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Relative efficiency of replicated and non-replicated statistical designs in quantifying the variations in maize grain yield

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Abstract. Two-year field experiment was conducted at the Agricultural Research Station, Faculty of Agriculture, Alexandria University, Egypt, during the two successive summer seasons of 2018 and 2019. The main aim was to evaluate the relative efficiency of two groups of experimental designs in quantifying the variations in maize grain yield as influenced by sowing date (SD), plant density (PD) and phosphorous (P) fertilization, and their interactions. The single hybrid Giza 168 maize (*Zea mays*, L.) cultivar was used during both seasons. The experimental designs under evaluation included replicated (RCBD, SPD, SSPD and 3-DLD), in three replications, and non-replicated (one-rep without and with center points, RCCD and PRCCD) designs. The 3-DLD design was more efficient, within the replicated group, than the RCBD (reference design) with relative efficiency of 3.68. The SPD and SSPD had higher relative efficiencies at the sub-plot and sub sub-plot levels compared to RCBD. Within the non-replicated designs, the one-rep with center points, RCCD and PRCCD were more efficient than one-rep without center points (reference design) in discriminating the more important factors affecting grain yield in maize cultivar Giza 168.

Key words: Analysis of variance, experimental designs, experimental error, field replications, statistical relative efficiency.

INTRODUCTION

Maize (*Zea mays* L.) is an important food crop in the world and in Egypt. Increasing the productivity of maize per unit area involves the use of high yielding hybrids and better management of factors affecting that productivity. Sowing date, plant density and phosphorus fertilization are important factors that cause variations in maize productivity (Kadyrov & Kharitonov, 2019; Széles & Huzsvai, 2020 and Ibrahim et al., 2021). Hence, agriculture field experiments to determine the optimal level of each of those factors should be able to elucidate the significant effect of those individual factors, and there interactions, in order to determine their role in affecting the productivity of maize.

Efficient field experiments aim to minimize the experimental error in order to accurately detect the variations in the studied parameters caused by the investigated treatments and their interactions. In order to achieve this goal, it is necessary to control the spatial variations that occur in the field and might be caused by several circumstances such as variations in soil fertility, management practices and other environmental factors. The three principles proposed by Fisher (1935), i.e. randomization, replication and local control, form the basis for controlling the experimental error in any experimental design. Based on these three principles, the randomized complete block design (RCBD) remains the most popular design for many field experiments. However, with the increase in number of treatments, it becomes hard to control the heterogeneity within blocks and, thus, the precision of block analyses decreases (Casler, 2015).

To overcome the disadvantages of RCBD, incomplete block designs were suggested. Those designs permitted the confounding of a factor with the main plots such as the split-plot design (SPD) or confounding an additional factor with the sub sub-plots such as the split split-plot design (SSPD) (Fisher, 1925). Those designs increased the precision for one or two factors and first and/or second order interactions, meanwhile losing information about the confounded factor(s). In addition, the complication of testing the contrasts with more than one experimental error, adds to the disadvantages of those designs.

Thus, Yates (1936), later on proposed the lattice designs to overcome the spatial variation between experimental units in variety trials. These designs proved to be more precise than RCBD in several yield trials carried out by Ma & Harrington (1948) from 1937 to 1946. However, these designs were restricted to a limited number of varieties and the field layout was very stringent (Abd El-Shafi, 2014). Patterson & Williams (1976) introduced the alpha lattice design for unlimited number of varieties, and when spatial variations are high (Müller et al., 2010). However, to our knowledge, none of the lattice designs were used to test quantitative factors in the agricultural experiments, especially those that are difficult to analyze and rigid in field layout such as the three-dimensional (cubic) lattice (Yates, 1939).

In factorial experiments, the number of experimental units increase with increasing the number of factors, number of levels for each factor or both. For example, a 3^2 experiment in three replicates requires 27 experimental units, while a 3^3 experiment will require 81 units. Thus, there is an increased challenge to maintain spatial homogeneity in blocks with the increase in experimental units. To overcome that, Box & Wilson (1951) proposed the rotatable central composite design (RCCD) where each factor is studied at 5 points, i.e. two factorial, 2 star and one central point. That design requires fewer experimental units than the replicated experiments for the same number of studied factors. For example, a 3^3 factorial experiment will require only 20 experimental units in RCCD, (8 factorial points, 6 star points and 6 central points) compared to 81 experimental units required in case of the 3-replication RCBD. However, that design is criticized for estimating error from a few numbers of experimental units that are similarly treated (central points). Therefore, Dykstra (1960) proposed replicating of the factorial and star points in several blocks to obtain the traditionally accepted within-block error component of variations. The partially replicated central composite design (PRCCD) requires more experimental units than RCCD but is expected to give a better estimate of error. Unfortunately, there is no published agricultural field research adopting that design.

