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Performance of Rhode Island Red, Black Australorp, and Naked Neck crossbreds under alternative production systems

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Abstract

The effects of the production system, breed cross, and their interaction on performance, egg quality, and hatching traits were evaluated. Rhode Island Red and Black Australorp were crossed with Naked Neck chickens (first generation RNN, and BNN, respectively). These crosses were mated among themselves and crossed to produce four crossbreds: RR (RNN x RNN), BB (BNN x BNN), RB (RNN x BNN), and BR (BNN x RNN). Thirty-six pullets and 9 cockerels from each crossbred were maintained in three production systems: the aviary system (AV), conventional cages (CC), and enriched cages (EC). Thus there were 48 pullets and 12 cockerels in each production system. Bodyweight, egg production percentage, and egg weight were highest in EC, followed by CC and AV. Higher egg weight, egg surface area, and egg volume were also observed in EC compared with CC and AV. Fertility and hatchability were higher and early embryonic mortality was lower in AV than in EC and CC. Bodyweight, egg production percentage, egg weight, egg volume, and surface area were higher for RB and BR than for BB and RR. Fertility and hatchability were similar for RB and BR. RR was similar to BR, but lower than RB. BB had the lowest fertility and hatchability. Thus, chickens in EC performed better than in the other systems, except that hatching traits were better in AV. RB and BR performed better than BB and RR.

Key words: breed crosses, chicken, egg quality, hatchability
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Introduction

The poultry sector in developing countries understands the pivotal significance of fulfilling dietary requirements and alleviating poverty, serving as a major animal protein source and delivering essential nutrients. This sector is reliant on commercial exotic breeds and pays no attention to rural chicken breeds. Thus indigenous chicken breeds are being ignored, although they still contribute to the national demand for meat and eggs (Anonymous, 2019). This triggers unintentional loss of birds that have the genetic potential to endure harsh climatic conditions, better robustness against stressors, and superior adaptability to local climatic conditions. Naked Neck is one of the most important dual-purpose utility breeds among rural chicken breeds in Pakistan. It has promising traits such as better productivity and survivability in a hot climate, better feed efficiency, and a larger egg size (Garces *et al.*, 2001; Nwachukwu *et al.*, 2006). Its average egg production is 138 eggs in 52 weeks, and the bodyweight of female and male are 1.1 kg and 1.5 kg (Grobbelaar *et al.*, 2010). In several countries, various strategies have been applied to develop a dual-purpose rural chicken breed with further improvement in its production traits (Mallia, 1999). This genetic improvement can be achieved through crossbreeding and selection. Cross breeding produces improvements in growth rate, reproductive traits and feed conversion efficiency without disturbing the potential of acclimatization, and ultimately reducing production costs (Adebambo *et al.*, 2011). Better productive performance and adaptability traits of Naked Neck can be exploited through heterosis and complementarity in crosses between Rhode Island Red and Black Australorp. These crosses have genetic potential for high levels of egg production and meat yield and a possibility of higher economic returns. This would help to develop a cross breed with improved production and maintained acclimatizing abilities.

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Better management and provision of a suitable environment are also necessary to exploit genetic potential (Menge *et al.*, 2005). Alterations in housing for chickens are required to achieve the optimum performance of genetically improved chickens (Preisinger, 2005). The conventional cage system (CC), which was developed in the 1930s, has been used since the 1950s to maximize profit and production by allowing an increased number of hens in a small area (Sosnowka-Czajka *et al.*, 2010; Jones *et al.*, 2014). However, increases in stocking density resulted in increased welfare concerns in Europe during the 1960s and thereafter questions were raised about restricted movement and inhibited expression of natural behaviours in the constricted bare environment of CC (Mench *et al.*, 2011). Continued amendments and improvements of CC led to development of the enriched cage system (EC) in Germany during the 1980s (Appleby, 1998). The EC featured more space per bird and tools such as perches, nests and scratching areas in which birds could express their natural behaviour (Lay *et al.,* 2011; Mench and Blatchford, 2014). Additionally, banning of the CC system led to development of new housing systems (van Asselt *et al.,* 2015). These newly developed systems included the aviaries, free range, barns ,and organic systems which have recently be studied for their effects on performance (Tactacan *et al.*, 2009) and health (Rodenburg *et al.*, 2008; Lay *et al.*, 2011). Production systems may affect production performance, egg quality, and the welfare of chickens, but the relationships between genotype and production system should not be undervalued, especially with genetically improved chickens. Indigenous chicken breeds are good in terms of adaptability, but their performance in alternative production systems after crossing with exotic breeds has not been evaluated. Therefore, the present trial was conducted to evaluate the production performance, egg quality attributes, and hatching traits of Naked Neck, Black Australorp, and Rhode Island Red crossbreds under alternative production systems.

Materials and Methods

The care and use of the birds were in accordance with the laws and regulations of Pakistan. The experimental procedures were approved by the Committee of Ethical Handling of Experimental Birds, University of Veterinary and Animal Sciences, Lahore, Pakistan (No. DR/124).

The trial was conducted at the Indigenous Chickens Genetic Resource Centre (ICGRC), Department of Poultry Production, Ravi Campus, University of Veterinary and Animal Sciences, Pattoki. This city is located at 73°50'60 E and 31°1'0 N at an altitude of 186 m and has a tropical hot and humid climate. The temperature ranges between 12 °C and 45 °C. The present study was a continuation of an earlier project, in which the performance of progeny (F1) from Rhode Island Red × Naked Neck (RNN) and Black Australorp × Naked Neck (BNN) was evaluated (Ahmad *et al.*, 2019). In the present study, reciprocal crosses of BNN and RNN were made to comprise a second generation (F2). For this purpose, 200 heterozygous partially feathered chickens comprising 50 birds (10 male × 40 female) from each crossbred of first generation were used to produce a two-breed diallel of BNN and RNN (Figure 1).

