An overview of crops experimental designs: Comparing their layout arrangements, merits and limitations

Jagdish P. Bhati[1] & Mohammed Umar[2]

ABSTRACT

The reliability and applicability of agricultural information rests on its validity. The validity of research information depends on the process through which it is generated. Hence, designing of experiments forms the backbone of any research endeavor in the discipline of agriculture and allied sciences. Therefore, it is very important to select the right kind of experimental design for generating relevant agricultural technology and innovations. This paper provides a comparative review of systematic and randomised arrangements in layouts of agricultural crop experiments. It compares unique characteristics, advantages and limitations of layout designs of major agricultural field experiments. The aim is to help enhance the knowledge, confidence and capabilities of the young agricultural researchers to critically evaluate and decide as to which type of field experimental design is more suitable for their particular location and agro-climatic condition.

Key words: Crop experimental layouts, merits of experimental layouts, experimental designs.

INTRODUCTION

The main reason for dismal success rate of agricultural development projects in developing countries like Pacific island countries (PICs) is that most of the projects were not based on research-evidence. The limited adoption of the recommended agri-cultural production techniques by farmers also reflects weaknesses of the new agricultural production methods suggested that do not compete favourably with ones farmers already use.

In the field of agriculture, an experi-mental research is conducted to answer a particular question or solve a particular problem. Agricultural research seeks to increase production by improving the yield of crops per unit area or by growing extra crop during the year by searching high yielding crop varieties, crop planting techniques, fertilisation and pest management methods that allow the formulation of new crop sequences and combinations that are managed differently from the existing ones. The reliability and applicability of agricultural research information is affected by the process through which it is generated. Selecting an appropriate type of experimental design is an important component of research process. Agricultural research is conducted to obtain data in stricter control under carefully specified conditions. This requires scientific designing of research experiments, partly to eliminate various disturbing effects that might creep in and partly to ensure that maximum precision is achieved for the amount of effort expended (Cox, 1958; Mead, 1990; Atkinson, *et al.,* 2007). Designing is done to increase the precision of the experiment by reducing the experimental error by various techniques (Cochran, 1957; Federer, 1967; Hicks, 1973; Fisher, 1990; Atkinson & Bailey, 2001). Experimental design is the conceptual structure within which research is conducted. It shows the layout arrangement of an experiment. It is the arrangement of conditions for data-gathering exercises where variation is present (Atkinson & Bailey, 2001; Hinkelmann & Kempthorne, 2008).

A range of experimental designs are available to suit a wide variety of agricultural circumstances (Little & hills, 1978; Peterson, 1994; Quinn & Keough, 2002; Hoshmand, 2006). A correct choice of experimental design depends partly on knowledge of the experimental material and partly on the kind of questions one wishes to tackle (Bailey, 2008). It is, therefore, extremely important that alternative designs be carefully considered before embarking on the actual procedure of

[1]School of Economics, The University of the South Pacific, Laucala Campus, Suva, Fiji.
[2]Institute for Research, Extension & Training in Agriculture, The University of the South Pacific, Alafua Campus, Apia, Samoa.
Corresponding author e-mail: bhati_j@usp.ac.fj

experimentation (Cox, 1958). If the research design is badly chosen, the data analysis may be unduly laborious, and it may even turn out that certain important questions regarding the research problem studied cannot be answered at all (Montgomery, 1991; Ghosh & Rao, 1996; Clewer & Scarisbrick, 2001; Bailey, 2008). Therefore, selecting a right type of experimental design for studying a particular agricultural problem is very important.

The root cause of inadequate agricultural research output in PICs is that there is a dearth of adequately trained staff to undertake scientific agricultural research. To overcome this handicap, it is important to build research capabilities of agricultural research staff. The first step in this direction would be to make them aware about the various types of layout arrangements for agricultural experimentation. This paper is an effort in this direction. The paper provides an overview of various agricultural experimental designs and their unique characteristics, comparative advantages and limitations. The two main questions discussed in the paper are: (1) What are the main research designs available to agricultural researchers? (2) Which design is most suitable for which type of research? The intention is to help enhance research skills of agricultural students and other potential researchers and to inspire self-confidence of young agricultural researchers in developing countries like PICs, thereby encouraging their overall research efforts and initiatives. This paper may also be of use to those active in management and funding of agricultural research and training of the agricultural research and extension staff. Boosting of agricultural research capabilities of the existing and potential agricultural research staff of PICs will accelerate output of location-specific agricultural technologies and innovations suitable for adoption on smallholder farms under varied resource constraints and agro-climate conditions in the South Pacific region.

The paper is organized in six sections, starting with an introduction. The next section provides definition of some basic terms and concepts used in agricultural research discussions. The third section describes broad classes of agricultural experimental layouts. In the fourth section, various types of single factor designs are discussed. Multi-factor experiment -tal designs are discussed in the fifth section. Finally, summary and conclusions are presented.

SOME BASIC TERMS AND CONCEPTS

Research: Research means systematic investigation to establish facts. It is systematic because all the activities are planned and executed based on rules so everything can be repeated.

Data: These are the information collected about various variables of experiment in which a researcher is interested. Data are collected by experimentation, sampling or routine observations.

***Variable*:** A variable/factor denotes a feature of an item that we measure. It denotes a situation, number or quantity that can vary (change) or be varied. Some important variables related to agriculture experiments include: (i) *Agronomic variables* - germination and survival percentages, plant height and growth, stem form, biomass weight, crop yield, etc.; (ii) *Soil chemical variables* - soil fertility (nutrients type and level); (iii) *Plant chemical variables* - levels of essential elements (N, P, K, etc.); (iv) *Socio-economic variables* perceived to be of importance to the farmers (farmers' views of the importance of a particular treatment, costs and benefits of improved techniques, adoption rates); and (v) *Derived variables*, e.g., differences in response of control and introduced treatments.