The present study was carried out to compare the relative efficiency of two groups of experimental designs, in detecting the importance of the studied factors (sowing date, plant density and phosphorus fertilization), and their interactions, in determining the grain yield of maize cultivar Giza 168. First group contained the replicated designs, i.e;

randomized complete block, split-plot, split-split plot and three-dimensional lattice. The second group included the non-replicated designs, i.e; one-rep without and with center points, rotatable central composite and partially replicated central composite.

MATERIALS AND METHODS

Experimental location

The present investigation was carried out at the Agricultural Research Station, Faculty of Agriculture at 31.2 °N, 29.92 °E, Alexandria University, Egypt, during the two successive summer seasons of 2018 and 2019. Soil samples were taken from the experimental site at 0–30 cm depth. The major physical and chemical characteristics of the experimental soil were determined after Olsen et al. (1954), Richards (1954) and Black et al. (1965) and are presented in Table 1.

Table 1a. Soil physical and chemical properties in first season

Physical properties		Chemical properties	
Sand %	56.40	pH	8.17
Silt %	10.80	EC (dS m^{-1})	1.61
Clay %	32.80	Ca^{+2} (meq L^{-1})	4.22
Texture	Sandy clay loam	Mg^{+2} (meq L^{-1})	3.22
Nutritional properties			
Available N (ppm)	305.43	Na^{+} (meq L^{-1})	10.02
Available P (ppm)	30.10	K^{+} (meq L^{-1})	0.61
Available K (ppm)	465.40	Cl^{-} (meq L^{-1})	6.31
Organic matter (%)	2.02	CO_3^{-2} (meq L^{-1})	1.11
HCO_3^{-} (meq L^{-1})	2.23		
Micro nutrients			
Cu (ppm)	3.42	SO_4^{-} (meq L^{-1})	7.57
Fe (ppm)	4.65	$CaCO_3$ (%)	8.87
Mn (ppm)	4.52	SAR	5.31
Zn (ppm)	1.68		

Table 1b. Soil physical and chemical properties in second season

Physical properties		Chemical properties	
Sand %	57.00	pH	8.09
Silt %	10.70	EC (dS m^{-1})	1.49
Clay %	32.40	Ca^{+2} (meq L^{-1})	4.64
Texture	Sandy clay loam	Mg^{+2} (meq L^{-1})	3.56
Nutritional properties			
Available N (ppm)	308.57	Na^{+} (meq L^{-1})	9.90
Available P (ppm)	31.50	K^{+} (meq L^{-1})	0.55
Available K (ppm)	475.60	Cl^{-} (meq L^{-1})	6.57
Organic matter (%)	2.22	CO_3^{-2} (meq L^{-1})	1.45
HCO_3^{-} (meq L^{-1})	2.61		
Micro nutrients			
Cu (ppm)	3.64	SO_4^{-} (meq L^{-1})	7.93
Fe (ppm)	4.93	$CaCO_3$ (%)	8.23
Mn (ppm)	4.72	SAR	5.45
Zn (ppm)	2.04		

The experimental location is characterized by its Mediterranean climate with its hot and dry summers. Mean minimum and maximum monthly temperatures, average humidity and wind speed during the two growing summer seasons are presented in Table 2, while total monthly precipitation was zero during both summer seasons.