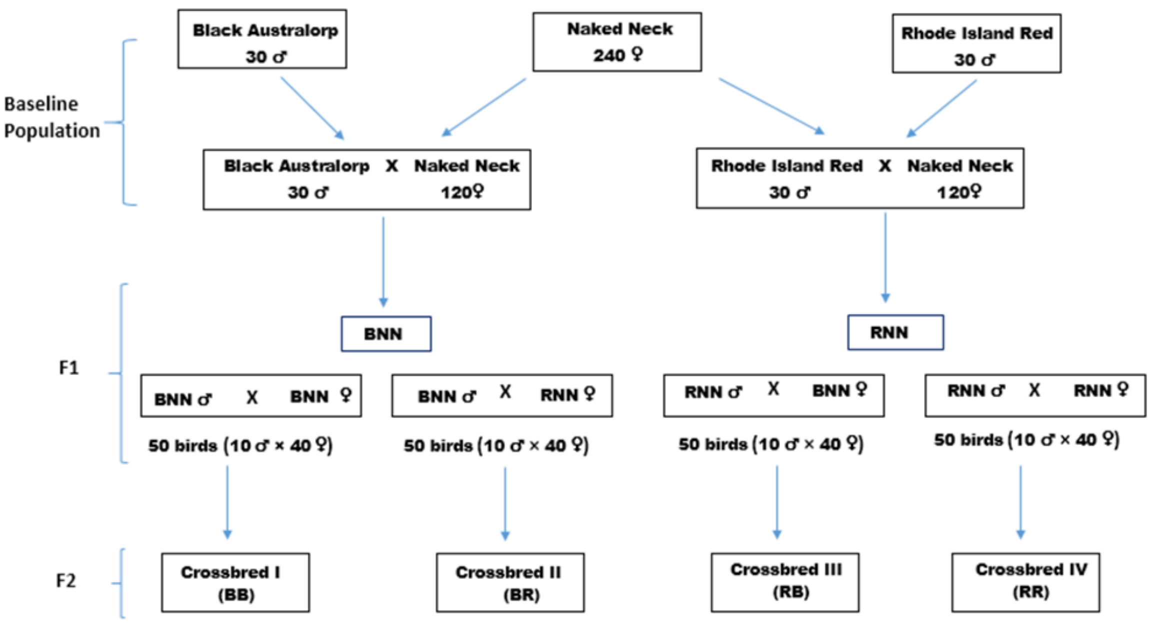

Figure 1 Breeding plan to generate crosses of Naked Neck, Black Australorp & Rhode Island Red chickens

More than 1200 hatching eggs were acquired when the birds were 33 weeks old. A total of 720 day-old chicks in the second generation; 180 each from BB, BR, RR, and RB, which were hatched at Avian Research and Training Centre (ARTC), UVAS, Lahore, were transported to ICGRC, Ravi Campus, UVAS, Pattoki. The birds were fed a commercial breeder ration (Leeson & Summers, 2005) (Table 1). The chicks were brooded under standard managerial conditions up to six weeks of age. During the brooding phase, the birds were vaccinated against Infectious Bronchitis (IB) and Newcastle Disease (ND) according to the local area schedule. To evaluate the productive efficiency and hatching traits, 180 birds, comprising 144 pullets with 36 cockerels (36 pullets and 9 cockerels from each crossbred), were maintained in three production systems with 48 pullets and 12 cockerels in each during the production phase (27 - 46 weeks). Thus, the experiment had a 3 × 4 factorial arrangement of treatments in which housing systems and breed cross were main effects.

Table 1 Nutrition value and composition of experimental rations for males and females during growing phase

Feed ingredients	Male formulation, %	Female formulation, %
Corn	39.40	42.61
Soybean meal	10.45	15.62
Rice tips	31.00	19.00
Corn gluten (60%)		1.00
Wheat bran	15.80	13.00
Calcium Carbonate	2.65	7.42
Digestible crude protein	0.70	1.20
DL-Methionine		0.15
Calculated nutrient composition		
Metabolizable energy (Kcal/kg)	2848	2682
Crude protein (%)	13.13	15.04
Phosphorus (%)	0.22	0.34
Calcium (%)	1.09	2.81
Methionine (%)	0.39	0.45

Chickens that were reared in ECs and AVs were provided with perches and dust bathing areas. They were kept in open-sided windowed enclosures that were ventilated with ceiling fans and galvanized round feeders and plastic manual drinkers were used. Birds reared in CC were maintained in environmentally controlled poultry sheds, equipped with galvanized three-tiered battery cage systems, automatic manure belts, automatic water nipple lines and feed trolleys (FACCO, Poultry Equipment-C3, San Martino, Italy). Fresh water was supplied ad libitum. The physical characteristics of each system are explained in Table 2.

The experiments lasted about five months (August to December), during which the minimum to maximum temperature and humidity were maintained in the range of 18 °C to 30 °C and 55% to 72%, respectively, in open-sided enclosures (AV and EC), whereas in environmentally controlled houses (CC), the minimum and maximum temperature and humidity ranged between 18 °C and 25 °C and 64% and 76%, respectively. The lighting schedule for the CC system was applied according to the HyLine W36 management guide (2018) (Table 3). Rice husk was used as litter in ECs and AVs. Approximately 10 cm depth of bedding material was maintained and was racked daily to retain the condition.

Egg collection records were used to calculate hen/day egg production percentage and egg weight (g) (Shafik *et al.*, 2013). To evaluate internal and external egg quality parameters (egg weight, shell thickness, Haugh unit score and yolk index), a total of 60 eggs (five eggs per treatment group) were used at the start and the end of the experiment (adapted from Gikunju *et al.*, 2018). Eggs were stored at 14 - 16 °C with 70-80% relative humidity and transported to the hatchery (Victoria Inc.) at ARTC to evaluate fertility, hatchability, dead in shell, and dead germ percentage (adapted from Adeleke *et al.*, 2012).

Table 2 Physical characteristics of alternative production systems

Specifications	Conventional cage (separate by sex)	Aviary (straight run)	Enriched cage (separate by sex)
Dimension (length × depth × height), cm	51 × 61 × 41	305 × 305 ×305	91 × 91 × 91
Stocking density	5 birds / cage	30 birds / aviary	5 birds / cage
Sex ratio (male: female)	1:4	6:24	1:4
Space per bird	613.16 cm^2	3093.67 cm^2	1672 cm^2
Nesting space		580.64 cm^2	1083.87 cm^2
No. of nests		5	1
Dust bath (length × width), cm		137 x 137	55 × 25
Dust bathing space/bird		622.45 cm^2	276 cm^2
Perches			
Number		2	1
Material		Wooden	Wooden
Shape		Round	Round
Dimension (diameter x length), cm		4.2 x 304	1.8 x 122
Height from floor, cm		91	46

Table 3 Light provided to chickens in conventional cage, aviary, and enriched cage production systems