***Experiment*:** An experiment is the act of conducting a controlled test or investigation. Most of, if not all, the conditions that happened or were used in the experiment are known or regulated. In experimental research, different kinds or levels of a particular factor or several factors are evaluated. Thus, experiment is a research situation in which at least one independent variable, called the experimental variable, is deliberately manipulated or varied by the researcher. Most agricultural field experiments are based on the concepts of replication, local control (blocking) and randomisation (Atkinson & Bailey, 2001; Hinkelmann & Kempthorne, 2008).

Design: Design means arrangement. It is the conceptual structure which shows the layout arrangement of an experiment with respect to the number of treatments and replications and the spatial relations to one another. In agricultural research, proper design is important because we want to establish or find the true results without any doubt in mind. With improper or wrong design, results may

not be convincing or reliable. We need experimental design to control variability so that treatment effects can be identified.

***Treatments*:** They denote different conditions, processes or interventions under which experimental and control groups are put in the experimental design. These are materials being forced on the subject (experimental unit) and whose effect is to be monitored. A treatment can be either qualitative (e.g. species, fertiliser types) or quantitative (e.g. quantified levels of a particular fertiliser type).

Replication: It denotes the repetition of a test or complete experiment. Treatments are repeated to help identify the sources of variation and to better estimate the true effects of treatments. Replication allows for estimation of the experimental error by applying treatments to different plots under the same experimental conditions (Fisher, 1990; Ghosh & Rao, 1996). Sufficient replication is needed to distinguish treatments from background variability (Fisher, 1990; Atkinson *et al.*, 2007).

Local-control (or Blocking): A process of research design which minimizes the influence or effect of extraneous variables that are not related to the purpose of study but may affect the dependent variables. For example, the soils generally constitute a continuum with variability at different scales. Thus, the structure of soil variability in the experimental area has important implications for the design of experiments (Fagroud & van Meirvenne, 2002). Local-control by blocking is the arrangement of grouping experimental units into homogeneous groups (blocks) consisting of units that are similar to one another. A block is a relatively large area or several identical units receiving all or most of the treatments. Blocking is used in agricultural field experiments to control the adverse effects of soil heterogeneity (Martin, 1986; Calinski & Kageyama, 2000).

***Randomisation*:** It is the process of making allocation of treatments to experimental units by means of some appropriate random method. Random is the process in which each item has an equal chance of being chosen. Basic purpose of randomisation is to remove bias from the estimation of treatment effects (Atkinson & Bailey, 2001), and to equalize the error over all treatment differences (Fagroud & van Meirvenne, 2002).

***Experimental units*:** The pre-determined smallest units (e.g. plots) where different treatments are used. The information (data) for comparison is collected from such single units.

***Hypothesis*:** It is a statement that has to be verified or disproved through experimentation. It is based on the researcher's past experiences, observations and/or theoretical considerations.

TYPES OF AGRICULTURAL EXPERIMENTAL LAYOUTS

Paper describes the most common layout arrangements of crop experiments that arise in practice and point out the advantages and weaknesses of each experimental design.

A range of experimental designs are available to suit a wide variety of agricultural circumstances. Experiments can be classified into two broad categories, namely, single-factor experiments and multifactor experiments. In the single-factor experiment, only one factor is varied while all others are kept constant. In such experiments, the treatments consist solely of the different levels of the single variable factor, while all other factors are applied uniformly to all plots at a constant prescribed level (Cochran, 1957; Federer, 1967: Mead, 1990). Examples are: fertiliser trials (where several rates of a single fertiliser element are tested); insecticide trials (where different concentration levels of a chemical are used); plant-population trials (where several plant densities of a crop are tested). In fertiliser trials, several rates of single fertiliser element, say nitrogen, may be tested. All other factors such as agronomic practices, irrigation, and insect control are kept at uniform level.

When response to the factor of interest is expected to differ under different levels of the other factors, the use of those experimental designs which can handle simultaneously two or more variable factors are considered (Cochran, 1957; Cox, 1958; Hicks, 1973, Mead, 1990). Such experiments are known as multi-factor experiments. These experiments help evaluate the individual effects of each factor as well as their interaction, if the effect of one factor changes as the level of other factor changes (Little & Hills, 1978; Kuehl, 2000; Hosmand, 2006)

A correct choice of experimental design depends partly on the experimental material studied and partly on the kind of research problem one wishes to tackle (Bailey, 2008). It is, therefore, extremely important to

carefully consider the unique characteristics of alternative designs before selecting any one for the actual procedure of experimentation (Cox, 1958).

Most agricultural research is of comparative nature concerned with comparing effects of different factors or treatments. Hence, the majority of research needs can be met sufficiently well by a fairly small number of experimental designs (Hinkelmann & Kempthorne, 2008). Most commonly used experimental designs are listed in Table 1.

Three most commonly used single factor experimental designs are: (i) completely randomised design (CRD), (ii) randomised complete block design (RCBD), and (iii) Latin square design (LS design). Under the multi-factor experimental designs the two most commonly used arrangements are: (i) Factorial experiments, and (ii) the Split-plot design. The term "factorial" describes a specific way in which the treatments are formed. A Factorial experiment can be laid out using randomised arrangement of treatments to plots in a CRD, RCBD or LS design. Split-plot experiment is laid out by using random arrangements separately for main-plot treatments and split plot treatments. In the following section, the layout arrangements for various types of single -factor experiments are compared.

