# Combining Ability of Channel Catfish, *Ictalurus punctatus*, Females and Blue Catfish, *I. furcatus*, Males for Early Growth, Growth Variation, Disease Resistance, and Carcass Yield of their Progeny

by

Ramjie Yusop Odin

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Approved by

Rex A. Dunham, Chair, Professor, School of Fisheries, Aquaculture, and Aquatic Sciences
Donald Allen Davis, Professor, School of Fisheries, Aquaculture, and Aquatic Sciences
Charles Y. Chen, Professor, Department of Crop, Soil and Environmental Sciences
Jeffery Scott Terhune, Associate Professor, School of Fisheries, Aquaculture, and Aquatic Sciences

# Abstract

The hybrid between channel catfish (*I. punctatus*) females and blue catfish (*I. furcatus*) males is considered the best catfish genotype for commercial catfish farming due to their faster growth rate, better survival rate, disease resistance, better carcass yield and seinability. However, the hybrid is not a panacea, and genetically improved hybrids might be developed by improving the parent species, especially by selecting for female channel catfish and male blue catfish that have increased combining abilities. Reciprocal recurrent selection for the parent species could be conducted to improve traits of the hybrid progeny, however estimation of general combining ability (GCA) and specific combining ability (SCA) is necessary to determine the feasibility and the best approach to the reciprocal recurrent selection.

Twenty channel catfish females and twelve blue catfish males were crossed in a 20 x12 factorial mating design, but an unbalanced design resulted as only 40 families had adequate hatch. The 40 hybrid families were evaluated for their early performance traits in three different rearing systems at two ages. The body weight, weight gain, coefficient of variation (CV) in body weight, survival rate from natural *Aeromonas hydrophila* infection, and dressout percentage were analyzed to estimate genetic component variances.

The estimates for variance of combining ability showed that variance for early growth of hybrid catfish in all the three rearing systems at two ages was significantly ($P<0.05$) affected by the additive gene actions attributable to the channel catfish female parent. The genetic effects controlling the CV in body weight when hybrids were reared in flow-through system was additive gene actions However, when the hybrids were further reared in recirculating system, the CV became attributable to dominant gene actions. The resistance of hybrid catfish to *Aeromonas hydrophila* was significantly affected by the additive gene effects of the blue catfish male parent. The dressout percentage of hybrid catfish was affected by the dominant gene actions attributable to the specific cross of channel and blue catfish parents. Overall, the combining abilities indicate that reciprocal recurrent selection for early traits appears to have potential to improve the performance of F1 hybrid catfish.

# Dedication

To my dearest Ama and Ina

My sibs: Rajia, Jehan, Riaz, Hanie, and Nizhar

My little angels: Jannan, Rheanor, Jibran, Rashdan, and Razana

Odin and Yusop Family

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# List of Abbreviations

| | |
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| AU | Auburn University |
| GCA | General Combining Ability |
| SCA | Specific Combining Ability |
| REML | Restricted Estimation of Maximum Likelihood |
| BLUP | Best Linear Unbiased Prediction |
| LHRHa | Luteinizing Hormone Releasing Hormone analogue |

# CHAPTER ONE

## General Introduction and Literature Review

Aquaculture has always been considered as a sustainable food producing sector that can address the increasing demand for food of the increasing human population. The world aquaculture production continued to grow in 2015, reaching 106 million tonnes (live weight) with an estimated value of US$157 billion, contributing 45.3 percent (%) of the total world fish production (Zhou 2017). Although there is an overall increase in the aquaculture production, which can be attributed to the increasing demand for food fish from around the world, the production in developed countries such as the USA, Japan, Korea, and various European countries has declined the past few years. The importation of fish from developing countries where production costs are relatively low is seen as a major reason for this decline.

The channel catfish (*Ictalurus punctatus*), which is mostly produced in the southern parts of the United States, accounted for up to 68% of the total aquaculture production in the USA at its peak in 2003. Since that time, the US industry has been greatly affected by the importation of catfish from other countries (NOAA 2016). The cheaper price, $1.50-$2 per pound, of the imported catfish than the American variety of catfish is attracting most of the US consumers. The imports account for 80% of all U.S. sales of frozen catfish and catfish-like fillet products. Over the last 10-13 years, the US catfish industry has declined to more than 50% of its production (Hanson and Sites, 2015). During the past decade, the 40% of the catfish farms were lost. Factors that can be considered to have contributed to this crisis in the catfish industry are competition with cheap imports, which now have more than 50% of the US catfish market, increasing production costs and fish disease control (Wagner et al. 2002, FAO 2011).

The current levels of aquaculture production of important food fish like catfish have been attained through improved hatchery and grow-out culture techniques, disease diagnosis and treatments and application of genetics and biotechnology. Several genetic enhancement programs for catfish have been examined such as strain selection, intraspecific crossbreeding, mass selection, and interspecific hybridization (Yant et al. 1975; Green et al. 1979; Dunham and Smitherman 1984). The hybrid between channel catfish females and blue catfish (*I. furcatus*) males was found to have exceptional heterotic growth (Giudice 1966) and at commercial densities, its growth, feed conversion ratio (FCR) (Yant et al. 1976; Li et al. 2004), survival, disease resistance (Ella 1984; Wolters et al. 1996; Dunham et al. 2008; Arias et al. 2012), dressout percentage and fillet yield (Yant 1975; Chappell 1979; Huang et al. 1994; Argue et al. 2003; Bosworth et al. 2004; Bosworth 2012) and seinability (Yant et al. 1976; Chappell 1979; Dunham and Argue 1998) were found to be superior to that of the channel and blue catfish (Dunham 2011). The Auburn University has played an important role in developing the farming techniques for hybrid catfish in the US (Dunham and Perera 2014). An increasing number of catfish farmers are utilizing hybrid catfish, which has been a key component that has allowed the catfish industry to survive and perhaps becomes stronger in the future. In 2014, about 200 million hybrid catfish fry were produced and now the industry has shifted to a majority hybrid catfish industry with 50-70% of all production and processing accounted to hybrid catfish (Multistate Research Project 2015).

### *Current Status of the Catfish Industry*

Catfish growers of food fish, stockers, and fingerlings and fry in the US had sales of US$361 million in 2015 which is 3% higher than in previous year, and 96% of these catfish were produced in Mississippi, Alabama, Arkansas, and Texas (National Agricultural Statistics Service (NASS) 2016). The total food size sales also increase to 4% during 2015 from its previous year and 95.9% of these were directly sold to processors. The sales of stockers in 2015 was US$8.20 million which was 8% lower than the previous year while the sales of fingerlings and fry in 2015 was US$7.69 million, which was 25% lower than 2014. The direct sales of stockers to other catfish grow-out producers decreased by 3% in 2015 from the previous year. The number of broodfish was down 10%, production and survival of fingerlings and stockers declined almost 30% from 2015-2016, resulting in a decrease in total hectares used for production of broodfish, fingerlings, and stockers and a decrease in sales of fingerlings and stockers (NASS 2016)

Seed production is an important component of hybrid catfish industry. It is vital that attention be given to boosting the production of quality broodfish, and quality fingerlings and stockers to augment catfish sales and strengthen the industry.

### *Quantitative Genetics and Its Application to Catfish Production*

Geneticists have been successful in producing and improving performance traits of plants and animals through selective breeding. Traits which are of economic importance include growth performance, survival, disease resistance, tolerance to myriad of environmental stressors, harvestability, and processing characteristics. Such traits are usually controlled by actions of multiple genes. The work of Galton and Pearson in 1880-1900 resulted in many of the basic statistical tools (such as regression and correlation) that led to the development of methods for the analyses of important quantitative traits (Stanton 2001). The formal beginning of this field started with the treatment of the inheritance of quantitative characters, which showed how explicit Mendelian genetic models of inheritance could account for the resemblance in continuous traits between relatives (Fisher 1918). Fisher's findings introduced the powerful statistical method of analysis of variance (ANOVA), which is now applied widely even outside the field of quantitative genetics. Thus, many of the basic statistical tools we used today were first introduced and developed for quantitative genetics.

The important performance and production traits of catfish which, are usually recorded per individual and are referred to as phenotype are the bases of quantification of the multiple genes for the desired traits. Information from such records are statistically analyzed to select for the best performing fish in a breeding program. Breeding programs require data collection and data analysis to determine if the phenotypic goal can be achieved through selection or crossbreeding and hybridization (Tave 1993).

