



Comprehensive Genetic Evaluation of Performance and Carcass Characteristic Traits Through a Diallel Cross among New Zealand White, Papillon and Flemish Giant Rabbits

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ABSTRACT

Background: Commercial rabbit producers lack clear genetic guidelines on combining new zealand white (NN), papillon (PP) and flemish giant (FF) breeds to optimize carcass and non-carcass traits. This study employed a comprehensive 3×3 diallel cross to identify genetic factors governing these traits and to support effective crossbreeding decisions.

Methods: Non-carcass traits were evaluated in 270 rabbits from nine genetic groups (30 each), while carcass traits were assessed in 180 rabbits (20 per group) slaughtered at 12 weeks. Data were analyzed using SAS-GLM with Duncan test and diallel analysis followed Griffing fixed-effects model via GSCA to estimate general combining ability (GCA), specific combining ability (SCA) and reciprocal effects (RC).

Result: Genetic group significantly influenced most carcass and non-carcass traits (P<0.05). PF and PN crossbreds showed reduced head and ear percentages, while PF exhibited the highest "mesenteric fat (1.24%)". The PF cross achieved maximum carcass output (51.09%) and intramuscular fat (6.3%), whereas the NF cross demonstrated elevated carcass weight and a superior muscle-to-fat ratio, yielding optimal carcass composition. Non-additive genetic effects (SCA and RC) predominated over additive factors. The FP cross showed significant positive SCA for pre-slaughter weight but adversely affected meat quality, while NF exhibited the most favorable SCA for carcass weight, muscle percentage and muscle-to-fat ratio. Significant reciprocal effects in the FN cross indicated a pronounced maternal influence from New Zealand White dams. Overall, the NF cross is best suited for high-quality lean carcasses, the FP cross for increasing live weight and the FN cross for exploiting maternal effects to enhance muscling and carcass yield.

Key words: Carcass traits, Combining ability, Crossbreeding performance, Diallel cross, Rabbit genetics.

INTRODUCTION

Rabbit farming is increasingly integrated into global livestock systems as a source of essential animal protein for a reliable food supply (Lavanya *et al.*, 2017). Domestic rabbits (*Oryctolagus cuniculus*) contribute positively to the economy in developing regions due to their rapid growth, high reproductive rates and efficient feed conversion (Lavanya *et al.*, 2017; Gupta *et al.*, 2000; Krupová *et al.*, 2020; Mukaila, 2023; Abd El-Aziz *et al.*, 2025; Goswami *et al.*, 2025; Zawiślak *et al.*, 2025). Improving production efficiency, carcass yield and meat quality is essential to address the global demand for lean, nutritious animal protein and enhance the profitability of rabbit farming (Garcia and Argente, 2020; Mukaila, 2023; Składanowska-Baryza *et al.*, 2025).

Genetic enhancement through systematically designed breeding programs is essential for improving animal production systems, with crossbreeding historically acknowledged as one of the most effective methods (Garcia *et al.*, 2025, Teshome *et al.*, 2025). Crossbred animals may exceed their purebred counterparts in economically important traits, including growth rate, reproductive efficiency and disease resistance, due to heterosis, or hybrid vigor (Falconer and Mackay, 1996, Khattab *et al.*, 2025). The genetic complementarity of parental lines and

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their combining abilities determine the potential level of heterotic expression, which affects the effectiveness of crossbreeding efforts.

Divide genetic diversity into additive and non-additive components and evaluate their impacts on phenotypic performance to develop suitable crossbreeding strategies (Abdel-Ghany *et al.*, 2024; Ayyat *et al.*, 2024). The diallel cross design effectively measures general combining ability (GCA), specific combining ability (SCA) and reciprocal effects (RC) (Griffing, 1956; Adenaike *et al.*, 2013; Skråppa *et al.*, 2023; Teshome *et al.*, 2025). GCA evaluates the average performance of a breed across various crosses, mainly due to additive genetic effects (Babu *et al.*, 2025). Unlike GCA and SCA evaluates deviations from expectations due to non-additive factors such as dominance and epistasis, which are the main genetic contributors to heterosis (Griffing, 1956; Falconer and Mackay, 1996). Reciprocal effects, often ascribed to maternal influence or sex-linked inheritance, clarify cross-reverse discrepancies (Ragab *et al.*, 2016; Abdel-Ghany *et al.*, 2024).

