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Original Research Article

Morphometric Characterization, Heterosis Expression, and Growth Performance of Genetically Improved Farmed Tilapia and Red Tilapia Hybrids for Sustainable Aquaculture Development

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Hybrid Tilapia,
Growth Performance,
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ABSTRACT
Aquaculture is the practice of developing aquatic animals and plants under artificial environmental conditions, either in a controlled or semi-controlled environment. Tilapia stands out as one of the most extensively farmed and consumed fish species globally, valued for its ease of preparation and relative affordability. This study investigated the morphometric characteristics, growth performance, feed utilization, and heterosis expression of hybrids derived from crosses between Genetically Improved Farmed Tilapia (GIFT) and Red Tilapia. Controlled breeding trials were conducted to produce F_1 hybrids alongside purebred GIFT and Red Tilapia groups. A 12-week growth experiment was carried out under standardized aquaculture conditions, during which growth indices, feed conversion ratio (FCR), and survival were assessed. Morphometric and meristic traits were measured and analyzed through Principal Component Analysis (PCA) and Discriminant Function Analysis (DFA) to evaluate hybrid distinctiveness. Results showed that hybrids significantly outperformed parental strains in final body weight, weight gain, and specific growth rate, while recording a lower FCR, thereby confirming the expression of heterosis in growth and feed efficiency traits. Survival rates were high and comparable across groups, indicating that enhanced performance did not compromise viability. Morphometric assessment revealed intermediate phenotypes in hybrids, with DFA achieving over 90% classification accuracy, while meristic traits remained stable across groups. PCA highlighted body size descriptors as key contributors to hybrid distinctiveness. The findings demonstrate the potential of GIFT × Red Tilapia hybrids as valuable genetic resources for sustainable aquaculture improvement, combining superior biological performance with market appeal.

CITATION
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INTRODUCTION

Tilapia is widely recognized as one of the most important aquaculture species globally due to its rapid growth, environmental adaptability, and increasing consumer demand across both local and international markets (Cai, 2025). Over the past three decades, the development of genetically improved strains, particularly the Genetically Improved Farmed Tilapia (GIFT), has significantly advanced aquaculture productivity by enhancing growth performance, feed efficiency, and resilience relative to unimproved stocks (Pant *et al*., 2024). Similarly, Red Tilapia has attracted considerable attention because of its adaptability, competitive growth capacity, and especially its distinctive pigmentation, which enhances market value in regions where consumer preferences are shaped by visual appeal (Dee *et al*., 2021).

The hybridization of GIFT and Red Tilapia represents a strategic approach to exploiting hybrid vigor, with the potential to improve growth, survival, feed utilization, and commercial desirability beyond that of the parental strains (Liu *et al*., 2025). Hybridization has long been recognized as a cost-effective and practical genetic improvement strategy in aquaculture, offering solutions to key challenges of productivity, profitability, and sustainability (Šimková *et al*., 2021).

Morphometric and meristic characterization continues to provide reliable and inexpensive tools for differentiating fish stocks, assessing hybridization outcomes, and capturing phenotypic variability relevant to breeding programs (Hasan *et al*., 2022). Such analyses are particularly useful for hybrids, which typically display greater variability than purebred populations. This variability can serve as a diagnostic indicator of hybrid identity, growth potential, and culture resilience (Vasconcelos *et al*., 2025). When integrated with performance metrics such as growth rate, survival, and feed conversion efficiency, morphometric evaluations provide a holistic framework for assessing the biological and commercial benefits of hybrids (Barzkar *et al*.., 2024).

Although extensive studies have examined Nile Tilapia and Red Tilapia across diverse ecological settings, limited research has systematically evaluated GIFT × Red Tilapia hybrids using standardized morphometric and performance assessments (Phuc *et al*., 2025). This lack of empirical data restricts the ability of breeders and farmers to fully exploit the benefits of hybridization and constrains the optimization of genetic improvement strategies in tilapia aquaculture (Ramírez-Coronel *et al*.,2024). Moreover, the absence of comprehensive hybrid performance evaluations poses challenges for their adoption in breeding programs, particularly in developing regions where aquaculture must balance gains in productivity with cost-effectiveness and sustainability (Lenka *et al*., 2024).

Against this background, the present study was designed to evaluate morphometric and performance traits of hybrids generated from GIFT and Red Tilapia strains. Specifically, the objectives were to: (i) characterize morphometric and meristic features using standardized measurement protocols (Shettima *et al*., 2020), (ii) quantify phenotypic variability and heterosis expressed in hybrid populations (Špelić *et al*., 2021), (iii) compare growth performance, survival, and feed conversion efficiency of hybrids with parental strains (Rahman and Arifuzzaman, 2021), and (iv) identify morphometric traits that can serve as reliable markers for hybrid identification and selection in aquaculture programs (Gonzalez-Martinez *et al*., 2020).