Quantitative phenotypes exhibit continuous variation, requiring analyses and partitioning of phenotypic variance into independent components. Phenotypic variance ($V_P$) reflects the sum of genetic variance ($V_G$), environmental variance ($V_E$), and the genetic environmental interaction variance ($V_{GxE}$).

$$V_P = V_G + V_E + V_{GxE}$$

The $V_G$, $V_E$, and $V_{GxE}$ are equally important and critical from a commercial stand point. Partitioning of phenotypic variation into genetic and environmental components permits breeders to make decisions for resource allocation and response to selection (Hallauer and Miranda 1981; Hill et al. 1998). A breeding program is designed to exploit and maximize available genetic variance through the use of its main components: additive variance ($V_A$), dominance variance ($V_D$), and epistatic variance ($V_I$).

$$V_G = V_A + V_D + V_I$$

Because of the difficulty to exploit and measure the epistatic variance, breeders assume its non-existence. And so, $V_A$ and $V_D$ are considered the two most important genetic components. Additive variance is attributed to additive effects which are related to the heritability of various traits and consequently are the basis for selection (Tave 1993). When additive effects influence a continuous trait, choosing those organisms presenting the best performing traits as broodstock should result in the overall improvement of the offspring (Lutz 2001). Dominance variance ($V_D$) describes the variance associated with dominance genetic effects, which are expressed based on combinations of specific alleles, or combinations of individuals, strains or species that carry those alleles. Dominance effects are the basis of genetic improvement from hybridization and crossbreeding and are expressed as heterosis, commonly described as hybrid vigor, increased performance of hybrids or crossbred individuals over that of the parental lines (Hallauer and Miranda 1988).

Other genetic components, such as maternal and strain effects include both additive and dominance effects. Maternal effect is the source of variance attributed to the maternal genotype and phenotype and the environment it provides for the offspring (Falconer and McKay 1996). It can therefore be both environmental and genetic in origin. It reflects the differences in either environment or genetic merit of the female parent on the performance of her progeny (Wilham 1980). In fish and shellfish, maternal effects are related to variation in egg size and quality, which results in variation in hatching and survival during the early stage of growth and development. In channel catfish, egg size was found to affect its early growth rate (Reagan and

Conley 1977). Maternal effects on growth of brown trout, *Salmo trutta fario* (Vandeputte et al. 2002), rainbow trout, *Onchorhynchus mykiss* (Henryon et al. 2002), hybrid striped bass, *Morone chrysops* × *Morone saxatilis* (Wang et al. 2006) and Atlantic cod, *Gadus morhua* (Tosh et al. 2010) decline as the progeny age.

The strain effects of parents on a myriad of traits such as body weight, growth rate, survival, reproduction traits, sexual maturity, immunological parameters and disease resistance of their progeny have been reported in aquaculture species like salmonids (Kanis et al. 1976; Refstie et al. 1977; Gunnes and Gjedrem 1978; Jonasson 1996; Unwin et al. 2003), rainbow trout (Kincaid 1981; Okamoto et al. 1993; Overturf et al. 2003; Quinton et al. 2004), striped bass, *Morone saxatilis* (Jacobs et al. 1999), tilapia, *Oreochromis niloticus* (Eknath et al. 1993; Macaranas et al. 1997), common carp, *Cyprinus carpio L*. (Vandeputte et al. 2004), rohu, *Labeo rohita* (Reddy et al. 2002) and catfish (Dunham and Smitherman 1984; Smitherman and Dunham 1985; Dunham et al. 1987; Rezk et al. 2003; Bosworth et al. 2004; Dunham et al. 2014a, 2014b).

Quantitative genetics research has greatly impacted production of other farm animals through improved breeding since the 1930s until today (Wolters and Tiersch 2004). Channel catfish genetics and breeding began in the late 1960s and early 1970s (Dunham and Smitherman 1987). The realized response to selection in fish has been much higher than in farm animals (Gjerde 1986; Dunham et al. 2001). Catfish genetic improvement has been projected to be larger than other farm animals in terms of potential for increased food production efficiency from 2000 to 2030 (Smith 1991).

Selective breeding programs have been conducted for channel catfish to improve its growth as length and weight, time of spawning, viability, disease resistance, dressout percentage (El-Ibiary et al. 1976; El-Ibiary and Joyce 1978; Reagan 1979; Dunham 1981; Bondari 1983, Dunham and Smitherman 1983, 1985; Dunham et al. 1987; Rezk 1993; Dunham and Brummett 1999; Rezk et al. 2003; Small 2005; Gima et al. 2014). The initial genetic enhancement programs conducted for catfish were strain selection, intraspecific crossbreeding, mass selection, and interspecific hybridization (Yant et al. 1976; Green et al. 1979; Dunham and Smitherman 1983a, 1983b).

Dunham and Smitherman (1984) first documented the origin, history, breeding and performance traits of various channel catfish strains used by university, state, federal, and private hatcheries in the US. During 80's, channel catfish, blue catfish, white catfish (*I. catus*), and flathead (*Pylodictus olivaris*) and the major catfish species in the US. The channel catfish was the primary species propagated because it has superior culture traits. This species grows faster and has more disease resistance than other species. They are native to the Mississippi-Missouri river system southward into northeastern Mexico, but their range has been expanded through introductions to almost all parts of North America where there are suitable waters. The blue catfish has relatively uniform growth and body conformation, high dressing percentage, and high vulnerability to seining. They native to the main channels of the Mississippi River and its major tributaries from Minnesota and South Dakota southward into Mexico. The white catfish have poor bacterial resistance and poor dressout percentage and are more difficult to catch during seining. They are native to lower reaches of coastal streams from Delaware and New Jersey south into Florida, including a few streams entering the Gulf of Mexico. The flathead catfish which are native to large rivers of the Mississippi, Missouri, and Ohio basins, and south into Mexico were only used for sport fishing before.

A strain is a population of fish within a single species that has the same history, the same origin and has at least one trait or a suite of traits that make it unique or make it different from other strains (Dunham 2011). The National Fish Strain Registry for catfish contains important and substantial information on the broodfish strains of channel catfish, blue catfish, and white catfish and their history, origin, behavior, reproduction, disease resistance, availability and other important traits (Kincaid et al. 2000). Strain evaluation and selection is the first step to any genetic improvement program (Dunham 2011). Basically, the best performing domestic strains of catfish are selected. In channel catfish, variation in strains was reported for growth, disease resistance, body conformation, dressing percentage, vulnerability to angling and seining, age of maturity, time of spawning, fecundity and egg size (Dunham and Smitherman 1984; Smitherman and Dunham 1985). Strains have a major impact on the success and ultimate outcome of all genetic enhancement programs. Channel catfish strains affected the production, meat yield and quality traits of channel catfish female x blue catfish male hybrids (Bosworth et al. 2004). In addition, the strain of parent species was also reported to affect the level of heterosis/ performance for growth (Dunham et al. 1987; Dunham et al. 2014a), vulnerability to angling (Dunham et al. 1986), survival and sexual dimorphism (Dunham et al. 2014a) and tolerance to low dissolved oxygen (Dunham et al. 2014b) observed in channel catfish x blue catfish hybrids. Variability in production of hybrid catfish due to the strain effects of channel and blue catfish parents used was also observed for growth rate and processing yield traits (Bosworth et al. 1998).

Selection is the classical method of screening, selecting, and breeding of better performing individuals and/or groups to improve desirable quantitative or production traits. The two basic types of selection are individual or mass (where individuals are selected based on their own performance) and family selection (where individuals are selected based on the mean performance of their family). Combined selection can also be done where best performing individuals are selected from the best performing families. Realized response to selection in fish is generally very high compared with what has been obtained in farm animals (Gjerde 1986; Dunham et al. 2001). Like in other fish species, selection was also reported to improve growth rate in catfish (Dunham and Perera 2014). Selection has improved the body weight of channel catfish by 12–20% with one or two generations of mass selection (Bondari 1983; Dunham and Smitherman 1983a; Smitherman and Dunham 1985; Dunham and Brummet 1999;). Selection has been successful in all eight lines of channel catfish that were evaluated, and the fastest growing strains yielded the fastest-growing select lines (Smitherman and Dunham 1985). The best select line grew twice as fast as average strains of channel catfish (Burch 1986). Responses to one generation of selection in Rio Grande, Marion, and Kansas strains of channel catfish were reported to improve body weight of catfish by 17%, 18%, and 12%, respectively (Dunham and Smitherman 1983a, 1983b), suggesting the importance of strain effects in selective breeding programmes. After three generations of selection, growth rate of channel catfish was improved by 20–30% when grown in ponds (Rezk 1993) and four generations of selection in Kansas strain resulted in a 55% improvement in growth rate (Padi 1995). The selective breeding research made a larger impact in the 1990s through the mid-2000s by commercial farms taking the results and applying them to their own brood stock rather than through release of improved germplasm from research institutions (USDA 2003; Steeby and Wagner 2006; Dunham and Perera 2014). Improved selected lines were developed. Some farmers have employed their own crossbreeding programs to enhance performance or to avoid inbreeding. By 2005, 70% of the catfish industry was utilizing selected fish that were a result of Auburn research or were developed following the program demonstrated by Auburn (Dunham and Perera 2014).