Age, weeks	Natural day length, hours	Artificial light, hours	Total light
27	13.62	1.63	15.25
28	13.43	2.03	15.50
29	13.30	2.45	15.75
30	13.12	2.88	16.00
31	12.90	3.10	16.00
32	12.70	3.30	16.00
33	12.48	3.52	16.00
34	12.27	3.63	16.00
35	12.08	3.92	16.00
36	11.83	4.17	16.00
37	11.62	4.38	16.00
38	11.40	4.60	16.00
39	11.20	4.80	16.00
40	11.00	5.00	16.00
41	10.80	5.20	16.00
42	10.63	5.37	16.00
43	10.48	5.52	16.00
44	10.35	5.65	16.00
45	10.25	5.75	16.00
46	10.18	5.82	16.00

Effects of the production systems and breed crosses were evaluated for productive performance, egg quality and hatching traits. The GLM procedure of SAS (SAS Institute, Inc., Cary, North Carolina, USA) was used to test the main effects and their interaction. The model was:

$$Y_{ijk} = \mu + P_i + C_j + PC_{ij} + e_{ijk}$$

where: Y_{ijk} = an observation of a dependent variable from the kth experimental unit,
μ = population mean,
P_i = the effect of the ith production system,
C_j = the effect of the jth breed cross,
PC_{ij} = the interaction between the ith production system and jth breed cross, and
e_{ijk} = the residual effect after having accounted for the other effects in the model (NID ~ 0, σ^2).

Tukey's HSD test (Tukey, 1953) was used to compare treatment means at a significance level of *P* =0.05. For initial and final egg quality traits, independent student's t-tests were applied.

Results and Discussion

Significant differences were observed between the production system and breed (Table 4). Chickens that were reared in EC had the highest (all *P* <0.0001) initial bodyweight, final bodyweight, egg production percentage, and egg weight, followed by those reared in CC and AV. Initial bodyweight final bodyweight, egg production percentage and egg weight were higher (all *P* <0.0001) in RB and BR than in RR and BB. Significant interactions were observed between production system and breed crosses. However, these interactions only resulted in changes in the magnitude of differences between the levels of the main effects and not in any changes in rank. Egg weight in RB and BR crosses reared in EC was higher than in the other treatment groups.

Significant differences were observed between production systems and breed crosses in egg morphometric traits and egg quality traits at 26 weeks old (Tables 5, 6, and 7). Higher (all *P* <0.005) egg weight, surface area, volume and Haugh unit score were observed in the eggs of chickens reared in ECs than those of CCs and AVs. Eggs from chickens reared in EC and CC had higher shape index (*P* =0.0002) than those of AVs. Non-significant differences were observed in yolk index (*P* =0.14) and shell thickness (*P* =0.14) between these systems. Higher egg weight (*P* =0.02) and volume (*P* <0.0001) were found in the eggs of RB and BR chickens than in those of RR and BB. Higher surface area (*P* =0.0074) was observed in the eggs of BR chickens, followed by RB, BB and RR. The shape index (*P* =0.05) remained the same in RR, BR, and RB, but was lower in BB. Non-significant differences were observed in Haugh unit score (*P* =0.22), yolk index (*P* =0.14) and shell thickness (*P* =0.58) among crosses. Significant (all *P* <0.01) interactions between production system and breed crosses were observed in egg weight, egg surface area, egg volume, egg shape index and Haugh unit score. Non-significant interactions were observed for the egg yolk index (*P* =0.12) and eggshell thickness (*P* =0.50).

Table 4 Effects of production system, breed cross, and their interaction on productive performance

PS	BC	HDEP	EW	BW at 26 weeks	BW at 46 weeks
CC		60.04 ± 0.66[b]	51.16 ± 0.58[b]	1474.58 ± 20.15[b]	1710.83 ± 21.74[b]
AV		57.69 ± 0.68[c]	48.81 ± 0.31[c]	1425.83 ± 19.12[c]	1654.58 ± 21.87[c]
EC		62.28 ± 0.63[a]	54.34 ± 0.50[a]	1581.25 ± 22.42[a]	1817.08 ± 23.00[a]
	RB	61.99 ± 0.61[a]	52.84 ± 0.89[a]	1566.11 ± 24.74[a]	1802.22 ± 27.71[a]
	RR	57.73 ± .79[b]	50.18 ± 0.70[b]	1450.56 ± 23.57[b]	1683.33 ± 23.59[b]
	BR	62.04 ± 0.85[a]	53.04 ± 0.91[a]	1539.44 ± 29.38[a]	1772.22 ± 31.49[a]
	BB	58.25 ± 0.61[b]	49.69 ± 0.75[b]	1419.44 ± 23.94[b]	1652.22 ± 27.71[b]
CC	RB	60.88 ± 0.10[c]	52.75 ± 0.43[bc]	1543.33 ± 20.27[b]	1783.33 ± 30.86[b]
CC	RR	58.01 ± 0.05[d]	49.40 ± 0.04[de]	1436.67 ± 17.63[de]	1671.67 ± 10.92[de]
CC	BR	63.20 ± 0.14[b]	53.36 ± 0.31[b]	1520.00 ± 25.65[b]	1755.00 ± 31.75[bc]
CC	BB	58.05 ± 0.55[d]	49.13 ± 0.18[e]	1398.33 ± 23.15[ef]	1633.33 ± 30.86[ef]
AV	RB	60.66 ± 0.33[c]	49.82 ± 0.18[d]	1501.67 ± 22.04[bc]	1736.67 ± 31.92[bcd]
AV	RR	54.96 ± 0.67[f]	48.26 ± 0.23[f]	1383.33 ± 14.52[ef]	1610.00 ± 7.63[ef]
AV	BR	58.78 ± 0.14[d]	49.76 ± 0.03[de]	1458.33 ± 21.66[cd]	1685.00 ± 36.05[cde]
AV	BB	56.36 ± 0.19[e]	47.41 ± 0.12[g]	1360.00 ± 20.20[f]	1586.67 ± 31.92[f]
EC	RB	64.42 ± 0.05[a]	55.95 ± 0.16[a]	1653.33 ± 17.63[a]	1886.67 ± 36.78[a]
EC	RR	60.23 ± 0.17[c]	52.88 ± 0.26[bc]	1531.67 ± 22.42[b]	1768.33 ± 11.66[b]
EC	BR	64.14 ± 0.72[ab]	56.01 ± 0.10[a]	1640.00 ± 26.45[a]	1876.67 ± 13.64[a]
EC	BB	60.34 ± 0.53[c]	52.52 ± 0.12[c]	1500.00 ± 26.45[bc]	1736.67 ± 36.78[bcd]
Source			ANOVA		
PS		<.0001	<.0001	<.0001	<.0001
BC		<.0001	<.0001	<.0001	<.0001
PS × BC		<.0001	<.0001	<.0001	<.0001

