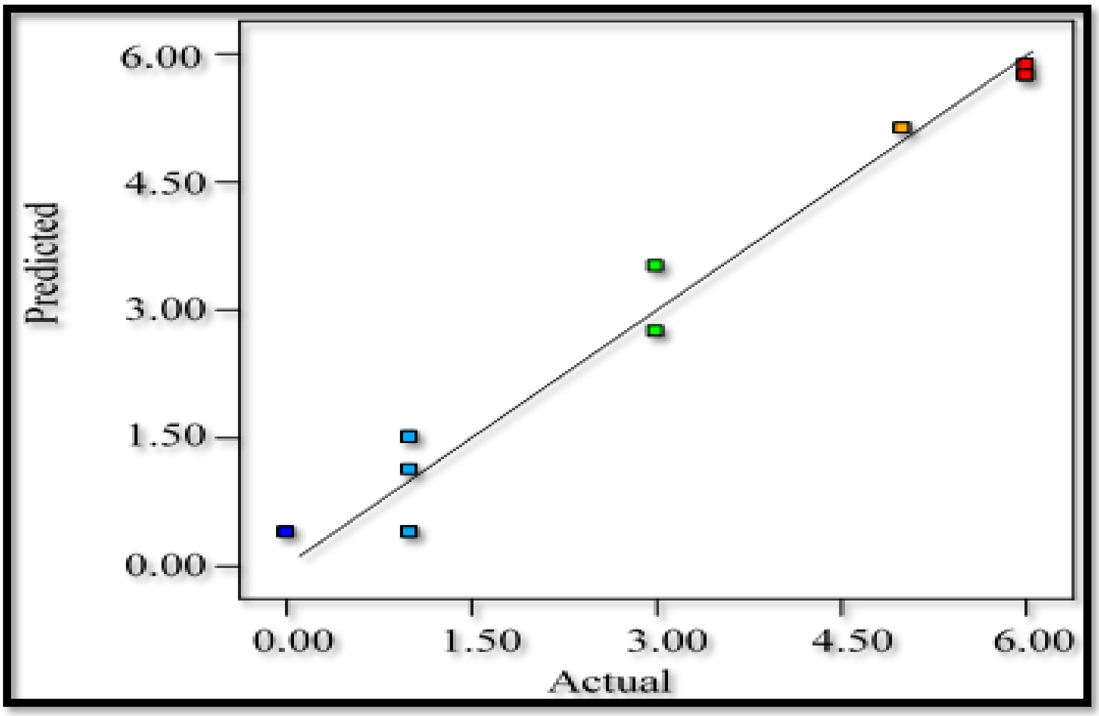


Figure 18: Plot on fitted model's crop infection's predicted values verses actual values for untested soils.

(iii) Pods

Analysis of pods data

Table 27 shows the output for the fitted pods model from untested soils data.

From Table 27 and the accompanying model, manure and spacing have a positive effect on number of pods while water has a negative effect. However, the effect of water is significant while that of manure and spacing are not. This means that, additional water lowers number of pods significantly. The interaction between manure and water as well as manure and plant spacing have a negative effect on number of pods while the relationship between water and spacing affects pods positively. The three quadratic terms have negative effects but that of manure is not significant.

Table 27: Number of pods' model for untested soils.

	Estimate	Std. Error	t-value	p-value
Intercept	20.9167	0.2007	104.2221	0.0000
X_1	0.1406	0.2310	0.6089	0.5692
X_2	-1.3594	0.2310	-5.8861	0.0020
X_3	0.3906	0.2310	1.6914	0.1516
X_1:X_2	-0.5729	0.2393	-2.3940	0.0621
X_1:X_3	-0.8229	0.2393	-3.4387	0.0185
X_2:X_3	0.1771	0.2393	0.7400	0.4926
X_1^2	-1.0677	0.4379	-2.4380	0.0588
X_2^2	-2.5677	0.4379	-5.8632	0.0021
X_3^2	-1.8177	0.4379	-4.1506	0.0089

$$y_3 = 20.9167 + 0.1406X_1 - 1.3594X_2 + 0.3906X_3 - 0.5729X_1X_2 - 0.8229X_1X_3 + 0.1771X_2X_3 - 1.0677X_1^2 - 2.5677X_2^2 - 1.8177X_3^2$$

In terms of the actual factors, the model from the computer software is given by:

$$No.of\ Pods = -52.4906 + 1.9828 * manure + 13.5962 * water + 4.0691 * spacing - 0.0689 * manure * water - 0.0378 * manure * spacing + 0.0400 * water * spacing - 0.0261 * manure^2 - 1.5194 * water^2 - 0.1572 * spacing^2$$

Table 28 shows the ANOVA output for the fitted pods model from untested soils data. From Table 28, the p-values corresponding to first order, two-way interaction and pure quadratic terms of the model are all less than 5% level of significance. Consequently, the 1st order, the 2-way interactions and the pure quadratic terms contribute to the fitted model significantly. The p-value= 0.2262 for lack of fit from the same table is greater than 5% level of significance and therefore, the lack of fit is not significant. Considering the overall p-value= 0.0003, the conclusion is made that the model fits the data well since this value is less than the 5% level of significance. The multiple R^2= 0.9884 and adjusted R^2= 0.9676 in the same table help support the overall fitting of the model. The two are above 0.8 and hence there is goodness of fit to the data. Thus, the fitted model fits the obtained data well and there's no lack of fit.

Table 28: Table showing ANOVA for no. of pods' model for untested soils.

	Df	Sum Sq	Mean Sq	F-value	p-value
FO(X_1, X_2, X_3)	3	15.131	5.0436	20.8700	0.0029
TWI(X_1, X_2, X_3)	3	11.314	3.7713	15.6055	0.0057
PQ(X_1, X_2, X_3)	3	76.747	25.5823	105.8578	0.0000
Residuals	5	1.208	0.2417		
Lack of fit	1	0.408	0.4083	2.0417	0.2262
Pure error	4	0.800	0.2000		
Multiple R^2= 0.9884,			**Adjusted R^2**= 0.9676		
F-Statistic= 47.44,		**df**= (9,5),		p-value= 0.0003	

The Eigen-values associated with the response surface are -0.8348, -1.9976 and -2.6208 and all are negative values. This means that the response surface is a maximizing response surface. The stationary points for the model are X_1 = 0.1133, X_2 = -0.2750 and X_3 = 0.0684. The stationary points can be converted to the original/non-coded/natural variables using the formula corresponding to each factor as follows:

$\frac{Manure-24.4}{6.4}$ = 0.1133 ⇒ Manure = 25.1249 ≅ 25.1 g.

$\frac{Water-4.4}{1.3}$ = -0.2750 ⇒ Waters = 4.0425 ≅ 4.0 ℓ.

$\frac{Spacing-10.2}{3.4}$ = 0.0684 ⇒ Spacing = 10.4326 ≅ 10.4 cm.

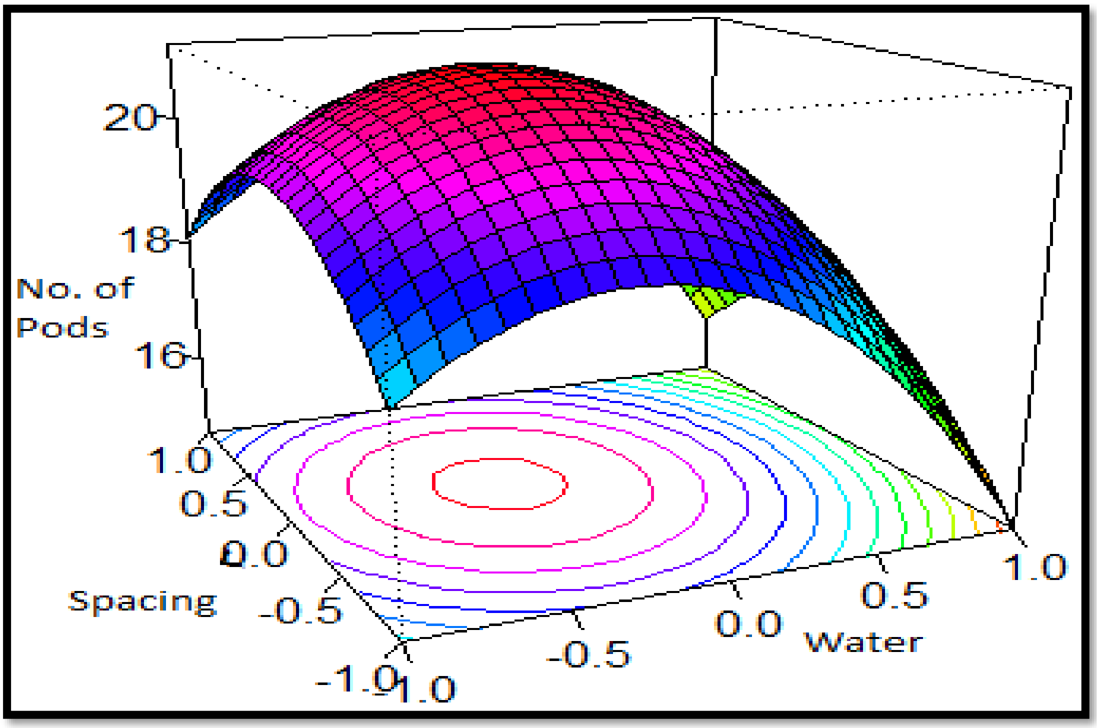


Figure 19: Response surface plot on immature pods' data for untested soils.

Figure 19 shows the response surface plot for the immature pods from untested soils data. The plot in Figure 19 shows that the response surface is a maximizing one since it is dome shaped. The highest number of pods that can be obtained is about 20 pods. The optimal value is obtained at the middle levels of manure and water.

Figure 20 shows the response surface plot for the immature pods from untested soils data. From Figure 20, the contours are increasing inwards hence it is a maximizing response surface. The optimal number of pods is 21.

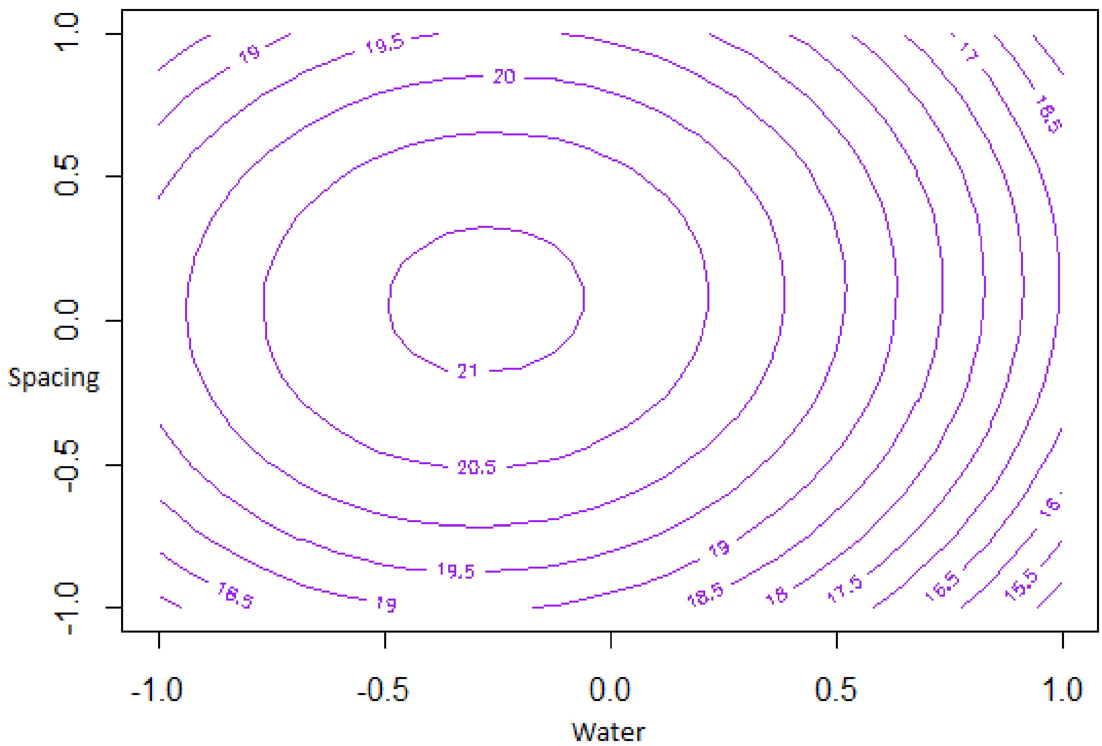


Figure 20: Contour plot on immature pods' data for untested soils.

Testing for the response values that are not predicted well by the fitted second order model, the plot for actual response values verses the model's predicted response values yields the graph shown in Figure 21. From Figure 21, one can see that all the data points are almost split evenly by the 45^0 line (the straight line in the graph). This is an indication that almost all values are predicted well by the model. Therefore, the model fits the data well and hence it is appropriate as was indicated by the model's p-value, the multiple R^2 and the adjusted R^2.