By providing empirical evidence on the biological performance and economic potential of GIFT × Red Tilapia hybrids, this study contributes to the refinement of selective breeding strategies in tilapia aquaculture. Beyond its immediate breeding implications, the research aligns with broader sustainability goals by supporting food security, strengthening farmer livelihoods, and enhancing the resilience of aquaculture systems in regions where tilapia production continues to expand rapidly (Akpalu and Nnaemeka, 2025; El-Sayed and Fitzsimmons, 2023). While molecular genetics and marker-assisted analyses were beyond the present scope, their future integration is strongly recommended to validate hybrid identity, monitor genetic diversity, and safeguard the long-term sustainability of breeding programs (Lenka *et a*l., 2024; Akpomughe *et al*., 2023).

MATERIALS AND METHODS

Study Area

The investigation was carried out at the Aquaculture Research Unit of Delta State University, Abraka, Nigeria, geographically situated at latitude 5°47'44"N and longitude 6°6'4"E. The site is characterized by a humid tropical climate, with average daily temperatures ranging between 26 and 32 °C and relative humidity of 65–85%. These conditions provide an optimal thermal and ecological environment for tilapia culture and experimental breeding trials.

Broodstock Source and Breeding Procedure

Mature broodstock of the Genetically Improved Farmed Tilapia (GIFT (G)) strain and Red Tilapia (R) were procured from government-certified hatcheries within Nigeria. Prior to experimentation, the broodstock were acclimated under uniform conditions in separate concrete tanks and maintained on a commercial diet.

Artificial pair crosses were established under controlled conditions. Male GIFT (G) were crossed with female Red Tilapia (R) to generate F_1 hybrids, while purebred GIFT (G) × GIFT (G) and Red × Red matings were produced as reference groups. Fertilized eggs were incubated in aerated aquaria until hatching, and larvae were reared in standard nursery systems until reaching fingerling stage.

Experimental Design and Fish Husbandry

The experiment adopted a completely randomized design (CRD) comprising three treatments:

1. Hybrid (H) group (H): GIFT (G) × Red Tilapia (R)
2. GIFT (G) group (G): Purebred GIFT (G)
3. Red group (R): Purebred Red Tilapia (R)

Each treatment was replicated three times, with 50 fingerlings per replicate (450 fish in total). Fingerlings had a mean initial weight of 4.1 ± 0.2 g. Fish were stocked in circular hapas (2 m^3 capacity) suspended in an earthen pond and reared for a 12-week growth trial.

A commercial pelleted diet containing 35% crude protein was administered twice daily (08:00 and 16:00 h). Feeding rates were adjusted from 5% of body weight per day during the first month to 3% per day thereafter.

Water quality was maintained by continuous pond inflow and was monitored weekly. Mean values were within optimal thresholds for tilapia aquaculture: temperature (27–30 °C), dissolved oxygen (5.1–6.2mg L^{-1}), pH (6.8–7.5), and ammonia (0.01–0.05mg L^{-1}) (Table 2).

Morphometric and Meristic Assessment

At the end of the growth trial, 30 individuals per strain (10 per replicate) were randomly selected to ensure representation across replicates.

1. Morphometric traits measured included: standard length, total length, body depth, head length, head depth, body width, pre-dorsal length, caudal peduncle depth, pectoral fin length, pelvic fin length, anal fin length, and dorsal fin base length. Measurements were taken using digital Vernier calipers (accuracy: 0.01 cm).
2. Meristic traits included dorsal fin rays, anal fin rays, pectoral fin rays, pelvic fin rays, and lateral line scales (Table 1).

Morphometric values were size-adjusted using an allometric transformation to minimize the effect of body length and allow accurate comparative analysis among groups.

Growth and Performance Evaluation

Growth performance was evaluated bi-weekly through batch weighing of fish in each replicate. At the end of the trial, the following indices were determined:

Weight Gain (WG, g):

$WG = W_f - W_i$

(where Wf = final weight, Wi = initial weight)

Specific Growth Rate (SGR, % day^{-1}):

$SGR = [(\ln W_f - \ln W_i) / t] \times 100$

(where t = duration in days; in this study, t = 84 days for the 12-week trial)

Feed Conversion Ratio (FCR):

FCR = Feed intake (g) / Weight gain (g)

Survival Rate (SR, %):

$SR = (N_f / N_i) \times 100$

(where Nf = final number of fish, Ni = initial number stocked)

Heterosis (H%):

$H\% = [(F1 - MP) / MP] \times 100$

(where F1 = hybrid mean, MP = mid-parent value)

Statistical Analysis

Data were subjected to one-way ANOVA, and treatment means were separated using Duncan's Multiple Range Test at $p < 0.05$.