[a-f] Within each column, values with similar superscripts did not differ significantly at P =0.05

PS: production system, BC: breed cross, (RNN: Rhode Island Red × Naked Neck, BB: BNN × BNN and BNN: Black Australorp × Naked Neck), RR: RNN × RNN, RB: RNN × BNN, BR: BNN × RNN, ANOVA: analysis of variance, EC: enriched cages, AV: aviaries, CC: conventional cages, HDEP: hen/day egg production %, EW: egg weight (g), BW: bodyweight

Table 5 Main effects of production system and breed cross on external and internal measures of egg quality when hens were 26 and 46 weeks old: initial and final values

Parameter		Production system			*P*-value	Breed cross				*P*-value
		CC	AV	EC		RB	RR	BR	BB	
EW	Initial	42.46 ± 0.52$^{b, y}$	39.36 ± 0.64$^{c, y}$	45.25 ± 0.62$^{a. y}$	<.0001	43.23 ± 1.30$^{a, y}$	41.42 ± 0.66$^{b, y}$	43.52 ± 1.23$^{a, y}$	41.24 ± 0.81$^{b, y}$	0.0226
	Final	50.40 ± 0.75$^{b, x}$	47.63 ± 0.50$^{c, x}$	53.78 ± 0.50$^{a, x}$	<.0001	52.43 ± 0.84$^{a, x}$	50.23 ± 0.83$^{b, x}$	51.87 ± 1.12$^{a, x}$	47.88 ± 0.94$^{c, x}$	<.0001
P-value		<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	<.0001	
ESI	Initial	72.42 ± 0.40$^{a, y}$	69.88 ± 0.98$^{b, y}$	74.07 ± 0.53$^{a, y}$	0.0002	71.68 ± 1.22^{ab}	73.17 ± 0.76$^{a, y}$	73.11 ± 0.79^{a}	70.54 ± 0.88$^{b, y}$	0.0481
	Final	75.74 ± 1.06 ^{x}	77.09 ± 0.99 ^{x}	77.44 ± 1.14 ^{x}	0.5063	77.25 ± 1.74	77.82 ± 1.08 ^{x}	75.03 ± 1.00	76.94 ± 0.91 ^{x}	0.4292
P-value		0.0160	0.0002	0.0310		0.0622	0.0007	0.0709	0.0003	
ESA	Initial	56.16 ± 0.46$^{b, y}$	54.22 ± 0.47$^{c, y}$	58.61 ± 0.53$^{a, y}$	<.0001	56.89 ± 1.11$^{a, y}$	55.30 ± 0.56$^{b, y}$	57.56 ± 0.82$^{a, y}$	55.57 ± 0.52$^{b, y}$	0.0031
	Final	62.99 ± 0.63$^{b, x}$	60.66 ± 0.43$^{c, x}$	65.80 ± 0.41$^{a, x}$	<.0001	64.68 ± 0.70$^{a, x}$	62.86 ± 0.70$^{b, x}$	64.21 ± 0.93$^{a, x}$	60.86 ± 0.80$^{c, x}$	<.0001
P-value		<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	<.0001	
EV	Initial	38.76 ± 0.47$^{b, y}$	37.91 ± 0.58$^{b, y}$	41.31 ± 0.56$^{a, y}$	<.0001	40.72 ± 0.62$^{a, y}$	37.53 ± 0.80$^{b, y}$	40.50 ± 0.73$^{a, y}$	38.56 ± 0.45$^{b, y}$	<.0001
	Final	46.01 ± 0.68$^{b, x}$	43.49 ± 0.46$^{c, x}$	49.10 ± 0.46$^{a, x}$	<.0001	47.87 ± 0.77$^{a, x}$	45.86 ± 0.76$^{b, x}$	47.36 ± 1.02$^{a, x}$	43.71 ± 0.86$^{c, x}$	<.0001
P-value		<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	0.0001	
HU	Initial	75.23 ± 0.43$^{b, y}$	73.85 ± 0.61$^{b, y}$	77.41 ± 1.01$^{a, y}$	0.0050	76.66 ± 1.33 ^{y}	75.89 ± 0.83 ^{y}	75.17 ± 0.88 ^{y}	74.25 ± 0.59 ^{y}	0.2156
	Final	78.77 ± 1.12$^{b, x}$	80.42 ± 1.15$^{ab, x}$	82.51 ± 0.66$^{a, x}$	0.0190	83.67 ± 1.01$^{a, x}$	80.23 ± 1.36$^{b, x}$	78.74 ± 0.74$^{b, x}$	79.63 ± 1.25$^{b, x}$	0.0099
P-value		0.0070	0.0005	0.0002		0.0018	0.0122	0.0039	0.0051	
YI	Initial	49.29 ± 0.65 ^{x}	47.62 ± 0.58	49.63 ± 1.00 ^{x}	0.1365	48.57 ± 1.06	48.81 ± 0.48	50.44 ± 1.26	47.57 ± 0.36	0.1417
	Final	43.16 ± 2.75 ^{y}	47.16 ± 3.48	44.66 ± 1.89 ^{y}	0.6216	46.22 ± 3.34	45.00 ± 3.20	45.22 ± 3.34	43.55 ± 3.30	0.9552
P-value		0.0543	0.9036	0.0221		0.5802	0.2506	0.1628	0.2611	
ST	Initial	0.33 ± 0.00	0.34 ± 0.00	0.32 ± 0.00	0.1419	0.34 ± 0.00	0.33 ± 0.01	0.33 ± 0.00	0.34 ± 0.00	0.5775
	Final	0.31 ± 0.01	0.31 ± 0.01	0.34 ± 0.01	0.4321	0.34 ± 0.01	0.31 ± 0.01	0.31 ± 0.01	0.31 ± 0.01	0.5115
P-value		0.3884	0.0841	0.4748		0.7418	0.6011	0.5145	0.1773	