Three economically important rabbit breeds used in meat production systems include the New Zealand White (NN), widely recognized as a medium sized maternal line with high prolificacy and good growth for meat production (e.g. Commercial Rabbit Raising; New Zealand rabbit, 2024); the Papillon (PP), which has been reported to provide favorable carcass quality and meat to bone ratio among meat type rabbits and the Flemish giant (FF), a large frame breed commonly used in crossbreeding schemes to increase body size and growth potential in meat rabbits. These breeds are employed in commercial breeding, but diallel genetic researches are rare. These studies are crucial for determining the best breed combinations for production efficiency and understanding carcass and non-carcass trait genetics (Derewicka *et al.*, 2020). This study compared carcass and non-carcass features of purebred and crossbred New Zealand White, Papillon and Flemish Giant breeds. The study calculated general, specific and reciprocal combining ability contributions. Finally, the analysis found the best crossbreeding and parental pairings to boost performance.

MATERIALS AND METHODS

Experimental design and animals

The experiment was conducted over an 8-week post-weaning period, commencing at 4 weeks of age and concluding at 12 weeks, which corresponds to the normal market age for meat rabbits.

Three genuine rabbit breeds-New Zealand White (N), Papillon (P) and Flemish Giant (F)-were used in a full 3×3 diallel cross design. Foundation breeding stock consisted of an equal number of bucks and does from each breed, which were mated to generate all purebred and crossbred progeny used in the study. The diallel design produced nine genetic groups: Three purebreds (NN, PP, FF) and six crossbreds, including both direct and reciprocal crosses.

The nine genetic groups were as follows: NN (New Zealand White × New Zealand White), PP (Papillon × Papillon), FF (Flemish Giant × Flemish Giant), NF (New

Zealand White × Flemish Giant), FN (Flemish Giant × New Zealand White), NP (New Zealand White × Papillon), PN (Papillon × New Zealand White), FP (Flemish Giant × Papillon) and PF (Papillon × Flemish Giant). A total of 270 weaned rabbits were obtained from these matings and allocated equally to the nine genetic groups, with 30 offspring per group at 4 weeks of age. This allocation ensured a balanced experimental design with equal replication across genotypes. All 270 rabbits were followed for growth and non carcass traits and from within these, 180 rabbits (20 per genetic group) were later selected at random for carcass evaluation at 12 weeks of age, as described in the slaughter procedures section.

Housing and management

Animals were kept in individual wire mesh flat deck cages equipped with nipple drinkers and feeders, providing continuous access to clean water and feed. Each cage measured about 80 × 60 × 40 cm (length × width × height), which is within the recommended range for medium to large meat type rabbits and only one growing rabbit was housed per cage during the fattening period. Cages were arranged in rows with adequate spacing between units and alleys to facilitate cleaning, ventilation and routine management. As advised by the National Research Council (NRC, 1977), the experimental diet was a commercial pelleted feed designed to satisfy the nutrient requirements for growing rabbits. The diet provided 18% crude protein and 2,800/ kcal of digestible energy/ kg⁻¹ diet, commensurate with nutritional requirements for healthy growth and intestinal health (Blas and Wiseman, 2020). Throughout the trial, conventional sanitation and biosecurity procedures were followed to guarantee high standards of animal care and health and no routine prophylactic antibiotics were administered. Therapeutic drugs were used only when clinically indicated under veterinary supervision, in accordance with institutional animal use and food safety guidelines.

Slaughter procedures and carcass evaluation

The experimental population comprised 270 rabbits from nine genetic groups, of which 180 rabbits (20 per group) were randomly selected and slaughtered at 12 weeks of age. Before slaughter, animals were fasted for 12 hours to ensure empty gastrointestinal tracts, after which final body weight and pre slaughter weight were recorded. Rabbits were slaughtered humanely according to Blasco *et al.* (2010) and in accordance with the institutional animal care protocols approved by the King Faisal University Research Ethics Committee. Dressing percentage was calculated from the hot carcass weight after evisceration. Non carcass components, including edible offal (liver, kidneys and heart), non edible offal (head, ears, lungs and spleen) and internal visceral fat (cardiac, perirenal, mesenteric and caul fat), were weighed and expressed as a proportion of pre slaughter weight.

Carcasses were chilled for 24 hours and then dissected according to the method described by Croda-Andrade *et al.* (2022)

to determine the yield of commercial cuts and tissue composition. For each rabbit, the weights of muscle, fat and bone were summed to obtain total dissected weight, which was used to calculate carcass composition, muscle to bone ratio and muscle to fat ratio.