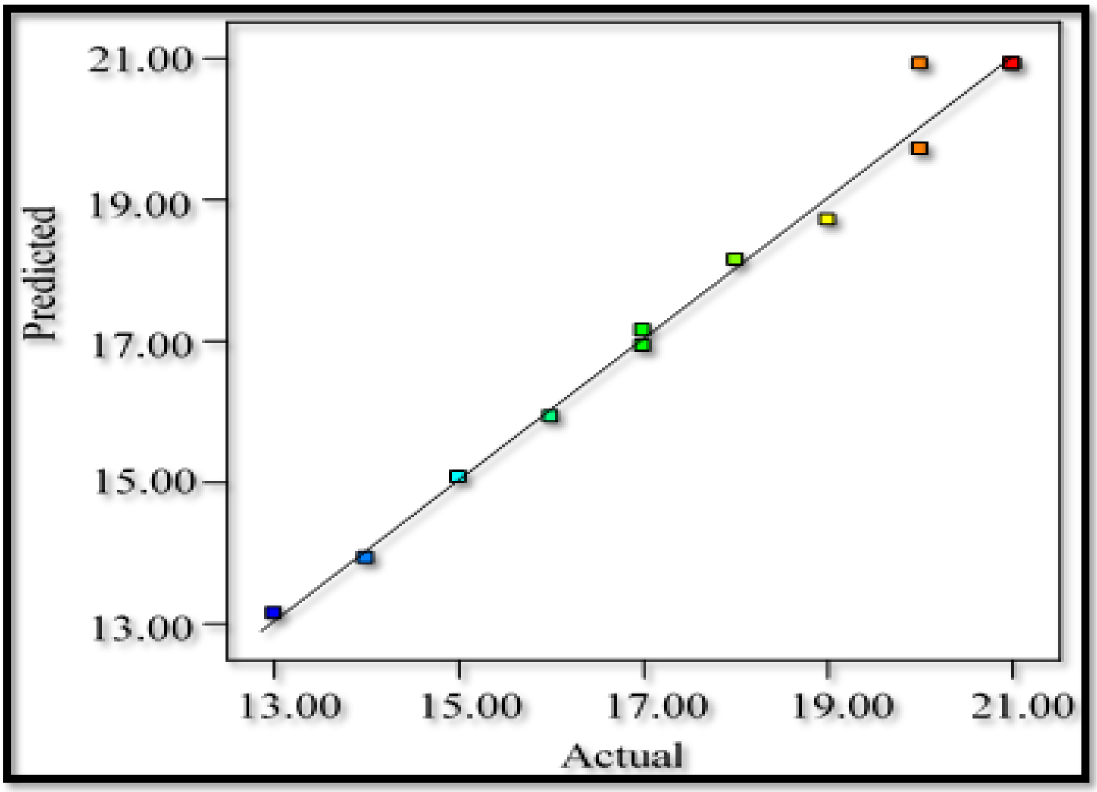


Figure 21: Plot on fitted model's immature pods' predicted values verses the actual values for untested soils.

(b) Tested soils' case

(i) Yield

Analysis of yield data

Table 29 has the output for yields model fitted from tested soils data. From Table 29 and the accompanying model, it can be seen that all the factor effects, both main and interactions, have negative effects on yield. Increase in any of the factors lowers yield. Considering the significance of the factor effects, it can be seen that all the effects are significant except that of spacing. Therefore, the negative effect of spacing of crops is insignificant statistically. This can be seen from the p-values corresponding to each effect- in which all the p-values are less than

5% level of significance except the p-value= 0.0701 corresponding to spacing. In general, an increase in factors levels lowers yield.

Table 29: Yield's model for tested soils.

	Estimate	Std. Error	t-value	p-value
Intercept	28.3833	0.0792	358.229	0.0000
X_1	-0.6094	0.0912	-6.6835	0.0011
X_2	-0.7844	0.0912	-8.6028	0.0004
X_3	-0.2094	0.0912	-2.2964	0.0701
X_1:X_2	-0.8646	0.0945	-9.1511	0.0003
X_1:X_3	-0.6896	0.0945	-7.2988	0.0008
X_2:X_3	-0.6146	0.0945	-6.5050	0.0013
X_1^2	-2.0510	0.1729	-11.8630	0.0000
X_2^2	-1.2260	0.1729	-7.0912	0.0009
X_3^2	-1.1510	0.1729	-6.6574	0.0012

$$y_1 = 28.3833 - 0.6094X_1 - 0.7844X_2 - 0.2094X_3 - 0.8646X_1X_2 - 0.6896X_1X_3 - 0.6146X_2X_3 - 2.0510X_1^2 - 1.2260X_2^2 - 1.1510X_3^2$$

In terms of the actual factors, the model from the computer software is given by:

$$Yield = -45.5111 + 3.1289 * manure + 9.7346 * water + 3.3547 * spacing - 0.1039 * manure * water - 0.0317 * manure * spacing - 0.1391 * water * spacing - 0.0501 * manure^2 - 0.7255 * water^2 - 0.0996 * spacing^2$$

Table 30 displays the ANOVA output for the fitted yields model from the tested soils data. From Table 30, the 1st order, the 2-way interactions and the pure quadratic terms contribute to the fitted model significantly. The p-value= 0.6891 for lack of fit from the same table is greater than 5% level of significance and hence the lack of fit is not significant. So, statistically there is no lack of fit. Considering the overall p-value= 1.337exp(-05), the conclusion is made that the model fits the data well since the value is extremely smaller than the α=5% level of significance. The multiple R^2= 0.9965 and adjusted R^2= 0.9902 in the same table help support the overall fitting of the model. The two are above 0.8 and hence there is goodness of fit to the data. Thus, the fitted model fits the obtained data well.

Table 30: ANOVA for yield's model for tested soils.

	Df	**Sum Sq**	**Mean Sq**	**F-value**	**p-value**
FO(X_1, X_2, X_3)	3	1.873	0.6245	16.5784	0.0050
TWI(X_1, X_2, X_3)	3	1.371	0.4572	12.1371	0.0099
PQ(X_1, X_2, X_3)	3	50.391	16.7969	445.9365	0.0000
Residuals	5	0.188	0.0377		
Lack of fit	1	0.008	0.0083	0.1852	0.6891
Pure error	4	0.180	0.0450		
Multiple R^2= 0.9965,			**Adjusted R^2**= 0.9902		
F-Statistic= 158.2,		df= (9,5),		**p-value**= 1.337e-05	

The Eigen-values associated with the response surface are -0.8778, -1.1578 and -2.3925 and all are negative values. This means that the response surface is a maximizing response surface. The stationary points for the model are X_1 = -0.0894, X_2 = -0.2918 and X_3 = 0.0137. The stationary points can be converted to the original/non-coded/natural variables using the formula corresponding to each factor as follows:

$\frac{Manure-24.4}{6.4}$ = -0.0894 ⇒ Manure = 23.8281 ≅ 23.8 g.

$\frac{Water-4.4}{1.3}$ = -0.2918 ⇒ Water = 4.0206 ≅ 4.0 ℓ.

$\frac{Spacing-10.2}{3.4} = 0.0137 \Rightarrow$ Spacing = 10.2467 ≅ 10.2 cm.

Figure 22 shows the response surface plot for the yields from tested soils data. The plot in Figure 22 shows a maximum response surface due to its dome shape. The maximum yield is about 28 g and is obtained at lower levels of water and medium levels of spacing.

Figure 23 shows the contour plot for the yields from tested soils data. The contour plot in Figure 23 shows that the response surface is maximum since the values of response are increasing towards the centre. The plot shows maximum yield as 28.5 g.

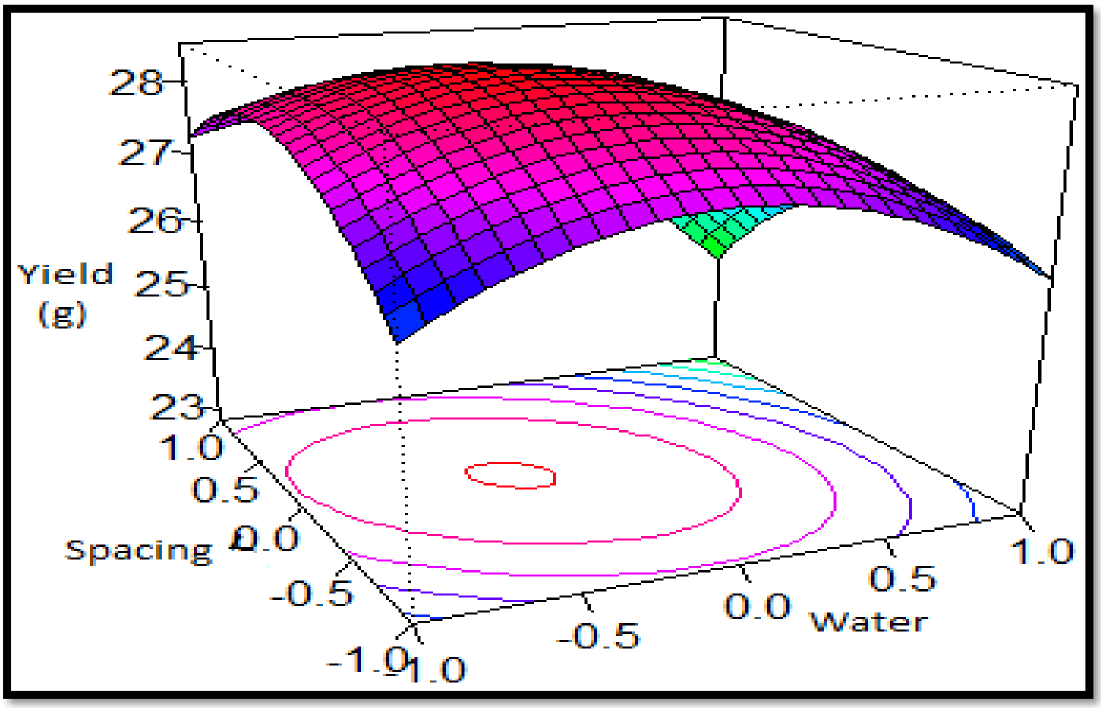


Figure 22: Plot on tested soils' yield's data- the response surface plot.

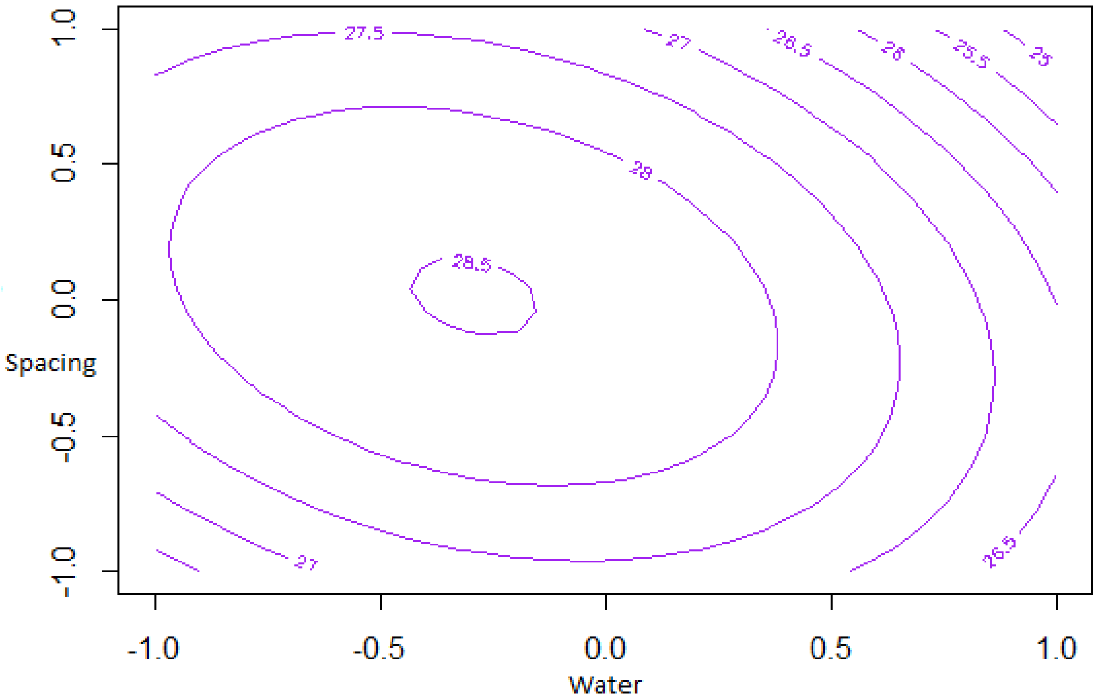


Figure 23: Contour plot on yield's data for tested soils.

Testing for the response values that are not predicted well by the fitted second order model, the plot for actual response values verses the model's predicted response values yields the graph shown in Figure 24.

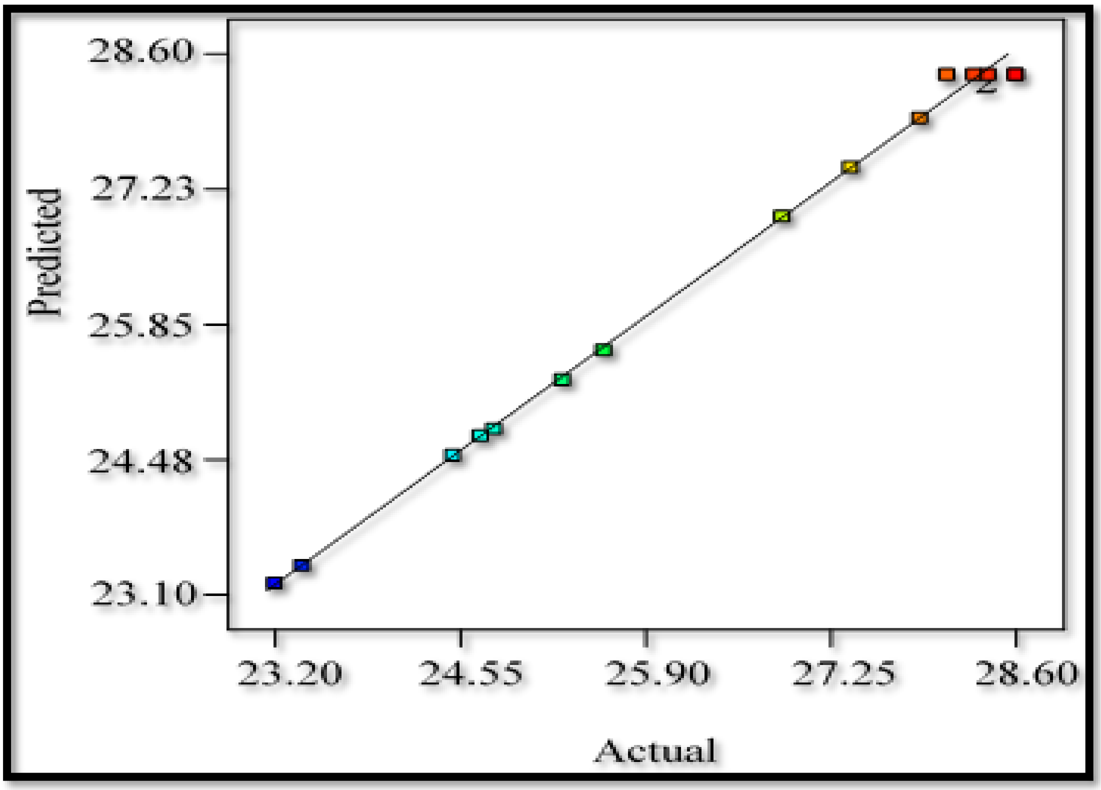


Figure 24: Plot on fitted model's yield's predicted values verses actual values for tested soils.