To explore multivariate differentiation, Principal Component Analysis (PCA) was applied to standardized morphometric variables. PCA was used to reduce dimensionality, identify the main axes of variation, and visualize clustering patterns among hybrids and parental strains (Špelić *et al.,* 2021). Principal components with eigenvalues >1 were retained, and trait loadings were examined to identify the characters most responsible for group separation.

Additionally, Discriminant Function Analysis (DFA) complemented PCA by maximizing group separation and quantifying classification accuracy. Together, PCA and DFA provided a robust framework: PCA revealed underlying variation patterns, while DFA tested discriminatory power between hybrids and parental groups (Jafari *et al.*, 2022).

Heterosis estimates were descriptively interpreted with confidence intervals derived from replicate means, ensuring reliability in hybrid performance assessment (Šimková *et al*., 2021).

Table 1: Mean meristic traits of GIFT (G), Red Tilapia (R), and their hybrid

Trait (count)	GIFT (Mean ± SE)	Red Tilapia (Mean ± SE)	Hybrid (Mean ± SE)	p-value
Dorsal fin rays	16.8 ± 0.4	16.5 ± 0.5	16.7 ± 0.3	0.412
Anal fin rays	11.2 ± 0.3	11.0 ± 0.2	11.1 ± 0.2	0.288
Pectoral fin rays	13.1 ± 0.2	13.3 ± 0.2	13.2 ± 0.2	0.351
Pelvic fin rays	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	–
Lateral line scales	32.7 ± 1.1	33.5 ± 1.2	33.0 ± 1.0	0.297

No significant differences ($p > 0.05$).

Table 2: Water quality parameters during the experiment

Parameter	Range Observed	Optimal range for Tilapia
Temperature (°C)	27.0-30.2	25-32
Dissolved oxygen (mg/L)	5.1-6.2	>5.0
pH	6.8-7.5	6.5-8.5
Ammonia (mg/L)	0.01-0.05	<0.2

All parameters remained within optimal limits for tilapia culture.

RESULTS AND DISCUSSION

Growth Performance

Growth outcomes differed significantly among the experimental groups (Table 3). The F_1 hybrids of GIFT × Red Tilapia attained the greatest final mean weight (55.3 ± 2.8 g), surpassing both the GIFT line (47.1 ± 2.3 g) and the Red Tilapia strain (43.9 ± 2.0 g) at $p < 0.05$. Similarly, weight gain was highest in the hybrids (50.2 ± 2.7 g), which was significantly superior to that of the parental groups, thereby confirming the presence of hybrid vigor. Specific growth rate (SGR) also followed the same pattern: hybrids recorded 3.82% day^{-1}, compared to 3.65% day^{-1} in GIFT and 3.51% day^{-1} in Red Tilapia. These outcomes highlight that crossbreeding enhanced growth efficiency, consistent with reports that hybridization stimulates heterosis in tilapia and related aquaculture species (Dee *et al*., 2021; Rahman and Arifuzzaman, 2021; Mengistu *et al.*, 2020).

Feed utilization further reflected the hybrid advantage. Hybrids exhibited a significantly lower feed conversion ratio (FCR) of 1.38, compared with 1.47 in GIFT and 1.52 in Red Tilapia, indicating a more efficient conversion of feed into biomass. Similar improvements in FCR have been documented as critical determinants of aquaculture profitability (Pant *et al.*, 2024; Limbu *et al.*, 2022; Ovie *et al.*, 2025). Survival rates were uniformly high across treatments (91–94%) and showed no significant differences ($p > 0.05$), suggesting that enhanced hybrid performance did not compromise viability.

Table 3: Growth performance of GIFT (G), Red Tilapia (R), and GIFT (G) × Red Tilapia (R) hybrids

Parameter	GIFT (Mean ± SE)	Red Tilapia (Mean ± SE)	Hybrid (Mean ± SE)	p-value
Initial body weight (g)	4.1 ± 0.2	4.2 ± 0.2	4.1 ± 0.2	0.874
Final body weight (g)	47.1 ± 2.3	43.9 ± 2.0	55.3 ± 2.8	0.031*
Weight gain (g)	43.0 ± 2.1	39.7 ± 2.0	50.2 ± 2.7	0.027*
Specific Growth Rate (SGR, % day^{-1})	3.65 ± 0.15	3.51 ± 0.14	3.82 ± 0.16	0.022*
Feed Conversion Ratio (FCR)	1.47 ± 0.06	1.52 ± 0.05	1.38 ± 0.04	0.041*
Survival rate (%)	93.4 ± 1.5	91.2 ± 1.3	94.0 ± 1.6	0.379

*Significant at $p < 0.05$.
Formulas for WG, SGR, FCR, and SR are defined in Methods section.