$^{a-c}$ Within each row, values with similar superscripts did not differ at *P* =0.05
$^{x-y}$ Within each column, values with similar superscripts did not differ at *P* =0.05
Breed cross: (RNN: Rhode Island Red × Naked Neck, BB: BNN × BNN and BNN: Black Australorp × Naked Neck), RR: RNN × RNN, RB: RNN × BNN, BR: BNN × RNN, production system: EC: enriched cage, AV: aviary, CC: conventional cage, Initial: egg quality at 26 weeks old, Final: egg quality at 46 weeks old, EW: egg weight (g), ESI: egg shape index, ESA: egg surface area (cm^2), EV: egg volume (cm^3), HU: Haugh unit score, YI: yolk index. ST: shell thickness (mm)

Table 6 Interaction effects of production system and breed cross on egg geometry at 26 and 46 weeks old, initial and final values

PS	BC	Egg weight, g		*P*-value	Egg shape index		*P*-value	Egg surface area, cm^2		*P*-value	Egg volume, cm^3		*P*-value
		Initial	Final		Initial	Final		Initial	Final		Initial	Final	
CC	RB	43.81 ± $0.67^{ab, y}$	52.36 ± $0.78^{b, x}$	0.0011	72.82 ± 0.19^{a}	77.28 ± 4.16	0.3811	57.36 ± $0.59^{bc, y}$	64.64 ± $0.64^{b, x}$	0.0010	40.00 ± $0.61^{b, y}$	47.81 ± $0.71^{b, x}$	0.0011
	RR	41.18 ± $0.37^{bc, y}$	50.32 ± $0.55^{cd, x}$	0.0027	72.22 ± 0.50^{a}	75.33 ± 1.48	0.0876	55.03 ± $0.33^{bcde, y}$	62.94 ± $0.46^{cd, x}$	0.0026	37.60 ± $0.34^{cd, y}$	45.94 ± $0.50^{cd, x}$	0.0027
	BR	43.95 ± $0.73^{ab, y}$	52.31 ± $0.76^{b, x}$	0.0024	73.73 ± 0.82^{a}	74.28 ± 0.30	0.6217	57.48 ± $0.64^{b, y}$	64.60 ± $0.63^{b, x}$	0.0024	40.13 ± $0.67^{b, y}$	47.76 ± $0.69^{b, x}$	0.0024
	BB	40.88 ± $0.85^{bc, y}$	46.60 ± $0.17^{ef, x}$	0.0258	70.91 ± 0.67^{ab}	76.07 ± 1.75	0.1681	54.76 ± $0.77^{de, y}$	59.79 ± $0.14^{ef, x}$	0.0268	37.33 ± $0.77^{d, y}$	42.55 ± $0.15^{ef, x}$	0.0258
AV	RB	38.91 ± $1.71^{c, y}$	49.72 ± $0.54^{d, x}$	0.0301	67.93 ± 2.29^{b}	78.81 ± 1.77	0.1128	53.20 ± $1.45^{e, y}$	62.44 ± $0.46^{d, x}$	0.0274	39.26 ± $0.55^{bcd, y}$	45.39 ± $0.50^{d, x}$	0.0009
	RR	39.46 ± $0.67^{c, y}$	47.42 ± $0.57^{e, x}$	0.0214	73.03 ± 1.73^{a}	78.11 ± 0.48	0.0740	53.66 ± $0.47^{e, y}$	60.48 ± $0.48^{e, x}$	0.0160	35.17 ± $1.41^{e, y}$	43.29 ± $0.52^{e, x}$	0.0514
	BR	39.60 ± $1.70^{c, y}$	47.91 ± $0.54^{e, x}$	0.0379	70.80 ± 1.63^{ab}	75.02 ± 3.06	0.1164	55.05 ± $0.75^{bcde, y}$	60.90 ± $0.46^{e, x}$	0.0219	38.46 ± $0.36^{bcd, y}$	43.74 ± $0.50^{e, x}$	0.0112
	BB	39.47 ± $1.64^{c, y}$	45.48 ± $0.45^{f, x}$	0.0492	67.75 ± $1.00^{b, y}$	76.43 ± 2.21^{x}	0.0303	54.98 ± $0.82^{cde, y}$	58.82 ± $0.39^{f, x}$	0.0392	38.74 ± $0.16^{bcd, y}$	41.52 ± $0.41^{f, x}$	0.0189
EC	RB	46.99 ± $0.64^{a, y}$	55.21 ± $0.45^{a, x}$	0.0029	74.29 ± 1.21^{a}	75.65 ± 3.66	0.8057	60.12 ± $0.55^{a, y}$	66.98 ± $0.36^{a, x}$	0.0031	42.90 ± $0.58^{a, y}$	50.41 ± $0.41^{a, x}$	0.0029
	RR	43.63 ± $0.59^{b, y}$	52.97 ± $0.34^{b, x}$	0.0009	74.26 ± 1.66^{a}	80.03 ± 2.47	0.1049	57.20 ± $0.52^{bcd, y}$	65.14 ± $0.28^{b, x}$	0.0011	39.83 ± $0.54^{bc, y}$	48.36 ± $0.31^{b, x}$	0.0009
	BR	47.02 ± $0.98^{a, y}$	55.40 ± $0.28^{a, x}$	0.0078	74.79 ± 0.18^{a}	75.77 ± 1.48	0.6140	60.14 ± $0.83^{a, y}$	67.14 ± $0.23^{a, x}$	0.0084	42.93 ± $0.89^{a, y}$	50.58 ± $0.26^{a, x}$	0.0078
	BB	43.38 ± $0.79^{b, y}$	51.55 ± $0.24^{bc, x}$	0.0055	72.95 ± $1.01^{a, y}$	78.31 ± 0.73^{x}	0.0192	56.98 ± $0.69^{bcd, y}$	63.97 ± $0.20^{bc, x}$	0.0059	39.61 ± $0.72^{bcd, y}$	47.06 ± $0.22^{bc, x}$	0.0054
P-value		<.0001	<.0001		0.0046	0.8259		<.0001	<.0001		<.0001	<.0001	

$^{a-e}$ Within each row, values with similar superscripts did not differ at $P = 0.05$
$^{x-y}$ Within each column, values with similar superscripts did not differ at $P = 0.05$
PS: production system, EC: enriched cage, AV: aviary, CC: conventional cage; BC: breed cross (RNN: Rhode Island Red × Naked Neck, BB: BNN × BNN and BNN: Black Australorp × Naked Neck), RR: RNN × RNN, RB: RNN × BNN, BR: BNN × RNN

