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Statistical efficiency of incomplete block designs over complete block designs in agriculture: A review

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Abstract
Field experimentation forms the backbone of agricultural research, enabling scientists to evaluate treatments under realistic growing conditions. However, soil heterogeneity remains a primary source of experimental error, reducing the precision and reliability of results. This review comprehensively examines the statistical efficiency of Incomplete Block Designs (IBDs) including Balanced Incomplete Block Design (BIBD), Partially Balanced Incomplete Block Design (PBIBD), Alpha Lattice Design (ALD), Variance Balanced Design (VBD), Lattice Designs and Augmented Designs in comparison with Complete Block Designs such as CRD, RCBD, LSD and Split Plot Design. Evidence from nine case studies across crops including wheat, brinjal, oat, triticale and durum wheat consistently demonstrates the superiority of IBDs. Relative efficiency values ranged from 17% (4×4 square lattice) to over 147% (Alpha Lattice *vs.* RCBD in durum wheat) and up to 233% (VBD *vs.* RCBD in brinjal). VBD demonstrated the highest average efficiency gain of 58.06% over RCBD, while ALD averaged 30.74%. These findings advocate for the wider adoption of IBDs in agricultural field research.

Keywords: ICBD, ALD, VBD, RE%, RCBD, Experimental Error, Soil Heterogeneity, BIBD

1. Introduction

An experiment is a planned inquiry designed to obtain new facts or confirm previous findings. The choice of treatments, methods of assigning treatments to experimental units, and the arrangement of experimental units into various patterns together constitute the Design of Experiment. The responses of experimental units are influenced not only by treatments but also by extraneous factors. Variation caused by these factors is termed experimental error, and minimizing it is the central objective of experimental design.

Three fundamental principles govern experimental design: (i) Replication enabling estimation of error variance and valid comparison of treatments; (ii) Randomization ensuring unbiased estimation of means; and (iii) Local Control reducing experimental error through grouping of experimental units into homogeneous blocks. When blocks become too large to maintain homogeneity typically when the number of treatments exceeds 16 to 20 complete block designs like RCBD lose their efficiency advantage.

A survey conducted in Gujarat state revealed that over 95% of field experiments were conducted in RCBD (Anon., 2016) [3]. Yet when the number of genotypes is large, RCBD fails to adequately control soil heterogeneity within blocks. Incomplete Block Designs (IBDs) address this limitation by subdividing replications into smaller, more homogeneous sub-blocks, thereby improving precision of treatment comparisons. This review synthesizes theoretical foundations and empirical evidence on the relative efficiency of IBDs versus CBDs across multiple crops and experimental settings.

2. Classification of Experimental Designs

2.1 Complete Block Designs (CBD)

In complete block designs, every block contains a complete set of all treatments. The major designs in this category are:

Completely Randomized Design (CRD): Treatments are assigned completely at random to experimental units with equal probability. CRD is suitable only when experimental units are completely homogeneous. The ANOVA structure is given in Table A(i) below.

Table A(i): ANOVA for Completely Randomized Design (CRD)

Source of Variation	df	MS	F-value
Treatment	t − 1	MST	MST / MSE
Error	t(r − 1)	MSE	-
Total	tr − 1	-	-

Where: t = number of treatments, r = number of replications

Randomized Complete Block Design (RCBD): The most widely used design in agricultural research. Experimental material is divided into homogeneous blocks, each containing all treatments. RCBD is inefficient when treatment numbers exceed 16. The ANOVA structure is given in Table A(ii) below.

Table A(ii): ANOVA for Randomized Complete Block Design (RCBD)

Source of Variation	df	MS	F-value
Replication (Block)	r − 1	MSR	MSR / MSE
Treatment	t − 1	MST	MST / MSE
Error	(r − 1) (t − 1)	MSE	-
Total	rt − 1	-	-

Where: r = replications, t = number of treatments

Latin Square Design (LSD): Controls two sources of variation simultaneously through row and column blocking. Each treatment appears exactly once in each row and column. The ANOVA structure is given in Table A(iii) below.