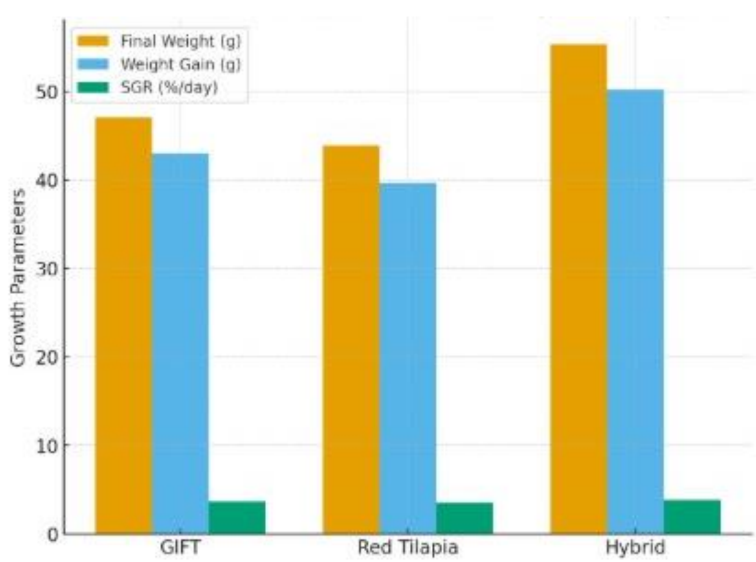

Figure 1: Growth performance (final body weight, weight gain, and specific growth rate) of GIFT, Red Tilapia, and their hybrids

Figure 1 illustrates growth performance parameters of the three experimental groups. Hybrids recorded significantly higher final body weight, weight gain, and specific growth rate compared to both GIFT and Red Tilapia, confirming the expression of heterosis in growth traits (Šimková *et a*l., 2021; Liu *et al.,* 2025). These improvements are consistent with earlier studies showing that hybridization enhances growth efficiency and overall aquaculture productivity (Mengistu *et al.,* 2020).

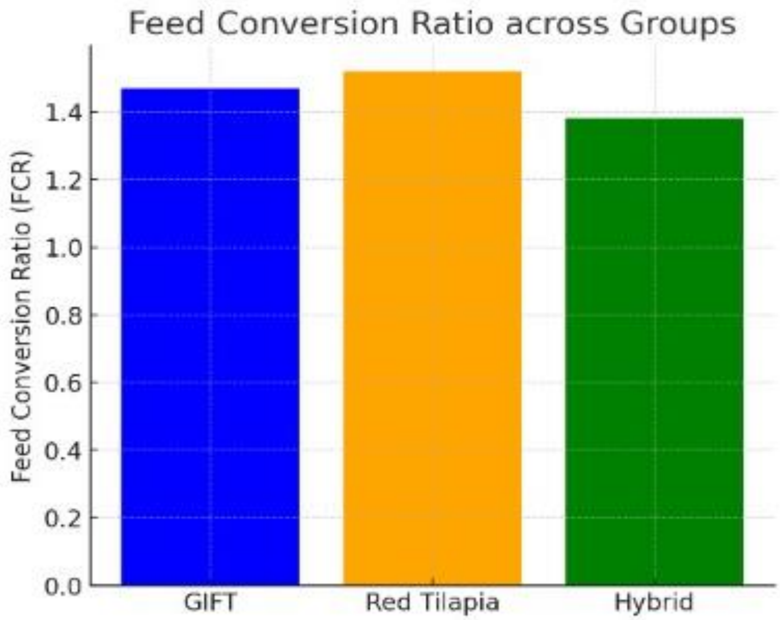

Figure 2: Feed Conversion Ratio (FCR) of GIFT, Red Tilapia, and their hybrids

The hybrids exhibited a lower FCR (1.38) than purebred GIFT (1.47) and Red Tilapia (1.52), indicating greater efficiency in converting feed into biomass. This result reflects favorable negative heterosis, which is particularly advantageous since feed represents the largest cost in aquaculture (Pant *et al.*, 2024; Ovie *et al*., 2025).