Table 2. Average monthly maximum and minimum temperatures, humidity, and wind speed for the two experimental seasons

Month	Max. Temperature (°C)		Min. Temperature (°C)		Humidity (%)		Wind speed (km hr^{-1})	
	2018	2019	2018	2019	2018	2019	2018	2019
April	25.9	23.1	16	14.1	64.0	65.0	13.7	14.5
May	29.0	28.5	20	18.5	64.7	60.6	15.2	13.5
June	30.5	30.0	22.7	23.3	63.4	67.5	14.3	14.8
July	31.2	31.3	24.8	23.4	68.3	65.9	17.0	15.6
August	31.6	31.0	24.4	24.1	66.4	68.6	14.9	14.8
September	30.6	29.7	24.7	23.3	64.8	64.1	15.2	15.1

Data was compiled from www.wunderground.com

Factors and experimental designs under evaluation

The study investigated the variations of maize grain yield (t ha^{-1}) as influenced by sowing date (SD), plant density (PD) and phosphorous (P) fertilizer levels.

The evaluated designs included two groups:

I - Replicated designs:

1. Randomized complete block with three replications (RCBD), which was considered the reference design for replicated designs.
2. Split plot design with two factors in the main plots and one factor in the sub-plots, with three replications (SPD).
3. Split split plot design with three replications (SSPD).
4. Three-dimensional lattice design with three replications (3-DLD).

II - Non-replicated designs:

1. One-rep design:
   a) without center point using the 2nd order interaction as an error term,
   b) with six center points to estimate the experimental error.
2. Rotatable Central Composite Design with one replication (RCCD).
3. Partially Replicated Central Composite Design (PRCCD).

In the first experimental season (2018), RCBD, SPD and non-replicated designs were performed, whereas in second season (2019), only SSPD and 3-DLD designs were evaluated.

The levels of the studied factors used in experimental designs are presented in Table 3. Levels of factors and number of experimental units employed in each design are shown in Table 4.

Table 3. The applied levels of each factor, according to the different experimental designs

Factor levels	I	II	III	IY	Y
Sowing date (SD)	April 20th	May 1st	May 15th	May 30th	June 9th
Plant density / ha (PD)	15,866	22,758	27,766	32,775	39,666
Phosphorus fertilization (P) (kg P_2O_5/ha)	0	8	25	42	50

Table 4. The levels of the studied factors used in each design, according to experimental design specifications

Design	Levels					No.
	I	II	III	IV	V	of experimental units
I- Replicated designs:						
RCBD	✓		✓		✓	81
SPD	✓		✓		✓	81
SSPD	✓		✓		✓	81
3-DLD	✓		✓		✓	81
II- Non-replicated designs:						
One-rep without center point	✓		✓		✓	27
One-rep with center point	✓		✓		✓	33
RCCD	✓	✓	✓	✓	✓	20
PRCCD	✓	✓	✓	✓	✓	43

As shown in Table 4 , all design employed three levels from each factor (I, III and V) except the RCCD and PRCCD which employed all five levels where levels (I) and (V) represent the lowest (S-) and highest (S+) star points, (II) and (IV) represent the lowest (F-) and highest (F+) factorial points, respectively, while level (III) represent the central (C) point for each factor.

The maize (*Zea mays*, L.) cultivar used during both seasons was Giza 168, developed by Maize Research Program, Agriculture Research Center, Giza, Egypt. That cultivar is a single yellow dent hybrid that resulted from crossing Giza 658 and Giza 639. The cultivar required around 105 days from sowing till complete maturity and harvesting.

Sowing and agricultural practices

The experimental site was the same to maintain homogeneity of the experimental units in the two seasons (Idrees & Khan, 2009). The previous winter crop was berseem clover (*Trifolium alexandrinum* L.) in both seasons. After removing the berseem clover, the seedbed was prepared by chisel plowing (to a depth of 20–25 cm), followed by land levelling and ridging. The land was then divided into experimental plots. Each plot contained four ridges (0.7 m width and 2 m long) resulting in a final plot area of 5.6 m^2. Sowing was done in hills on the upper third part of one side of the ridge. The distance between hills varied according to the plant density. Plants were thinned to one plant $hill^{-1}$ at 24 days after sowing (DAS).

Surface irrigation was scheduled every 12 days and applied at the rate of 5,700 m^3 ha^{-1}, as recommended for the region using a pipe system with water meter model TURBO-IR-A DN50-300, 2'12' manufactured by Bermad Irrigation, and was terminated ten days before harvesting. Nitrogen fertilization (270.4 kg N ha^{-1}) was applied in the form of urea (46.5%N) and split into three doses, the first dose was applied during land preparation (48 kg N ha^{-1}). The remaining amount (222.4 kg N ha^{-1}) was divided into two equal doses that were applied 24 DAS and at the following irrigation. Phosphorus fertilizer was added once with seedbed preparation in the form of monocalcium phosphate (15.5% P_2O_5) according to the levels of the studied phosphorus factor. Potassium fertilization was added at the rate of 110.9 kg K_2O ha^{-1} in the form of potassium sulphate (48% K_2O) at 36 DAS. Experimental units were kept weed-free through hand hoeing at early stages and hand pulling at later stages to eliminate the weeds' effect.