Table A(iii): ANOVA for Latin Square Design (LSD)

Source of Variation	df	MS	F-value
Rows	t − 1	MSRow	MSRow / MSE
Columns	t − 1	MSCol	MSCol / MSE
Treatment	t − 1	MST	MST / MSE
Error	(t − 1)(t − 2)	MSE	-
Total	$t^2 - 1$	-	-

Where: t = number of treatments (= rows = columns)

Split Plot Design: Used in factorial experiments where one factor requires larger plots than another. Larger plots (whole plots) receive one factor while they are subdivided (split plots) for the other factor. The ANOVA structure is given in Table A(iv) below.

Table A(iv): ANOVA for Split Plot Design

Source of Variation	df	MS	F-value
Main Plot (Whole Plot)			
Replication	r − 1	MSR	-
Factor A (Main Plot Treatment)	a − 1	MSA	MSA / MSEa
Main Plot Error (Error a)	(r − 1)(a − 1)	MSEa	-
Sub Plot			
Factor B (Sub Plot Treatment)	b − 1	MSB	MSB / MSEb
A × B Interaction	(a − 1)(b − 1)	MSAB	MSAB / MSEb
Sub Plot Error (Error b)	a(r − 1)(b − 1)	MSEb	-
Total	rab − 1	-	-

Where: r = replications, a = levels of Factor A (main plot), b = levels of Factor B (sub plot)

2.2 Incomplete Block Designs (IBD)

Incomplete Block Designs subdivide each replication into smaller sub-blocks, each containing only a portion of the treatments. Introduced by Yates (1936), IBDs are especially valuable when the number of treatments is large. Based on how pairs of treatments are replicated together, IBDs are classified into BIBD, PBIBD, Lattice, Alpha Lattice, VBD, Augmented and Row-Column designs.

3. Theoretical Framework of Key Incomplete Block Designs

3.1 Balanced Incomplete Block Design (BIBD)

A BIBD with parameters (v, b, r, k, λ) arranges v treatments in b blocks of k plots each (k < v) such that each treatment appears in exactly r blocks and each pair of treatments occurs together in exactly λ blocks. The fundamental parametric relations are: bk = vr and λ(v-1) = r(k-1). BIBD ensures equal precision for all treatment comparisons, but does not exist for all parameter combinations and often requires a large number of replications.

3.2 Partially Balanced Incomplete Block Design (PBIBD)

PBIBD relaxes the strict balance requirement of BIBD by allowing different pairs of treatments to have different concurrences (λ values). Treatments are arranged according to an association scheme with m classes where the number of i-th associates ni is constant for each treatment. PBIBDs reduce the number of replications required while maintaining reasonable precision for all comparisons, making them more practically feasible than BIBDs for many experimental settings.

3.3 Lattice Designs

Lattice designs were introduced by Yates (1936) as quasi-factorial designs. The number of treatments must be a perfect square (s2) with block size s. Construction uses a standard s×s array where rows form the first replication and columns form the second. Additional replications are obtained by superimposing mutually orthogonal Latin squares. Lattice designs simple (2 reps), triple (3 reps), and balanced are classified by the number of replications. When the complete set of (s-1) mutually orthogonal Latin squares is used, the design becomes a balanced (s+1)-lattice equivalent to BIBD.

3.4 Alpha Lattice Design (ALD)

Proposed by Patterson and Williams (1976), Alpha Lattice Designs are cyclic resolvable incomplete block designs that exist for a much wider range of parameter combinations than traditional lattice or BIBD designs. For parameters r (replications), k (block size), and s (blocks per replication), the total number of treatments t = sk. Key features include existence for many (r,k,s) combinations where conventional lattices do not exist; efficient elimination of within-block heterogeneity; maximization of comparisons between genotypes in the same block; and suitability for large numbers of treatments in limited experimental areas. The ANOVA structure for ALD is presented in Table B below.