Intraspecific crossbreeding is the mating of unrelated individuals of the same species (Dunham 2011). Dunham and Smitherman (1985) reported the effects of crossbreeding between the two channel catfish strains to increase their growth and reproductive performance. The goal of crossbreeding and hybridization is to produce progeny that performs better than the existing parents. The two selection programs in crossbreeding and hybridization with little genetic issues are recurrent selection (which is selection of purebred parental line based on its performance) and reciprocal recurrent selection (which is selection of parents based on the hybrid progeny performance) (Bosworth and Waldbieser 2014).

Another genetic enhancement program with the goal of producing heterosis is interspecific hybridization. Hybrids between the seven-major species of North American catfish (*Ictalurids*) were first evaluated in 1966 (Giudice 1966; Dupree and Green 1969; Chappell 1979; Dunham and Smitherman 1984; Masser and Dunham 2012). Giudice (1966) indicated that the cross between channel catfish female and blue catfish male showed increased growth and production compared to channel catfish. This hybrid has shown superior characteristics (heterosis) for many traits such as faster growth 20 - 100% (Giudice 1966; Dunham et al. 1987, 1990; Dunham and Brummet 1999; Argue et al. 2003; Brown et al. 2011), especially at high densities, 15-20% better feed conversion (Yant et al. 1976; Li et al. 2004), 50- 100% higher tolerance to low oxygen levels (Dunham and Smitherman 1984), increased resistance to many common diseases, especially bacterial (Ella 1984; Wolters et al. 1996; Dunham et al. 2008; Arias et al. 2012), higher dress-out percentage (Yant 1975; Bosworth et al. 2004; Bosworth 2012) and increased harvestability by seining (Dunham and Argue 1998) and vulnerability to angling (Tave et al. 1981; Dunham et al. 1986).

### *Combining Ability: Concepts and Principles*

Combining ability is defined as the estimation of the genetic value of the parents/cross on based on the performance of their progeny in some definite mating design (Allard 1960). Since this is measured by progeny testing it can be used in reciprocal recurrent selection. This concept was introduced in 1942, and was originally developed and applied in corn breeding (Sprague and Tatum 1942). This has also been widely adopted in plant breeding to determine genetic components influencing agronomic traits. Combining ability has also been adopted in aquaculture species like hybrid striped bass (*Morone chrysops* × *Morone saxatilis*) (Wang et al. 2006), sea bass (*Dicentrarchus labrax L.*) (Saillant et al. 2006), common carp (Vandeputte et al. 2004; Su et al. 2013), blunt snout bream, *Megalobrama amblycephala* (Luo et al. 2014), channel catfish (Wolters and Johnson 1995), hybrid catfish (Bosworth and Waldbieser 2014; Drescher 2017) and tilapia (Lutz et al. 2016).

There are two types of combining ability. The first is the general combining ability (GCA) which measures the additive genetic effects of the parent. This is simply the breeding value of a parent. The second is the specific combining ability (SCA), which measures the dominance genetic effect of the cross. This is the genetic value of a cross. Sprague and Tatum (1942) defined GCA as the average performance of an individual parent in a series of hybrid combinations. They defined SCA as those cases in which certain hybrid combinations perform better or poorer than would be expected on the basis of the average performance of the parental inbred lines. Parents showing a high average combining ability in crosses are considered to have good GCA, while if their potential to combine well is bounded to a particular cross, they are considered to have good SCA.

From a statistical point of view, the GCA is a main effect and the SCA is an interaction effect (Kulembeka et al. 2012). Based on Sprague and Tatum (1942), GCA is the activity of genes which are largely additive in their effects as well as additive × additive interactions (Griffing 1956). Specific combining ability is regarded as an indication of loci with dominance variance (non-additive effects) and all the three types of epistatic interaction components if epistasis were present. They include additive × dominance and dominance × dominance interactions.

The concept of GCA has been effectively used in crop and livestock breeding for more than 70 years (Sprague and Tatum 1942; Shikano et al. 2000; Adebambo 2011; Wang et al. 2014). This is an effective tool used in selection of elite parents based on the performance of their progenies, usually the F1 but it has also been used in F2 and later generations (Fn) (Fasahat et al. 2016). A low GCA value, positive or negative, shows that the mean of a parent in crossing with the other does not vary largely from the population mean. In contrast, a high GCA value shows that the parental mean is superior or inferior to the population mean. This indicates a potent evidence of desirable gene flow from parents to offspring at high intensity and represents information regarding the concentration of predominantly additive genes (Franco et al. 2001). A high GCA estimate indicates higher heritability and less environmental effects. It may also result in less gene interactions and higher achievement in selection (Topal et al. 2004; Chigeza et al. 2014). One of the main features of the elite parent with high GCA effect is its large adaptability. A parent good in per se performance may not necessarily produce better hybrids when used in hybridization (Allard 1960; Shukla and Pandey 2008). One parent of the worst combination could make the best combination if the other parent was selected properly (Bao et al. 2009).

The impact of SCA is decreased when genetically broad testers or increased number of testers are used in a mating design (Hallauer and Miranda 1988). Selection of parents based only on the SCA effect have limited value in breeding programs. Therefore, SCA effect should be used in combination with a high performing hybrid, favorable SCA estimates, and involving at least one parent with high GCA estimates (Franco et al. 2001; Joshi et al. 2004; Makanda et al. 2010).

The varying patterns of performance of crosses based on SCA have also revealed the gene actions involved in the expression of the traits. High SCA effects resulting from crosses where both parents have good GCA estimates may be ascribed to additive × additive gene action (Dey et al. 2014). The high SCA effects derived from crosses of parents with good × poor GCA estimates (Milić et al. 2011; Dey et al. 2014) may be attributed to favorable additive effects of the parent with good GCA and epistatic effects of parent with poor GCA. High SCA effects manifested by both parents having poor × poor GCA (Dey et al. 2014) may be due to dominance × dominance type of non-allelic gene interaction producing over dominance. Predominance of non-additive effects has been reported for inheritance of pod yield and related traits in groundnut under salinity stress in which there were cross combinations with high SCA effects arising from parents with high and low GCA, and another set of crosses with high SCA effects arising from both parents with good GCA effects (Azad et al. 2014).

Among the three commonly used mating designs/techniques (diallel, line x tester, and North Carolina design) for estimation of combining ability, the North Carolina (NC II) designs proposed by Comstock and Robinson (1952), which is defined as a class of factorial mating designs or schemes where certain groups of parents are designated male (factor 1) and others female (factor 2) in crosses could be the most appropriate technique for estimating GCAs in hybrid catfish since the parents are interspecific. Hence, the GCA of individual maternal and paternal parent should be estimated. Hallauer (2007) suggested the NC II as a preferable design, which can make use of a larger number of parents resulting in a fewer crosses generated than a diallel mating design. The NC II mating design is a factorial experiment that measures the variance of male and female main effects and male × female interaction effects (Comstock and Robinson 1952). According to Hallauer & Miranda (1988), male and female main effects, and the male × female interaction effects in a NC II mating design are equivalent to the GCA and the SCA effects in a diallel. The main difference between a diallel and NC II is that there are two independent estimates for the GCA effects in the NC II, which is an advantage of the NC II over the diallel. Two independent estimates of GCA allow determination of maternal effects and calculation of heritability based on male variance, which is free from maternal effects. Another advantage is that the NC II can handle more parents and produce fewer crosses than the diallel. This is achieved by dividing parents into sets as described by Hallauer and Miranda (1988). Because fish species exhibit reproduction singularities especially, high fecundity, easy in vitro fertilization in many species, NC II is an efficient mating design can be used for inference of genetic parameters. In fact, this design has been applied in fish species (Dupont-Nivet et al. 2002; Dupont-Nivet et al. 2006; Bosworth and Waldbieser 2014), hybrid striped bass (Wang et al. 2006), sea bass, *Dicentrarchus labrax L.* (Saillant et al. 2006), and carp (Vandeputte et al. 2004). This design has also been used to increase effective number of breeders in fish hatcheries (Busack and Knudsen 2007). Since catfish have high fecundity and have external fertilization which allows access and handling of gametes from male and female parents, the use of NC II mating design to estimate additive (GCA) and dominance (SCA) genetic effects is possible.