Looking at Figure 24, one can see that all the data points are split evenly by the 45^0 line (the straight line in the graph). This is an indication that almost all values are predicted well by the model. Therefore, the model fits the data well and hence it is appropriate as was indicated by the model's p-value, the multiple R^2 and the adjusted R^2.

(ii) Infection rate

Analysis of crop infection data

Table 31 gives the output for the fitted infection model from tested soils. From Table 31 and the accompanying model, manure and spacing have a negative effect on infection and hence have a positive effect on plant health. Increasing manure and spacing improves plant health but only the manure effect is significant statistically because its p-value = 0.0428 is less than the level of significance (5%). All the interaction effects are insignificant since their corresponding p-values are greater than 5% level of significance. It can be noted that, the interactions involving manure have positive effects on infection hence have negative effects on plant health. All the quadratic effects on infection are positive but only that of water is significant since the p-value= 0.0363 is less than 5% level of significance.

Table 31: Infections' model for tested soils.

	Estimate	**Std. Error**	**t-value**	**p-value**
Intercept	0.2083	0.1635	1.2741	0.2586
X_1	-0.5078	0.1882	-2.6988	0.0428
X_2	0.2422	0.1882	1.2871	0.2544
X_3	-0.2578	0.1882	-1.3702	0.2290
X_1:X_2	0.2448	0.1950	1.2555	0.2648
X_1:X_3	0.2448	0.1950	1.2555	0.2648
X_2:X_3	-0.0052	0.1950	-0.0267	0.9797
X_1^2	0.2630	0.3568	0.7372	0.4941
X_2^2	1.0130	0.3568	2.8391	0.0363
X_3^2	0.5130	0.3568	1.4378	0.2100

$$y_2 = 0.2083 - 0.5078X_1 + 0.2422X_2 - 0.2578X_3 + 0.2448X_1X_2 + 0.2448X_1X_3 - 0.0052X_2X_3 + 0.2630X_1^2 + 1.0130X_2^2 + 0.5130X_3^2$$

In terms of the actual factors, the model from the computer software is given by:

$$Infection = 28.0488 - 0.6369 * manure - 5.7945 * water - 1.2505 * spacing + 0.0294 * manure * water + 0.0113 * manure * spacing - 0.0012 * water * spacing + 0.0064 * manure^2 + 0.5994 * water^2 + 0.0444 * spacing^2$$

Table 32 shows the ANOVA output for the fitted infection model form tested soils data. From Table 32, the p-values corresponding to first order and pure quadratic terms of the model are all less than 5% level of significance. Therefore, the first order and the pure quadratic terms are significant and hence the two contribute significantly to the fitted model. On the other hand, the two-way interaction term is not significant and hence it does not contribute significantly to the fitted model. The lack of fit is not significant. So, statistically there is no lack of fit. Considering the overall p-value= 0.0118, the conclusion is made that the model fits the data well because this value is less than the 5% level of significance. The multiple R^2= 0.9443 and adjusted R^2= 0.8440 in the same table help support the overall fitting of the model: the two are above 0.8 and hence there is goodness of fit to the data. Thus, the fitted model fits the obtained data well and there's no lack of fit.

Table 32: ANOVA for infection's model for tested soils.

	Df	**Sum Sq**	**Mean Sq**	**F-value**	**p-value**
FO(X_1, X_2, X_3)	3	4.2305	1.4102	8.7906	0.0194
TWI(X_1, X_2, X_3)	3	0.9550	0.3183	1.9845	0.2349
PQ(X_1, X_2, X_3)	3	8.4124	2.8041	17.4803	0.0044
Residuals	5	0.8021	0.1604		
Lack of fit	1	0.0021	0.0021	0.0104	0.9236
Pure error	4	0.8000	0.2000		
Multiple R^2= 0.9443,			**Adjusted R^2**= 0.8440		
F-Statistic= 9.4180,		df= (9,5),		**p-value**= 0.0118	

The Eigen-values associated with the response surface are 1.0330, 0.5591 and 0.1970 and all are positive values. This means that the response surface is a minimizing response surface. The stationary points for the model are $X_1 = 1.0863$, $X_2 = -0.2508$ and $X_3 = -0.0092$. The stationary points can be converted to the original/non-coded/natural variables using the formula corresponding to each factor as follows:

$\frac{Manure - 24.4}{6.4} = 1.0863 \Rightarrow$ Manure = 31.3525 ≅ 31.4 g.

$\frac{Water - 4.4}{1.3} = -0.2508 \Rightarrow$ Water = 4.0739 ≅ 4.1 ℓ.

$\frac{Spacing - 10.2}{3.4} = -0.0092 \Rightarrow$ Spacing = 10.16878685 ≅ 10.2 cm.

Figure 25 shows the response surface plot for the infection from tested soils data. The response surface plot in Figure 25 shows the surface is minimum response surface. The minimum value of response can be up to 0 and this means there is possibility of eliminating infections completely since 0 is the minimum number of infected leaves that can exist. The minimum value can be obtained at medium levels of both water and spacing.

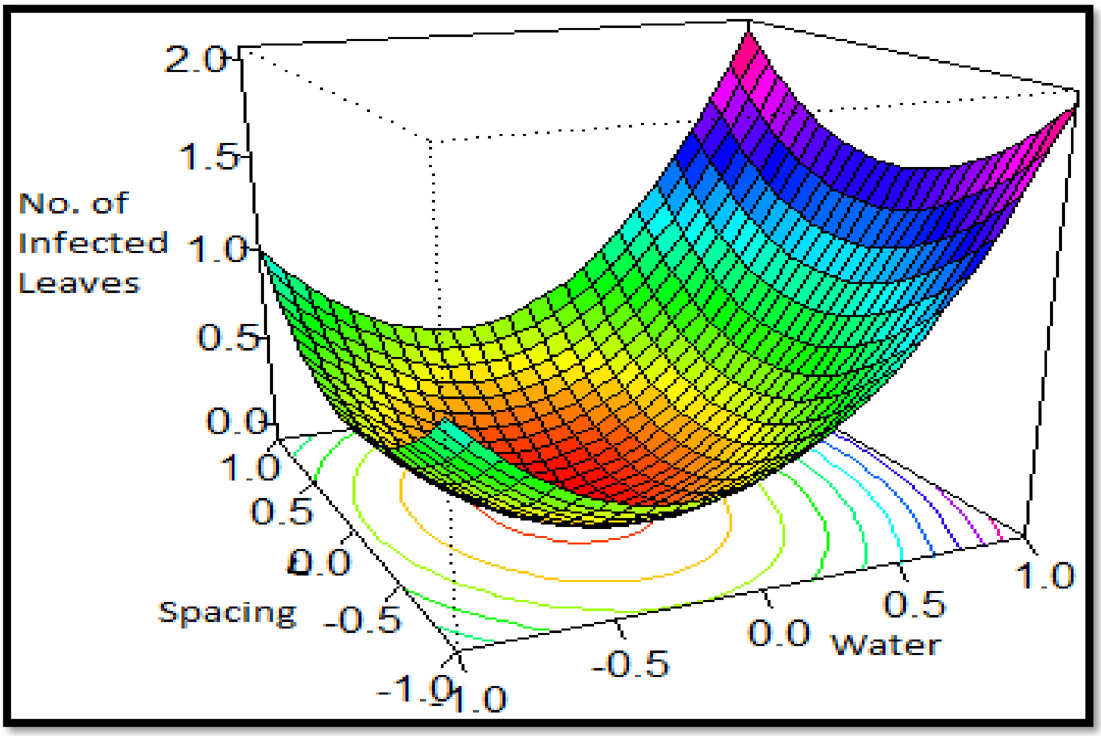


Figure 25: Response surface plot on crop infection's data for tested soils.

Figure 26 shows the contour plot for the infection from tested soils data. It can be depicted from the contour plot in Figure 26, that the process is minimizing response surface since values of response decrease towards the centre of the contours. The minimum value is 0 hence it is possible to have fully healthy crops. The plot confirms that the process is minimizing and hence a minimum response surface.

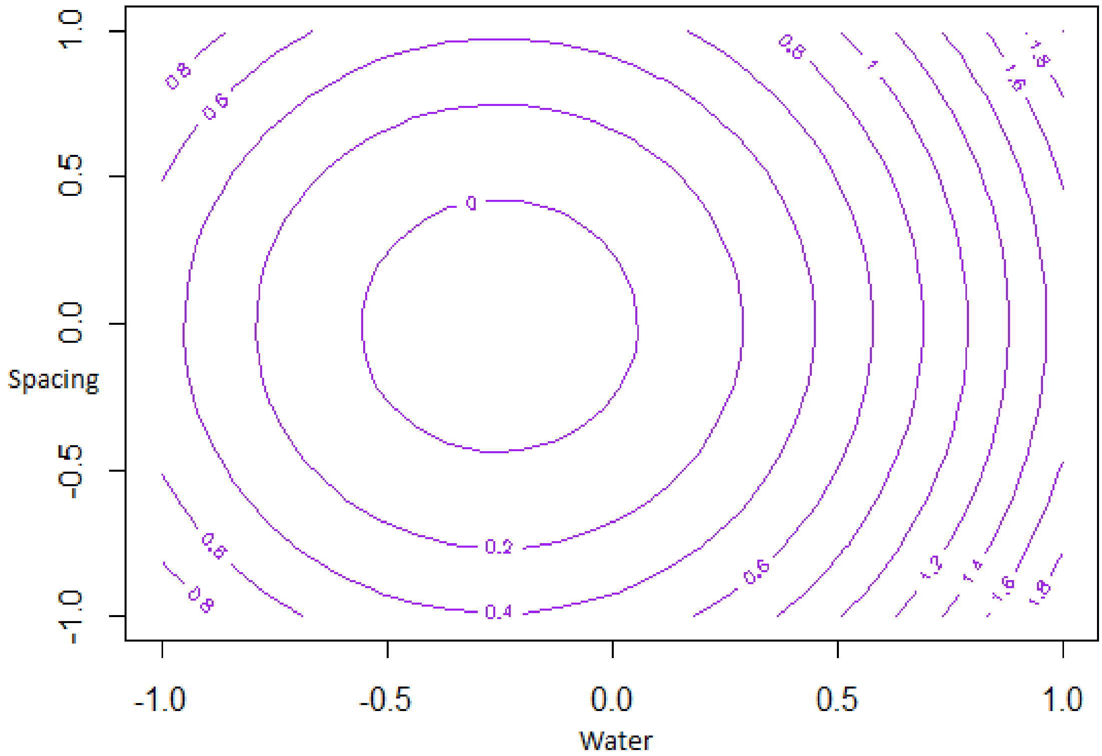


Figure 26: Contour plot on crop infection's data for tested soils.

Testing for the response values that are not predicted well by the fitted second order model, the plot for actual response values verses the model's predicted response values yields the graph shown in Figure 27 and looking at it, one can see that all the data points are split evenly by the 45^0 line (the straight line in the graph). This is an indication that all values are predicted well by the model. Therefore, the model fits the data well and hence it is appropriate as was indicated by the model's p-value, the multiple R^2 and the adjusted R^2.