SINGLE-FACTOR EXPERIMENTAL DESIGNS

In single factor experimental designs, levels of **one** factor (e.g. varieties of a crop, fertiliser levels) with several replications in each are tested while all other factors (such as agronomic practices, insect control, irrigation, weeding, etc.) are kept at uniform level. The three most commonly used single-factor experimental designs are: (i) completely randomised design, (ii) randomised complete block design, and (iii) Latin square design. Each of these layouts are discussed in the following sub-sections.

1). Completely Randomised Design

In Completely randomised design (CRD), various levels (treatments) of **one** factor with several replications in each are tested while all other factors are kept at uniform level. The treatments are arranged completely at random over the **whole** experimental units (e.g. plots). Each experimental unit has an equal chance of receiving a certain treatment. Each treatment can appear anywhere among total plots, even in adjacent plots. It is called completely randomised design because selection of plot for each treatment is done considering all total plots and all treatments together.

Suppose there are (t) treatments that are replicated (r) times each. The experiment will require, t x r = n number of crop experimental plots. Let us suppose there are **five** treatments designated as **A, B, C, D** and **E** which are to be evaluated using their **four** replications in the CR design. The total number of plots required for this experiment will be, n = 5 x 4 = 20 plots. Any one of the five treatments, say C, will occupy any **four** plots (r) of the total 20 plots of experimental area.

The process used in layout of experiment in CRD is as follows. (1) Determine the number of treatments and the number of replications in the experiment. (2) Determine the number of plots (n) required for the experiment by multiplying number of treatments (t) with the number of replications (r), i.e., n = t x r. (3) Divide the environmental area into (n) number of plots of equal size and assign each plot a serial number in any manner starting with one. (4) Arrange treatment units equal to number of replications (r) of each

Table 1. Commonly used layout arrangements for assigning treatments (or treatment combinations) to agricultural experimental plots.

Single factor experimental layouts	Multi-factor experimental layouts
i) Completely randomised design (CRD) ii) Randomized complete block design (RCBD) iii) Latin square design (LS design)	**i) Factorial designs:** Using randomisation arrangements of (a) CRD (b) RCBD (c) LS design **ii) Split-plot designs:** Using randomisation arrangements of (a) CRD (b) RCBD

treatment. (5) Put serial number on all the experimental treatment units together. (6) Assign each of the treatments (experimental material units) to each of experimental plots without any restriction by any randomisation scheme.

A sample layout of CRD is shown in Table 2. It may be noted that each treatment occurs four times in the total 20 plots but not necessarily in each row or column of the layout.

Table 2. An example of single factor experimental layout in Completely Randomised Design with five treatments (A, B, C, D and E) each replicated four times. Total number of plots in experimental layout is 5 x 4 = 20. (Numerals denote plot numbers in the experimental area).

1 B	2 A	3 E	4 A	5 D
6 B	7 C	8 D	9 A	10 E
11 E	12 D	13 B	14 C	15 C
16 D	17 E	18 A	19 B	20 C

The CRD layout has many advantages. (1) It is a very flexible design as any number of treatments can be used. (2) The number of replications per treatment need not be the same, i.e. it allows for unequal replications between the treatments and this is useful if some treatments have inadequate experimental resources and therefore will have less replication than others. (3) The statistical analysis of CRD data is comparatively easy and unaffected if some observations for any treatment are lost or missing. (4) Comparatively, it provides researcher with more error degrees of freedom.

There are some limitations of CRD layout. (1) This design is suitable only if the experimental units are uniform or homogeneous. It does not account for heterogeneity in experimental material, e.g. fluctuation due to variation in soil fertility in the experimental field. (2) Because the randomisation is unrestricted, systematic error, if any present, will render the estimate of variance an invalid estimate of random variation. (3) The statistical efficiency of the CR design reduces significantly when the number of treatments and/or replications increase as this will require a larger experimental field to accommodate/fit the increased number of plots which may result in the loss of homogeneity amongst the plots.

Completely Randomised Design is generally used when experimental area happens to be homogenous. This design is generally used in laboratory experiments where homogeneity of experimental materials can be easily achieved. In experiments using CRD layout, the total source of variation is made up of differences between treatments and within treatments (Snedecor & Cochran, 1980; Sokal & Rohlaf, 2011).

2). Randomised Complete Block Design

The Randomised Complete Block Design (RCBD) is most suitable if the experimental area is unidirectional heterogeneous, say due to soil fertility gradient or slop of experimental field etc. Main purpose of blocking is to reduce a known source of systematic variation among experimental material (plots) by grouping them into homogenous blocks. Each block of experimental area is kept of equal size and subdivided into the number of plots according to the number of treatments (t) planned to be applied in the experiment. Unlike CRD layout where the treatments are arranged randomly over the whole experimental units (e.g. plots), in RCBD, the random allocation of a treatment to each plot in the block is done separately and independently of other blocks. Hence, each treatment can appear only once anywhere among the plots of a block and each block contains the entire set of treatments (complete block). In CRD layout each treatment can appear anywhere among total plots, even in adjacent plots, but in RCBD this is not possible.