Table 7 Interaction effects of production system and breed cross on egg quality at 26 and 46 weeks old, initial and final values

PS	BC	Haugh unit score		*P*-value	Yolk index		*P*-value	Shell thickness, mm		*P*-value
		Initial	Final		Initial	Final		Initial	Final	
CC	RB	76.35 ± 0.63[bc, y]	83.03 ± 1.42[a, x]	0.0484	51.81 ± 1.83	40.33 ± 4.09	0.1386	0.34 ± 0.00	0.32 ± 0.02	0.5135
	RR	75.31 ± 0.19[bc]	76.86 ± 2.95[bc]	0.6706	48.64 ± 0.70	44.66 ± 4.70	0.4809	0.32 ± 0.01	0.33 ± 0.02	0.8020
	BR	74.31 ± 0.79[bc]	79.19 ± 1.22[abc]	0.0690	49.24 ± 0.52	51.66 ± 6.35	0.7467	0.34 ± 0.02	0.34 ± 0.04	1.0000
	BB	74.94 ± 1.38[bc]	76.02 ± 1.02[c]	0.2150	47.49 ± 0.49	36.00 ± 4.50	0.1408	0.33 ± 0.01	0.28 ± 0.02	0.1628
AV	RB	72.50 ± 0.81[c]	83.11 ± 2.91[a]	0.1027	45.85 ± 0.83	58.00 ± 2.64	0.0624	0.34 ± 0.00	0.36 ± 0.01	0.6039
	RR	76.16 ± 1.56[bc]	81.04 ± 1.80[abc]	0.1226	47.98 ± 0.72	47.33 ± 9.33	0.9466	0.36 ± 0.01	0.29 ± 0.04	0.3591
	BR	73.82 ± 0.99[bc, y]	76.48 ± 0.70[bc, x]	0.0452	49.81 ± 1.25 [x]	35.66 ± 4.17 [y]	0.0540	0.33 ± 0.01	0.27 ± 0.00	0.0696
	BB	72.92 ± 0.46[c]	81.04 ± 2.37[abc]	0.0610	46.84 ± 0.69	47.66 ± 5.54	0.8949	0.35 ± 0.00	0.33 ± 0.02	0.5973
EC	RB	81.15 ± 1.23[a, y]	84.88 ± 0.94[a, x]	0.0123	48.06 ± 0.70	40.33 ± 2.60	0.0910	0.33 ± 0.01	0.36 ± 0.02	0.1181
	RR	76.21 ± 2.36[bc, y]	82.77 ± 1.05[a, x]	0.0381	49.82 ± 0.98	43.00 ± 3.00	0.1435	0.30 ± 0.01	0.32 ± 0.03	0.7376
	BR	77.39 ± 1.98[b]	80.54 ± 0.56[abc]	0.3269	52.29 ± 3.84	48.33 ± 2.33	0.4024	0.32 ± 0.00	0.34 ± 0.02	0.6254
	BB	74.88 ± 0.87[bc]	81.84 ± 1.53[ab]	0.0859	48.37 ± 0.49	47.00 ± 6.11	0.8388	0.34 ± 0.02	0.33 ± 0.03	0.8399
P-value		0.007	0.0177		0.1184	0.145		0.5011	0.5259	

[a-c] Within each row, values with similar superscripts did not differ at P =0.05
[x-y] Within each column, values with similar superscripts did not differ at P =0.05
PS: production system, EC: enriched cage, AV: aviary, CC: conventional cage; BG: breed group (RNN: Rhode Island Red × Naked Neck, BB: BNN × BNN and BNN: Black Australorp × Naked Neck), RR: RNN × RNN, RB: RNN × BNN, BR: BNN × RNN

Significant differences were observed in the hatching traits (Table 8). Chickens reared in AVs had higher fertility (*P* =0.0027) and hatchability percentage (*P* <0.0001) than those reared in ECs and CCs. Higher infertility (*P* =0.0012) and dead germ percentage (*P* =0.0397) were observed in the chickens reared in CCs and ECs. Late embryonic mortality did not differ (*P* =0.0951) between systems. RB chickens showed the highest fertility (*P* =0.0002) and hatchability (*P* <0.0001) percentages, followed by BR, RR, and BB. A higher infertility (*P* =0.0366) percentage was observed in chickens of BB genotype than in BR, RR, and RB.

Table 8 Interaction effects of production system and breed cross on hatching traits