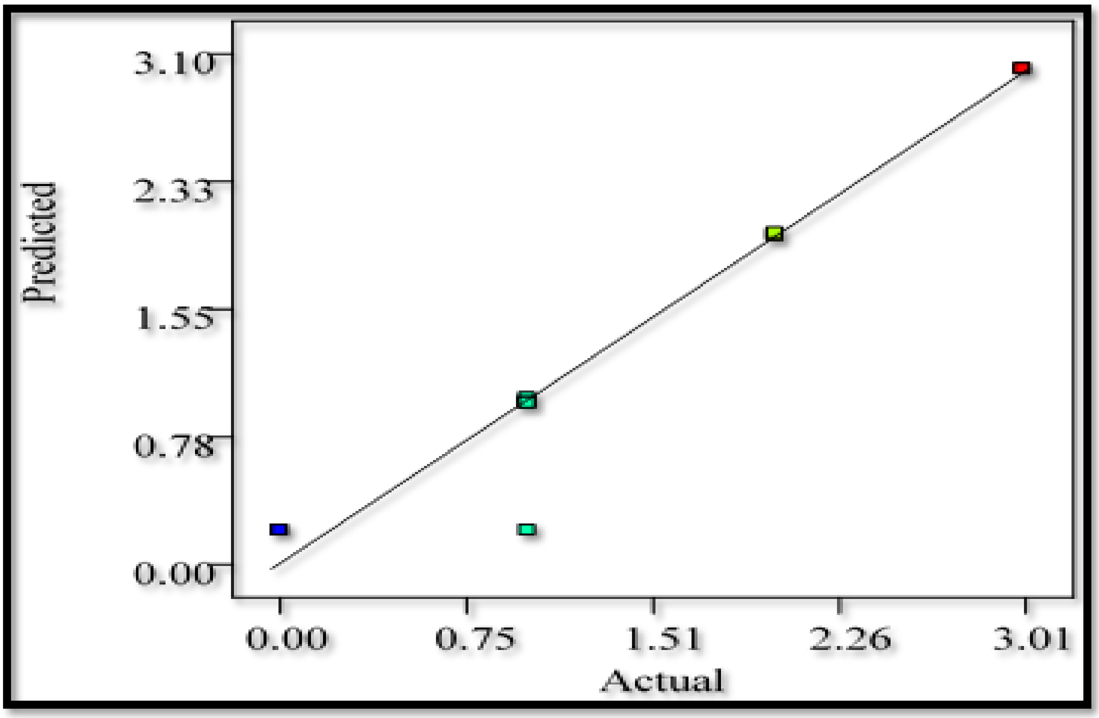


Figure 27: Plot on fitted model's infection's predicted values verses actual values for tested soils.

(iii) Pods

Analysis of pods data

Table 33 gives the output for the fitted pods model from tested soils data. From Table 33 and accompanying model, all the factors affect the number of pods negatively. Increasing any of the factors lowers number of pods per crop point but not all are significant statistically. The p-values corresponding to main effect of water, interaction between manure and spacing and all the quadratic effects are less than the level of significance (5%). This means that their corresponding effects are significant on the number of pods. All the other effects are insignificant since their corresponding p-values are greater than 5% level of significance, and conclusion made that their effects are not significant on the number of pods.

Table 33: Table showing the number of pods' model for tested soils.

	Estimate	Std. Error	t-value	p-value
Intercept	31.7292	0.4813	65.9190	0.0000
X_1	-1.1836	0.5539	-2.1369	0.0857
X_2	-2.1836	0.5539	-3.9422	0.0109
X_3	-0.4336	0.5539	-0.7828	0.4692
X_1:X_2	-0.7057	0.5740	-1.2296	0.2736
X_1:X_3	-2.9557	0.5740	-5.1497	0.0036
X_2:X_3	-0.4557	0.5740	-0.7940	0.4632
X_1^2	-4.7357	1.0503	-4.5087	0.0063
X_2^2	-3.7357	1.0503	-3.5566	0.0163
X_3^2	-2.9857	1.0503	-2.8426	0.0361

$$y_3 = 31.7292 - 1.1836X_1 - 2.1836X_2 - 0.4336X_3 - 0.7057X_1X_2 - 2.9557X_1X_3 - 0.4557X_2X_3 - 4.7357X_1^2 - 3.7357X_2^2 - 2.9857X_3^2$$

In terms of the actual factors, the model from the computer software is given by:

$$No.of\ Pods = -141.1066 + 7.2159 * manure + 20.8937 * water + 8.9093 * spacing - 0.0848 * manure * water - 0.1358 * manure * spacing - 0.1031 * water * spacing - 0.1156 * manure^2 - 2.2105 * water^2 - 0.2583 * spacing^2$$

Table 34 displays the ANOVA output for the fitted pods model from tested soils data. From Table 34, the p-values corresponding to two-way interaction and pure quadratic terms of the model are all less than 5% level of significance. Therefore, the 2-way interaction and the pure quadratic terms of the model are statistically significant and hence they contribute meaningfully to the fitted model. On the other hand, for first order term, the p-value= 0.1165 is greater than the level of significance and hence the first order term is not significant and hence does not contribute significantly to the model fitted. The p-value= 0.7809 for lack of fit from the same table is greater than 5% level of significance. Therefore, lack of fit is not significant. So, statistically there is no lack of fit. Considering the overall p-value= 0.0007, the conclusion is made that the model fits the data well because this value is less than the 5% level of significance. The multiple R^2 = 0.9828 and adjusted R^2 = 0.9518 in the same table help support the overall fitting of the model since the two are above 0.8 and hence there is goodness of fit to the data.

Table 34: ANOVA for number of pods' model for tested soils.

	Df	**Sum Sq**	**Mean Sq**	**F-value**	**p-value**
FO(X_1, X_2, X_3)	3	13.70	4.568	3.2861	0.1165
TWI(X_1, X_2, X_3)	3	47.21	15.737	11.3210	0.0115
PQ(X_1, X_2, X_3)	3	335.73	111.911	80.5055	0.0002
Residuals	5	6.95	1.390		
Lack of fit	1	0.15	0.151	0.0885	0.7809
Pure error	4	6.80	1.700		
Multiple R^2= 0.9828,			**Adjusted R^2**= 0.9518		
F-Statistic= 31.70,		df= (9,5),		**p-value**= 0.0007	

The Eigen-values associated with the response surface are -2.1429, -3.6450 and -5.6691 and all are negative values. This means that the response surface is a maximizing response surface. The stationary points for the model are X_1 = -0.1041, X_2 = -0.2825 and X_3 = 0.0005. The stationary points can be converted to the original/non-coded/natural variables using the formula corresponding to each factor as follows:

$\frac{Manure-24.4}{6.4}$ = -0.1041 ⇒ Manure = 23.7340 ≅ 23.7 g.

$\frac{Water-4.4}{1.3}$ = -0.2825 ⇒ Water = 4.0328 ≅ 4.0 ℓ.

$\frac{Spacing-10.2}{3.4}$ = 0.0005 ⇒ Spacing = 10.2015 ≅ 10.2 cm.

Figure 28 shows the response surface plot for the immature pods from tested soils data. The response surface plot in Figure 28 shows the surface is maximum response surface. The optimal value of response can reach up to slightly above 30 pods. The maximum value can be obtained at medium levels of both water and spacing.

Figure 29 shows the contour plot for the immature pods from tested soils data. As it can be depicted by the contour plot in Figure 29, the process is maximizing response surface since values of the response increase towards the centre of the contours and the maximum value is 32 pods. The plot confirms that the process is maximizing and hence a maximum response surface.

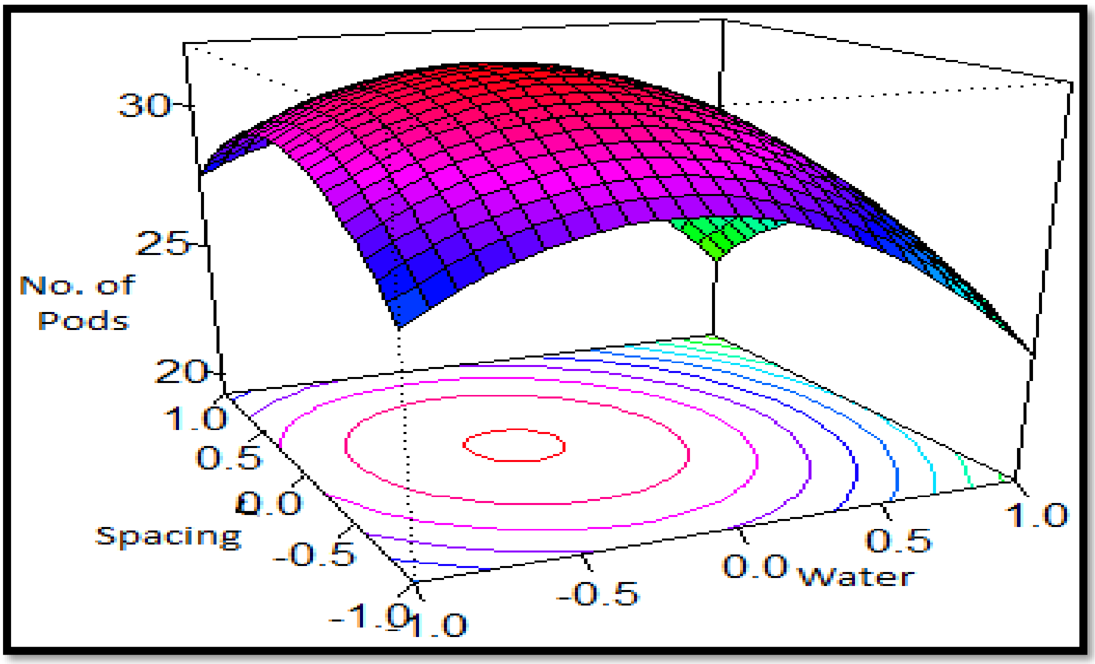


Figure 28: Response surface plot on immature pods' data for tested soils.

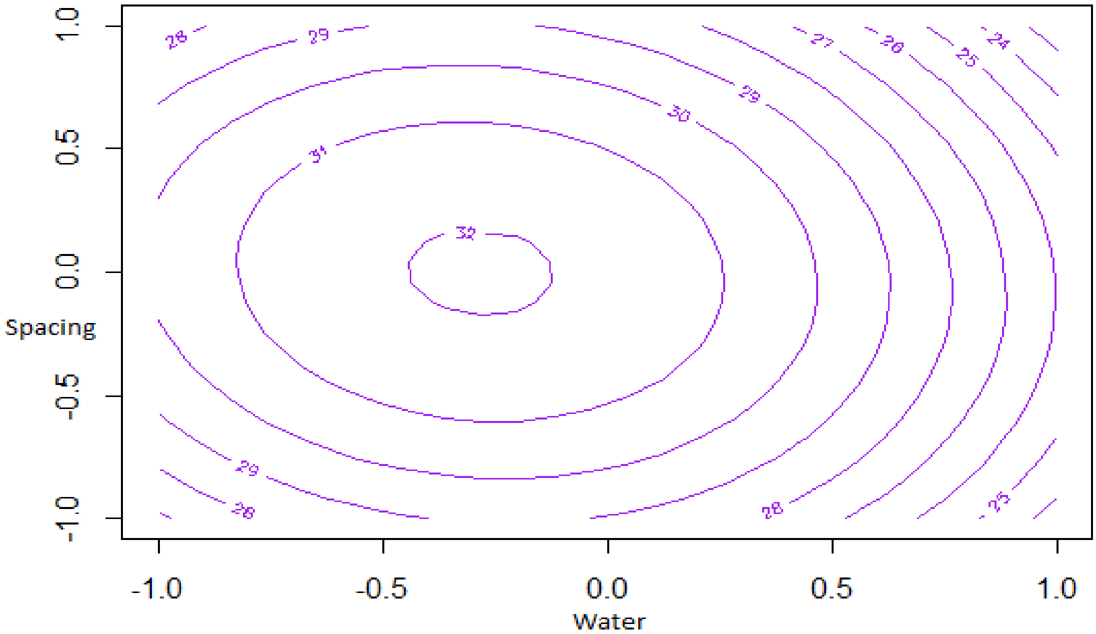


Figure 29: Contour plot on immature pods' data for tested soils.

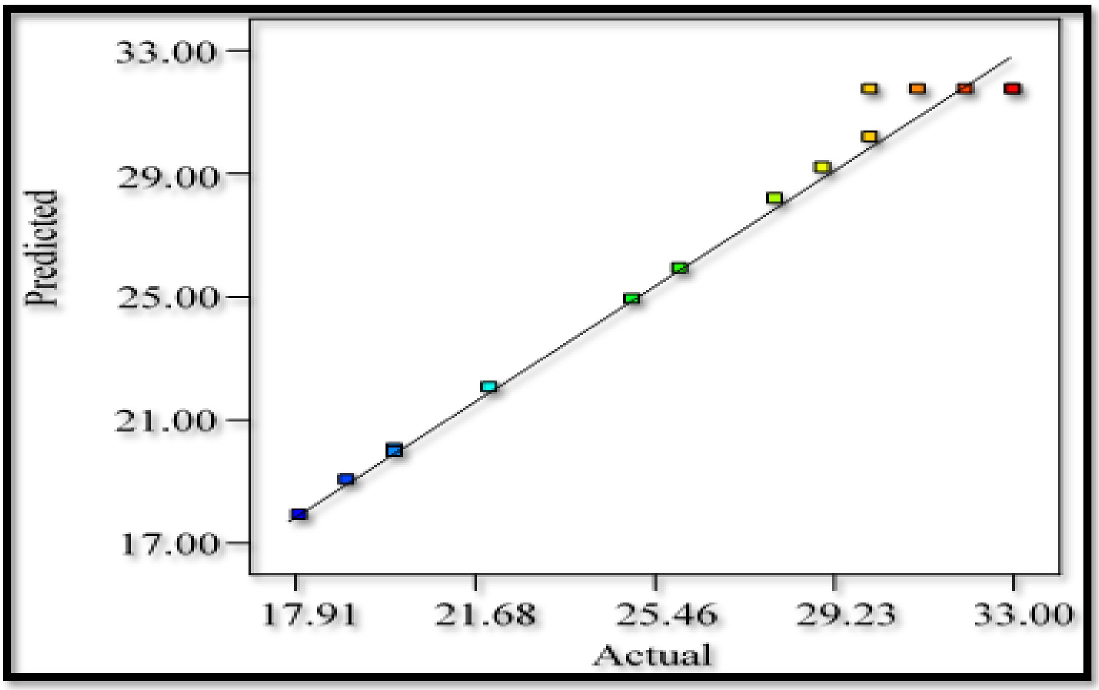


Figure 30: Plot on fitted model's immature pods' predicted values verses the actual values for tested soils.

Testing for the response values that are not predicted well by the fitted second order model, the plot for actual response values verses the model's predicted response values yields the graph shown in Figure 30.