The process used in RCBD layout is as follows. (1) Decide the number of treatments (t) and the number of their replications (r) to determine the total number of plots (t x r) required for the experiment. (2) Divide the experimental area into homogenous blocks of equal sizes; their number being equal to number of replications (r). (3) Divide each block into equal sized plots their number being equal to the number of treatments (t) in the experiment. (4) Give serial number to plots of each block. (5) Assign treatment to each plot of a block independently without regard to plots of other blocks by any randomisation scheme.

Suppose there are four treatments, say nitrogen levels ($\mathbf{N_0}$, $\mathbf{N_1}$, $\mathbf{N_2}$, and $\mathbf{N_3}$) to be replicated **five** times in a fertiliser trial on a

crop. Then the experimental area is to be divided into five blocks for replication and each block is divided into four plots. A sample layout of RCB design for an experimental field having North-South gradient is shown in Table 3 and a sample layout of RCB design for a field having gradient from West to East is shown in Table 4.

Table 3. An example of RCBD layout for four nitrogen treatments (N_0, N_1, N_2, and N_3) and five blocks (Gradient of field: North to South ↓).

Five Blocks (Replications)	Four Plots: Random allotment of four treatments of N to four plots of each block 1	2	3	4
I	N_3	N_0	N_1	N_2
II	N_0	N_1	N_3	N_2
III	N_1	N_0	N_2	N_3
IV	N_0	N_2	N_3	N_1
V	N_2	N_3	N_1	N_0

Table 4. An example of RCBD layout for four nitrogen treatments (N_0, N_1, N_2, and N_3) and five blocks (Gradient of field: West to East →).

Plots (four plots)	Five Blocks (replications): Random allotment of four treatments of N to four plots of each of five blocks I	II	III	IV	V
1.	N_3	N_0	N_1	N_0	N_2
2.	N_0	N_1	N_0	N_2	N_3
3.	N_1	N_3	N_2	N_3	N_1
4.	N_2	N_2	N_3	N_1	N_0

The Randomised Complete Block Design is an improvement over Completely Randomised design because it provides the block variation separately. By grouping the experimental units into blocks, variability within each block is minimised and variability among blocks is maximised. The total source of variation may be categorised as differences between blocks, differences between treatments, and interaction between blocks and treatments. The latter is usually taken as the error term for testing differences in treatments. An experiment laid out in RCBD has two main advantages. (1) The treatments are compared equally in each block as all the treatments are included in each block. Hence, each block can also be considered as a separate experiment. (2) Treatment effects are estimated more precisely as error mean square is expected to be smaller due to formation of homogenous blocks.

There are two main limitations of RCBD layout. (1) If more treatments are included in the experiment, the block size increases and the within block variability tends to increase. (2) RCBD layout is useful for eliminating the contribution of one directional source of variation only, i.e. it will be efficient only if the variability in experimental units exists in one direction. If variation exists in two directions, the experiment with RCBD layout will not be efficient (Peterson, 1994; Quinn & Keough, 2002).

3). Latin Square Design

When the variation in experimental field occurs in two directions, perpendicular to each other, and each is equally strong, then a two-way blocking will be needed in the experiment, one for each variation. Latin square design (LS design) treats two sources of variations as two-independent blocking criteria, instead of only one as in the RCBD layout.

Supposing an experimental area has two sources of variation: (i) cropping history, and (ii) soil fertility gradient. Suppose direction of fertility gradient is from West to East and direction of cropping history is from North to South at right angle as is shown below:

Soil fertility gradient →
Cropping history↓

In such cases, two-way blocking is necessary in the experimental layout. The two-directional blocking in a LS design is commonly referred to as row-blocking and column-blocking. In LS design each row and each column is a complete block or replication. This blocking is accomplished by ensuring that every treatment occurs only once in each row-block and once in each column-block. This necessitates that the number of replication-blocks is equal to the number of treatment-blocks. Hence, in the layout of LS design the number of rows is equal to the number of columns, forming shape of the layout arrangement as a square matrix. In the Latin square design, each row as well as each column is a replication containing all the treatments of the experiment. The

randomisation process is performed in such a way that each treatment appears once, and only once, in each column (e.g. fertility gradient blocks) and in each row (e.g. cropping history blocks).

Latin square design is identified as 4 x 4 Latin square, 5 x 5 Latin square, etc., according to the number of rows and columns in the layout arrangement. The number of treatments shall not be less than four so that degrees of freedom associated with the experimental error are adequate.

The process used in the layout of LS design is as follows. (1) Decide the number of treatments (t) in the experiment. (2) Determine the total number of plots (t x r) required for the experiment; the number of replications (r) equal number of treatments. (3) Divide the experimental area into homogenous blocks of equal sizes; their number being equal to number of replications (r = t). (4) Divide each block into equal-sized plots, their number being equal to the number of treatments (t) in the experiment. (5) Give serial number to plots of each block separately. (6) Assign treatment to each plot of a block in such a way that each row as well as each column contains all the treatments of the experiment. A sample layout arrangement of LS design is shown in Table 5. The four row blocks correspond to four different cropping histories, and four column blocks correspond to four different varieties of crop.

Table 5. A sample layout of 4 x 4 Latin square design, with four treatments (i.e. four varieties of rice crop: V_1, V_2, V_3 & V_4) and four crop history on experimental plots, showing two way blockings.

Row-blocking: (Cropping history) ↓	**Column-blocking: Random allotment of four varieties of rice crop to four soil fertility gradient plots →**			
	1	**2**	**3**	**4**
Fallow	V_1	V_2	V_3	V_4
Maize	V_2	V_1	V_4	V_3
Taro	V_3	V_4	V_1	V_2
Cassava	V_4	V_3	V_2	V_1

The LS design thus minimises the effect of differences in fertility status within each cropping history block. In this layout design, it is possible for the researcher to estimate variation among row-blocks as well as among column-blocks, and to isolate them from experimental error. The total sources of variation are made up of treatment differences, experimental error and two known sources of variations running at right angles to each other. The main advantage of LS design is that it is more efficient than RCBD and CRD layouts, if more than one source of known systematic variations exist in two different directions normally perpendicularly to each other.