PS	BC	Hatchability, %	Fertility, %	Unfertilized eggs, %	Late embryonic mortality, %	Early embryonic mortality, %
CC		68.86 ± 1.00^{c}	84.70 ± 0.78^{b}	14.31 ± 0.69^{a}	8.39 ± 0.52	8.42 ± 0.61^{a}
AV		75.60 ± 0.79^{a}	88.10 ± 0.97^{a}	10.61 ± 0.85^{b}	6.97 ± 0.48	6.80 ± 0.42^{b}
EC		70.88 ± 0.70^{b}	86.15 ± 0.68^{b}	12.72 ± 0.50^{a}	7.71 ± 0.43	8.67 ± 0.64^{a}
	RB	74.36 ± 1.10^{a}	88.88 ± 0.80^{a}	11.11 ± 0.80^{b}	7.42 ± 0.50^{ab}	7.09 ± 0.53
	RR	71.30 ± 1.14^{b}	85.88 ± 0.80^{b}	11.87 ± 0.86^{ab}	8.45 ± 0.44^{a}	8.37 ± 0.44
	BR	72.98 ± 0.99^{ab}	86.84 ± 0.92^{ab}	13.15 ± 0.92^{ab}	6.58 ± 0.47^{b}	7.27 ± 0.66
	BB	68.47 ± 1.40^{c}	83.67 ± 0.90^{c}	14.07 ± 0.96^{a}	8.31 ± 0.68^{a}	9.13 ± 0.92
CC	RB	71.66 ± 1.04^{cd}	87.44 ± 1.46^{abc}	12.55 ± 1.46	7.77 ± 0.99	8.00 ± 0.72
CC	RR	68.65 ± 1.12^{d}	84.33 ± 1.30^{cd}	13.71 ± 1.24	8.45 ± 0.95	9.17 ± 0.77
CC	BR	71.10 ± 0.86^{cd}	84.45 ± 1.48^{bcd}	15.55 ± 1.48	6.87 ± 0.41	6.47 ± 0.99
CC	BB	64.02 ± 0.98^{e}	82.60 ± 1.19^{d}	15.44 ± 1.25	10.46 ± 0.64	10.06 ± 1.57
AV	RB	78.42 ± 0.77^{a}	90.75 ± 1.13^{a}	9.24 ± 1.13	6.42 ± 0.98	5.91 ± 0.44
AV	RR	75.46 ± 1.04^{ab}	88.11 ± 1.04^{abc}	9.32 ± 1.13	7.72 ± 0.91	7.50 ± 0.46
AV	BR	76.59 ± 0.96^{a}	88.97 ± 1.07^{ab}	11.02 ± 1.07	6.23 ± 1.17	6.14 ± 0.12
AV	BB	71.91 ± 0.37^{cd}	84.56 ± 2.70^{bcd}	12.87 ± 2.79	7.52 ± 1.02	7.65 ± 1.55
EC	RB	73.02 ± 0.54^{bc}	88.45 ± 1.22^{abc}	11.54 ± 1.22	8.07 ± 0.61	7.35 ± 1.22
EC	RR	69.80 ± 0.20^{cd}	85.20 ± 0.95^{bcd}	12.57 ± 0.95	9.17 ± 0.34	8.45 ± 0.93
EC	BR	71.24 ± 0.54^{cd}	87.12 ± 1.28^{abcd}	12.88 ± 1.28	6.65 ± 1.03	9.22 ± 1.21
EC	BB	69.44 ± 2.49^{d}	83.85 ± 0.30^{cd}	13.91 ± 0.29	6.95 ± 0.73	9.68 ± 1.94
				P-values		
PS		<.0001	0.0027	0.0012	0.0951	0.0397
BC		<.0001	0.0002	0.0366	0.0535	0.0870
PS × BC		<.0001	0.0071	0.0576	0.0681	0.1855

$^{a-e}$ Within each column, values with similar superscripts did not differ at *P* =0.05
PS: production system, EC: enriched cage, AV: aviary, CC: conventional cage; BC: breed cross (RNN: Rhode Island Red × Naked Neck, BB: BNN × BNN and BNN: Black Australorp × Naked Neck), RR: RNN × RNN, RB: RNN × BNN, BR: BNN × RNN

The lowest embryonic mortality (*P* =0.0535) was observed in BR compared with RB, RR, and BB. Non-significant differences were observed in early embryonic morality (*P* =0.0870) among breed crosses. A higher fertility (*P* =0.0071) percentage was observed in chickens of RB genotype reared in AV, whereas a higher hatchability (*P* <0.0001) percentage was observed in RB and BR reared in AV. Non-significant interactions were observed in infertility (*P* =0.0576), early embryonic mortality (*P* =0.1855), and late embryonic mortality (*P* =0.0681.

Chickens in the EC system showed the highest egg production percentage and egg weight, whereas chickens in AVs had the lowest. The higher egg weight and greater number of eggs in EC could be attributed to the stress-free environment and efficient utilization of nutrients in the formation of eggs. In previous studies, non-significant differences were reported in the egg production of hens reared in AVs, CCs, barns and ECs (Neijat *et al.*, 2011; Ahammed *et al.*, 2014). However, a higher egg production percentage was reported in chickens reared in CCs compared with free range and AVs (Tauson *et al.*, 1999; Leyendecker *et al.*, 2001). A higher production percentage, egg weight, bodyweight and cumulative egg mass were reported by Ahmad *et al.* (2019) in an intensive system compared with semi-intensive and free-range systems. Poor feed conversion was observed in Lohmann LSL white layer and Lohmann LT brown layer hens in a free range system compared with AV, EC, and CC (Leyendecker *et al.*, 2001). The influence of the production system on the feed conversion ratio of Hisex Brown layers (Englmaierova *et al.*, 2014) and Lohmann LSL and Lohman Brown Classic (Onbasilar *et al.*, 2015) was also observed. Higher feed intake and feed conversion ratio was observed in Lohmann Brown layers reared in a barn system compared with AV and CC (Ahammed *et al.*, 2014). Rehman *et al.* (2016) reported improvement in the production performance of native Aseel chicken reared in semi-intensive and confined systems. The effect of rearing system on egg mass has also been observed (Hidalgo *et al.*, 2008; Tactacan *et al.*, 2009; Onbasilar *et al.*, 2015). The bodyweight of hens reared on a floor system was higher compared with a cage system (Singh *et al.*, 2009).

In terms of genotype, a higher egg weight and egg production percentage were observed in RB and BR crosses than in RR and BB crosses, which could be attributed to heterosis. In crossbreeding, favourable alleles from RNN and BNN masked the less favourable alleles. Saadey *et al.* (2008) also reported that crossbreeding is useful to obtain offspring that combine the characteristics of their parental ancestries and ultimately produce an animal with hybrid vigour. Ahmad *et al.* (2019) reported higher egg weights from RNN (53.16 g) and BNN (53.13 g) compared to purebred Naked Neck (46.68 g), and likewise that egg production percentage was higher for BNN (60.71) and RNN (60.21) compared to Naked Neck (54.13) chickens. In the present study, egg weight and production percentage were further improved in the F_2 generation. Egg weights in RB (52.84 g) and BR (53.04 g) were higher than for RR (50.18 g) and BB (49.69 g). Furthermore, the egg production percentage of RB (61.99) and BR (62.04) was also higher than RR (57.73) and BB (58.25). Another possible reason for the improvement of egg production and egg weight in crossbred chickens is breed complementarity. For example, Razuki *et al.* (2011) explained the improvement in egg production and egg weight after crossbreeding between White Leghorn, Iraq Brown, and New Hampshire as the result of breed complementarity.

In this study, overall egg quality was better for birds housed in EC. This might be attributed to an increase in nutrients for egg formation and growth. A reduction in energy expenditure for locomotor activities in this environment might result from reduced stress as a result of enhanced expression of natural behaviours. Another possible reason for the higher egg weight in EC is the greater bodyweights of chickens in this system, because egg weight and bodyweight are positively correlated (Nigussie *et al.*, 2011). Higher egg surface area, egg volume, and Haugh unit score in EC might be due to a proportional correlation of egg components with egg weight. Differences in egg quality characteristics could be a manifestation of genetic and environmental discrepancies (Falconer & Mackay, 1996). The egg quality might be influenced by the genotype and breeder age (Monira *et al.*, 2003), production system and environment (Travel *et al.*, 2010).