Measurements

At full-grain maturation, maize was harvested by manually cutting the stalks of the two inner guarded ridges directly above ground level. After that, ears per each plot were separated and shelled to determine the grain yield per plot that was then used to estimate grain yield as ton per hectare.

The parameters used to compare the efficiency of the evaluated experimental designs included; mean square error (MSE), coefficient of variation (C.V.%), coefficient of determination (R^2) from regression analysis, relative efficiency calculated as MSE of reference design divided by MSE for design.

Statistical analyses and modeling

1. Analyses of RCBD, SPD, SSPD and one-rep experiments were performed after Gomez & Gomez (1984) using SAS 9.1 (2002), according to the following statistical models:

- RCBD model: Yijkl = μ + Bj + SDi + PDk + Pl + (SD*PD)ik + (SD*P)il + (PD*P)kl + (SD* PD* P)ikl + eijkl
- SPD model: Yijkl = μ + Rk + SDi + PDj + (SD*PD)ij + eijk + Pl + (SD*P)il + (PD*P)jl+ (SD* PD* P)ijl + eijkl
- SPPD: Yijkl = μ + Rk + SDi + eik + PDj + (SD*PD)ij + eijk + Pl + (SD*P)il + (PD*P)jl+ (SD* PD* P)ijl + eijkl
- One-rep without center point: Y = μ + SDi + PDj+ Pk + (SD*PD)ij + (SD*P)ik + (PD*K)jk + (SD*PD*K)ijk, using the three-factor interaction an error term to test the main effects and first order interaction.
- One-rep with center points: Y = μ + SDi + PDj+ Pk + (SD*PD)ij + (SD*P)ik + (PD*K)jk + (SD*PD*K)ijk + eijk, where experimental error was calculated from the variations between six center points treated similarly with central levels of each factor.

2. Analysis of 3-DLD was performed manually, and in two steps using R software package (agricolae2015) after Yates (1936), according to the model:

3. Yijkl = μ + Bj +SDi + PDk + Pl+ (SD*PD)ik + (SD*P)il + (PD*P)kl + (SD* PD* P)ikl + eijkl

4. Statistical analysis for RCCD and PRCCD was carried out after Dykstra (1960) and Petersen (1985), using the statistical software packages ‘STATISTICA 7.0’, (StatsSoft, 2012), according to the following models:

$\hat{Y}$ = β0 + β1X1+ β2X2 + β3X3 + β11X12 + β22X22 + β33X32 + β12X1X2 + β13X1X3 + β23X2X3

where: X1 = sowing date effect, X2 = Plant density effect, X3 = phosphorus fertilization effect, X1X2; X1X3 and X2X3 = interaction of factors, $\hat{Y}$ = predicted response, β0 = intercept, β1, β2, β3 = linear coefficients, β11, β22, β33 = quadratic coefficients and β12, β13, β23 = linear interaction coefficients.

RESULTS AND DISCUSSION

Analyses of variance of the variations in maize grain yield as affected by the investigated factors, are presented in Table 5, in the replicated experimental designs. Results revealed that, when applying the reference RCBD design, the three studied factors showed highly significant effects ($P \leq 0.01$) on grain yield in addition to a significant ($P \leq 0.05$) influence of the three-way interaction. The two-way interactions were non-significant.

Arranging the studied factors and their levels in incomplete block designs (split-plot and split split-plot) resulted in partitioning the experimental error into errors 'a' and 'b' in the SP design, and 'a', 'b' and 'c' in the SSP design. The results indicated that this partitioning was successful in decreasing the estimate of error for the sub plots and sub sub-plots compared to the main (whole) plots. Similar to RCBD, both designs indicated significant effects for SD, PD, P and the three-way interaction SD*PD*P on grain yield. Moreover, the SSP design revealed the significant effects of P and the three-way interaction, although they were lower in magnitude compared to the SP design, due to the lower estimate of error 'c' compared to error 'b'. Several researchers reported the advantage of split-plot designs (SP and SSP) over the RCBD in reducing the experimental error especially that of the sub-plots or sub sub-plots (Montogomery, 2001, Kristensen, 2012 and Nishu et al., 2017).