Statistical analysis

All data were analyzed using the General Linear Model (GLM) procedure in SAS software (SAS Institute, 2009). Mean comparisons among genetic groups were conducted using Duncan's multiple range test at a significance level of $P < 0.05$.

Diallel cross analysis was performed employing Griffing (1956) Method 1, Model 1, using the GSCA 1.0 software package to estimate general combining ability (GCA), specific combining ability (SCA) and reciprocal (RC) effects for all evaluated carcass and non-carcass traits.

RESULTS AND DISCUSSION

Non-carcass traits

Table 1 illustrates the variation in proportions of non-carcass characteristics across the nine genetic groups. The findings indicated that the genetic group significantly influenced ($P < 0.05$) the weights of the head, ear and mesenteric fat. The groups possessed comparable quantities of edible offal, including liver, kidneys and heart. The purebred FF group exhibited the highest relative head weight at 6.28%, whereas the PF crossbreed demonstrated the lowest head percentage at 5.13%, performing optimally for this trait. The FP and NF crosses exhibited the highest ear percentages, recorded at 1.76% and 1.72%, respectively. The PN and PF crosses exhibited the highest appeal while demonstrating the lowest ear percentages, recorded at

1.21% and 1.22%, respectively. The PF cross exhibited a mesenteric fat percentage of 1.24%, significantly exceeding that of other genetic groups ($P < 0.05$). This indicates significant fat accumulation. This cross exhibits a genetic predisposition for internal fat storage. The NP and purebred FF groups exhibited the lowest levels of mesenteric fat, recorded at 0.56% and 0.59%, respectively. Although not statistically significant, the PF cross exhibited the highest kidney fat percentage at 1.00%, indicating its propensity for fat storage.

Phenotypic correlations among non-carcass traits

The phenotypic correlations among these non-carcass traits revealed several significant relationships (Table 2). A significant positive correlation was observed between the relative weights of the head and both kidney fat ($r = 0.68$, $P < 0.01$) and mesenteric fat ($r = 0.60$, $P < 0.01$). This indicates that rabbits with larger heads also exhibited a higher fat content. This is consistent with the findings for the PF group, which demonstrated the lowest head percentage while exhibiting the highest levels of mesenteric and kidney fat, suggesting a complex trade-off among these traits. A significant positive correlation was observed between the relative weights of the liver and kidneys ($r = 0.64$, $P < 0.01$), indicating that these two primary edible organs developed concurrently. The non-consumable respiratory organs exhibited significant positive correlations. Lung weight demonstrated a significant correlation with ear weight ($r = 0.54$, $P < 0.01$) and spleen weight ($r = 0.64$, $P < 0.01$). A significant negative correlation was observed between kidney fat content and the relative weights of the ears ($r = -0.38$, $P < 0.05$) and lungs ($r = -0.41$, $P < 0.05$). This indicates that an increased fat presence in the kidneys correlates with a reduced quantity of non-edible offal components.

Table 1: Non-carcass traits for new zealand white (NN), papillon (PP) and flemish giant (FF) rabbits and their crosses.

Trait	Genetic group									Sig.
	NN	PP	FF	NP	NF	FP	PN	FN	PF	
Edible offal percentage in:										
Liver	4.64	4.46	3.24	3.95	4.98	3.37	4.75	4.16	3.58	NS
Kidneys	0.73	0.73	0.66	0.73	0.79	0.71	0.72	0.76	0.70	NS
Heart	0.27	0.29	0.30	0.31	0.28	0.29	0.30	0.32	0.31	NS
Non-edible offal percentage:										
Head	5.57 ^{abc}	6.15 ^{ab}	6.28 ^a	6.11 ^{ab}	6.14 ^{ab}	6.07 ^{ab}	5.62 ^{abc}	5.50 ^{bc}	5.13 ^c	*
Ear	1.35 ^{bc}	1.63 ^{ab}	1.44 ^{abc}	1.49 ^{abc}	1.72 ^a	1.76 ^a	1.21 ^c	1.27 ^{ab}	1.22 ^c	*
Lungs	0.60	0.67	0.71	0.73	0.66	0.72	0.68	0.71	0.64	NS
Spleen	0.04	0.07	0.06	0.08	0.08	0.09	0.07	0.07	0.06	NS
Internal viscera fat percentage in:										
Heart fat	0.19	0.23	0.16	0.16	0.21	0.20	0.17	0.18	0.21	NS
Kidneys fat	0.97	0.61	0.65	0.67	0.90	0.75	0.74	0.90	1.00	NS
Mesenteric fat	0.75 ^b	0.78 ^b	0.59 ^b	0.56 ^b	0.79 ^b	0.75 ^b	0.76 ^b	0.73 ^b	1.24 ^a	*
Caul fat	0.24	0.19	0.18	0.17	0.22	0.25	0.18	0.22	0.23	NS

^{a,b,c} Means with differ letters in the same raw are differ significantly ($P < 0.05$).