Looking at Figure 30, one can see that all the data points are split evenly by the 45^0 line (the straight line in the graph). Therefore, the model fits the data well and hence it is appropriate as was indicated by the model's p-value, the multiple R^2 and the adjusted R^2.

1. Summary on factor effects

(a) Untested soils

Individually, water affects yield negatively while manure and spacing have a positive effect on it. All the interactions and quadratic terms bring negative effects on yield. At individual levels, plant health improves with manure and spacing while it is negatively affected by water. Any interaction of factors involving manure has a positive effect on plant health while all the quadratic effects lower plant health. Number of pods increases insignificantly with increase in spacing and manure while water increase lowers it significantly. The interaction of manure and spacing, and the quadratic effect of water and spacing reduces number of pods significantly. In general, increase in water amount for irrigation lowers yield, number of pods and plant health while increase in manure and spacing of the crops leads to increased yields, number of pods and better plant health.

(b) Tested soils

Results show that, all the main effects, the interaction terms as well as the quadratic effects lower yields. On plant health, manure and spacing have positive effect while water affects it negatively. All the interactions and quadratic effects affect it negatively except the interaction between water and spacing. All the factors lower the number of pods with water lowering it significantly. In general, increase in factor levels lowers yields and number of pods, increase in manure and spacing improves plant health while increase in water levels reduces it.

2. Summary on models

(a) Untested soils' case

$y_1 = 23.9 + 0.54X_1 - 1.08X_2 + 0.39X_3 - 0.96X_1X_2 - 0.49X_1X_3 - 0.01X_2X_3 - 1.51X_1^2 - 2.03X_2^2 - 0.76X_3^2$ implying that,

$Yield = -45.79 + 2.62 * manure + 12.60 * water + 2.01 * spacing - 0.12 * manure * water - 0.02 * manure * spacing - 0.003 * water * spacing - 0.04 * manure^2 - 1.20 * water^2 - 0.07 * spacing^2$ …………………………………. (13)

$y_2 = 0.40 - 0.56X_1 + 0.44X_2 - 1.31X_3 - 0.12X_1X_2 - 0.37X_1X_3 + 0.63X_2X_3 + 0.56X_1^2 + 1.56X_2^2 + 1.81X_3^2$ implying that,

$Infection = 47.65 - 0.51 * manure - 8.85 * water - 3.78 * spacing - 0.01 * manure * water - 0.02 * manure * spacing + 0.14 * water * spacing + 0.01 * manure^2 + 0.92 * water^2 + 0.16 * spacing^2$ …………………………………. (14)

$y_3 = 20.92 + 0.14X_1 - 1.36X_2 + 0.39X_3 - 0.57X_1X_2 - 0.82X_1X_3 + 0.18X_2X_3 - 1.07X_1^2 - 2.57X_2^2 - 1.82X_3^2$ implying that,

$No.of\ Pods = -52.49 + 1.98 * manure + 13.60 * water + 4.07 * spacing - 0.07 * manure * water - 0.04 * manure * spacing + 0.04 * water * spacing - 0.03 * manure^2 - 1.52 * water^2 - 0.16 * spacing^2$ ……………..…………. (15)

(b) Tested soils' case

$y_1 = 28.38 - 0.61X_1 - 0.78X_2 - 0.21X_3 - 0.86X_1X_2 - 0.69X_1X_3 - 0.61X_2X_3 - 2.05X_1^2 - 1.23X_2^2 - 1.15X_3^2$ implying that,

Yield= -45.51 + 3.13*Manure + 9.73*Water + 3.35*Spacing - 0.10*Manure*Water - 0.03*Manure*Spacing - 0.14*Water*Spacing - 0.05*Manure^2 - 0.73*Water^2 - 0.10*Spacing^2……………...……………………………………………………. (16)

$Yield = -45.51 + 3.13 * manure + 9.73 * water + 3.35 * spacing - 0.10 * manure * water - 0.03 * manure * spacing - 0.14 * water * spacing - 0.05 * manure^2 - 0.73 * water^2 - 0.10 * spacing^2$ .... (16)

$y_2 = 0.21 - 0.51X_1 + 0.24X_2 - 0.26X_3 + 0.24X_1X_2 + 0.24X_1X_3 - 0.01X_2X_3 + 0.26X_1^2 + 1.01X_2^2 + 0.51X_3^2$ implying that,

$Infection = 28.05 - 0.64 * manure - 5.79 * water - 1.25 * spacing + 0.03 * manure * water + 0.01 * manure * spacing - 0.001 * water * spacing + 0.006 * manure^2 + 0.60 * water^2 + 0.04 * spacing^2$ .... (17)

$y_3 = 31.73 - 1.18X_1 - 2.18X_2 - 0.43X_3 - 0.71X_1X_2 - 2.96X_1X_3 - 0.46X_2X_3 - 4.74X_1^2 - 3.74X_2^2 - 2.99X_3^2$ implying that,

$No.of\ Pods = -141.11 + 7.22 * manure + 20.89 * water + 8.91 * spacing - 0.08 * manure * water - 0.14 * manure * spacing - 0.10 * water * spacing - 0.12 * manure^2 - 2.21 * water^2 - 0.26 * spacing^2$ .... (18)

4.3.4 Locating optimal levels of factors

Using these results, analysis was done to determine the optimal levels of factors that optimize the outputs and plant health simultaneously. This is to mean, finding the factor levels that can maximize yields and number of pods as well as minimize infections (minimizing the number of leaves that are infected or maximizing the plant health) concurrently. This was done in Design Expert software to locate the optimal levels. The results are displayed below in terms of numerical and graphical optimization.

(a) Untested soils' case

(i) Numerical optimization technique

Table 35 shows the numerically optimized values for both control factors and responses for untested soils case. The optimization was done with the actual factors and the results would be the same even when the coded variables are used. As can be seen from Table 35, optimal amount of manure is 26.06 g (0.2500 in coded form), optimal water amount is 4.03 ℓ (-0.2846 in coded form) and optimal spacing is 11.13 cm (0.2735 in coded form) from one crop to another. Included therein are the theoretical expected outcomes at the optimal factor levels. These are yield, infected leaves and number of pods per crop point which are given as 24.1719 g, 0 leaves and 21 pods respectively. The desirability value is 0.9930 which is very acceptable since it is very close to 1. When equal to or close to 0, the results are not acceptable.

Table 35: Table showing the numerical optimization for untested soils' models.

Optimal Levels of Control Factors			**Expected Responses**			**Desirability**
Manure (g)	Water (ℓ)	Spacing (cm)	Yield (g)	No. of Infected Leaves (Infection)	No. of Pods	
26.06	4.03	11.13	24.1719	0.0000	21	0.9930

(ii) Graphical optimization of responses

This technique uses the overlay contours plot in locating the overall optimizing factor levels as well as the expected outcome at optimal factor levels. Figure 31 is the overlay plot for the untested soils experimental data.

The overlay contour plot in Figure 31, incorporates all the three contour plots for optimization. It can be seen that it shows all the optimal responses and factor levels in one plot. The optimized yield, infection and pods are shown in the flag coloured white and they are all in agreement with the previous individual table and graphs. The optimizing factors levels are 26.06 g, 4.03 ℓ and 11.13 cm for manure, water and spacing respectively. In this overlay contour plot, infection is shown as 0 in the plot. All these results are in agreement with the results in Table 35 on numerical optimization.

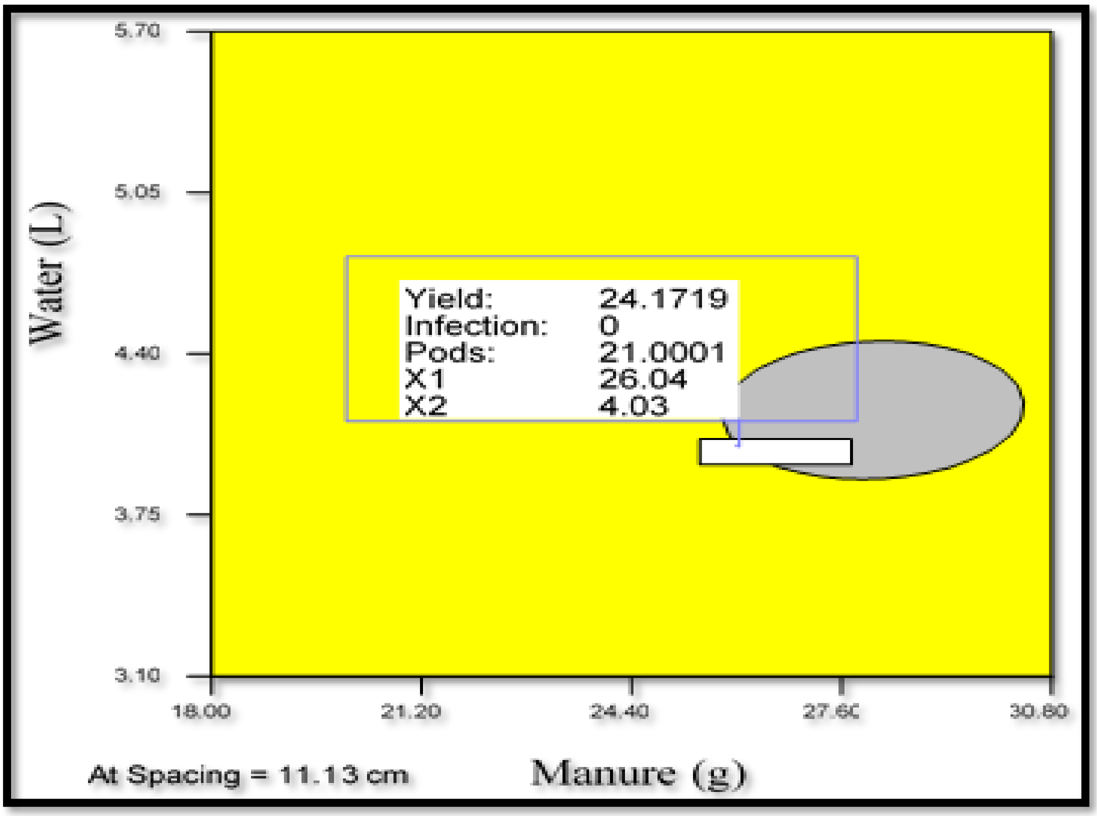


Figure 31: An overlay contour plot for untested soils.

(b) Tested soils' case

(i) Numerical optimization on responses

Table 36 shows the numerically optimized values for both control factors and responses for tested soils case. The optimization was done with the actual factors and the results would be the same even when the coded variables are used.

Table 36: Numerical optimization for tested soils' models.

Optimal Levels of Factors			Expected Outcome			Desirability
Manure (g)	Water (ℓ)	Spacing (cm)	Yield (g)	No. of Infected Leaves (Infection)	No. of Pods	
24.54	4.10	10.33	28.4851	0.1861	31.9919	0.9500

From Table 36, optimizing factor levels are 24.54 g (0.0219 in coded form), 4.10 ℓ (-0.2308 in coded form) and 10.33 cm (0.0382 in coded form) for manure, water and spacing respectively. The theoretical predicted optimal responses are 28.4851 g, 0.1861 leaves and 31.9919 pods for yield, infection and number of pods respectively. Desirability is 95.0% or 0.950 which is close to 1 and hence acceptable.

(ii) Graphical optimization

Figure 32 is the overlay plot for the tested soils experimental data. The overlay contour plot in Figure 32 incorporates all the three plots for optimization. It can be seen that it shows all the optimal responses and factor levels in one plot. The optimized yield, infection and pods are shown in the flag coloured white and they are all in agreement with the previous individual table and graphs. The optimizing factors levels are 24.54 g, 4.10 ℓ and 10.33 cm for manure, water and spacing respectively. All these results are in agreement with the results obtained in Table 36 on numerical optimization.

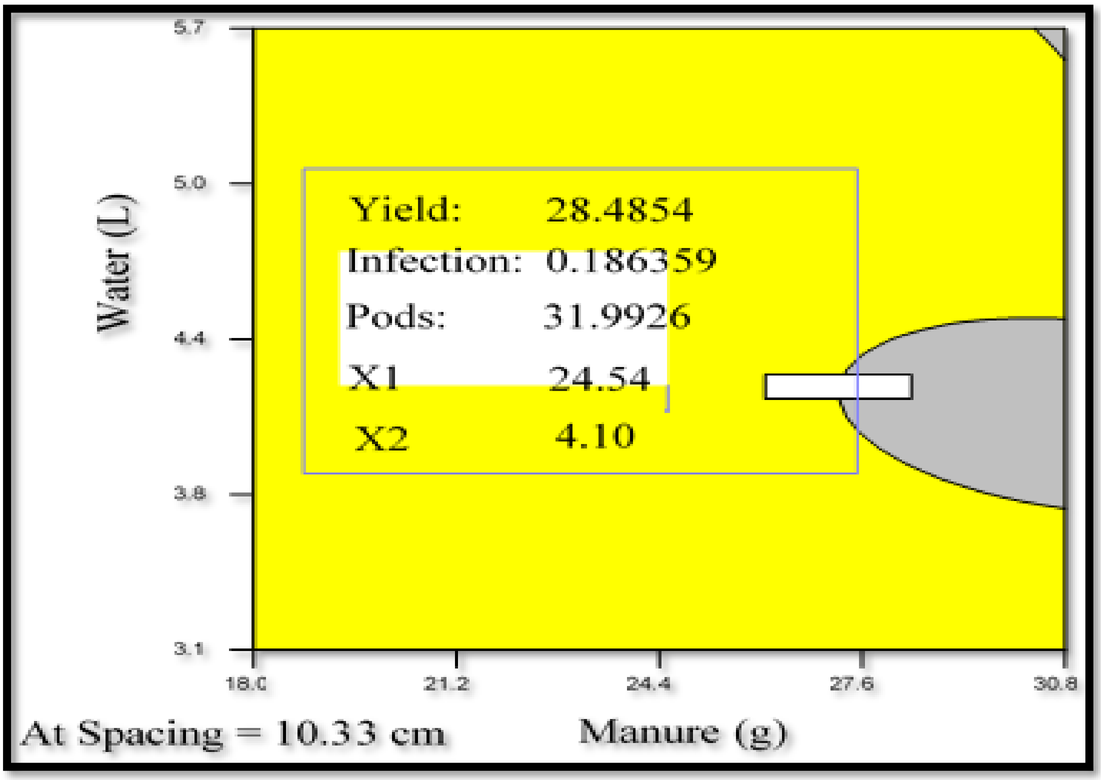


Figure 32: An overlay contour plot for tested soils.