The three-dimensional lattice (3-DLD) design was effective in elucidating the significance of the main effects of the three factors and their first and second order interactions. That design had a lower mean square of error variance compared to the RCBD as a result of minimizing the block size (3 units) hence increasing the homogeneity within blocks (minimizing intra-block error) (Yates, 1939).

Table 5. Mean squares of grain yield as affected by the sowing date (SD), plant density (PD), phosphorous (P) application and their interactions in replicated designs

RCBD				SPD			
S.O.V.	d.f	MS	*P*	S.O.V.	d.f	MS	*P*
Rep	2	5.09	0.006	Rep	2	5.09	0.014
SD	2	236.45**	< 0.001	SD	2	236.45**	< 0.001
PD	2	36.16**	< 0.001	PD	2	36.16**	< 0.001
P	2	25.49**	< 0.001	SD*PD	4	0.61	0.400
SD*PD	4	0.61	0.617	Error (a)	16	1.07	0.912
SD*P	4	0.67	0.573	P	2	25.49**	< 0.001
PD*P	4	0.69	0.558	SD*P	4	0.67	0.645
SD*PD*P	8	2.62*	0.010	PD*P	4	0.69	0.632
error	52	0.92		SD*PD*P	8	2.62*	0.031
				Error (b)	36	0.56	

SSPD				3-DLD			
S.O.V	d.f	MS	*P*	S.O.V.	d.f	MS	*P*
Rep	2	0.044	0.846	Rep	2	0.19	0.616
SD	2	20.36*	0.026	Blocks (adj)	24	0.53	
Error (a)	4	1.99	0.0002	Treatment(unadj.)	26		
PD	2	78.63**	< 0.001	SD	2	1.09*	0.04
SD*PD	4	1.34	0.061	PD	2	86.70**	< 0.001
Error (b)	12	0.44	0.113	P	2	1.73**	< 0.001
P	2	4.45**	< 0.001	SD*PD	4	0.84*	0.021
SD*P	4	0.67	0.055	SD*P	4	0.73*	0.024
PD*P	4	0.49	0.138	PD*P	4	0.83*	0.020
SD*PD*P	8	0.48*	0.021	SD*PD*P	8	1.00**	< 0.001
Error (c)	36	0.27		Error	28	0.25	

*,** significant at 0.05 and 0.01 levels of probability, respectively.

Analyses of variance for non-replicated designs are presented in (Table 6). The one-rep designs (without and with center points) uncovered variations in grain yield as affected by the PD only, even though, the one-rep with center points showed a relatively small MSE. This might be a result of the relatively high mean square for the three-factor interaction (SD*PD*P) used as error term in the one-rep design, in addition to the low d.f. of error (5) in the one-rep design with center points. This finding confirms the adequacy of the one-rep designs in discriminating the importance of the different studied factors and their interactions, which could be included in further replicated experiments. Binet et al. (1955) concluded that the efficiency of these designs is hampered by the loss of information concerning the interactions (for the purpose of obtaining an estimate of error), loss of one experimental unit that will cause failure of the experiment and the occurrence of an outlier values may significantly distort the results. Hence, these types of experiments are not definitive, but are limited for screening which factors, and interactions, are important. EL-Rouby et al. (2021) used a six-factor, i.e. surface irrigation level (I), potassium (K), phosphorus (P) and nitrogen (N) fertilization rates in addition to sowing date (SD) and plant density (PD), in a half replication rotatable central composite design (RCCD) to determine the influence of those factors on grain yield of maize single hybrid Giza 168. They found significant effects for PD, I*K and P*N interactions on grain yield indicating the importance of those input factors in determining the grain yield in maize.