The main limitation of the LS design is that it is not as flexible as the RCB D layout as the number of treatments in it is limited, being equal to the number of rows and columns of the layout.

As pointed out previously, the main aim in CRD is to compare and estimate effect of a single set of treatments randomised over all experimental units. In RCBD, blocking of experimental units is done to make allowance for unwanted but unavoidable heterogeneity of experimental units. In LS design which is a further improvement on RCBD, number of replications and number of treatments are kept equal and the application of treatments is randomised in such a way that they all appear in each row-blocks and in each column-blocks of the layout.

MULTI-FACTOR EXPERIMENTAL LAYOUTS

In the single-factor experimental designs, the effects of a single set of treatments are estimated and compared by holding most of the variable factors constant and allowing only one or two to vary in each experiment. When response to the factor of interest is expected to differ under different levels of other factors, the use of single factor experimental design would require a series of single-factor experiments in which only one factor is varied at a time. This research procedure would be both lengthy and costly. Use of wide range of factor combinations in one multi-factorial experiment would provide a reliable basis for making practical recommendations that will be valid in variable circumstances. Moreover, if the factors are not independent of one another, factorial experiment can give a satisfactory account of their interaction. Hence, the advantage of using multi-factor experiments is that the researcher can obtain a broad picture of the effect of each factor in the different conditions due to variations in the other factors.

Two most commonly used multi-factor experimental layout arrangements are: (i)

Factorial experiments, and (ii) Split-plot experiments. Factorial experimental designs and Split-plot designs are most commonly used in the multi-factor experiments. In factorial experiments, all possible combinations of factors are formed and considered as independent treatments which are assigned randomly to various plots of the experimental area by using randomisation procedure of CRD, RCBD, or LS design. The Split-plot design is useful when one of the treatments requires larger size plots than others. In this design, main treatments are first applied to main-plots and the second factor is assigned to subplots of the main-plot using randomisation procedure of CRD or RCBD layouts. This experimental design provides researcher with increased precision for the effects of sub-plot treatments and interaction between main-plot and sub-plot treatments. Layout arrangements and other characteristics of multi-factor experimental designs are described below.

1). Factorial Experimental Layout

In the Factorial experiment all combinations of all the levels of two or more factors are included in the layout design. The term "factorial" describes a specific way in which the treatments are formed in the experiment. Wide range of factor combinations helps the researcher to predict what will happen when two or more factors are used in combination. Studies such as fertiliser trials combined with weeding, pest control, crop variety or rate of planting commonly use factorial experiments. There is a considerable saving of the experimental resources in the factorial experiments.

A design for two factors each at two levels is referred to as a 2x2 or a 2^2 factorial design requiring four plots for each replication. A Factorial experiment can be laid out in CRD, RCBD, or LS design arrangement.

Supposing there are two factors each at two levels, such as two levels of nitrogen fertiliser (N_0 and N_1) and two levels of weeding of crop (W_0 and W_1). This experiment will have four treatment combinations as shown in Table 6.

If a 2x2 factorial experiment is in a Complete Randomised Block Design, then it is called a 2^2 factorial experiment in a randomised complete block design. Sample layouts of 2^2 Factorial experiments with Completely Randomised Design, with Randomised Complete Block Design, and with Latin Square design are shown in Tables 7, 8 and 9, respectively. In these three sample layouts each of four treatment combinations is replicated four times requiring 16 experimental plots.

The procedure of Factorial experiment layout involves the following steps. (1) Decide the factors and their levels in the experiment. (2) Identify treatment combinations and number them serially. (3) Decide the number of replications of the treatment combinations in the experiment. (4) Subdivide experimental area into different blocks of equal size, the number of blocks being equal to the number of replications of the treatment combinations. (5) Subdivide each block into different plots of equal size, the number of plots being equal to the number of treatment combinations. (6) Randomly assign treatment combinations to the plots by following a randomisation scheme of CRD, RCBD, or LS design. In the randomisation process, all factor combinations (treatments) are considered as unrelated treatments.

If the above mentioned example of two factor (fertiliser, N and weeding, W) factorial experiment is expanded to include a third factor, say pesticide (Z), with two levels (Z_0 and Z_1), the experiment will become a 2x2x2 or a 2^3 factorial experiment. A factorial experiment of three factors with two levels each will have eight possible treatment combinations. Treatment combinations for

Table 6. Possible treatment combinations of the two factors each with two levels (a 2^2 factorial experiment).

Treatment number	Two factors with two levels		Treatment combinations	Explanation
	N	W		
1	N_0	W_0	N_0 W_0	No fertiliser, no weeding
2	N_0	W_1	N_0 W_1	No fertiliser, weeding only
3	N_1	W_0	N_1 W_0	No weeding, fertiliser only,
4	N_1	W_1	N_1 W_1	Both fertiliser and weeding

Table 7a. A sample layout of a 2^2 Factorial experiment with Completely Randomized Design having **four** treatment combinations with **four** replications and requiring 16 experimental plots.