Sig. = Significance, NS= Non-significant, * = Significant ($P < 0.05$).

Combining ability and reciprocal effects for non-carcass traits

Table 3 presents estimations for non-carcass traits, including GCA, SCA and RC. No non-carcass traits exhibited statistically significant GCA estimates. The PP breed exhibited a negative GCA estimate for head percentage (-0.90), indicating its superior ability as a general combiner for reducing this trait. The FF breed exhibits favorable GCA scores for head (+0.07) and ear (+0.08) percentages. The genetic correlation analysis (GCA) for ear percentage is -0.07, indicating a favorable outcome for NN breeds. Significant SCA effects ($P < 0.05$) were observed for several traits. The NP cross exhibited a significant positive SCA for liver percentage (+0.54) in edible offal, whereas the NF cross demonstrated a substantial negative effect (-0.73). The FP cross exhibits a negative SCA for head percentage (-0.80) concerning non-edible

offal. The NF cross exhibited a negative-positive SCA for head percentage, quantified at +0.40. The FP cross adversely impacted internal fat deposition; however, it exhibited a significant positive SCA for kidney fat (+0.25) and mesenteric fat (+0.19). The NF cross demonstrated superior efficacy in reducing kidney fat and mesenteric fat, evidenced by a negative SCA of -0.30 and -0.14, respectively. Significant RC effects ($P < 0.05$) were observed in the percentage of ear and mesenteric fat. A significant and adverse positive RC effect was noted for ear percentage in the PN (+0.28) and PF (+0.25) crosses. Conversely, mesenteric fat in the PF cross exhibited a significant negative correlation coefficient of -0.28.

Carcass traits

The genetic group markedly affected all evaluated carcass characteristics ($P < 0.01$), with the exception of total bone

Table 2: Simple correlations among non-carcass traits of New Zealand white (NN), papillon (PP) and Flemish giant (FF) rabbits and their crosses.

Trait	Liver	Kidneys	Heart	Head	Ears	Lungs	Spleen	Heart fat	Kidneys fat	Mesenteric fat	Caul fat
Liver	-										
Kidneys	0.64**	-									
Heart	-0.19	0.13	-								
Head	0.05	0.14	0.07	-							
Ears	-0.28	0.13	0.19	0.40*	-						
Lungs	-0.15	0.39*	0.48**	0.24	0.54**	-					
Spleen	0.14	0.27	0.22	0.20	0.52**	0.64**	-				
Heart fat	-0.17	-0.17	-0.24	-0.19	0.39*	0.10	0.30	-			
Kidneys fat	0.22	0.16	-0.20	-0.68**	-0.38*	-0.41*	-0.25	-0.04	-		
Mesenteric fat	0.07	0.11	-0.04	-0.60**	-0.30	-0.14	-0.06	0.23	0.56**	-	
Caul fat	0.25	0.10	-0.09	-0.21	-0.19	-0.43*	-0.08	-0.09	0.49**	0.37*	-

* = Significant ($P < 0.05$), ** = Significant ($P < 0.01$).

Table 3: General, specific combining ability and reciprocal cross effects on non-carcass traits at marketing age of New Zealand white (NN), papillon (PP) and Flemish giant (FF) rabbits and their crosses.