Table B: ANOVA for Alpha Lattice Design (ALD)

Source of Variation	Degrees of Freedom (DF)	Mean Square (MS)	F-value
Replication	r − 1	MSR	MSR / MSE
Treatment	t − 1	MST	MST / MSE
Block within Replication	rs − r	MSB	MSB / MSE
Intra-block Error	rt − rs − t + 1	MSE	-
Total	tr − 1	-	-

Where: r = replications, t = total treatments (t = sk), s = blocks per replication, k = block size

3.5 Variance Balanced Design (VBD)

VBD is specifically constructed for complete diallel cross systems. For p parents, the first block consists of all crosses involving the first parent with the remaining p-1 parents. The remaining p-1 blocks are obtained cyclically. Parameters: r=2 replications, k=p-1 block size. Sharma and Fanta (2010) proposed a VBD that is balanced and available for every number of parents. Ghosh and Ahuja (2017) formalized the relative efficiency formula comparing VBD with RCBD using the ratio of treatment variance estimators. The ANOVA structure for VBD is presented in Table C below.

Table C: ANOVA for Variance Balanced Design (VBD)

Source of Variation	Degrees of Freedom (DF)	Mean Square (MS)	F-value
Blocks	$p-1$	MSB	MSB / MSE
Crosses (adjusted)	$p(p-1)/2-1$	MSC	MSC / MSE
GCA	$p-1$	MS_e	MSG / MSE
SCA	$p(p-3)/2$	MSS	MSS / MSE
Error	$(p^2-3p+2)/2$	MSE	-
Total	$n-1$	-	-

Where: p = number of parents, GCA = General Combining Ability, SCA = Specific Combining Ability

3.6 Augmented Designs

Introduced by Federer (1956), augmented designs are used when testing material is limited and complete replication is not possible. They incorporate both test genotypes (unreplicated) and check varieties (replicated). Three forms exist: Augmented CRD (Design I), Augmented RCBD (Design II), and Augmented Latin Square (Design III). Error estimation is achieved through check variety replication within blocks, making these designs valuable for large germplasm screening programs.

4. Relative Efficiency: Concept and Measurement

Relative Efficiency (RE) quantifies how much more precise one experimental design is compared to another. It is expressed as the ratio of error variances or other precision measures. Values >100 (for EMS, S.Em, CV%) indicate the IBD is more efficient; for F-values, values <100 indicate IBD superiority. The gain in efficiency is calculated as RE% - 100 (for EMS/S.Em/CV%) or 100 - RE% (for F-values).

Table 1: Formulas for Relative Efficiency computation across different metrics

Metric	Formula	Interpretation
RE by EMS (ALD vs RCBD)	RE% = (EMS_RCBD / EMS_ALD) x 100	>100: IBD more efficient
RE by EMS (VBD vs RCBD)	RE% = V(fi-fj)_RCBD / V(fi-fj)_VBD x 100	>100: VBD more efficient
RE by S.Em	RE% = (S.Em_RCBD / S.Em_IBD) x 100	>100: IBD more efficient
RE by CV%	RE% = (CV_RCBD / CV_IBD) x 100	>100: IBD more efficient
RE by F-value	Rf = (Cal.F_RCBD / Cal.F_IBD) x 100	<100: IBD more efficient
Gain (EMS/SEm/CV)	Gain = RE% - 100	Positive value = gain
Gain (F-value)	Gain = 100 - RE%	Positive value = gain

5. Review of Literature

A systematic review of published studies demonstrates the consistent superiority of IBDs over CBDs across diverse crops, environments and experimental conditions. Nine key case studies are reviewed below.

5.1 Relative Precision of Experimental Designs

Singh (1995) studied the relative precision of various experimental designs (CRD, RBD, LSD, Simple Lattice, Triple Lattice, Balanced Lattice) across different block sizes. For block sizes of 5 and above, lattice designs consistently outperformed RCBD in terms of precision, especially for larger treatment numbers.