1 N_0 W_0	2 N_1 W_0	3 N_0 W_1	4 N_0 W_0
5 N_0 W_1	6 N_1 W_0	7 N_1 W_1	8 N_1 W_1
9 N_0 W_1	10 N_0 W_1	11 N_0 W_0	12 N_1 W_0
13 N_1 W_1	14 N_0 W_0	15 N_1 W_0	16 N_1 W_1

Note: Figures in numerals denote plot number.

Table 7b. A sample layout of a 2^2 Factorial experiment with Randomized Complete Block Design having **four** treatment combinations with **four** replications and requiring 16 experimental plots.

Blocks (for five replications)	**Random allotment of four treatment combinations to four plots of each block**			
	1	**2**	**3**	**4**
I	N_0 W_0	N_1 W_1	N_0 W_1	N_1 W_0
II	N_0 W_1	N_1 W_1	N_1 W_0	N_0 W_0
III	N_1 W_1	N_0 W_1	N_0 W_0	N_1 W_0
IV	N_1 W_0	N_1 W_1	N_0 W_0	N_0 W_1

Table 7c. A sample layout of a 2^2 Factorial Experiment with Latin Square Design having four treatment combinations and four replications requiring 16 experimental plots.

Row blocks (for four replications)	**Random allotment of four treatment combinations to four plots of each block (Column blocks)**			
	1	**2**	**3**	**4**
I	N_0 W_0	N_1 W_0	N_0 W_1	N_1 W_1
II	N_0 W_1	N_1 W_1	N_1 W_0	N_0 W_0
III	N_1 W_1	N_0 W_1	N_0 W_0	N_1 W_0
IV	N_1 W_0	N_0 W_0	N_1 W_1	N_0 W_1

three factors (N, W and Z) each at two levels are shown in Table 8.

If these **eight** treatment combinations are replicated **four** times, the experiment will require 32 (i.e., 8 x 4) plots. A sample layout of a 2^3 factorial design for determining the effect of fertiliser (N), weeding (W) and pesticide (Z) on the crop yield is shown in Table 9.

Now supposing we want to conduct a factorial experiment involving **four** rates of fertiliser (N_0, N_1, N_2, N_3), and **three** crop varieties (V_1, V_2, V_3), this experiment will have 12 possible treatment combinations as shown in Table 10.

If the treatment combination of this experiment is replicated three times, the total number of plots required for the experiment

Table 8. Possible treatment combinations of three factors (N, W & Z) each with two levels (a 2^3 factorial experiment).

Treatment number	**Three factors with two levels each**			**Treatment combinations**	**Explanation**
	N	**W**	**Z**		
1	N_0	W_0	Z_0	N_0 W_0 Z_0	No fertiliser, no weeding, and no pesticide
2	N_0	W_0	Z_1	N_0 W_0 Z_1	No fertiliser, no weeding, and pesticide
3	N_0	W_1	Z_0	N_0 W_1 Z_0	No fertiliser, weeding, and no pesticide
4	N_0	W_1	Z_1	N_0 W_1 Z_1	No fertiliser, weeding, and pesticide
5	N_1	W_0	Z_0	N_1 W_0 Z_0	Fertiliser, no weeding, and no pesticide
6	N_1	W_0	Z_1	N_1 W_0 Z_1	Fertiliser, no weeding, and pesticide
7	N_1	W_1	Z_0	N_1 W_1 Z_0	Fertiliser, weeding, and no pesticide
8	N_1	W_1	Z_1	N_1 W_1 Z_1	Fertiliser, weeding, and pesticide

Table 9. A sample layout of a 2^3 factorial design of eight treatment combinations with four replications using RCBD process.

Plot number in each block	Random allotment of eight treatment combinations to 8 plots of each of the four blocks			
	I	II	III	IV
1	$N_1 W_0 Z_1$	$N_0 W_1 Z_1$	$N_0 W_1 Z_0$	$N_0 W_1 Z_1$
2	$N_0 W_0 Z_0$	$N_0 W_1 Z_0$	$N_1 W_0 Z_1$	$N_1 W_1 Z_0$
3	$N_0 W_1 Z_1$	$N_1 W_1 Z_1$	$N_0 W_0 Z_0$	$N_1 W_1 Z_1$
4	$N_0 W_0 Z_1$	$N_0 W_0 Z_0$	$N_1 W_0 Z_0$	$N_0 W_0 Z_1$
5	$N_1 W_0 Z_0$	$N_0 W_0 Z_1$	$N_1 W_1 Z_0$	$N_1 W_0 Z_0$
6	$N_1 W_1 Z_1$	$N_1 W_0 Z_0$	$N_0 W_0 Z_1$	$N_0 W_0 Z_0$
7	$N_0 W_1 Z_0$	$N_1 W_1 Z_0$	$N_0 W_1 Z_1$	$N_1 W_0 Z_1$
8	$N_1 W_1 Z_0$	$N_1 W_0 Z_1$	$N_1 W_1 Z_1$	$N_0 W_1 Z_0$

Table 10. Possible treatment combinations of a 3 x 4 factorial experiment with three varieties of the crop (V) and four levels of fertiliser (N).

Treatment combination number	Two factors (4 fertiliser levels and 3 crop varieties)		Treatment combination
	Nitrogen (kg/ha)	Crop variety	
1	$0 = N_0$	V_1	$N_0 V_1$
2	$40 = N_1$	V_1	$N_1 V_1$
3	$80 = N_2$	V_1	$N_2 V_1$
4	$120 = N_3$	V_1	$N_3 V_1$
5	$0 = N_0$	V_2	$N_0 V_2$
6	$40 = N_1$	V_2	$N_1 V_2$
7	$80 = N_2$	V_2	$N_2 V_2$
8	$120 = N_3$	V_2	N_3V_2
9	$0 = N_0$	V_3	$N_0 V_3$
10	$40 = N_1$	V_3	$N_1 V_3$
11	$80 = N_2$	V_3	$N_2 V_3$
12	$120 = N_3$	V_3	$N_3 V_3$

will be 36 (i.e. 12 x 3). A sample layout of this type of factorial experiment using randomised complete block design process is shown in Table 11.