# References

Adebambo, A.O. 2011. Combining abilities among four breeds of chicken for feed efficiency variation: a preliminary assessment for chicken improvement in Nigeria. Tropical Animal Health and Production 43:1465-1466.

Allard, R.W. 1960. Principles of Plant Breeding, John Wiley and Sons Inc, New York, USA.

Argue, B.J., Z. Liu, and R.A. Dunham. 2003. Dress-out and fillet yields of Channel Catfish, *Ictalurus punctatus*, Blue Catfish, *I. furcatus*, and their F1, F2 and backcross hybrids. Aquaculture 228:81–90.

Arias, C.R., W. Cai, E.J. Peatman, and S.A. Bullard. 2012. Catfish hybrid *Ictalurus punctatus* × *I. furcatus* exhibits higher resistance to columnaris disease than the parental species. Diseases of Aquatic Organisms 100:77–81.

Azad, M.A.K., M. Shah-E-Alam, M.A. Hamid, M.Y. Rafii, and M.A. Malek. 2014. Combining ability of pod yield and related traits of groundnut (*Arachis hypogaea L.*) under salinity stress. The Scientific World Journal 589586:1-7.

Bao, Y., S. Wang, X. Wang, Y. Wang, X. Li, et al. 2009. Heterosis and combining ability for major yield traits of a new wheat germplasm Shannong 0095 derived from Thinopyrum intermedium. Agricultural Sciences in China 8(6):753-760.

Bondari, K., 1983. Response to bidirectional selection for body weight in channel catfish. Aquaculture 33, 73–81.

Bosworth, B.G. 2012. Effects of winter feeding on growth, body composition, and processing traits of co-cultured blue catfish (*Ictalurus furcatus*), channel catfish (*I. punctatus*) and channel catfish × blue catfish hybrids. National American Journal of Aquaculture 74:553–559.

Bosworth, B.G. and G. Waldbieser. 2014. General and specific combining ability of male blue catfish (*Ictalurus furcatus*) and female channel catfish (*Ictalurus punctatus*) for growth and carcass yield of their F1 hybrid progeny. Aquaculture 420–421:147–153.

Bosworth, B.G., W.R. Wolters, J.L. Silva, R.S. Chamul, and S. Park. 2004. Comparison of production, meat yield, and meat quality traits of NWAC 103 line channel catfish (*Ictalurus punctatu*s), Norris line channel catfish, and channel catfish female × blue catfish male (*I. furcatus*) F1 hybrids. National American Journal of Aquaculture 66:177–183.

Bosworth, B.G., W.R. Wolters, J.L. Silva, R.S. Chamul, and S. Park. 2004. Comparison of production, meat yield, and meat quality traits of NWAC 103 line channel catfish (*Ictalurus punctatu*s), Norris line channel catfish, and channel catfish female × blue

catfish male (*I. furcatus*) F1 hybrids. National American Journal of Aquaculture 66:177–183.

Brown, T., J. Chappell, and C. Boyd. 2011. A commercial-scale, in-pond raceway system for Ictalurid catfish production. Aquacultural Engineering 72-79.

Burch, E.P. 1986. Heritabilities for body weight, feed consumption and feed conversion and the correlations among these traits in channel catfish, *Ictalurus punctatus*. Master's Thesis. Auburn University, Auburn, Alabama.

Busack, C., and C. M. Knudsen. 2007. Using factorial mating designs to increase the effective number of breeders in fish hatcheries. Aquaculture 273:24–32.

Chappell, J.A. 1979. An evaluation of twelve genetic groups of catfish for suitability in commercial production. Doctoral Dissertation. Auburn University, Auburn, Alabama.

Chigeza, G., K. Mashingaidze, and P. Shanahan. 2014. Advanced cycle pedigree breeding in sunflower. II: combining ability for oil yield and its components. Euphytica 195(2):183-195.

Comstock, R.E., and H.F. Robinson. 1952. General vs. specific combining ability in single crosses of corn. A breeding procedure designed to make maximum use of both general and specific combining ability. Journal of American Society of Agronomy 41:360–367.

Dey, S.S., N. Singh, R. Bhaatia, C. Parkash, and C. Chandel. 2014. Genetic combining ability and heterosis for important vitamins and antioxidant pigments in cauliflower (*Brassica oleracea var. botrytis L*.). Euphytica 195(2):169-181.

Drescher, D. 2017. Combining ability of channel catfish (*Ictalurus punctatus*) females and blue catfish (*I. furcatus*) males for tolerance of low oxygen. Master's Thesis. Auburn University, Auburn, Alabama.

Dunham, R. A. 2011. Aquaculture and fisheries biotechnology: genetic approaches, 2nd edition. CAB International, Cambridge, MA, USA.

Dunham, R. A., and D. A. Perera. 2014. The history of the aquaculture genetics program at Auburn University. Aquaculture 420–421:3–7.

Dunham, R. A., and R. O. Smitherman. 1984. Ancestry and breeding of channel catfish in the United States. Circular 273. Alabama Agricultural Experiment Station, Auburn University, AL.

Dunham, R.A. 1981. Response to selection and realized heritability for body weight in three strains of channel catfish grown in earthen ponds. Doctoral Dissertation, Auburn University, Alabama.

Dunham, R.A., A.C.R. Ramboux, and D.A. Perera. 2014a. Effect of strain on the growth, survival and sexual dimorphism of channel × blue catfish hybrids grown in earthen ponds. Aquaculture 420–421, S20–S24.

Dunham, R.A., A.C.R. Ramboux, and D.A. Perera. 2014b. Effect of strain on tolerance of low dissolved oxygen of channel × blue catfish hybrids. Aquaculture 420–421, S25–S28.

Dunham, R.A., and B.J. Argue. 1998. Seinability of Channel Catfish, Blue Catfish, and F1, F2, F3 and backcross hybrids in earthen ponds. Progressive Fish-Culturist 60:214–220.

Dunham, R.A., and R.E. Brummett. 1999. Response of two generations of selection to increased body weight in channel catfish, *Ictalurus punctatus* compared to hybridization with blue catfish, *I. furcatus,* males. Journal of Applied Aquaculture 9:37–45.

Dunham, R.A., and R.O. Smitherman, R.O., 1983b. Response to selection and realized heritability for body weight in three strains of channel catfish, *Ictalurus punctatus*, grown in earthen ponds. Aquaculture 33:88–96.

Dunham, R.A., and R.O. Smitherman. 1983a. Crossbreeding channel catfish for improvement of body weight in earthen ponds. Growth 47:97–103.

Dunham, R.A., and R.O. Smitherman. 1985. Improved growth rate, reproductive performance and disease resistance of crossbred and selected catfish from AU-M and AU-K lines. Circular 279. Alabama Agricultural Experiment Station, Auburn University, AL.

Dunham, R.A., and Smitherman, R.O., 1987. Genetics and breeding of catfish. Southern Cooperative Series Bulletin 325, Southern Regional Research Project S-168. Alabama Agricultural Experiment Station, Auburn University, Alabama.

Dunham, R.A., G.M. Umali, R. Beam, A.H. Kristanto, and M. Trask. 2008. Comparison of production traits of NWAC103 Channel Catfish, NWAC103 Channel Catfish × Blue Catfish hybrids, Kansas select 21 Channel Catfish, and Blue Catfish grown at commercial densities and exposed to natural bacterial epizootics. North American Journal of Aquaculture 70:98–106.