4.4 Objective 4- Comparison of results

The optimal factor levels obtained from objective 3 were applied in replicates and optimal responses obtained for both tested and untested soils. From the first and second experiments, results were obtained for yields for two-week harvests, number of infected leaves and number of immature pods after two-week harvesting, per crop point. These results were averaged and the average was used for analysis. The comparison of the models was done in R using t-tests for the data obtained from replicated experiments. Also, ANOVA was performed to compare data from the two models and the sample survey data.

4.4.1 Experimental data for optimal responses

The data obtained from experiments involving optimal factor levels are shown in the appendix 6. It is for both untested and tested soils' cases for all the three responses of interest.

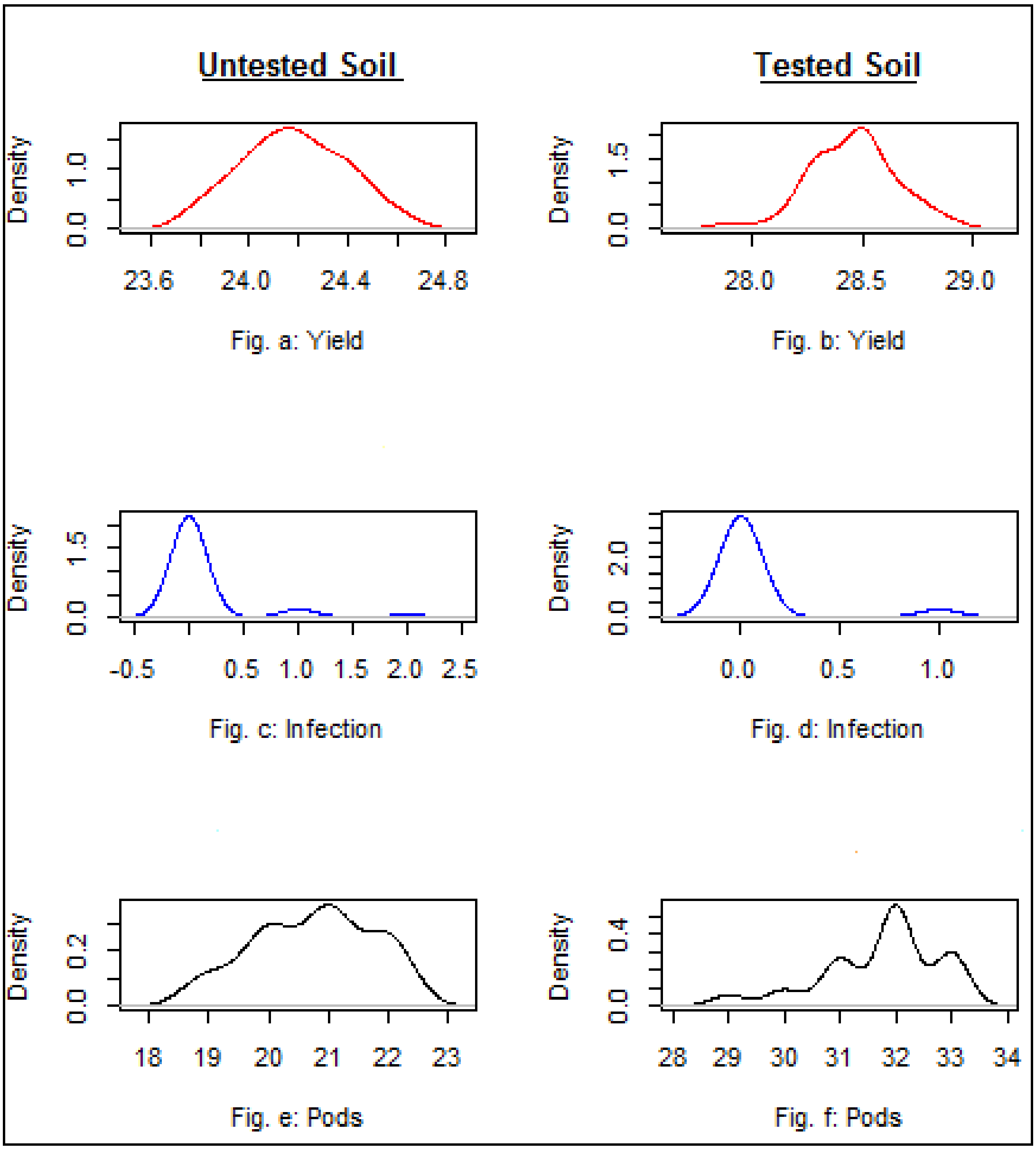


Figure 33: Normal curve plots on optimal responses' data for both untested and tested soils.

Figure 33 shows the plotted curves for the data from final experiments. The first 2 plots (Fig. a and Fig. b) of Figure 33 are for yield. They demonstrate that the data is approximately normally distributed. Fig. c and Fig. d for number of infected leaves do not show any bell-shapes and thus the data that is not normally distributed. Fig. e and Fig. f are for number of immature pods and they too do not show normally distributed data.

4.4.2 Statistical tests using t-tests and ANOVA

First, t-tests were performed for each set of data to test if the mean output is equal to the theoretical optimal response for all cases. For the untested soils, the optimal yield, infections and number of pods were tested if their means are statistically equal to the theoretical responses 24.1719 g, 0 leaves and 21 pods respectively. For the tested soils, the optimal yield, infections and number of pods were tested if their means are statistically equal to the theoretical responses 28.4851 g, 0 leaves and 31.9919 pods respectively.

(a) Untested soils' case

Table 37 displays the t-test results from the untested soils data. From Table 37, it can be seen that all the p-values are greater than the 5% level of significance. Therefore, the experimental optimal values for yield, infection and pods are all equal to the theoretical values optimized by the software.

Table 37: T-tests for untested soils responses.

Response	t-value	df	p-value	95% C. I	Sample Means
Yield	0.2955	42	0.7691	[24.1165, 24.2463]	24.1814
Infected Leaves	1.9505	42	0.0578	[-0.00403, 0.2366]	0.1163
No. of Pods	-1.7149	42	0.0937	[20.4432, 21.0452]	20.7442

(b) Tested soils' case

Table 38 displays the t-test results from the tested soils data. From Table 38, it is clear that all the p-values are greater than the 5% level of significance and hence all the null hypotheses are retained. Therefore, the experimental optimal values for yield, infection and pods are all equal to the theoretical values optimized by the software. This means that, the theoretical optimal values were found to be equal to the experimental optimal values for both cases.

Table 38: T-tests for tested soils responses.

Response	t-value	df	p-value	95% C. I	Sample Means
Yield	-0.9045	42	0.3709	[28.3980, 28.5183]	28.4581
Infected leaves	1.7748	42	0.0832	[-0.0096, 0.1491]	0.0698
No. of Pods	-1.5490	42	0.1289	[31.4215, 32.0669]	31.7442

4.4.3 Comparison of the models

Concerning the comparison of the two sets of models, the experimental optimal outputs were compared using t-test for the two sets of data. ANOVA was used to compare the two sets of data and the sample survey data. The t-tests and ANOVA outputs are as displayed in Table 39 and 40 respectively.

Table 39 has p-value = 0.0000 for the yield and number of pods. This p-value is less than α = 5% level of significance. Therefore, the optimal mean yield and number of pods are different for the two cases and hence, the optimal mean yield and number of immature pods for the tested soils' case are greater than those for untested soils' case. This makes sense because the minimum number of infected leaves that can be achieved is 0 and both cases had mean number of infected leaves statistically equal to 0. In general, the soil tested case has better results than the untested soils' case.

Table 39: T-tests for comparison between tested and untested soils responses.

Response	t-value	df	p-value	95% C. I	Sample Means
Yield (g)	-97.5710	84	0.0000	[-4.3639, -4.1896]	24.1814, 28.4581
Infected Leaves	0.6513	84	0.5169	[-0.0958, 0.1888]	0.1163, 0.0698
No. of Pods	-50.3000	84	0.0000	[-11.4349, -10.5651]	20.7442, 31.7442

ANOVA

Table 40 shows all the p-values are far much less than the 5% level of significance. This means that the means of the three responses are different across the three sets of data. Therefore, the mean yields, mean number of infected leaves and the mean number of immature pods are not equal for the three sets of data. Therefore, further tests such as Least significant difference (LSD), Bonferroni tests, and Tukey's Honestly Significant Difference (Tukey's HSD) are needed. Table 41 shows the results from further test (Tukey's HSD).

Table 40: ANOVA for comparison among the three sets of data.

Response	Sum of Squares	df	Mean	F-value	p-value
Yield	8065.0	2	4033	7698.4	<0.0001
Residuals	66.0	126	0.52381		
Infected Leaves	620.2	2	310.1	122.3	<0.0001
Residuals	319.4	126	2.53492		
No. of Pods	8765.0	2	4382.5	2432.6	<0.0001
Residuals	227.0	126	1.80159		

From Table 41 output, it is clear that all of the differences are significant since the upper and lower limits do not contain zero except for the case of untested-tested soils infection. Starting with yields, each case is different from the others since the three limits corresponding to yields exclude zero in the interval. For the infections, the only difference that is not significant is for that between tested and untested soils since the interval includes zero. This confirms what was found out when t-test was used to compare the models' optimal responses, that for both tested and untested soils' cases, their mean infected leaves are equal to 0. The other differences are significant. Turning the attention to the number of immature pods, all the intervals exclude zero hence the number of pods is different when compared across the three cases.

Table 41: Further tests on the three sets of data (Tukey's HSD).

Response	**Case**	**Difference**	**[Lower limit**	**Upper limit]**
Yield	Tested-Sample	18.4977	[18.1265	18.8689]
(g)	Untested-Sample	14.2209	[13.8497	14.5921]
	Untested-Tested	-4.2767	[-4.6479	-3.9056]
Infection	Tested-Sample	-4.6744	[-5.4888	-3.8600]
	Untested-Sample	-4.6279	[-5.4423	-3.8135]
	Untested-Tested	0.0465	[-0.7679	0.8609]
No. of Pods	Tested-Sample	20.1628	[19.4765	20.8491]
	Untested-Sample	9.1628	[8.4765	9.8491]
	Untested-Tested	-11.0000	[-11.6863	-10.3137]

Since the tested soils' case has the highest mean for yields and number of unharvested pods, as well as the lowest mean for the number of infected leaves then conclusion is that the tested soils' case has better models in terms of optimizing the three responses simultaneously. even the untested soils' case had better results than what the farmers are currently experiencing. This means that the farmers need only to balance what they have in terms of applying the right quantities of inputs for better outputs.

4.4.4 Investigating fixed factor levels for untested and tested soils' cases

Since the Tested Soils' Case was found to have the better set of models than the untested soils' case, investigation for the Tested Soils' Case was necessary to see the behaviour of the responses of interest at each fixed level of a given factor while the rest of the factors are at optimal point. This yielded three values for each response corresponding to each factor as discussed in the subsequent sub-sections. However, even for the untested soils' case, investigation was still done. Table 42 and 43 show the results for the behaviour of each response based on fixed levels of each control factor when the rest of factors are optimal.

(a) Untested soils' case

For the untested soils case, Table 42 shows the mean responses at the three levels of animal manure when water is at 4.03 ℓ and spacing is at 11.13 cm, at the three levels of water when animal manure is at 26.06 g and spacing is at 11.13 cm as well as at the three levels of crop spacing when animal manure is at 26.06 g and water is at 4.03 ℓ.

From Table 42, when water = 4.03 ℓ and spacing = 11.13 cm, the yield and immature pods are highest at the centre of the manure levels while infected leaves are fewest at the highest level of manure. Therefore, plant health gets better with increase in manure. When manure = 26.06 g and spacing = 11.13 cm, the yield and immature pods are highest at the centre of the water levels while infected leaves are least at the centre of the water levels. When manure = 26.06 g and water = 4.03 ℓ, the yield and immature pods are highest at the centre of the spacing levels while infected leaves are least at the centre of the spacing levels.

Table 42: Varying the levels of manure, water and spacing for untested soils' case.

At water = 4.03 ℓ and spacing = 11.13 cm			
Manure Levels (g)	18.0	24.4	30.8
Yield (g)	21.9	24.1	23.28
No. of Infected Leaves	1.31	0.12	0.06
No. of Immature Pods	19.9	21.05	20.06
At animal manure = 26.06 g and spacing = 11.13 cm			
Water Levels (ℓ)	3.1	4.4	5.7
Yield (g)	23.26	23.96	20.59
No. of Infected Leaves	1.01	0.04	2.18
No. of Immature Pods	19.68	20.79	16.77
At animal manure = 26.06 g and water = 4.03 ℓ			
Spacing Levels (g)	6.8	10.2	13.6
Yield (g)	23.13	24.15	23.67
No. of Infected Leaves	3.69	0.3	0.52
No. of Immature Pods	19.16	21.1	19.41

(b) Tested soils' case

For the tested soils case, Table 43 shows the mean responses at the three levels of animal manure when water is at 4.10 ℓ and spacing is at 10.33 cm, at the three levels of water when animal manure is at 24.54 g and spacing is at 10.33 cm as well as at the three levels of crop spacing when animal manure is at 24.54 g and water is at 4.10 ℓ.