As compared to a single-factor design, in the multi-factor design experiment, effect of many factors can be examined simultaneously for individual factor as well as for their combinations, in one experiment. Therefore, experiment with multi-factor design saves time, money and effort of the researcher. The Factorial experiment has two main advantages. (1) There is reduction in the number of experiments, if done separately for each factor. (2) There is a possibility of studying the impact of interactions among the various factors (Montgomery, 1991; Quinn & Keough, 2002). A significant interaction implies that changes in one factor may be dependent on the level of the other factor. If such dependency exists between the factors and the researcher adopts separate single-factor experimental designs for each of the factors separately, interpretation of the results obtained should be done cautiously.

2). Split-Plot Layout Arrangements

In Split-plot experiments also, various factors are applied simultaneously. This design

Table 11. A sample layout for a 3 x 4 factorial experiment having three varieties of the crop (V_1, V_2, V_3) and four levels of fertiliser (N_0, N_1, N_2, N_3) with three replications using RCBD process.

Plot No.	Three replication Blocks each with 12 plots (Random allotment of 12 treatment combinations independently to 12 plots of each of 3 blocks)		
	I	II	III
1	N_1 V_1	N_2 V_1	N_0 V_1
2	N_0 V_2	N_0 V_2	N_1 V_2
3	N_3 V_2	N_0 V_1	N_2 V_2
4	N_1 V_2	N_1 V_1	N_2 V_1
5	N_0 N_3	N_2 V_2	N_3 V_3
6	V_3 V_3	N_1 V_3	N_0 V_3
7	N_2 V_1	N_1 V_2	N_3 V_2
8	N_1 V_3	N_3 V_2	N_1 V_3
9	N_3 V_1	N_3 V_1	N_1 V_1
10	N_2 V_2	N_2 V_3	N_3 V_1
11	N_2 V_3	N_0 V_3	N_2 V_3
12	N_0 V_1	N_3 V_3	N_0 V_2

is very useful for combining certain treatments, one of which requires larger plots than others for practical convenience. Hence, the layout of this type of experiment is designed keeping in view the large plots (main-plots) and small sub-plots of the main-plots. The main factor is assigned to the main larger plots and, thus, is called the main-plot factor. Examples of main factors are situations requiring spraying insecticides, irrigation or tillage trials on various crops, etc. The second factor is assigned to the sub-plots of the main-plot and, thus, is called the sub-plot factor. Usually, the treatment on which maximum information is desired is placed in the split-plot or in the smallest plot.

The process of designing layout of split-plot experiments involves following steps. (1) Divide experimental area into required number of main-plot blocks so as to provide one main-plot to each main factor treatments in the experiment. (2) Divide main-plot into split-plots or sub-plots to provide one sub-plot to each of the sub-plot (second factor) treatments. For the sub-plot treatments, each main-plot is like a block. (3) Assign main factors to various main-plots at random. (4) Assign various levels of sub-plot factor to the sub-plots (small plots) within each main-plot separately by a randomisation process. Hence, split-plot design involves two separate randomisation processes – one for the main-plot in each replication and another for the sub-plot within each main-plot. Each randomisation is done by the CRD or RCBD randomisation process. (5) Replicate main-plot treatments in various replication blocks of the experimental area. (6) In each replication, repeat the same procedure to allot sub-plot treatments of the experiment to the subplots of main-plots.

An illustration of split-plot experimental design for evaluating effects of fertiliser on different varieties of a crop is shown in Table 12. In this example, three varieties of the crop are randomised in main-plots of each replication and the five levels of fertilisers are randomised in sub-plots of each main-plot. In this illustration, randomised complete block design procedure is followed in assigning main factor treatments to main-plots and sub-plot treatments to subplots in each of the main-plots.

Split-plot design has two main advantages. (1) It is very useful for combining certain treatments one of which requires larger plots than others. (2) This layout arrangement provides researcher with more precise results for the effects of sub-plot treatments and interaction between main-plot and sub-plot treatments equally (Montgomery, 1991; Kuehl, 2000; Sokal & Rohlf, 2011). In the example given in Table 12, increased precision of the estimation of the effects of the five nitrogen levels and the interactions between the three levels of variety and five levels of nitrogen are achieved, while the effects of the three levels of variety are poorly estimated. The major limitation of these types of research designs is that they require larger area for experiments (Kuehl, 2000; Quinn & Keough, 2002).

SUMMARY AND CONCLUSION

Importance of generating continuous flow of new relevant and adaptive agricultural technologies in response to the emerging agricultural problems of developing countries like PICs and to harness the existing vast potential for their agricultural development cannot be overstated. The statistical design of

Table 12. Sample layout of a split-plot design involving three varieties of crop (V_1, V_2, V_3) as the main-plot treatments for three main-plots with four replications and five levels of fertiliser (N_0, N_1, N_2, N_3, N_4) as the sub-plot treatments for five sub-plots of each main-plot.