Dunham, R.A., K. Majumdar, E. Hallerman, G. Hulata, G. Mair, D. Bartley, M. Gupta, Z. Liu, N. Pongthana, P. Rothlisberg, and G. Horstweeg-Schwark. 2001. Status of aquaculture genetics and prospects for the third millenium. Proceedings Conference on Aquaculture in the Third Millenium, Bangkok 129–157.

Dunham, R.A., R.E. Brummett, M.O. Ella, and R.O. Smitherman. 1990. Genotype-environment interactions for growth of Blue, Channel, and hybrid catfish in ponds and cages at varying densities. Aquaculture 85:143–151.

Dunham, R.A., R.O. Smitherman, and R.K. Goodman. 1987. Comparison of mass selection, crossbreeding, and hybridization for improving growth of Channel Catfish. Progressive Fish-Culturist 49:293–296.

Dunham, R.A., R.O. Smitherman, R. Goodman, and P. Kemp. 1986. Comparison of strains, crossbreeds and hybrids of channel catfish for vulnerability to angling. Aquaculture 57:193–201.

Dupont-nivet, M., M. Vandeputte, and B. Chevassus. 2002. Optimization of factorial mating designs for inference on heritability in fish species:361–370.

Dupont-nivet, M., M. Vandeputte, P. Haffray, and B. Chevassus. 2006. Effect of different mating designs on inbreeding , genetic variance and response to selection when applying individual selection in fish breeding programs 252:161–170.

EI-Ibiary, H.M., and J.A. Joyce. 1978. Heritability of body size traits, dressing weight, and lipid content in channel catfish. Journal of Animal Science 47:82–88.

El-Ibiary, H.M., J.W. Andrews, J.A. Joyce, J.W. Page, and H.L. Deloach. 1976. Sources of variations in body size traits, dressout weight, and lipid content in channel catfish, *Ictalurus punctatus*. Transactions of the American Fisheries Society 105:267–272.

Eknath, A.E., M.M. Tayamen, M.S. Palada-de Vera, J.C. Danting, R.A. Reyes, E.E. Dionisio, J.B. Capili, H.L. Bolivar, T.A. Abella, A.V. Circa, H.B. Bentsen, B. Gjerde, T. Gjedrem, and R.S.V. Pullin, 1993. Genetic improvement of farmed tilapias: the growth performance of eight strains of *Orechromis niloticus* tested in different farm environments. Aquaculture 111:171-188.

Ella, M.O. 1984. Genotype-environment interactions for growth rate of Blue, Channel, and hybrid catfish grown at varying stocking densities. Master’s Thesis. Auburn University, Auburn, Alabama.

Fahasat, P., A. Rajabi, J. M. Rad, and J. Derera. 2016. Principles and Utilization of Combining Ability in Plant. Biometrics and Biostatistics International Journal 4(1):1–24.

Falconer, D.S. and T.F.C. McKay. 1996. Introduction to quantitative genetics. 4th edition. Longman, Essex, England.

FAO. 2011. United States of America. National Aquaculture Sector Overview Fact Sheets. In FAO Fisheries and Aquaculture Department, Rome.

Fisher, R.A. 1918. The correlation between relatives on the supposition of Mendelian inheritance. Transactions of the Royal Society of Edinburgh 52:399-433.

Franco, M.C., S.T. Cassini, V.R. Oliveira, C. Vieira, S.M. Tsai, et al. 2001. Combining ability for nodulation in common bean (Phaseolus vulgaris L.) genotypes from Andean and Middle American gene pools. Euphytica 118(3):265-270.

Gima, M. E., A. Gima, A. Hutson, A. Chaimongkol, R. Beam, D. A. Perera, and R. A. Dunham. 2014. Realized heritability and response to selection for fecundity , hatching rate and fry / Kg for channel catfish females (*Ictalurus punctatus*) induced to ovulate and fertilized with blue cat fi sh (*Ictalurus furcatus*) males for the production of hybri. Aquaculture 420–421:S36–S41.

Giudice, J.J. 1966. Growth of Blue × Channel catfish hybrid as compared to its parent species. Progressive Fish-Culturist 28:142–145.

Gjerde, B. 1986. Growth and reproduction in fish and shellfish. Aquaculture 57:37–55.

Griffing, B. 1956. Concept of general and specific combining ability in relation to diallel crossing system. Australian Journal of Biological Science 9:463-493.

Gunnes, K., and T. Gjedrem. 1978. Selection experiments with salmon IV. Growth of Atlantic salmon during two years in the sea. Aquaculture 15:19-33.

Hallauer, A.R. 2007. History contribution and future of quantitative genetics in plant breeding: Lessons from maize. Crop Science 47:4-19.

Hallauer, A.R., and J.B. Miranda. 1981. Quantitative genetics in maize breeding. Iowa State University Press, Ames.

Hallauer, A.R., and J.B. Miranda. 1988. Quantitative genetics in maize breeding, 2nd edition. Iowa State University Press, Ames, IA, USA.

Hanson T., and D. Sites. 2015. 2014 U.S. Catfish Database. USDA National Agricultural Statistics Service (NASS), Mississippi Agricultural Statistics Service (MASS).

Hill, J., H.C. Becker, and P.M.A. Tigerstedt. 1998. Quantitative and ecological aspects of plant breeding. Chapman and Hall, UK, London.

Huang, Y.W., R.T. Lowell, and R.A. Dunham. 1994. Carcass characteristics of Channel and hybrid catfish, and quality changes during refrigerated storage. Journal of Food Sciences 59:64–66.

Jacobs, J.M., S. Lindell, W.V. Heukelem, E.M. Hallerman, and E.M. Harrell. 1999. Strain evaluation of striped bass (*Morone saxatilis*) under controlled conditions. Aquaculture 173:171-177.

Jonasson, J. 1996. Selection experiments on Atlantic salmon ranching. II. Variation among release sites and strains for return rate, body weight and ratio of grilse to total return. Aquaculture 144:277-294.

Joshi, S.K., S.N. Sharma, D.L. Singhania, and R.S. Sain. 2004. Combining ability in the F1 and F2 generations of diallel cross in hexaploid wheat (*Triticum aestivum L. em. Thell*). Hereditas 141(2):115-121.

Kanis, E., T. Refstie, and T. Gjedrem. 1976. A genetic analysis of egg, alevin and fry mortality in salmon (*Salmo salar*), sea trout (*Salmo trutta*) and rainbow trout (*Salmo gairdneri*). Aquaculture 8:259-268.

Kincaid, H.L. 1981. Trout Salmon Registry. FWS/NFC-L/81–1. US Fish and Wildlife Service, Kearneysville, West Virginia.

Kincaid, H.K., L.J. Mengel, and S. Brimm. 2000. National fish strain registry – catfish. Species tables of reported strains and broodstocks. Publication NFSR-C, U.S. Fish and Wildlife Service and U.S. Geological Survey, Wellsboro, Pennsylvania, USA.

Kulembeka, H.P., M. Ferguson, L. Herselman, E. Kanju, G. Mkamilo, et al. 2012. Diallel analysis of field resistance to brown streak disease in cassava (*Manihot esculenta Crantz*) landraces from Tanzania. Euphytica 187(2):277-288.

Li, M.H., E.H. Robinson, B.B. Manning, D.R. Yant, N.G. Chatakondi, B.G. Bosworth, and W.R. Wolters. 2004. Comparison of the Channel Catfish, *Ictalurus punctatus*, (NWAC103 strain) and the Channel × Blue catfish, *I. punctatus* × *I. furcatus*, F1 hybrid for growth, feed efficiency, processing yield, and body composition. Journal of Applied Aquaculture 15:63–71.

Luo, W., C. Zeng, S. Yi, N. Robinson, W. Wang, and Z. Gao. 2014. Heterosis and combining ability evaluation for growth traits of blunt snout bream (*Megalobrama amblycephala*) when crossbreeding three strains. China Science Bulletin 59(9):857-864.

Lutz, C.G. 2001. Practical genetics for aquaculture. Fishing News Books, Blackwell Scientific Publications, Iowa State Press, USA.

Lutz, C.G., A.M. Armas-Rosales, and A.M. Saxton. 2010. Genetic effect influencing in six varieties of tilapia (*Oreochromis*) and their reciprocal crosses. Aquaculture Research 41(11):e770-e780.

Macaranas, J.M., P.B. Mather, S.N. Lal, T. Vereivalu, M. Lagibalavu, and M.F. Capra. 1997. Genotype and environment: A comparative evaluation of four tilapia stocks in Fiji. Aquaculture 150:11-24.