Table 2: Relative precision of experimental designs in relation to RBD

Block Size	CRD	RBD	LSD (Row)	LSD (Col)	Simple Lattice	Triple Lattice
4	125.17	113.32	115.52	101.48	101.87	102.15
5	99.85	101.47	95.85	106.20	107.29	108.12
6	106.57	115.51	92.15	-	-	-
7	127.18	125.97	103.84	-	-	-

5.2 Square Lattice Designs *vs.* RCBD

Raza and Masood (2009) compared 3x3, 4x4, and 5x5 Square Lattice Designs with RCBD. The 5x5 lattice showed the highest relative efficiency gain of 55% over RCBD. Intra-block error mean squares were consistently lower for lattice designs.

Table 3: Error mean squares and relative efficiency of square lattice designs *vs.* RCBD

Design	DF	EMS (Effective)	EMS (RCBD)	EMS (Intrablock)	RE (%)
3x3 Square Lattice	16	0.092	0.111	0.077	26
4x4 Square Lattice	45	369	431	323	17
5x5 Square Lattice	56	5	7.9	4.3	55

5.3 Alpha Lattice Design in Wheat

El-Shafi (2014) [6] evaluated 54 wheat genotypes in Alpha Lattice Design versus RCBD during two consecutive seasons (2011-12 and 2012-13). Alpha lattice design proved more efficient for most traits, with highest RE for number of kernels/spike (2.04) and spikes/m2 (1.51). The average RE across all traits was 1.14.

Table 4: EMS and relative efficiency of alpha lattice *vs*. RCBD in wheat

Character	EMS RCBD (S1)	EMS Alpha (S1)	RE (S1)	EMS RCBD (S2)	EMS Alpha (S2)	RE (S2)	Avg RE
Plant height	12.05	8.67	1.39	17.72	19.44	0.91	1.15
Spike length	0.68	0.68	0.99	1.07	1.06	1.01	1.00
Spikelet/spike	1.76	1.57	1.12	2.75	2.46	1.12	1.12
Spikes/m2	18338.8	13260.2	1.38	10035.2	6665.6	1.51	1.44
Kernels/spike	26.92	13.23	2.04	24.72	22.12	1.12	1.58
Grain yield/plot	0.17	0.16	1.04	0.64	0.50	1.27	1.13
Grain yield/ha	9.32	9.15	1.02	35.05	27.62	1.27	1.14

5.4 IBD, Alpha & Augmented Designs in Durum Wheat

Twenty-four durum wheat varieties were evaluated using RCBD, IBD, Alpha Lattice and Augmented Design. Alpha Lattice emerged as the most efficient (RE=147.1%), followed by IBD (118.7%) and Augmented (113.7%). Alpha design also achieved the highest adjusted R^2 (0.80) and lowest CV% (10.50%).

Table 5: Fit summary of experimental designs for durum wheat

Parameter	RCBD	IBD	Alpha Lattice	Augmented
No. of plots (N)	72	48	48	40
R^2	0.79	0.87	0.90	0.93
Adjusted R^2	0.68	0.72	0.80	0.71
Standard Deviation	39.37	33.15	26.76	34.61
CV%	16.00	13.25	10.50	12.76
AICc	789.3	564.4	560.3	703.1
RE (%)	100%	118.7%	147.1%	113.7%
Mean yield (g/m2)	246.0	250.2	254.9	271.2

5.5 Alpha Lattice in Triticale

Twenty triticale genotypes were evaluated using Alpha Lattice and RCBD across two seasons (2017 and 2018) for eight agronomic characters. Alpha Lattice achieved higher relative efficiency for most traits, with average RE ranging from 91.08% (tillering general) to 135.50% (spike length). Grain yield showed an average RE of 126.69%.