Blocks (for four replication blocks)	**Random allotment of three varieties of crop to three Main-plots of each of 4 replication blocks**	**Random allotment of 5 levels of fertiliser treatments to five Sub-plots of each of three Main-plots**				
		1	**2**	**3**	**4**	**5**
I	V_3	N_2	N_1	N_3	N_0	N_4
	V_1	N_1	N_0	N_2	N_4	N_3
	V_2	N_3	N_2	N_4	N_0	N_1
II	V_1	N_1	N_3	N_2	N_0	N_4
	V_2	N_0	N_1	N_4	N_3	N_2
	V_3	N_3	N_4	N_1	N_2	N_0
III	V_2	N_0	N_2	N_1	N_4	N_3
	V_1	N_3	N_4	N_0	N_2	N_1
	V_3	N_4	N_3	N_2	N_1	N_0
IV	V_2	N_0	N_2	N_1	N_3	N_4
	V_3	N_4	N_1	N_2	N_0	N_3
	V_1	N_1	N_3	N_0	N_4	N_2

experiments is an essential ingredient of successful product development and improvement, and provides an efficient and scientific approach to obtaining meaningful information. Depending on the specific needs of particular experiment, researchers select an appropriate research design to obtain reliable and precise results from their experiments. The aim of experimental design is to ensure that the experiment is able to detect the treatment effects that are of interest, and that it uses available resources to get the best precision possible. The choice of design can make a huge difference. Hence, in any programme on building research capability of potential researchers, the first step would be to enhance their knowledge and understanding of layout arrangements of various types of experimental designs, their merits, and limitations for conducting agricultural research of particular interest. This article is an effort in this direction. It gives a brief overview of various crop experiment layouts, defining the purpose and scope of each experimental design, differentiating between alternative types of experimental variables, underlying environment and constraints, and explaining steps of experimentation. The focus here is on the fundamental elements of crop experimental designs and their advantages and weaknesses. The single-factor experimental designs reviewed are completely randomised design (CRD), randomised complete block design (RCBD), and Latin square (LS) design. The multi-factor experimental designs discussed are factorial layout arrangements and split-plot layout arrangements

In the small island countries of the South Pacific where agriculture is the mainstay of the people and the research activity is very slow, enhancing agricultural research capability of staff through education, training and motivation is very essential so that they keep up and expand their research skills and core competencies, develop professionally, and become more productive.

References

ATKINSON, A. C. & BAILEY, B. A. 2001. One hundred years of the design of experiments on and off the pages of Biometrica. *Biometrica*, **88**:53-97.

ATKINSON, A. C., DONEV, A. N. & TOBJAS, R. D. 2007. *Optimum Experimental Designs with SAS*. New York: Oxford University Press.

BAILEY, R. A. 2008. *Design of Comparative Experiments*. Cambridge, U.K : Cambridge University Press.

CALIŃSKI, T. & SANPEI, K. 2000. *Block Designs: A Randomization Approach, Volume I: Analysis*. Lecture Notes in Statistics. 150. New York: Springer-Verlag.

CLEWER, A. G. & SCARISBRICK, D. H. 2001. *Practical Statistics and Experimental Design for Plant and Crop Science*. John Wiley & Sons.

COCHRAN, W. G. & COX, G. M. 1957. *Experimental Designs*. 2nd edition. Wiley, New York.

COX, D. R. 1958. *Planning of Experiments*. New York: John Wiley & Sons.

FAGROUD, M. & van MEIRVENNE, M. 2002. Accounting for soil specific spatial autocorrelation in the design of experimental trails. *Social Science Society of America Journal,* **66**:1134-1142.

FEDERER, W. T. 1967. *Experimental Design*. New York: Macmillan.

FISHER, R. A. 1990. *Statistical Methods, Experimental Design, and Scientific Inference*. Oxford: Oxford University Press.

GHOSH, S. & RAO, C. R. (Eds.). 1996. *Design and Analysis of Experiments*. Handbook of Statistics. **13**. Amsterdam: North-Holland.

HICKS, C. R. 1973. *Fundamental Concepts in the Design of Experiments*. New York: Holt, Rinehart and Winston.

HINKELMANN, K. & KEMPTHORNE, O. 2008. *Design and Analysis of Experiments*. I and II. 2nd edition. New York: John Wiley & Sons.

HOSHMAND, A. R. 2006. *Design of Experiments for Agriculture and the Natural Sciences*. London: Chapman and Hall/CRC.

KUEHL, R. O. 2000. *Design of Experiments: Statistical Principles of Research Design and Analysis.* 2nd edition. Duxbury Press.

LITTLE, T. M. & HILLS, F. J. 1978. *Agricultural Experimentation*, Wiley, New York.

MARTIN, R. J. 1986. On the design of experiments under spatial correlation. *Biometrica ,* **73**:247-277.

MEAD, R. 1990. *The Design of Experiments*. Cambridge, U K: Cambridge University Press.

MONTGOMERY, D. C. 1991. *Design and Analysis of Experiments*. 3rd edition. Wiley, New York.

PETERSEN, R. G. 1994. *Agricultural Field Experiments: Design and Analysis*. New York.: Marcel Dekker.

QUINN, G. P. & KEOUGH, M. J. 2002. *Experimental Design and Data Analysis for Biologists*, Cambridge, UK : Cambridge University Press.

SNEDECOR, G. W. & COCHRAN, W. G. 1980. *Statistical Methods*. 7th edition. Ames, IA : Iowa State University Press.

SOKAL, R. R. & ROHLF, F. J. 2011. *Biometry : the Principles and Practice of Statistics in Biological Research*. 4th edition. New York, NY : W. H. Freeman.