Makanda, I., P. Tongoona, J. Derera, J. Sibiya, and P. Fato. 2010. Combining ability and cultivar superiority of sorghum germplasm for grain yield across tropical low- and mid-altitude environments. Field Crops Research 116:75-85.

Milić, D., S. Katić, Đ. Karagić, J. Gvozdanović-Varga, S. Petrović, and J. Boćanski. 2011. Genetic control of agronomic traits in alfalfa (*M. sativa ssp. sativa L.*). Euphytica 182(1):25-33.

Multistate Research Project. 2015. Hybrid catfish production and performance 1031:1-2.

National Agricultural Statistic Service (NASS). 2016. Catfish Processing Report.

National Oceanic and Atmospheric Administration (NOAA). Fisheries of the United States. 2015. http://www.st.nmfs.noaa.gov/commercial-fisheries/fus/fus15/.

Okamoto, N., T. Tayaman, M. Kawanobe, N. Fujiki, Y. Yasuda, and T. Sano. 1993. Resistance of a rainbow trout strain to infectious pancreatic necrosis. Aquaculture 117:71–76.

Overturf, K., M.T. Casten, S.L. LaPatra, C. Rexroad III, and R.W. Hardy. 2003. Comparison of growth performance, immunological response and genetic diversity of five strains of rainbow trout (*Oncorhynchus mykiss*). Aquaculture 217:93-176.

Padi, J.N. 1995. Response and correlated responses to four generations of selection for increased body weight in the Kansas strain channel catfish, *Ictalurus punctatus*, grown in earthen ponds. Master's Thesis. Auburn University, Auburn, Alabama.

Quinton, C.D., L.R. McKay, and I. McMillan. 2004. Strain and maturation effects on female spawning time in diallel crosses of three strains of rainbow trout (*Oncorhynchus mykiss*). Aquaculture 234:99-110.

Reagan, R.E. 1979. Heritabilities and genetic correlations of desirable commercial traits in channel catfish. Mississippi Agriculture and Forestry Experiment Station Resource Report. Stoneville, Mississippi.

Reagan, R.E., and C.M. Conley. 1977. Effect of egg diameter on growth of channel catfish. Progressive Fish-Culturist 39:133–134.

Reddy, P.V.G.K., B. Gjerde, S.D. Tripathi, R.K. Jana, K.D. Mahapatra, S.D. Gupta, J.N. Saha, M. Sahoo, S. Lenka, P. Govindassamy, M. Rye, and T. Gjedrem. 2002. Growth and survival of six stocks of rohu (*Labeo rohita, Hamilton*) in mono and polyculture production systems. Aquaculture 203:239-250.

Refstie, T., T.E. Steine, and T. Gjedrem. 1977. Selection experiments with salmon. II. Proportion of Atlantic salmon smoltifying at 1 year of age. Aquaculture 10:231-242.

Rezk, M.A. 1993. Response and correlated responses to three generations of selection for increased body weight in channel catfish, *Ictalurus punctatus*, grown in earthen ponds. Doctoral Dissertation, Auburn University, Alabama.

Rezk, M. A., R. O. Smitherman, J. C. Williams, A. Nichols, H. Kucuktas, and R. A. Dunham. 2003. Response to three generations of selection for increased body weight in channel catfish, *Ictalurus punctatus*, grown in earthen ponds. Aquaculture 228:69–79.

Saillant, E., M. Dupont-Nivet, P. Haffray, and B. Chatain. 2006. Estimates of heritability and genotype–environment interactions for bodyweight in sea bass (*Dicentrarchus labrax L.*) raised under communal rearing conditions. Aquaculture 254:139–147.

Shikano, T., M. Nakadate, and Y. Fujio. 2000. An experimental study on strain combinations in heterosis in salinity tolerance of the guppy *Poecilia reticulate*. Fisheries Science 66(4):625-632.

Shukla, S.K., and M.P. Pandey. 2008. Combining ability and heterosis over environments for yield and yield components in two-line hybrids involving thermosensitive genic male sterile lines in rice (*Oryza sativa L.*). Plant Breeding 127(1):28-32.

Small, B.C. 2006. Improvements in channel catfish growth after two generations of selection and comparison of performance traits among channel catfish, blue catfish, and hybrid catfish fingerlings in an aquarium rack system. North American Journal of Aquaculture 68:92–98.

Smitherman, R.O., and R.A. Dunham. 1985. Genetics and breeding. *in* C.S. Tucker, editor. Channel catfish culture. Developments in Aquaculture and Fisheries Science 15. Elsevier Science Publishing Company Inc., Amsterdam.

Sprague, G.F., and L.A. Tatum 1942. General vs. specific combining ability in single crosses of corn. Journal of American Society of Agronomy 34:923–932.

Stanton, J.M. 2001. Galton, Pearson, and the peas: A brief history of linear regression for statistics instructors. Journal of Statistics Education 9(3).

Steeby, J.A., and B.A. Wagner. 2006. Broodstock trends in the southeastern U.S. catfish industry. Abstract Catfish Research Symposium. Catfish Farmers of America, Annual Meeting 2006. San Antonio, TX, USA.

Su, S., P. Xu, and X. Yuan. 2013a. Estimates of combining ability and heterosis for growth traits in a full diallel cross of three strains of common carp , *Cyprinus carpio L*. African Journal of Biotechnology 12(22):3514–3521.

Tave, D. 1993. Genetics for fish hatchery managers. 2nd edition. New York: Van Nodtrand. Reinhold 212-213.

Tave, D., A. McGinty, J. A. Chappell, and R. O. Smitherman. 1981. Relative harvestability by angling of Blue Catfish, Channel Catfish, and their reciprocal hybrids. North American Journal of Aquaculture 1:73–76.

Topal, A., C. Aydın, N. Akgun, and M. Babaoglu. 2004. Diallel cross analysis in durum wheat (*Triticum durum Desf.*): identification of best parents for some kernel physical features. Field Crops Research 87:1-12.

Tosh, J.J., A.F. Garber, E.A. Trippel, and J.A.B. Robinson. 2010. Genetic, maternal, and environmental variance components for bodyweight and length of Atlantic cod at 2 points in life. Journal of Animal Science 88:3513–3521.

Unwin, M.J., M.T. Kinnison, N.C. Boustead, and T.P. Quinn. 2003. Genetic control over survival in Pacific salmon (*Oncorhynchus spp.*): experimental evidence between and within populations of New Zealand Chinook salmon (*O. tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences60:1-11.

USDA, 2003. Catfish 2003 part 1: reference of fingerling catfish health and production practices in the United States, 2003. USDA.APHIS.VS.CEAH, Fort Collins, CO, USA.

Vandeputte, M.K., E. Quillet, and B. Chevassus. 2002. Early development and survival in brown trout (*Salmo trutta fario L.*). Indirect effects of selection for growth rate and estimation of genetic parameters. Aquaculture 204:435–445.

Vandeputte, M.K., S. Mauger, M. Dupont-Nivet, D. De Guerry, M. Rodina, D. Gela, D. Vallod, B. Chevassus, and O. Linhart. 2004. Heritability estimates for growth-related traits using microsatellite parentage assignment in juvenile common carp (*Cyprinus carpio L.*). Aquaculture 235:223–236.

Wagner, B.A., D.J. Wise, L.H. Khoo, and J.S. Terhune. 2002. The epidemiology of bacterial diseases in food-size channel catfish. Journal of Aquatic Animal Health 14:263−272.

Wang, B., W. Gu, H. Gao, G. Hu, and R. Yang. 2014. Longitudinal genetic analysis for growth traits in the complete diallel cross of rainbow trout (*Oncorhynchus mykiss*). Aquaculture 430:173-178.

Wang, X., K.E. Ross, E. Saillant, D.M. Gatlin III, and J.R. Gold. 2006. Quantitative genetics and heritability of growth-related traits in hybrid striped bass (*Morone chrysops* × *Morone saxatilis*). Aquaculture 261:535–545.

Wilham, R.L. 1980. Problems in estimating maternal effects. Livestock Production Science 7:405–418.

Wolters, W. R., and M. R. Johnson. 1995. Analysis of a diallel cross to estimate effects of crossing on resistance to enteric septicemia in channel catfish, *Ictalurus punctatus*. Aquaculture 137(1–4):263–269.