Trait	General combining ability (GCA)				Specific combining ability (SCA)				Reciprocal effects (RC)			
	NN	PP	FF	Sig.	NP	NF	FP	Sig.	PN	FN	PF	Sig.
Edible offal's percentage in:												
Liver	0.19	-0.32	0.06	NS	0.54	-0.73	-0.13	*	-0.28	-0.30	0.34	NS
Kidneys	-0.05	-0.06	0.04	NS	0.03	-0.04	-0.05	NS	0.07	-0.08	0.06	NS
Heart	-0.05	0.04	0.06	NS	0.03	0.02	0.04	NS	-0.05	0.03	0.06	NS
Non-edible offal's percentage in:												
Head	0.04	-0.9	0.07	NS	0.07	0.40	-0.80	*	0.60	0.35	0.41	NS
Ear	-0.07	0.05	0.08	NS	-0.03	0.06	-0.10	NS	0.28	-0.03	0.25	*
Lungs	-0.04	0.05	-0.03	NS	-0.04	0.09	-0.05	NS	0.04	-0.05	0.04	NS
Spleen	-0.03	0.05	-0.04	NS	0.04	0.04	-0.01	NS	0.05	-0.03	0.04	NS
Internal viscera fat percentage in:												
Heart	-0.04	0.04	-0.05	NS	0.03	-0.04	-0.06	NS	0.04	0.05	-0.02	NS
Kidneys	-0.06	-0.04	0.06	NS	-0.04	-0.30	0.25	*	-0.06	0.02	-0.03	NS
Mesenteric	-0.05	0.05	0.05	NS	0.02	-0.14	0.19	*	0.03	0.05	-0.28	*
Caul	-0.02	0.05	-0.02	NS	-0.08	-0.09	0.01	*	0.02	0.03	-0.01	NS

Sig. = Significance, NS = Non-significant, * = significant ($P < 0.05$).

percentage and the muscle-to-bone ratio (Table 4). The PF crossbreed exhibited exceptional performance in meat yield, with a pre-slaughter weight of 2200 g and a carcass weight of 1124.2 g. The FN cross demonstrated exceptional performance, attaining a second-place position in both characteristics. The NF cross exhibited markedly worse performance, with a minimum pre-slaughter weight of 1460g and a carcass weight of 759.2 g. The purebred NN rabbits demonstrated the highest dressing percentage at 53.0%. The FP and FN crosses exhibited commendable performance, attaining rates of 52.2% and 52.6%, respectively. The NP and PN crosses demonstrated the poorest performance for this feature, with values of 50.2% and 50.3%, respectively. The FP cross had exceptional carcass composition, attaining the highest total muscle percentage at 85.4% and the lowest total fat percentage at 2.6%, resulting in a superior muscle-to-fat ratio of 32.8. Conversely, the PF cross, despite being the heaviest, demonstrated the poorest meat quality, marked by the lowest muscle percentage (82.2%) and an elevated total fat percentage (6.3%) relative to other groups. The NP hybrid displayed a markedly elevated muscle-to-fat ratio (32.8),

whereas the purebred NN group revealed the lowest ratio (13.0).

Phenotypic correlations among carcass traits

Table 5 displays the phenotypic correlation coefficients (r) among the different carcass characteristics. Pre-slaughter weight and carcass weight showed a very strong, positive and very significant connection ($r = 0.92$, $P < 0.01$). Nonetheless, a crucial trade-off between meat quality and carcass size was found. Pre-slaughter weight had a negative correlation ($r = -0.44$, $P < 0.05$) with the percentage of total muscle but a positive correlation ($r = 0.56$, $P < 0.01$) with the percentage of total fat. The considerable negative connection ($r = -0.60$, $P < 0.01$) between the muscle-to-fat ratio and pre-slaughter weight further supported this. In terms of carcass composition, the percentage of muscle and the percentage of fat showed a robust and very significant inverse association ($r = -0.68$, $P < 0.01$). The muscle-to-bone ratio and bone percentage had a very substantial negative correlation ($r = -0.90$, $P < 0.01$). The dressing percentage was found to be unrelated to the animal's live weight ($r = 0.03$, NS), but it had a substantial negative correlation ($r = -0.68$, $P < 0.01$) with the bone

Table 4: Carcass traits of New zealand white (NN), papillon (PP) and flemish giant (FF) rabbits and their crosses.