In the initial stage of the production cycle at 26 weeks old, the present study revealed higher egg weight and egg volume in RB and BR than in BB and RR. The surface area was also higher in BR than in other breed crosses. When egg quality was evaluated at the end of experiment at 46 weeks old, RB and BR had higher egg weight, egg surface area and egg volume than BB and RR. The Haugh unit score was higher in RB than in other crosses. Higher egg weight in RB and BR crosses could be because of higher bodyweights in these crosses, as it is well known that heavier breeds lay larger eggs (Du Plessis & Erasmus, 1972; Nigussie *et al.*, 2011). Khawaja *et al.* (2016) found higher egg weight in crosses between White Leghorn and Fayoumi than in crosses of Fayoumi with Rhode Island Red and attributed the increase in egg weight to its positive correlation with bodyweight.

In the present study, higher surface area and egg volume in RB and BR could be attributed to the shapes of their eggs with the long axis being slightly longer than the short one. Variations in internal and external egg quality traits could be attributed to the variations in genetic makeup of the birds. Monira *et al.* (2003) explained that variations in egg quality traits were mainly the result of differences on genotype and age. Variations in egg volume and egg surface area in the eggs of broiler breeder strains and Aseel varieties were explained by Rayan *et al.* (2010) and Rehman *et al.* (2017), respectively. Differences in egg surface area were observed to vary among strains (Anderson *et al.*, 2004) and breeds (Islam *et al.*, 2010. Dunga (2013) observed different Haugh unit scores in Aseel and Naked Neck chickens. On the other hand, non-significant differences were reported in Haugh unit score among breed types (Rajkumar *et al.*, 2009). Rayan *et al.* (2010) and Van Den Brand *et al.* (2004) found differences in the egg shape index of commercial layers and indigenous chickens, whereas Rehman *et al.* (2017) reported differences in the egg shape index of Aseel varieties. In the present study, non-significant differences were observed in shell thickness and egg yolk index among crosses. Similarly, non-significant differences in shell thickness of breed types were observed in numerous studies (Hocking *et al.*, 2003; Dukic-Stojcic *et al.*, 2009; Rehman *et al.*, 2017). However, significant variations in the yolk index among frizzle chickens and Naked Neck were also reported (Dunga, 2013). A lower yolk index in eggs of Naked Neck chicken than normal feathered chicken was reported by Rajkumar *et al.* (2009).

Cost effectiveness of a hatchery enterprise is determined mainly by the fertility and hatchability of the flock (Peters *et al.*, 2008b). Environmental temperature and mating combination are important factors in determining the hatchability of eggs (Mo *et al.*, 2007). In the present study, significant differences were observed in hatching traits of breed crosses reared in three production systems. When the production systems were compared, fertility and hatchability percentages were higher in AV than those of CC and EC systems. On the other hand, infertility and early embryonic mortality were same in the CC and EC systems and low in AV. However, late embryonic mortality was similar in all production systems. The most appropriate reasons behind the higher fertility and hatchability percentage in AV are more space per bird and lower stocking density which enhanced the mating activity of the chickens. Ahmad *et al.*'s (2019) findings support the present outcomes, in which the highest fertility and hatchability percentages were obtained in chickens reared in a free-range system followed by the chickens reared in semi-intensive and intensive systems. However, better semen quality resulted in an ultimately better fertility percentage in Botswana chicken breed crosses when reared under an intensive system (Mothibedi *et al.*, 2016).

Among the breed crosses in this study, fertility and hatchability were highest in the RB chickens. The variations in hatching traits among the breed crosses might be attributed to the use of crossbreeding. Ahmad *et al.* (2019) reported a higher fertility in RNN (87.4%) and BNN (86.7%) crossbreds than purebred Naked Neck (81.7%). Furthermore, hatchability was higher in RNN (71.6%), followed by BNN (69.2%) and purebred Naked Neck (64.1%). In the present trial, fertility and hatchability percentages were improved after reciprocal crossing of RNN and BNN (RB and BR) rather than inter mating (BB and RR). The fertility percentage was highest in RB (88.9%), followed by BR (86.8%), RR (85.9%), and BB (83.7%). Similarly, the hatchability percentage was highest in RB (74.4%), followed by BR (73.0%), RR (71.3%) and BB (68.57%). Peters *et al.* (2008a) explained the variations in fertility and hatchability percentages among pure and crossbreds of indigenous Nigerian chickens as being because of the gene segregation effect. In another study, Peters *et al.* (2008b) found comparable genetic variations between the semen quantity and quality traits of local and exotic cocks. However non-significant breed differences in hatchability of eggs have been reported (Islam *et al.,* 2002). Peters *et al.* (2004) reported the highest fertility and hatchability percentage in frizzle-feathered followed by formal feathered and Naked Neck chickens. Similarly, the higher fertility percentage (90.5%) in frizzle-feathered chickens compared with normal feathered chickens (84.4%) revealed the variation in hatching traits among breed crosses (Adeleke *et al.*, 2012). Merat (1986) reported higher (up to 10%) embryonic mortality in homozygous Naked Neck chicken than heterozygous partial feathered chickens. Reduction in embryonic survival up to 6.1% in Naked Neck chickens has been reported compared with normal-feathered chicken (Peters *et al.*, 2008a) which might have happened during last incubation stages and caused a higher dead-in-shell percentage (21.2%) than dead germ percentage in pure Naked Neck (Singh *et al.*, 2001). The effects of crossbreeding in INRA44 female duck also revealed a higher fertility percentage (85.5%) in purebred than in crossbreds (66.4%) (Brun & Larzul, 2003). Sellier *et al.* (2005) attributed this variation in response to the differences in fecundity according to the genetic type.

Conclusions

Among alternative production systems, hens housed in EC had higher production performance and egg quality than hens housed in AV or CC. However, AV may improve fertility and hatchability. In terms of breed crosses, RB and BR had increased performance relative to BB and RR.

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Author's Contributions

MU conducted this study as part of his Ph.D. research under the supervision of AM, JH and AJ. AM and AJ helped in reviewing the manuscript. JH helped in statistical analysis and formatting of manuscript.

Conflict of Interest Declaration

The authors declare no potential conflicts of interest.

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