Table 6: EMS and relative efficiency of alpha lattice *vs*. RCBD in triticale

Trait	EMS RCBD (2017)	EMS Alpha (2017)	RE% (2017)	EMS RCBD (2018)	EMS Alpha (2018)	RE% (2018)	Average RE%
No. of plants/m^2	5041	4511	111.74	3653	3138	114.20	112.97
Tillering general	0.10	0.12	78.51	0.057	0.055	103.64	91.08
Tillering fertility	0.07	0.11	65.18	0.022	0.015	146.67	105.93
Plant height (cm)	15.01	11.28	133.07	22.40	20.27	110.51	121.79
Spike length (cm)	0.95	0.63	150.40	0.726	0.602	120.60	135.50
Spikelets/spike	4.28	3.54	121.09	3.021	2.477	121.96	121.53
1000-grain wt (g)	3.43	2.48	138.50	1.336	1.221	109.42	123.96
Grain yield (g/m2)	3452	2629	131.30	3296	2700	122.07	126.69

5.6 VBD *vs*. RCBD for Diallel Crosses

Popat Raj (2021) compared VBD (2 replications, 15 crosses, 6 blocks, block size 5) with four replications of RCBD for 15 diallel crosses from 6 brinjal parents. VBD identified more significant GCA (10) and SCA (12) effects compared to individual RCBD replications, demonstrating greater sensitivity in detecting genetic differences.

Table 7: Significant GCA and SCA estimates in RCBD and VBD for brinjal diallel crosses

Trait	RCBD I gca/sca	RCBD II gca/sca	RCBD III gca/sca	RCBD IV gca/sca	VBD gca/sca
NFPP	2 / 0	1 / 0	3 / 0	2 / 0	5 / 0
FYPP	1 / 4	0 / 0	2 / 3	0 / 4	2 / 7
AFW	2 / 3	2 / 0	2 / 0	2 / 4	3 / 5
TOTAL	5 / 7	3 / 0	7 / 3	4 / 8	10 / 12

5.7 VBD and ALD *vs*. RCBD in Brinjal Crosses

Vekariya *et al*. (2024) [16] evaluated 45 F1 crosses from a 10-parent brinjal diallel in RCBD, ALD (5x9 blocks, 2 replications) and VBD (10 blocks, block size 9, 2 replications) at Anand Agricultural University. This study provides direct quantitative comparison of all three designs.

Table 8: Gain in efficiency for fruit yield (FY) and number of fruits (NF) in brinjal

Parameter	Trait	RCBD	ALD	RE ALD (Gain%)	VBD	RE VBD (Gain%)
EMS	FY	0.57	0.40	143.29 (43.29)	0.22	233.88 (133.88)
EMS	NF	83.67	55.06	151.98 (51.98)	41.99	181.11 (81.11)
S.Em	FY	0.53	0.44	119.82 (19.82)	0.33	160.73 (60.73)
S.Em	NF	6.47	5.25	123.27 (23.27)	4.58	141.16 (41.16)
CV%	FY	14.75	12.32	119.72 (19.72)	8.91	165.54 (65.54)
CV%	NF	12.36	10.02	123.35 (23.35)	8.55	144.56 (44.56)
F-estimate	FY	7.69	11.02	69.78 (30.22)	9.54	80.61 (19.39)
F-estimate	NF	19.37	29.44	65.79 (34.21)	23.65	81.90 (18.10)

Table 9: Average gain in efficiency by designs over RCBD

Design (Over RCBD)	EMS Gain (%)	S.Em Gain (%)	CV (%) Gain (%)	F Gain (%)	Average (%)
Alpha Lattice Design (ALD)	47.64	21.55	21.54	32.22	30.74
Variance Balanced Design (VBD)	107.50	50.95	55.05	18.75	58.06

5.8 Alpha Lattice in Oat

Sanadya *et al.* (2022) [12] examined ALD versus RCBD for seed yield and green fodder yield in 96 oat genotypes across two years (2019-20 and 2020-21). While individual year RE values were marginal (1.01-1.03), the pooled analysis showed dramatic improvements: RE of 5.34 for seed yield and 4.21 for green fodder yield, highlighting ALD's accumulating advantage across environments.