Trait	Genetic group									Sig.
	NN	PP	FF	NP	NF	FP	PN	FN	PF	
Pre-slaughter weight (g)	1725 ^{cd}	1708 ^{cd}	1873 ^{bc}	1800 ^{bc}	1460 ^d	1790 ^{bc}	1874 ^{bc}	2050 ^{ab}	2200 ^a	**
Carcass weight (g)	914.2 ^{bcd}	854.0 ^{cd}	977.7 ^{abc}	903.6 ^{bcd}	759.2 ^d	934.4 ^{abc}	942.6 ^{bcd}	1078.3 ^{ab}	1124.2 ^a	**
Dressing percentage	53.0 ^a	50.0 ^{bc}	52.2 ^{ab}	50.2 ^c	52.0 ^{ab}	52.2 ^a	50.3 ^{bc}	52.6 ^{ab}	51.1 ^{abc}	**
Carcass composition traits:										
Total muscle %	84.2 ^{bc}	83.3 ^{cd}	84.6 ^a	83.4 ^{cd}	84.1 ^{ab}	85.4 ^{ab}	83.5 ^{cd}	83.3 ^{cd}	82.2 ^d	**
Total bone %	11.8	12.9	10.8	12.7	11.9	12.0	12.8	12.0	11.5	NS
Total fat %	4.0 ^{bc}	3.8 ^{bc}	4.6 ^{bc}	3.9 ^{bc}	3.8 ^c	2.6 ^{bc}	3.7 ^{bc}	4.7 ^b	6.3 ^a	**
Muscle : bone ratio	7.1	6.5	7.8	6.6	7.1	7.1	6.5	6.9	7.1	NS
Muscle : fat ratio	21.0 ^{bc}	21.9 ^{bc}	18.4 ^c	21.4 ^{bc}	22.1 ^b	32.8 ^a	22.5 ^b	17.7 ^c	13.0 ^d	**

^{a,b,c} Means with different letters in each row are differ significantly ($P < 0.01$).

Sig. = significance, NS= non-significant and * = significant ($P < 0.05$), ** = significant ($P < 0.01$).

Table 5: Simple correlations among carcass traits of New zealand white (NN), papillon (PP) and flemish giant (FF) rabbits and their crosses.

Trait	Pre-slaughter weight	Carcass weight	Dressing %	Muscle %	Bon %	Fat %	M:B ratio	M:F ratio
Pre-slaughter weight	-							
Carcass weight (g)	0.92**	-						
Dressing percentage (g)	0.03	0.36*	-					
Carcass composition traits:								
Muscle percentage	-0.44*	-0.25	0.43*	-				
Bone percentage	-0.39*	-0.54**	-0.68**	-0.26	-			
Fat percentage	0.56**	0.54**	0.10	-0.68**	-0.53**	-		
Muscle : bone ratio	0.25	0.47**	0.65**	0.45*	-0.90**	0.37*	-	
Muscle : fat ratio	-0.60**	-0.56**	-0.14 ^{NS}	0.59**	0.51**	-0.87**	-0.34	-

M:B, Muscle: Bone ratio; M:F, Muscle: Fat ratio.

* = Significant ($P < 0.05$) and ** = Significant ($P < 0.01$).

percentage and a strong positive correlation ($r = 0.65$, $P < 0.01$) with the muscle-to-bone ratio.

Combining ability and reciprocal effects for carcass traits

Table 6 presents the genetic components of carcass traits. No significant general combining ability effects were observed for any of the carcass traits. The PP breed exhibited the highest positive general combining ability for pre-slaughter weight (+73.43 g), carcass weight (+44.80 g) and dressing percentage (+0.21%). The FF breed exhibited superior meat quality GCA, characterized by the highest estimates of muscle percentage (+0.14%) and muscle-to-fat ratio (+0.29). The NN breed exhibited the highest leanness, with an estimated fat percentage of -0.14%. The SCA significantly influenced most carcass characteristics ($P < 0.01$ or $P < 0.001$). The FP cross exhibited the highest positive SCA for pre-slaughter weight (+245.20g), yet demonstrated the most negative SCA effects for muscle percentage (-1.32%), fat percentage (+1.70%) and muscle-to-fat ratio (-8.10). The NF cross yielded the highest-quality carcasses, demonstrating the most favorable SCA for carcass weight (+128.82 g) and superior meat quality, evidenced by positive SCA effects for muscle percentage (+0.35%), fat percentage (-0.53%) and muscle-to-fat ratio (+2.00). The NP cross exhibited the poorest performance, with SCA impacts of -76.57 g in carcass weight and -2.00% in dressing percentage. Significant effects of RC ($P < 0.05$) were observed in dressing and muscle percentages. The FN cross demonstrated a significant positive effect on dressing percentage (+1.92%) and muscle percentage (+1.35%).