Wolters, W. R., and T. R. Tiersch. 2004. Genetics and breeding. Pages 95–128 *in* C.S. Tucker, and J.A. Hargreaves, editor. Biology and culture of channel catfish. Elsevier B.V. Amsterdam, The Netherlands.

Wolters, W.R., D.J. Wise, and P.H. Klesius. 1996. Survival and antibody response of Channel Catfish, Blue Catfish and Channel Catfish female × Blue Catfish male hybrids after exposure to *Edwardsiella ictaluri*. Journal of Aquatic Animal Health 8:249–254.

Yant, D. 1975. Production of hybrid blue *Ictalurus furcatus* (Lesueur) male, channel *I. punctatus* (Rafinesque) female catfish and channel catfish in earthen ponds. Master's Thesis. Auburn University, Alabama.

Yant, D.R., R.O. Smitherman, and O.L. Green. 1976. Production of hybrid (Blue × Channel) catfish and Channel Catfish in ponds. Proceedings of the Southeast Association of the Fish and Game Commission 29:82–86.

Zhou, W. 2017. An overview of recently published global aquaculture statistics. FAO Aquaculture Newsletter No. 56 (April):6-8.

# CHAPTER TWO

## Introduction

Catfish has been the leading aquaculture commodity in the US for 3-4 decades. However, in the past years few years, US catfish production has suffered decline because of increased production costs and failure to compete with imported cheap catfish, resulting in a significant decrease in the number of catfish farms and US catfish sales (USDA 2013).

The hybrid catfish from crossing the channel catfish female and blue catfish male (C×B) can help address the problems of the ailing catfish industry. The hybrid catfish is preferred for its faster growth (Giudice 1966; Yant et al. 1976; Dunham et al. 1987, 1990, 2008; Dunham and Brummett 1999; Argue et al. 2003; Li et al. 2004; Brown et al. 2011), better FCR (Yant et al. 1976; Li et al. 2004), tolerance to low dissolved oxygen (Dunham et al. 1983), increased bacterial disease resistance diseases (Ella 1984; Wolters et al. 1996; Dunham et al. 2008; Arias et al. 2012), uniformity in size and shape (Yant et al. 1976; Dunham et al. 1982; Brooks et al. 1982a, 1982b), high dressout percentage and fillet yield (Yant 1975; Chappell 1979; Huang et al. 1994; Argue et al. 2003; Bosworth et al. 2004; Bosworth 2012), increased harvestability (Yant et al. 1976; Chappell 1979; Dunham and Argue 1998), and angling vulnerability (Tave et al. 1981; Dunham et al. 1986).

Currently, approximately 70% of catfish production and processing is hybrid catfish in the US catfish industry (Nagaraj Chatakondi, USDA-ARS, personal communication). However, the performance of hybrid catfish varies due to parental strain and individual genetic effects (Dunham et al. 1987; Bosworth et al. 1998; Bosworth et al. 2004; Dunham et al. 2014a, 2014b).

Currently, a small number of catfish hatcheries produce most of the hybrid fingerlings, which are sold to numerous independent grow-out catfish farmers (Bosworth and Waldbieser, 2014). The hybrid catfish is not a panacea, and the early performance of the F1 C×B hybrid catfish during the fry and fingerling stage can be affected by infectious diseases and parasites (Silverstein et al. 2008; Beecham et al. 2011; Griffin et al. 2014). The early growth of the F1 C×B hybrid fingerlings has production implications. The ultimate goal is to grow fry to fingerlings and fingerlings to food fish as quickly as possible, preferably within a year for a single-batch cropping. Tucker and Robinson (1990) suggested that the optimum fingerling size for single-batch cropping in the case of channel catfish is a 30-40 g per fish. Pomerleau and Engle (2005) reported that stocking larger fingerlings significantly ($P<0.05$) increased the total yield, net yield, final weight, final length and FCR of catfish. Larger fingerlings grow faster to market-size. However, these fingerlings are more expensive as they require more space and time to produce. Hence, production of an F1 C×B hybrid catfish fingerling with a desirable early growth performance traits would be an important goal for selective breeding programs.

Reciprocal recurrent selection which is the selection of purebred parents based on the hybrid progeny performance offers great promise to genetically improve the desirable traits of hybrid catfish. To achieve this purpose, information about the combining ability of the parents and their performance in hybrid combination is a prerequisite to develop the most efficient and effective breeding plans (Salem and Ali 2012). Griffing (1956) proposed the partition of the total genetic variation into general combining ability (GCA) of the parents and specific combining ability (SCA) of the crosses. Sprague and Tatum (1942) defined GCA as the average performance of the parental lines in hybrid combinations while SCA as the performance of a combination of parents in a specific cross. The estimation of GCA and SCA has been widely used for developing the corn breeding program and has been applied to various breeding programs for plants and animals including fish (Wolters and Johnson 1995; Vandeputte et al. 2004; Saillant et al. 2006; Wang et al. 2006; Lutz et al. 2010; Su et al. 2013a; Bosworth and Waldbieser 2014; Luo et al. 2014; Drescher 2017).

However, there are very few analyses of GCA and SCA for economic traits of catfish such as growth and carcass yield of market size F1 hybrid catfish (Bosworth and Waldbieser 2014), oxygen tolerance (Drescher 2017) and resistance to enteric septicemia in channel catfish (Wolters and Johnson 1995).

Bosworth and Waldbieser (2014) reported that GCA of the parental dam was more important in controlling the carcass yield and harvest weight of F1 hybrids. Similarly, GCA was also found important in the expression of traits pertaining to the tolerance of hybrid catfish to low dissolved oxygen (Drescher 2017) and resistance to enteric septicemia in Norris and Marion x Kansas strains of channel catfish (Wolters and Johnson 1995). These results suggest the potential of combining ability estimation for selection to improve the desired traits of catfish.

Combining ability estimation is considered useful indirect criterion for selecting elite parents. With this, general and specific combining abilities are important indicators for expressing the potential value of catfish parents that can produce consistently better performing F1 hybrid catfish. The GCA and SCA variances provide estimation for additive and non-additive gene action, respectively (Falconer 1989). The exploration and estimation of such gene actions can be used to select for elite parent lines and produce improved F1 hybrid catfish.

Although, the channel blue hybrid catfish is genetically superior to the parent species, it could be further improved for growth rate, disease resistance and dressout percentage. Additionally, a recent industry problem is variable growth by hybrids and a partial solution to that problem could be from genetic selection. To determine the potential for genetically improving these traits for hybrid catfish, the combining abilities of the parent species must be estimated. No research has been conducted yet to determine and estimate the combining abilities for early performance traits of F1 hybrid catfish. In the current study, the GCA and SCA effects of parental channel catfish and blue catfish to the performance of their F1 hybrid progeny was estimated following NC II factorial mating design of Hallauer (2007).

The objectives of this research were to estimate the GCA and SCA for the early performance traits of channel catfish female x blue catfish male F1 hybrid progeny such as: a) body weight, and body weight gain; b) coefficient of variation in body weight; c) resistance to *Aeromonas hydrophila*, and; d) dressout percentage. Additionally, the individual combining abilities of the parents were determined. The genetic variance components for early performance traits of hybrids during an initial 311 days of tank rearing in a flow-through system, and after an additional 245 days of tank rearing in a recirculating system and communal rearing in split-pond were determined. The best parental genotypes with high GCA and best parental cross with high SCA that produce superior performing hybrid catfish were identified. This research will be beneficial to improving the selection and breeding programs for hybrid catfish production.

## Materials and Methods

### *Experimental fish*

Twenty females from nine strains of channel catfish were crossed with twelve males from four strains of blue catfish to produce F1 C×B hybrid catfish progeny. The nine strains of female channel catfish were Tishomingo, AR, Kansas Select, Kansas Random, ARMK, Kansas × Thompson, Rio Grande, Thompson, and mixed strains. The four strains of male blue catfish were D&B, Rio Grande, D&B × Rio Grande, and Tombigbee. These fish were maintained at the Fish Genetics Unit, E.W. Shell Fisheries Research Center, Auburn University, Alabama. All procedures involving the handling and treatment of fish in this study were approved by the Auburn University Institutional Animal Care and Use Committee (AU-IACUC).