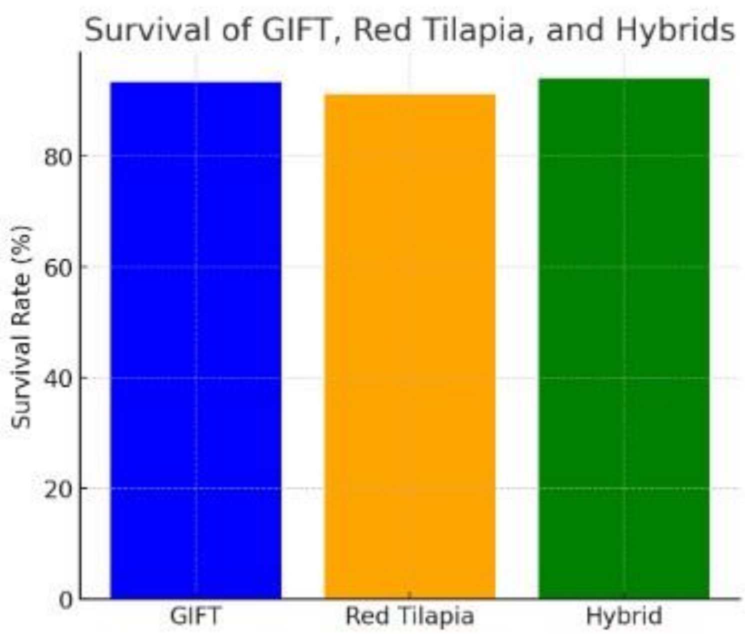

Figure 3: Survival rates of GIFT, Red Tilapia, and their hybrids

Figure 3 shows the survival rates of the three groups. Survival was consistently high (91–94%) across treatments, with no significant differences among them. This indicates that superior hybrid growth and feed utilization were not achieved at the expense of resilience (Abdel-Aziz *et al*., 2023).

Morphometric and Meristic Traits

Morphometric assessment revealed that the hybrids displayed intermediate phenotypes between parental groups, though certain traits leaned toward one lineage. For instance, body depth and caudal peduncle depth in hybrids closely resembled the GIFT line, while head length was more consistent with Red Tilapia. Statistical tests revealed significant differences ($p < 0.05$) for standard length, body depth, and head length, whereas caudal peduncle depth differences were marginal ($p = 0.051$) (Table 4). These results confirm that morphometric parameters are effective in discriminating hybrids, corroborating earlier studies that applied morphometrics for strain and hybrid identification in aquaculture (Gonzalez-Martinez *et al.*, 2020; Makeche *et al.*, 2022).

Discriminant Function Analysis (DFA) provided further clarity, correctly classifying more than 90% of individuals. The first two canonical functions explained over 80% of total variance, confirming the robustness of morphometric traits as discriminating markers. By contrast, meristic characters including dorsal, anal, and pectoral fin ray counts did not differ significantly among groups ($p > 0.05$), supporting prior findings that meristic characters are evolutionarily conserved and less responsive to hybridization (Shettima *et al.*, 2020; Lenka *et al.,* 2024).

Table 4: Selected morphometric traits (Mean ± SE) of GIFT (G), Red Tilapia (R), and hybrids

Trait	GIFT	Red Tilapia	Hybrid	p-value
Standard length (cm)	12.4 ± 0.6	11.9 ± 0.5	13.2 ± 0.7	0.048*
Body depth (cm)	4.2 ± 0.2	3.8 ± 0.2	4.3 ± 0.2	0.039*
Head length (cm)	3.1 ± 0.1	3.5 ± 0.2	3.3 ± 0.1	0.042*
Caudal peduncle depth (cm)	1.9 ± 0.1	1.8 ± 0.1	2.0 ± 0.1	0.051 (NS)

Significant at $p < 0.05$; NS = Not significant.

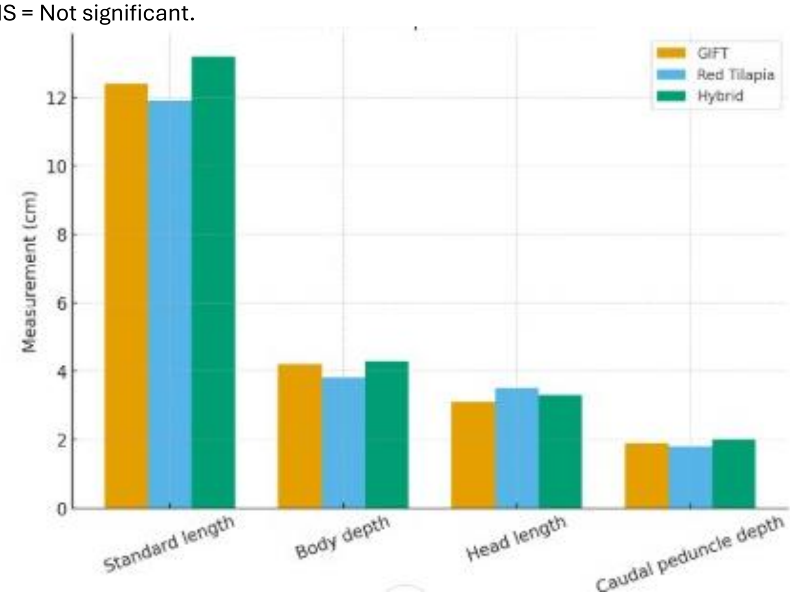

Figure 4: Selected morphometric traits (standard length, body depth, head length, caudal peduncle depth) of GIFT, Red Tilapia, and their hybrids

Hybrids displayed intermediate but distinct phenotypes, with standard length, body depth, and head length differing significantly from parental lines (Gonzalez-Martinez et al., 2020; Makeche et al., 2022). These findings support the value of morphometrics in hybrid differentiation.