From Table 43, when water = 4.10 ℓ and spacing = 10.33 cm, the yield and immature pods are highest at the centre of the manure levels while infected leaves are least at the highest level of the manure. When manure = 24.54 g and spacing = 10.33 cm, the yield and immature pods are highest at the centre of the water levels while infected leaves are least at the centre of the water levels. When manure = 24.54 g and water = 4.10 ℓ, the yield and immature pods are highest at the centre of the spacing levels while infected leaves are least at the centre of the spacing levels.

Table 43: Varying the levels of manure, water and spacing for tested soils' case.

At water = 4.10 ℓ and spacing = 10.33 cm			
Manure Levels (g)	18.0	24.4	30.8
Yield (g)	26.88	28.50	26.01
No. of Infected Leaves	1.02	0.20	0.09
No. of Immature Pods	28.41	32.02	26.16
At animal manure = 24.54 g and spacing = 10.33 cm			
Water Levels (ℓ)	3.1	4.4	5.7
Yield (g)	27.96	28.36	26.31
No. of Infected Leaves	0.95	0.19	1.45
No. of Immature Pods	30.16	31.68	25.73
At animal manure = 24.54 g and water = 4.10 ℓ			
Spacing Levels (g)	6.8	10.2	13.6
Yield (g)	27.42	28.49	27.26
No. of Infected Leaves	0.96	0.19	0.46
No. of Immature Pods	29.42	32.01	28.63

The photographs taken during the experiments are in the appendix 7.

4.5 Discussions

Table 44 is a summary of what it means by inputs and outputs based on (i) literature, (ii) what farmers are operating and (iii) the experimental findings. From Table 44, the figures in brackets are measurements per crop point on average. As can be seen, the recommended, farmers' practice and experimental spacings yield different number of crops in an acre of land, although all are still within the range of 60,000 to 160,000 crop points per acre. Translating these into inputs, farmers apply less manures, D.A.P and C.A.N while applying more water per crop point than what is recommended. This can be due to the fact that water is not bought or offered by companies but always available in plenty from rivers, pods and streams and hence farmers can apply as much as they want. Although farmers receive enough inputs on inorganic fertilizers from French bean companies, they do not apply the same as advised by the companies' staff. This is in agreement with other researchers that the farmers from developing countries ration the inputs because they do not take French beans as high-input-demanding crops and this affects production/outputs negatively. The experiments cases show that less inputs are required for both organic and inorganic manures while requiring more water compared to what is recommended. For the case of outputs, famers produce output that is very far from the upper limit of the recommended tonnes (t) per acre and the crops are unhealthy as evidenced by the number of infected leaves. However, the experiments have higher outputs than the farmers' case. The tested soils case has output that is close to the upper limit of what is recommended and it is possible to exceed it because there are still unharvested pods in the fields. In general, less inputs are required while more is obtained from the experimental point of view compared to the farmers' practice.

Table 44: Illustration of conversion of inputs into outputs.

	Land Size (m2)	Spacing (cm)	Crop Points	
Recomm.	4047 (Acre)	15 by 30	89,933	
Survey	4047 (Acre)	9.8 by 27	152,948	
Untested	4047 (Acre)	11.1 by 27	135,035	
Tested	4047 (Acre)	10.3 by 27	145,523	
Inputs	***Manure (t)***	***D.A.P (kg)***	***C.A.N (kg)***	***Water (ℓ/week)***
Recomm.	7.0 (77.8g)	80.0 (8.9g)	60.0 (6.7g)	2.25
Survey	3.8 (24.7g)	71.9 (4.7dg)	38.2 (2.5dg)	4.4
Untested	3.5 (26.1g)	76.3 (5.65dg)	35.8 (2.65dg)	4
Tested	3.6 (24.5g)	36.4 (2.5dg)	36.4 (2.5dg)	4.1
Outputs	***Yield (t)***	***Pods (*10^3)***	***Infection***	
Recomm.	4 to 18			
Survey	6.1	1,835 (12)	765,000 (5)	
Untested	13.1	2,836 (21)	0 (0)	
Tested	16.6	4,657 (32)	0 (0)	

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

A sample survey research on French beans production was done at Kariua sub-location in Kandara constituency, Murang'a county, Kenya, to helped assess the situation at which the farmers operate and to determine the levels of factors of interest at which the experiments could be conducted. The factors of interest were the amount of manure, the amount of water and spacing- which were found to be between 18.0 and 30.8 g, 3.1 and 5.7 ℓ, and 6.8 and 13.6 cm respectively. These measurements became the starting point for the experiments. The amounts of fertilizers (D.A.P and C.A.N) used were of interest in terms of comparing the sets of models developed during the experiments and these were found to be between 3 and 8.3 dg for D.A.P and 2.1 and 3.2 dg for C.A.N. The responses of interest were the mass of average harvest, the number of infected leaves and the number of unharvested/ immature pods and they were found to be between 7.3 and 13.4 g, 0 and 8 leaves, and 8 and 15 pods respectively. The farmers' fields were full of unhealthy crops whereas no factor of interest was found that could be used to predict any response of interest. This indicated an underlying problem(s) since some factors like spacing affect French beans output in one way or the other. The problems identified are low application of both organic and inorganic manures and the farm-land sizes below 120 m^2 as well as un-weeded lands are an indication of extremely limited resources at their disposal and poor farming techniques. All these findings support and agree with what the researcher had initially as was coined in the statement of the problem that there are limited resources like land in the area, rationing of inputs and poor farming practices.

Seven designs for fitting 2^{nd} order models were found to be commonly applied and one was chosen for application purposes using D-, A-, E- and T- optimality criteria in which the information matrices for the optimal designs were constructed and their determinants, Eigen-values, average variances and traces computed. Ranking of the values showed that the Hoke D2 design emerged the best in the three criteria (D-, A- and E-) while the same was 4^{th} in one criterion (T-), and this supports the fact that a design may be optimal in one criterion but fails in another because each is constructed to satisfy a certain criterion. Therefore, Hoke D2 was chosen as the best design for application and was the most economical among the seven due to its fewest number of runs.

Soil testing analysis was performed to determine the appropriate levels of fertilizers to be applied and this was found to be between 2 and 3 dg per crop point at any given application time, for both D.A.P and C.A.N. This is indeed micro-dosage and refutes the notion that an increase or continuous application of fertilizers improves outputs. From these recommendations and the survey findings, two sets of experiments were run concurrently using the RSM technique and the Hoke D2 design- one for untested soils involving application of 5.65 and 2.65 dg of D.A.P and C.A.N respectively and the other for tested soils involving application of 2.5 dg of both D.A.P and C.A.N. This is an indication that the fertilizers were acting like treatments along which comparisons of outputs could be made. The results showed that the optimal levels of factors were 26.06 g of manure, 4.03 ℓ of water and 11.13 cm of spacing for the untested soils' case while the same was found to be 24.54 g of manure, 4.10 ℓ of water and 10.33 cm of spacing for the Tested Soils' Case. Furthermore, both theoretical and practical optimal responses were found to be in agreement for both untested and tested soils' cases.

Comparing the results for untested soils with those of tested soils using t-tests, the means of yields and unharvested pods for tested soils were found to be higher than those from untested soils while the level of infection was the same for both cases. This implies that, the models developed using tested soils were better in optimizing French beans yields and health simultaneously. Furthermore, both sets of results were found to be better than the current situation that the farmers are experiencing. Therefore, farmers should apply low levels of inorganic fertilizers, 2.5 dg per crop point and 24.5 g of animal manure, 4.1 ℓ of water per crop-point per week and have their crops spaced up to 10.3 cm apart. This would guarantee them better results and more income. As was observed, the tested soils' case with micro-dosing of fertilizers had better outputs than the untested soils' case with more fertilizers applied and this could be an evidence of soils that are already accumulated with toxic levels of nutrients. This could be one of the reasons as to why majority of the farmers experience low outputs and unhealthy crops. The results also show that it is possible to use any factor and any factor interaction in predicting outputs and crop health, unlike the case practiced by farmers, and this is an indication that farmers could be experiencing low outputs and poor plant health due to poor combination of factors which can combine at levels that can create unconducive environment for crops to thrive. The findings also echo what experts and other researchers emphasize on, that soil testing analysis should be performed before farmers engage in efficient farming practices.

On factor effects, increase in manure and spacing leads to less infections and hence better plant health for both tested and untested soils' cases while more water leads to more infections and hence poor plant health for both tested and untested soils' cases. It's evident that more manure and more spacing for untested soils' case improve yield and pods while conversely, lowering the same in the tested soils' case. However, for both cases, increasing water for irrigation lowers yield and number of pods. Similarly, the quadratic effects lower yield and pods while increasing infections, in both tested and untested soils' cases. For both cases, interaction between manure and water lowers yield and number of pods, while on the other hand lowers the rate of plants infection in untested soils' case. The interaction between water and spacing lowers yield and increases infection and number of pods for untested soils' case while similarly lowering yield, number of pods and infections in tested soils' case.

In general, the difference in output between tested and untested soils' cases is an indication that crops do better with less amounts of fertilizers in the region. Therefore, the poor production in French beans in Kariua area can be attributed to accumulated amounts of the nutrients supplied by the fertilizers such as ammonia, phosphate, nitrogen and manure among others in soils. These results are in agreement with other researchers' findings that crops can do better even for many years without addition of some of these nutrients because they have accumulated to toxic levels in soils over time. Considering the soils analyst's recommendations on application of D.A.P and C.A.N, it can be seen that the dosage of between 2 and 3 dg is indeed micro-dosing and this has resulted in better yields and better crop health, which is in agreement with previous research where farmers in some regions rely on micro-dosage of inputs for better yields in sorghum and other crops. Farmers need to change their practices in application of inputs for their benefit by using the appropriate rates of control factors identified in this study.

5.2 Recommendations and way forward

This goes to the Kariua French bean farmers, companies and other researchers.

5.2.1 Recommendations

1. The farmers should adopt the findings and use the optimal factors' levels as were found; 24.5 g of manure per crop point, 4.1 ℓ of water per week per crop point and spacing of 10.3 cm, for maximum benefit from their limited land and scarce animal manures. This is because the factor levels combinations were found to be producing better results than any other levels combinations.
2. Farmers should apply low levels of fertilizers (2.5 dg per crop point at any application time for both D.A.P and C.A.N). This is because at lower levels, the crops were found to be doing better and are healthier than at higher levels of fertilizer application. Even the soil analyst's recommendations are in agreement with the output that more is obtained from less fertilizers.
3. Farmers can apply factor levels 26.1 g, 4.0 ℓ and 11.1 cm for manure, water and spacing respectively but this should be accompanied by higher amounts of fertilizers (5.65 and 2.65 dg of D.A.P and C.A.N respectively). However, this cannot guarantee them the maximum outputs though it would be better than what they are currently experiencing.
4. The French beans companies in Kariua region should embrace the new knowledge and advise their farmers accordingly; on how to apply the recommended rates of fertilizers so that they can save on the unnecessary costs previously incurred.
5. Researchers should employ the Hoke D2 design in experiments involving fitting of 2^{nd} order models, commonly used designs, D-, A-, E-, T- optimality criteria, 3 factors of interest and 5 centre points. This is because the design was found to be the best in the minimization of variance and most economical due to least number of runs compared to other designs.

5.2.2 Way forward

1. More researches should be done based on even less amounts of fertilizers since this research has revealed that more is produced with less fertilizers. This can help investigate whether more can still be achieved with the limited resources and even help in reducing the rate at which toxin can accumulate in soils due to overuse of these fertilizers.
2. More researches should be done to investigate optimization that is based on non-application of spraying chemicals in order to have produce that is suitable for consumption both locally and internationally. This research relied on spraying chemicals as farmers do and it is hard to know whether or not these chemicals contributed significantly in improving plant health and yields. Therefore, a research that doesn't rely on these chemicals can help compare and see the effects of the chemicals on yields and crop health improvement.
3. More research should be done to test other varieties of French beans apart from the Gregor variety that was tested in this research. This is because there are other varieties cultivated during other years and farmers keep interchanging the varieties with time. Also, different varieties depend on climate, soil contents, spacing and other factors and it would be better if farmers are given advice meet for any variety they cultivate.
4. A research to be done to investigate the loss incurred by farmers due to unwanted pods. This is because there were a lot of pods that went into waste when determining the suitable pods to be considered for mass recording during the sample survey exercise, ad this research didn't consider that for any analysis. Farmers could be producing more for "food to themselves" than to their clients (foreigners).
5. A research to be conducted based on a single seed per crop point. This research relied on the custom of the farmers in the region of sowing more than one seeds per crop point. A research relying on one seed per point could help compare the results and help in determining the better way for the farmers.
6. A research that is not relying on assumption of homogeneous soils in the whole region should be conducted. This should imply that blocks should be created and determine variations in soils for different parts of that region based on crops

results. This research assumed homogeneity of soils and hence blocking was not necessary and hence any variation in soils could not be detected with the results obtained.

7. In this research, only the infected leaves were used in determining the crops' health but infections occur in roots, stems and pods of the crops as well. The recommendation is that a research should be conducted that is based on all these parts of crops in determining the crops health since a crop may be affected more by diseases and pests on one part than on another.