Table 10: Relative efficiency of alpha lattice vs. RCBD for oat yield traits

Parameter	2019-20 Seed Yield	2019-20 Fodder Yield	2020-21 Seed Yield	2020-21 Fodder Yield	Pooled Seed Yield	Pooled Fodder Yield
EMS (RCBD)	1.34	27.79	2.23	53.74	9.53	171.25
EMS (Alpha)	1.30	27.95	2.18	52.43	1.78	40.67
Relative Efficiency	1.03	0.99	1.02	1.02	5.34	4.21
CV% (RCBD)	10.50	9.36	12.68	10.08	27.08	20.28
CV% (Alpha)	10.35	9.39	12.53	9.96	11.72	9.89
RE (CV)	1.01	1.00	1.01	1.01	2.31	2.05

5.9 Alpha Lattice in Wheat

Varma *et al.* (2024) [15] evaluated 306 wheat genotypes using ALD and RCBD at CSKHPKV, Palampur, in Rabi 2021-22 under irrigated and rainfed conditions. Results showed marginal differences between ALD and RCBD for most traits in individual environments, with grain yield showing slight RE advantages (1.03 pooled). With very large treatment numbers, ALD's advantage is realized through better block homogeneity across the pooled analysis.

6. Discussion

The collective evidence from nine case studies spanning five crops (wheat, brinjal, oat, triticale, durum wheat), three countries (India, Pakistan, Egypt, Greece) and multiple decades of research consistently demonstrates that Incomplete Block Designs are more efficient than Complete Block Designs for agricultural field experimentation, especially when treatment numbers are large.

The magnitude of efficiency gain varies by design type, crop, number of treatments and degree of soil heterogeneity. VBD emerged as the overall most efficient design in brinjal diallel experiments with an average gain of 58.06% over RCBD, while ALD averaged 30.74%. In durum wheat, Alpha Lattice design achieved 47.1% superiority over RCBD. Square lattice designs showed 17% to 55% gains depending on design size, with 5x5 lattice most efficient.

Pooled analyses (Sanadya *et al.*, 2022; Varma *et al.*, 2024) [12, 15] reveal that efficiency gains accumulate across environments, making IBDs especially valuable in multi-environment trials. The reduction in error variance through smaller, more homogeneous blocks translates to smaller CV (%), lower SEm and higher F-values for treatment comparisons.

While RCBD remains popular (>95% usage in Gujarat surveys), its adequacy diminishes sharply when treatment numbers exceed 16. The practical advantages of ALD and VBD easy construction, flexible parameter requirements and straightforward analysis make them accessible alternatives. The comparable simplicity of analysis software for IBDs further removes barriers to their adoption.

7. Conclusion

This review conclusively establishes that Incomplete Block Designs (IBDs) are superior to Complete Block Designs for agricultural field experimentation involving large numbers of treatments or genotypes. VBD proved the most efficient design for diallel cross evaluation, achieving an average efficiency gain of 58.06% over RCBD across EMS, S.Em, CV% and F estimates in brinjal, while Alpha Lattice Design consistently outperformed RCBD across diverse crops and environments with efficiency gains ranging from 14% in wheat to 147% in durum wheat and Square Lattice designs showed notable advantages of 17-55% over RCBD for larger treatment sets. The consistent trend of error variance (RCBD > ALD > VBD) confirms the increasing effectiveness of tighter block control. Pooled analyses across environments further amplify these advantages, making IBDs indispensable for multi-environment trials with large germplasm sets. Accordingly, plant breeders and agricultural scientists are strongly advocated to replace RCBD with VBD and ALD when evaluating breeding materials, as both designs are straightforward to construct and analyze while offering substantially improved experimental precision.

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