The notable differences in non-edible offal components, including head and ear percentages, across genetic groups highlight the potential for economic benefits via selective breeding (Ozimba and Lukefahr, 1991). The enhanced performance of Papillon-sired crosses (PF and PN) in minimizing non-valuable portions is consistent with prior research emphasizing the significance of sire breed selection in optimizing carcass yield (Ragab *et al.*, 2016; Khattab *et al.*, 2025). The pronounced negative GCA

of the Papillon breed for head percentage, while not statistically significant, reinforces its applicability as a purebred line for this purpose. The simultaneous observation of markedly increased mesenteric and renal fat in the PF cross indicates a complex genetic antagonism. This indicates that genes associated with smaller frame or head size in this cross may be pleiotropically connected to those regulating increased internal fat deposition, a result that requires further molecular investigation (Carneiro *et al.*, 2011, Ping *et al.*, 2025). This study presents a novel finding: a positive correlation between head size and internal fat (Table 2), which contrasts with the conventional expectation that larger-framed animals possess more fat. This may suggest a distinct metabolic pathway in the PF cross. The absence of notable GCA effects, alongside highly significant SCA and RC effects for the majority of non-carcass traits, strongly suggests that non-additive gene actions (dominance and epistasis) are the main contributors to performance (Teshome *et al.*, 2025). The negative SCA for head percentage in the FP cross (-0.80) exemplifies positive heterosis, indicating that the crossbred exceeds the parental average. The negative positive SCA for internal fat in the same cross indicates the presence of negative heterosis. The reciprocal effects observed, notably the decrease in mesenteric fat with the use of FF as a dam in the PF cross, underscore the importance of maternal genetics, potentially linked to cytoplasmic inheritance or maternal nutritional programming (Mínguez *et al.*, 2015; Setiaji *et al.*, 2022; Birolo, 2023; Zawicelak *et al.*, 2025).

The findings regarding carcass traits illustrate the established genetic antagonism between production quantity and quality, a fundamental concept in meat animal breeding (Blasco *et al.*, 2010). The PF cross demonstrated enhanced growth and carcass weight; however, it exhibited a higher fat content and a reduced muscle percentage compared to other groups. This aligns with the significant negative phenotypic correlation identified between pre-slaughter weight and muscle-to-fat ratio ($r = -0.60$). The trade-off presents a significant challenge for breeders,

Table 6: General, specific combining ability and reciprocal cross effects on carcass traits of new zealand white (NN), papillon (PP) and flemish giant (FF) Rabbits and their crosses.

Trait	General combining ability				Specific combining ability				Reciprocal effects			
	NN	PP	FF	Sig.	NP	NF	FP	Sig.	PN	FN	PF	Sig.
Pre-slaughter weight (g)	-47.91	73.43	-27.30	NS	-65.53	77.48	245.20	***	-81.20	34.40	-74.20	NS
Carcass weight (g)	-27.85	44.80	-14.68	NS	-76.57	34.82	128.82	***	-37.30	57.55	-40.25	NS
Dressing percentage	-0.20	0.21	0.12	NS	-2.00	-0.91	0.10	***	0.14	1.92	0.23	*
Carcass composition	-0.06	-0.12	0.14	NS	-0.48	0.35	-1.32	***	-0.16	1.35	0.60	*
Traits: Muscle percentage												
Bone percentage	0.13	-0.08	-0.09	NS	0.75	0.21	-0.38	NS	0.36	-0.64	0.41	NS
Fat percentage	-0.14	0.23	-0.12	NS	-0.28	-0.53	1.70	***	-0.21	-0.24	-0.83	NS
Muscle: Bone	-0.08	0.05	0.04	NS	-0.35	-0.08	0.06	NS	-0.20	0.54	-0.23	NS
Muscle: Fat	0.05	-0.33	0.29	NS	1.30	2.00	-8.10	**	-1.02	1.05	2.43	NS

Sig. = Significance, NS= Non-significant, * = Significant ($P < 0.05$), ** = Significant ($P < 0.01$) and *** = Significant ($P < 0.001$).