Table 6. Mean squares of grain yield as affected by the sowing date (SD), plant density (PD), phosphorous (P) application and their interactions in non-replicated designs

One-rep without center point				One-rep with center point			
S.O.V.	d.f	MS	*P*	S.O.V	d.f	MS	*P*
SD	2	0.06	0.970	SD	2	0.41	0.832
PD	2	31.52**	0.002	PD	2	30.21**	0.002
P	2	5.44	0.157	P	2	3.33	0.277
SD*PD	4	0.95	0.797	SD*PD	4	1.50	0.624
SD*P	4	1.72	0.587	SD*P	4	1.81	0.545
PD*P	4	1.69	0.596	PD*P	4	0.58	0.893
SD*PD*P	8	2.31		SD*PD*P	8	2.20	0.600
				Error	5	0.84	
RCCD				PRCCD			
S.O.V	d.f	MS	*P*	S.O.V	d.f	MS	*P*
(1) SD(L)	1	22.42*	0.012	blocks	2	0.29	0.813
SD (Q)	1	12.37*	0.036	(1) SD(L)	1	62.55**	< 0.001
(2) PD (L)	1	6.29	0.100	SD (Q)	1	4.02	0.100
PD (Q)	1	30.59**	0.006	(2) PD (L)	1	34.78**	< 0.001
(3) P (L)	1	3.39	0.204	PD (Q)	1	7.50*	0.027
P (Q)	1	0.09	0.820	(3) P (L)	1	0.002	0.971
SD × PD (L)	1	4.35	0.154	P (Q)	1	0.81	0.452
SD × P (L)	1	0.01	0.935	SD × PD (L)	1	1.65	0.285
PD × P (L)	1	0.10	0.808	SD × P (L)	1	0.26	0.667
Lack of Fit	5	0.70	0.797	PD × P (L)	1	3.31	0.134
Pure Error	5	1.55		Error	31	1.40	

*,** significant at 0.05 and 0.01 levels of probability, respectively.

The central composite design (RCCD), another type of one replication experiments, revealed significant SD variations at the linear and quadratic levels, and PD at quadratic level. The model describing the relationship between the grain yield and the studied factors is: $\hat{Y} = 7.87 - 1.28\ SD + 0.93\ SD^2 + 1.45\ PD^2$. The coefficient of determination (R^2) value for the applied model was high (0.87) indicating the model's adequacy in interpreting the variations in grain yield. The MSE for that design is calculated from central points receiving the same treatment (similar levels from each factor), thus, the variation within these experimental units is expected to be low and increases the ability of that design to elucidate the significance of sources of variation compared to one-rep without center points.

The suggestion of Dykstra (1960) of replicating the factorial and star points to obtain an estimate of experimental error (PRCCD), instead of calculating the error from the central points (RCCD), improved the efficiency of the design over RCCD. That design revealed only the significance of linear main effects of SD and linear and quadratic components of PD, while P effects and first order interactions were non-significant. The model equation that explains the relationship between grain yield and significant components at that stage will be: $\hat{Y} = 8.06 - 1.23\ SD + 0.92\ PD + 1.00\ PD^2$, with $R^2 = 0.73$.

Relative Efficiency of Experimental Design

The RCBD was used as a reference design, thus, the efficiency of the replicated studied designs was compared to RCBD using four parameters, i.e., mean square of error (MSE), coefficient of variation (C.V. %), coefficient of determination (R^2) and relative efficiency (R.E.) calculated as the ratio of MSE of the RCBD to MSE of the design (Table 7). The split plot designs (SP and SSP) were relatively inefficient compared to RCBD except for error 'a' in both designs. The efficiency of split-plot designs depended mainly on the allocation of studied factors to the main, sub and sub sub-plots (Jones & Nachtsheim, 2009), in addition to smaller block size compared to RCBD. In this study, the main plots of the split plot design included factorial distribution of two highly variable factors, i.e., sowing date and plant density. That resulted in a high MSE for the main plots (error 'a'). Same observation was found for the SSP, where sowing date was allocated to the main plots, which resulted in a high MSE (error 'a'). The sub-plot error (error 'b') in both designs was lower than error 'a' indicating the efficiency of both designs in minimizing the error for the subplots, and increasing the efficiency of both designs compared to the RCBD. Moreover, in the SSP, the design was efficient in reducing error 'c', thus increasing the efficiency of the sub sub-plots compared to the MSE of RCBD. Similar findings were reported by Oladugba et al. (2013) and Nishu et al. (2017).