Principal Component Analysis (PCA)

To complement DFA, Principal Component Analysis was applied to the standardized morphometric dataset. The first three components accounted for 84.4% of the total variance (Table 5). PC1 (46.8%) was strongly associated with body size descriptors, particularly standard length, body depth, and caudal peduncle depth. PC2 (24.1%) was defined by head length and body width, capturing cranial and lateral body dimensions. PC3 (13.5%) was dominated by pectoral and pelvic fin lengths, reflecting differences in fin development and locomotory traits.

Scatter plots of PC1 versus PC2 demonstrated clear separation between hybrids and the parental strains. Hybrids clustered in an intermediate position but displayed greater dispersion than pure lines, reflecting both intermediate and transgressive morphologies. These findings indicate that PCA effectively highlighted the morphometric dimensions most responsible for hybrid distinctiveness, supporting its value in aquaculture breeding studies (Špelić *et al*., 2021; Gonzalez-Martinez *et al.*, 2020).

Table 5: Principal Component Analysis (PCA) of morphometric traits of GIFT, Red Tilapia, and their hybrids

Trait	PC1 (46.8%)	PC2 (24.1%)	PC3 (13.5%)
Standard length	0.82	0.26	0.14
Body depth	0.78	0.34	0.11
Caudal peduncle depth	**0.80**	0.18	0.09
Head length	0.33	**0.75**	0.22
Body width	0.29	**0.71**	0.27
Pectoral fin length	0.21	0.24	**0.74**
Pelvic fin length	0.25	0.28	**0.77**
Anal fin base length	0.37	0.39	0.52
Eigenvalue	3.74	1.93	1.08
Variance explained (%)	46.8	24.1	13.5
Cumulative variance (%)	46.8	70.9	84.4

Note: Bold values indicate high factor loadings (>0.70).

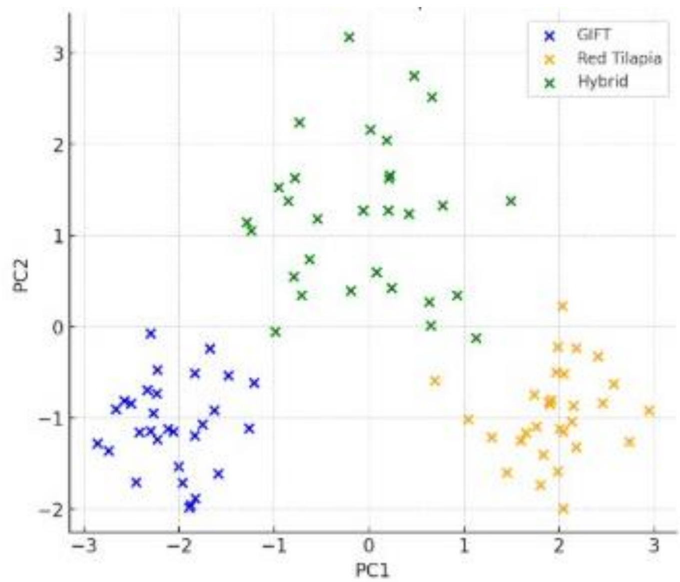

Figure 5: Principal Component Analysis (PCA) scatter plot showing morphometric differentiation among GIFT, Red Tilapia, and their hybrids

Hybrids occupied an intermediate but distinct morphometric space between GIFT and Red Tilapia, while also displaying broader dispersion, reflecting greater phenotypic diversity. Body size traits such as standard length and body depth were the strongest contributors to variation (Špelić et al., 2021). This outcome is consistent with the expectation that hybrid populations exhibit wider morphological variability (Gonzalez-Martinez *et al*., 2020).

Heterosis Estimates

Mid-parent heterosis further demonstrated a hybrid advantage in growth-related traits (Table 6). Positive heterosis was expressed for weight gain (+12.7%) and SGR (+7.1%), while negative heterosis was recorded for FCR (–7.7%), which is beneficial since lower FCR values indicate superior feed efficiency. These findings align with prior studies documenting heterotic improvements in nutrient assimilation and feed conversion in hybrid fish species (Šimková *et al.,* 2021; Phuc *et al*., 2025). Survival showed minimal heterosis (+1.3%), consistent with the lack of statistical differences in survival rates across groups.

Table 6: Mid-parent heterosis estimates (%) for performance traits of hybrids

Trait	Mid-parent Value	Hybrid Mean	Heterosis (%)
Weight gain (g)	41.3	50.2	+12.7
Specific Growth Rate (% day^{-1})	3.58	3.82	+7.1
Feed Conversion Ratio (FCR)	1.495	1.38	–7.7 (improved efficiency)
Survival rate (%)	92.3	94.0	+1.3%

Note: Negative heterosis for FCR indicates improvement, since lower FCR values reflect better feed efficiency.