as prioritizing rapid growth may unintentionally result in reduced carcass quality (Blas and Wiseman, 2020; Runcie *et al.*, 2021). The significant SCA effects noted in the FP cross, characterized by a substantial positive impact on weight (+245.20 g) and a pronounced negative effect on meat quality (-8.10 for muscle-to-fat ratio), exemplify this genetic conflict effectively. This indicates a significant overdominance or epistatic interaction in the FP combination that concurrently enhances growth and fat deposition (Michelland *et al.*, 2011; Bigot *et al.*, 2024; Xiao *et al.*, 2024). The NF cross has proven to be a significant combination, effectively separating high carcass weight from inferior quality. The notable positive SCA for both carcass weight and muscle-to-fat ratio suggests a synergistic interaction of genes from the NN and FF breeds that enhances lean tissue development while minimizing fat accumulation. This finding holds significant practical relevance, as it identifies a specific cross capable of overcoming the conventional quantity-quality trade-off. The independence of dressing percentage from live weight ($r = 0.03$) is a significant finding, indicating that selecting for heavier animals does not inherently enhance yield (Pla, 2008; Paci *et al.*, 2012). Dressing percentage exhibited a strong negative correlation with bone content ($r = -0.68$), suggesting that a finer bone structure is essential for achieving higher yields. The notable reciprocal effects observed in the FN cross regarding dressing percentage and muscle percentage indicate a substantial positive maternal influence from the New Zealand White dam. The findings indicate that the maternal environment or cytoplasmic DNA from the NN breed improves the growth and muscling potential of its offspring, which is essential for developing three-way terminal crossing systems (Al-Saef *et al.*, 2008; Abdel-Hamid, 2015).

This study evaluates the genetic and phenotypic factors affecting non-carcass and carcass traits in a diallel cross involving three rabbit breeds. The primary theme derived from the results is the essential trade-off between production quantity and meat quality. Genetic groups exhibiting superior growth and weight, such as the PF and FP crosses, consistently displayed inferior meat quality, marked by increased fat content and reduced muscle-to-fat ratios. The observed antagonism in phenotypic correlations and specific combining ability effects presents a considerable challenge for rabbit breeders. Focusing on a single trait, such as market weight, may result in unintended adverse effects on carcass composition. The results support the implementation of crossbreeding to leverage heterosis, given that specific combining ability effects were significantly more impactful than the general combining ability of purebreds (Al-Saef *et al.*, 2008; Ragab *et al.*, 2016; Abdel-Ghany *et al.*, 2024). Nonetheless, the findings indicate that heterosis is not universally advantageous (Teshome *et al.*, 2025). The FP cross exhibited positive heterosis regarding growth, while demonstrating negative heterosis in terms of meat quality. This highlights the importance of testing particular crosses to determine

optimal combinations. The NF cross (New Zealand White $\times$ Flemish Giant) has been recognized as a notably advantageous combination, exhibiting favorable specific combining ability for both carcass weight and various meat quality indicators, thereby successfully challenging the conventional quantity-quality trade-off. The significance of reciprocal effects, particularly the enhanced performance of the FN cross (Flemish Giant $\times$ New Zealand White) regarding dressing percentage and muscle percentage, underscores the importance of maternal effects and the strategic selection of dam lines. The New Zealand White breed, utilized as a dam, seems to enhance carcass yield and muscling in its offspring. In summary, breeders seeking to optimize meat production by weight should consider the FP cross, which demonstrates the greatest growth potential, albeit with reduced leanness (Krupová *et al.*, 2020). The NF cross is the optimal selection for producing high-quality, lean carcasses. The FN cross is recommended for its ability to enhance yield and muscling through positive maternal effects. This study illustrates that an effectively structured crossbreeding program, grounded in the meticulous selection of particular breed combinations and dam lines, is crucial for the concurrent enhancement of production and quality traits in commercial rabbit farming.

CONCLUSION

The genetic architecture of production traits in a complete diallel cross of New Zealand White, Papillon and Flemish Giant rabbits was successfully assessed. The data show that crossbreeding can improve performance, but the results rely on the genetic combinations and cross direction. The strongest finding is that carcass weight and meat quality are strongly antagonistic, as shown by phenotypic correlations and particular combining ability effects. The Papillon $\times$ Flemish Giant (PF) and FP crosses achieved higher growth and live weight, but at the expense of fat deposition and inferior meat quality. The New Zealand White $\times$ Flemish Giant (NF) cross was found to be the most promising for commercial production due to its balanced, high carcass weight, higher meat quality and high muscle-to-fat ratio. The study also showed that maternal effects are important, with the New Zealand White breed enhancing dressing percentage and muscle percentage in its offspring. Thus, breeders should choose the FP cross to maximize weight and the NF or FN crossings to produce high-quality, slim carcasses. These findings outline a strategy for improving rabbit meat production through genetically guided crossbreeding.

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Informed consent

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Conflict of interest

There are no perceived conflicts of interest between the writers and their publishing this work, as far as the authors are concerned.

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