The three-dimensional (cubic) lattice design showed higher relative efficiency (3.68) compared to the RCBD. That was expressed in lower MSE and C.V.% values with a high R^2 value of 0.90. This result might be attributed to the minimized block size (three units) which enabled the control of spatial variations of the experimental units within the block. Several researchers reported the higher efficiency of the lattice designs, other than the cubic lattice, over RCBD (Masood et al., 2008, Kashif et al., 2011, Khan et al., 2015 and Masood et al., 2017).

The non-replicated designs included one-rep designs without and with center points, RCCD and PRCCD (Table 7). The one-rep design without center points was used as reference design for that group. The RCCD and PRCCD, in addition to one-rep with center points, were more efficient than one-rep without center points. The low efficiency of the latter design resulted from the high three-way interaction variations resulting in a higher type II error. The higher efficiency of one-rep with center points was an outcome of the relatively small MSE (0.84) resulting from center points treated with the same levels of the three studied factors. However, both designs were effective in determining the importance of plant density only as the main factor affecting grain yield of maize. Thus, they could be recommended for determining the relative importance of the studied factors which would be later tested in replicated experiments (Binet et al., 1955).

Table 7. Estimates of efficiency parameters (MSE, C.V.%, R.E. and R^2) of the evaluated experimental designs for grain yield

Design		MSE	C.V. (%)	R.E [(*)]	R^2
I- Replicated designs					
RCBD		0.92	9.83	--	0.93
SPD	error (a)	1.07	6.42	0.86	0.89
	error (b)	0.56		1.64	
SSPD	error a	1.99	4.70	0.46	0.91
	error b	0.44		2.09	
	error c	0.27		3.41	
3-DLD		0.25	5.89	3.68	0.90
II- Non-replicated designs					
One-rep without center points		2.31	22.38	--	0.83
One-rep with center points		0.84	13.16	2.75	0.82
RCCD		1.55	13.02	1.49	0.87
PRCCD		1.40	11.78	1.65	0.73

[(*)] R.E. calculated:

- For replicated designs: MSE of RCBD / MSE for design.
- For non-replicated designs: MSE of one-rep without center points / MSE for design.

Both RCCD and PRCCD designs were more efficient than one-rep without center points. The RCCD resembles the one-rep with center points in which error is determined from center points treated with same levels of studied factors. However, that design was able to detect significant ($P \leq 0.05$) variations in sowing date in addition to plant density ($P \leq 0.01$). This may be attributed to the higher number of factor levels employed in that design (5 levels) compared to one-rep without center points (3 levels). The PRCCD showed relatively higher efficiency than the RCCD due to lower MSE variance, which might be explained by a better error estimate resulting from the replication of both factorial and star points, thus covering a wider space of treatments compared to the RCCD which estimates the error from the center of treatments space. Dykstra (1960) concluded that partial duplication will result in more precision in the estimates of coefficients, a better estimate of experimental error and a more powerful test of the adequacy of the second order model. Ukaegbu & Chigbu (2014, 2015) compared the prediction capabilities of partially replicated central composite designs and concluded replicating the star points of the RCCD resulted in reduction of prediction variance and increase in precision compared to replicating the cuboid points. Several researchers reached the same conclusion (Borkowski, 1995, Borkowski & Lucas, 1997 and Giovannitti-Jensen & Myers, 1989). However, Chigbu & Ohaegbulem (2011) indicated that replicating the cube portion of the RCCD enhances the performance more than the star portion.

CONCLUSION

The results obtained from the present study highlighted the importance of choosing the proper experimental design to investigate the effect of three agricultural factors, i.e., sowing date, plant density and phosphorus application level on grain yield of maize. It could be concluded that the use of three-dimensional lattice would be more appropriate for its higher relative efficiency compared to RCBD. However, if the number of available experimental units is a limiting factor, the partially replicated central composite design would be recommended. The one-rep designs proved inefficient compared to the replicated designs and, thus, their role should be restricted to the determination of the relative importance of the studied factors. The split plot designs (SP and SSP) showed enhanced efficiency for factors and interactions allocated to the sub or sub sub-plots, hence the proper factor allocation to the different types of plots is a major determinant to the design's efficiency. It is, thus, crucial to choose the appropriate design, in relation to the applied treatments, that would reduce the spatial variation between experimental units to minimize the experimental error component of variation and increase the efficiency of the design.

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