8. A wide range of optimality criteria to be employed in choosing design. This is because there are so many criteria that can be used in optimality of designs and hence a way of not limiting the criteria to just D-, A-, E- and T- optimality is required. Even more designs can be included apart from the seven designs considered in this research.
9. Another research to be done involving all the seven designs practically in the field. This research chose only one design but a research can be done where all the seven designs are involved and compare the designs based on the results from the experiments. This would help understand whether a design is optimal theoretically and practically too.
10. The research to be extended to other areas where farmers do not practice soil testing before applying various inputs. This is because, experts recommend analysis of soil testing before farmers can engage in any form of crop farming. However, most farmers do not consider soil analysis in their farming activities due to various reasons such as inability to hire soil analysts.
11. More research on optimal design to be done to test optimality based on different number of centre points. This research considered only 5 centre points and Hoke D2 emerged as the design of choice. The 3 and 4 centre points can also be considered and see if the results would be different or not.

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APPENDICES

Appendix I: The questionnaire used during the sample survey data collection.

The aim of this questionnaire is to collect data on French bean farming that shall help guide the researcher into experiments. Any data provided in this research shall be considered for that purpose only. Please provide accurate information for the sake of reliable results meet for valid advice to the stakeholders. THANK YOU in advance for your support.

1. Choose your gender a) Male b) Female
2. Specify your age (in years) ……………………….
3. Family size (number of members) ……………………...
4. Land-size under the common beans farming (m^2) …………………………...
5. Types and amounts of fertilizers applied on average:

Type	Amount (grams) per crop-point
…………………………………	……………………………………
…………………………………	……………………………………

6. Types and amounts of manures applied:

Type	Amount (grams)
…………………………………	……………………………………
…………………………………	……………………………………

7. Number of times of irrigation in a week and litres of water per crop-point:

Times/week	Amount (ml)
…………………………………	……………………………………

8. Spacing on average from one crop-point to another (in cm) …………………………………...
9. Level of infection- number of infected leaves per crop point …………………………………
10. Yield- weight on average in grams per crop point in each harvest ………………………………
11. Number of unharvested pods after two weeks of harvest ………………………….

Appendix II: Data from the sample survey research from French bean farmers at Kariua area.

Gender	Age	Family Size	Land Size	D.A. P	C.A. N	Manure Source	Manure Amount	Times Watered	Amount Watered	Spacing	Infected Leaves	Yield	Infection	Immature Pods
0	21	7	81.9	3	2.8	Cow	29.3	3	4.8	12	0	10.2	0	13
1	33	8	99.9	4.9	2.7	Cow	20.1	3	4.6	9.7	6	9.7	1	10
0	38	5	106.1	4	2.7	Cow	26.5	3	4.4	8.5	6	10.6	1	10
1	22	8	90.3	4.7	2.4	Cow	24.5	4	5.6	8.5	8	9.5	1	11
0	24	4	43.3	5.6	2.5	Cow	19.7	4	3.8	13.6	5	8.7	1	10
1	33	9	91.1	5.6	2.3	Cow	23	3	4.2	9.2	5	9.1	1	11
1	31	2	85.5	8.3	2.7	Cow	27.8	3	3.4	8.8	1	11.3	1	10
0	36	5	98.6	4.7	2.7	Cow	26.8	3	3.1	7.7	8	11.6	1	11
1	32	4	57.7	4.6	2.3	Cow	19.9	3	4.5	9.3	3	12.4	1	8
1	28	2	77.7	5.6	2.8	Cow	28.2	3	5.7	10.7	4	9.9	1	8
0	24	4	81	4.8	2.7	Cow	27	3	3.9	11.4	3	11.3	1	12
0	31	5	79.8	4.2	2.6	Cow	27.1	4	3.5	8.6	6	9.1	1	15
1	43	7	71.7	3.6	2.1	Cow	26.8	3	5.4	9.2	4	8.6	1	10
1	31	2	69.1	5	2.4	Cow	30.2	3	4.7	10	0	9.4	0	8
1	27	9	91.7	4.7	2.2	Cow	27.9	4	3.8	9.1	6	8.1	1	13
0	30	2	108	3.7	2.6	Cow	30.4	3	3.3	12.4	6	8.7	1	15
1	44	5	76	6	2.3	Goat/ Sheep	20.4	4	4.4	8	7	7.3	1	13
0	39	2	116	4.4	2.7	Cow	24.7	3	5.1	6.9	1	10.9	1	11
1	19	4	81.8	5.4	2.4	Cow	18	3	3.7	10.1	2	7.8	1	14
0	20	3	85.1	4.4	2.1	Cow	29.2	4	5	8.7	7	8.6	1	9
0	21	3	57	6.7	2.7	Cow	26.3	3	4.3	9.4	3	11.1	1	11
1	21	6	111	6.2	2.6	Cow	22.3	3	5.3	8.7	4	9.8	1	15
1	35	4	78.6	4.5	2.6	Cow	21.7	3	4.5	8.8	8	9.4	1	12
1	29	7	57.3	4	2.8	Cow	22.5	4	3.2	8.8	8	9.9	1	13
1	29	7	102.3	4.2	2.3	Cow	27.9	3	4.8	11.4	1	10.3	1	12
1	37	8	55.5	4.7	2.6	Cow	30.8	3	3.3	13.5	1	13.4	1	11
0	41	6	89.9	5.5	2.2	Cow	27.4	3	5.4	8	1	9.9	1	10
0	37	6	65.2	5.1	2.3	Cow	20	4	4.4	6.8	7	9.9	1	11
0	22	8	87.3	5.2	2.9	Cow	19.5	3	5.5	9.9	8	10.2	1	12
0	27	2	79.9	4.4	2.1	Cow	18.8	3	4.3	13.1	5	10.6	1	11
0	30	4	106.2	5.6	2.4	Cow	24	3	3.2	10	6	11.1	1	9

1	24	8	93.4	3.1	2.4	Cow	25.9	3	3.5	6.8	6	9.4	1	11
0	22	8	61.9	4	2.1	Cow	22.4	3	4.9	8.7	0	10.8	0	12
1	21	6	44.5	5.2	2.5	Cow	24.4	3	5.7	7.9	8	11.5	1	13
0	24	8	59.1	3.6	3.2	Cow	21.6	3	5.4	13.5	7	8.8	1	13
1	31	8	58.1	3.9	2.1	Cow	28.2	3	5.4	12.5	8	10.6	1	12
1	34	3	114.1	5.2	2.4	Goat/ Sheep	25	3	3.3	7.5	1	11	1	10
1	39	7	84.3	4.9	2.3	Cow	21.8	3	4.8	10.2	1	10.1	1	13
0	25	3	55.3	4.2	2.7	Cow	29.4	3	3.9	11.9	6	10.9	1	13
1	36	5	83.4	4.5	2.5	Cow	27.1	3	3.1	12.7	8	9.4	1	13
1	21	2	60.9	3.5	2.4	Cow	24.3	4	5.6	12.8	6	9.3	1	13
1	27	5	88.3	3.8	2.6	Cow	19.4	3	3.9	7	6	8.7	1	12
0	24	4	45.5	4.9	2.4	Cow	23.6	3	3.8	9.5	7	9.4	1	14

Appendix III: Factor level combinations for Box-Behnken, Face Centred, Rotatable and Spherical designs.

Box-Behnken Design			CCD- Face Centred			CCD- Rotatable			CCD -Spherical		
X_1	X_2	X_3	X_1	X_2	X_3	X_1	X_2	X_3	X_1	X_2	X_3
-1	-1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	0	1	-1	-1	1	-1	-1	1	-1	-1
1	-1	0	-1	1	-1	-1	1	-1	-1	1	-1
1	1	0	1	1	-1	1	1	-1	1	1	-1
-1	0	-1	-1	-1	1	-1	-1	1	-1	-1	1
-1	0	1	1	-1	1	1	-1	1	1	-1	1
1	0	-1	-1	1	1	-1	1	1	-1	1	1
1	0	1	1	1	1	1	1	1	1	1	1
0	-1	-1	-1	0	0	-1.68	0	0	-1.73	0	0
0	-1	1	1	0	0	1.68	0	0	1.73	0	0
0	1	-1	0	-1	0	0	-1.68	0	0	-1.73	0
0	1	1	0	1	0	0	1.68	0	0	1.73	0
			0	0	-1	0	0	-1.68	0	0	-1.73
			0	0	1	0	0	1.68	0	0	1.73

Appendix IV: Factor level combinations for 3^k Factorial, Hoke D2 and D6 designs.

3^k Factorial Design						**Hoke D2 Design**			**Hoke D6 Design**		
X_1	X_2	X_3				X_1	X_2	X_3	X_1	X_2	X_3
-1	-1	-1	1	0	0	-1	-1	-1	-1	-1	-1
0	-1	-1	-1	1	0	1	1	-1	1	1	-1
1	-1	-1	0	1	0	1	-1	1	1	-1	1
-1	0	-1	1	1	0	-1	1	1	-1	1	1
0	0	-1	-1	-1	1	1	-1	-1	1	-1	-1
1	0	-1	0	-1	1	-1	1	-1	-1	1	-1
-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1
0	1	-1	-1	0	1	-1	0	0	-1	0	0
1	1	-1	0	0	1	0	-1	0	0	-1	0
-1	-1	0	1	0	1	0	0	-1	0	0	-1
0	-1	0	-1	1	1				1	1	0
1	-1	0	0	1	1				1	0	1
-1	0	0	1	1	1				0	1	1
0	0	0									

Appendix V: Natural and coded variables as used in the initial experiments with and without soil testing.

Original variables			
Variables	**Low**	**High**	**Centre**
Manures (coded as X_1)	18.0 g	30.8 g	24.4 g
Water (coded as X_2)	3.1 ltr	5.7 ltr	4.4 ltr
Spacing (coded as X_3)	6.8 cm	13.6 cm	10.2 cm
Coded Variables			
Variables	**Low**	**High**	**Centre**
X_1	-1	1	0
X_2	-1	1	0
X_3	-1	1	0

Appendix VI: Data from final experiments involving optimal factor levels.

Optimal Responses- Untested Soils			Optimal Responses- Tested Soils		
Yield	No. of Infected Leaves	No. of Unharvested Pods	Yield	No. of Infected Leaves	No. of Unharvested Pods
24.1	0	22	28.7	0	33
24.2	0	20	28.5	0	32
24.6	0	20	28.1	1	32
24	0	22	28.2	0	32
24.6	0	22	28.6	0	33
24.2	0	21	28.5	0	31
24.1	0	20	28.3	0	32
24.2	1	22	28.4	0	30
24	0	22	28.5	0	30
24.2	0	20	28.6	0	31
24.3	0	21	28.5	0	32
24.3	0	21	28.5	0	32
24.4	0	21	28.8	0	32
24.2	0	19	28.3	0	33
24.2	0	22	28.3	0	31
23.8	0	19	28.5	0	32
24.1	0	22	28.6	0	30
24.3	0	19	28.5	0	31
23.9	0	21	28.2	0	31
24.3	0	20	28.3	0	32
23.8	0	20	27.9	0	32
24.1	0	21	28.5	0	32
24	0	22	28.3	1	33
24.4	0	20	28.4	0	32
24.4	0	22	28.6	0	31

24.1	0	21	28.4	0	32
24.2	0	21	28.7	0	33
24.4	0	20	28.5	0	31
24	1	22	28.3	0	33
24.1	0	20	28.5	0	32
24.5	0	21	28.9	0	29
24	0	21	28.5	0	29
24.5	0	20	28.3	0	31
23.9	0	19	28.4	0	32
24.4	0	20	28.7	0	32
24.4	1	19	28.3	1	33
23.8	0	21	28.5	0	32
24.4	0	21	28.3	0	32
24.1	0	21	28.7	0	33
24.2	2	21	28.5	0	31
24	0	21	28.8	0	32
24.2	0	20	28.5	0	33
23.9	0	22	28.3	0	33

Appendix VII: Plates showing photographs taken during the research.

Plates of photographs from sample survey exercise

The following are the photographs taken during the sample survey exercise. These photographs were taken using cell-phone (Tecno J8 Boom).

Plate 1: Crops at 3-leaf stage in one of the farmer's land (Source: Author, 2017).

Plate 2: Poor germination of the crops in one of the farmers' land (Source: Author, 2017).

Plate 3: Retarded developing of the crops (Source: Author, 2017).

Plate 4: Leaves with both infections and pests underneath at development stage (Source: Author, 2018).

Plate 5: Infected leaves at maturity (Source: Author, 2018).

Plate 6: Unattended French bean crops- evidenced by the weeds and unhealthy crops-heavily intercropped with maize and kales in one of the farmers' land (Source: Author, 2018).

Plate 7: Farmers harvesting their crops (Source: Author, 2018).

Plates showing photographs from experiments' exercise

Below are the images taken during the experiments. These photographs were taken using cell-phone (Tecno J8 Boom).

Plate 8: Land preparation for experiments (Source: Author, 2018).

Plate 9: Furrows with manure, D.A.P fertilizer and French bean seeds sown (Source: Author, 2018).

Plate 10: Irrigating the French bean crops at 2-leaf stage (Source: Author, 2018).

Plate 11: One of the replicates at development stage, intercropped with maize and kales (Source: Author, 2018).

Plate 12: Crops at flowering stage (Source: Author, 2018).

Plate 13: Crops ready for harvesting (Source: Author, 2018).

Plate 14: Some of the crops at their best in yields (Source: Autor: 2018).

Plate 15: Labourers harvesting the matured pods in one of the experimental lands (Source: Author, 2018).

Plate 16: Harvested pods (Source: Author, 2018).

Plate 17: A replicate in the final experiment for optimization at optimal factor levels (Source: Author, 2019).