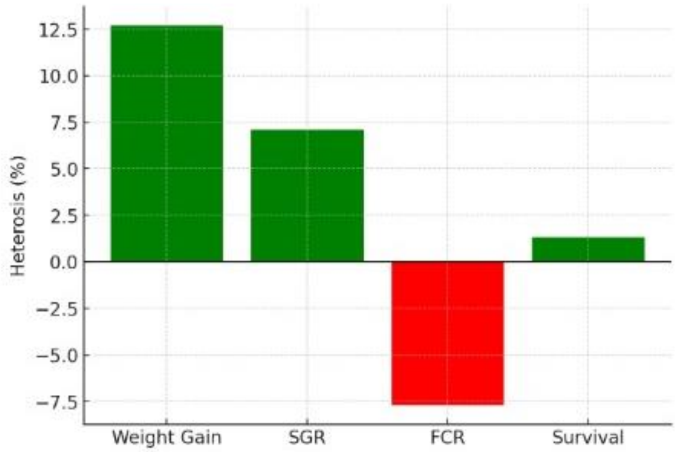

Figure 6: Mid-parent heterosis estimates (%) for growth performance traits of hybrids

Figure 6 depicts heterosis estimates for growth traits. Positive heterosis was recorded for weight gain (+12.7%) and SGR (+7.1%), while negative heterosis was observed for FCR (–7.7%), indicating improved feed efficiency. Survival showed minimal heterosis (+1.3%), consistent with the non-significant differences reported (Phuc *et al*., 2025; Barzkar *et al.,* 2024). These findings confirm the genetic advantage of hybridization in enhancing aquaculture performance.

Water Quality Parameters

Throughout the 12-week experimental period, water quality remained stable and within the optimal ranges recommended for tilapia culture (Table 2). Recorded values included temperature (27.0–30.2 °C), dissolved oxygen (5.1–6.2 mg L^{-1}), and pH (6.8–7.5). Ammonia levels (0.01–0.05 mg L^{-1}) were well below toxic thresholds. These consistent conditions ensured that observed performance and morphometric differences were attributable to genetic factors rather than environmental variation, a conclusion consistent with earlier controlled tilapia studies (Abd El-Hack *et al*., 2022; Azaza *et al*., 2020; Dai *et al*., 2025).

Discussion

Growth Performance and Feed Utilization

The results demonstrated that GIFT × Red Tilapia hybrids attained significantly higher final body weight, weight gain, and specific growth rate compared to purebred parental strains, confirming the presence of heterosis in growth-related traits (Šimková *et al*., 2021; Liu *et al.,* 2025). These findings support previous reports that crossbreeding enhances genetic complementarity and stimulates vigor-related advantages in fish, thereby improving production outcomes (Mengistu *et al*., 2020). Improved growth performance is particularly important in developing aquaculture systems where faster growth reduces production cycles and enhances profitability (Pant *et a*l., 2024).

Feed conversion ratio was significantly lower in hybrids, highlighting their superior efficiency in transforming feed into biomass compared with GIFT and Red Tilapia (Rahman and Arifuzzaman, 2021). Negative heterosis for FCR is advantageous since reduced feed costs directly improve economic returns, given that feed accounts for up to 70% of aquaculture production expenses (Limbu *et al*., 2022; Ovie *et al*., 2025). Similar improvements in feed efficiency have been documented in hybrid catfish and shrimp, where heterosis improved nutrient assimilation and production economics (Hasan *et al*., 2022; Barzkar *et al*., 2024). Importantly, survival rates were high and statistically similar across groups, indicating that the improved growth and feed utilization of hybrids were not achieved at the expense of resilience (Abdel-Aziz *et al*., 2023).

The graphical representations (Figures 1–6) further highlight the superiority of the hybrids over the parental strains. Growth-related figures (Figures 1–3) confirm that hybrids consistently attained higher final weight, weight gain, and specific growth rate while maintaining a lower feed conversion ratio, illustrating both the expression of heterosis and the economic importance of improved feed efficiency (Pant *et al*., 2024; Ovie *et al*., 2025). Morphometric differentiation (Figure 4) and multivariate analyses (Figure 5) visually reinforce the intermediate yet distinct phenotypes of hybrids, with greater variability reflecting enhanced phenotypic diversity (Špelić et al., 2021; Gonzalez-Martinez et al., 2020). The heterosis plot (Figure 6) clearly demonstrates the magnitude of hybrid vigor, particularly positive heterosis for weight gain and SGR and favorable negative heterosis for FCR, which are critical traits for sustainable aquaculture improvement (Phuc *et al*., 2025; Barzkar *et al*., 2024). Together, these figures provide strong visual evidence that complements the tabulated results, underscoring the genetic and production advantages of GIFT × Red Tilapia hybrids.

Morphometric and Meristic Differentiation

Morphometric evaluation revealed that hybrids expressed intermediate phenotypes, with significant differences in traits such as standard length, body depth, and head length compared to parental lines (Gonzalez-Martinez *et al.,* 2020; Makeche *et al.,* 2022). Discriminant Function Analysis achieved more than 90% classification accuracy, while canonical functions explained over 80% of the variance, underscoring the diagnostic power of morphometric traits for distinguishing hybrids (Špelić *et al.*, 2021; Jafari *et al.*, 2022).

In contrast, meristic traits such as dorsal and anal fin rays did not differ significantly among groups, reflecting their evolutionary stability and limited responsiveness to hybridization (Shettima *et al.*, 2020; Lenka *et al.,* 2024). This indicates that while meristic characters remain useful for species-level taxonomy, morphometric traits are more reliable markers for hybrid identification in aquaculture.

Principal Component Analysis and Phenotypic Diversity

Principal Component Analysis further confirmed that body size descriptors such as standard length, body depth, and caudal peduncle depth were the strongest contributors to group differentiation, accounting for nearly half of the total variance (Špelić *et al.,* 2021). Hybrids occupied an intermediate but distinct morphometric space, with broader dispersion reflecting higher phenotypic variability than purebred lines (Gonzalez-Martinez *et al.*, 2020). This wider variation is consistent with expectations for hybrids, which typically express greater morphological diversity compared to their parental strains.

Heterosis Expression and Genetic Implications

The positive heterosis observed for weight gain (+12.7%) and SGR (+7.1%) confirmed the growth advantage of hybrids, while the favorable negative heterosis for FCR (–7.7%) emphasized their superior feed utilization efficiency (Phuc *et al.,* 2025; Barzkar *et al*., 2024). These results align with previous research showing that heterosis in aquatic organisms leads to improvements in nutrient assimilation and overall production performance (Hasan *et al.*, 2022; Šimková *et al.*, 2021). However, heterosis is not universally stable and may be affected by genotype-by-environment interactions (Phuc *et al.,* 2025). Although this study was conducted under controlled pond conditions, broader evaluations in cages, tanks, and recirculating aquaculture systems are necessary to confirm the stability of hybrid advantages across environments (Dai *et al.,* 2025).

Environmental Stability and Experimental Validity

Water quality parameters remained within optimal limits for tilapia throughout the experiment, ensuring that observed differences in growth and morphometric traits were attributable to genetic factors rather than environmental variability (Abd El-Hack *et al.*, 2022; Azaza *et al.*, 2020). This strengthens the conclusion that the enhanced performance of hybrids resulted from hybridization outcomes rather than culture conditions (Dai *et al.*, 2025).

Implications for Aquaculture Development

The combination of high growth rates, efficient feed utilization, and intermediate phenotypes makes GIFT × Red Tilapia hybrids valuable genetic resources for aquaculture development. By merging the rapid growth of GIFT with the pigmentation and consumer appeal of Red Tilapia, hybrids offer both production and market advantages (Dee *et al.*, 2021). Their improved feed efficiency also supports sustainable aquaculture by lowering costs and minimizing resource use, which aligns with global objectives of profitability and environmental responsibility (El-Sayed and Fitzsimmons, 2023; Akpalu and Nnaemeka, 2025).

CONCLUSION

This study demonstrates that hybridization between GIFT and Red Tilapia yields hybrids with distinct biological and economic benefits. The hybrids consistently exhibited superior final body weight, weight gain, and specific growth rate, alongside a lower feed conversion ratio, confirming the expression of heterosis in growth and feed utilization traits. Importantly, survival rates remained high and did not differ from purebred strains, indicating that enhanced performance was not achieved at the expense of resilience.

Morphometric analyses revealed intermediate hybrid phenotypes, with discriminant and principal component analyses providing reliable classification and confirming their distinctiveness. In contrast, meristic traits remained stable, reaffirming their limited value for strain-level differentiation. The positive heterosis in growth traits and favorable negative heterosis in FCR highlight the potential of these hybrids for sustainable genetic improvement programs in tilapia aquaculture. The consistency of water quality within optimal ranges confirms that observed differences were genetically determined rather than environmentally induced. Consequently, GIFT × Red Tilapia hybrids represent a strategic resource for aquaculture intensification, with direct implications for food security, profitability, and sustainability in developing regions. Future adoption should be supported by molecular genetic validation, resilience testing under variable environments, and farmer training to maximize the benefits of hybrid dissemination. With these measures, GIFT × Red Tilapia hybrids can play a transformative role in advancing aquaculture development globally.

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