The twenty channel catfish females (dams) were from nine strains. The strains used included Kansas Random which originated from Ninnescah River in 1911, and is the oldest domestic strain of channel catfish (Dunham and Smitherman 1984). This strain was randomly bred and has the traits increased resistance to disease, rapid growth, and late sexual maturity. Kansas Select, a line derived from Kansas random that has been selected for body weight for eight generations. AR line which was derived from the crossbreeding of Auburn and Rio Grande strains followed by 6 generations of mass selection for body weight. Traits of this line include spawning late in the season. ARMK, was initiated by producing a 4-way crossbreed (Auburn X Rio Grande) X (Marion X Kansas) followed by 6 generations of mass selection, these fish are also late spawners. Thompson strain originated from the Yazoo River, MS, and on-farm selection was conducted for several traits including body size, disease resistance, and early spawning. Tishomingo strain originated from the Tishomingo federal hatchery in Oklahoma. Kansas X Thompson was a F1 crossbreed between Kansas random females and Thompson males. Rio

Grande a single surviving wild female of a collection of 50 fish from the Rio Grande River, Texas. Traits of individuals of this strain collected 40 years ago included high dress out percentage, susceptibility to disease, slow growth, large sexual dimorphism for body weight, high fecundity, small egg size, and maturity at two years of age. Mix strain was initiated by the mixing of multiple strains.

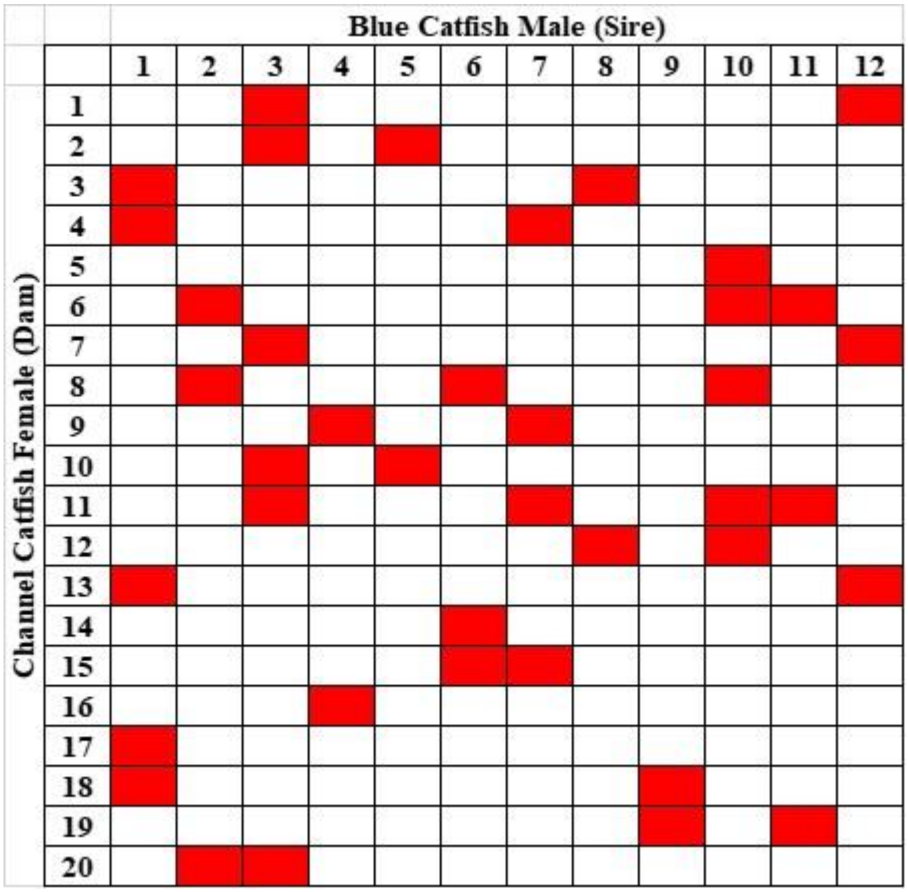
The twelve blue catfish males (sires) were from four strains. These included: Tombigbee (TBB), which originated from the Tombigbee River. Rio Grande was from the Rio Grande River in Texas, and has distinctive spots on the entire body. D&B originating from D&B Fish Farms in Crockett, TX and, were selected for small head size (Dunham and Smitherman 1984). DxR was an F1 crossbreed between D&B females and Rio Grande males.

### *Matings*

Twenty channel catfish females were crossed with twelve blue catfish males following a complete factorial mating design in May 2015. Maternal half-sib, paternal half-sib, and full-sib families of F1 C×B hybrid catfish progeny were produced. However, due to poor survival of some crosses, 40 families were obtained resulting in an unbalanced design (Fig. 2.1).

### *Spawning procedures*

Sexually mature male blue catfish with large muscular heads were selected and sacrificed by cranial percussion. The testes were surgically excised and macerated in 0.9% salt solution to produce sperm suspensions. The suspensions were stored in plastic tubes and refrigerated.



| | | Blue Catfish Male (Sire) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Channel Catfish Female (Dam) | 1 | | | 🟥 | | | | | | | | | 🟥 |
| | 2 | | | 🟥 | | 🟥 | | | | | | | |
| | 3 | 🟥 | | | | | | | 🟥 | | | | |
| | 4 | 🟥 | | | | | | 🟥 | | | | | |
| | 5 | | | | | | | | | | 🟥 | | |
| | 6 | | 🟥 | | | | | | | | 🟥 | 🟥 | |
| | 7 | | | 🟥 | | | | | | | | | 🟥 |
| | 8 | | 🟥 | | | | 🟥 | | | | 🟥 | | |
| | 9 | | | | 🟥 | | | 🟥 | | | | | |
| | 10 | | | 🟥 | | 🟥 | | | | | | | |
| | 11 | | | 🟥 | | | | 🟥 | | | 🟥 | 🟥 | |
| | 12 | | | | | | | | 🟥 | | 🟥 | | |
| | 13 | 🟥 | | | | | | | | | | | 🟥 |
| | 14 | | | | | | 🟥 | | | | | | |
| | 15 | | | | | | 🟥 | 🟥 | | | | | |
| | 16 | | | | 🟥 | | | | | | | | |
| | 17 | 🟥 | | | | | | | | | | | |
| | 18 | 🟥 | | | | | | | | 🟥 | | | |
| | 19 | | | | | | | | | 🟥 | | 🟥 | |
| | 20 | | 🟥 | 🟥 | | | | | | | | | |

Figure 2. 1 Lay-out of factorial mating design used to cross twenty channel catfish (*I. punctatus*) females with twelve blue catfish (*I. furcatus*) males. The 40 hybrid families obtained are highlighted with red.

The females with the classic signs of readiness for spawning, including a soft, distended belly and a genital opening that is red and swollen (Dunham and Masser 2012; Su et al. 2013b) were selected for hormone induced ovulation. These females were injected with luteinizing hormone analog (LHRHa) at 100 µg/kg via intraperitoneal implants and were placed in spawning bags (the same as ¼-inch mesh laundry bags) suspended in holding vats with flow-through water and aeration. The dissolved oxygen was maintained above 5 mg/L and the water temperature at 26-30°C. The females were checked for ovulation (presence of eggs released and sticking in their bags) about 36-72 hours after hormone injection. Females that had ovulated were anesthetized with 150 parts per million (ppm) of buffered 100ppm tricaine methane sulfonate (MS-222), rinsed with hatchery water, and dried with towel. Through application of abdominal pressure, the eggs were hand stripped and placed into a stainless pan coated with vegetable oil to prevent the eggs from sticking to the pan. Eggs from each female were divided equally into aliquots based on the number of males for the factorial mating design and placed in a pan coated with vegetable oil. Sperm solution from each male was mixed with each aliquot of eggs. Hatchery water was then added to activate the fertilization. The fertilized egg masses were moved to a trough to allow them to water harden for 15-20 minutes. After this, the eggs were moved to another trough with egg baskets and fry catchers. Fry catchers made of fine mesh nylon netting were used to prevent the newly hatched fry from escaping outside the basket.

### *Fish husbandry*

After the eggs hatched, 210 fry from each family were stocked in three replicate 60cm x 30cm x 50cm glass aquaria at a stocking density of 70 fry per aquarium with flow-through water and aeration. The water quality parameters were maintained at flow rate of 4 L/minute, water temperature at 26 – 28°C and dissolved oxygen at >5 mg/L with the use of air diffusers. Each aquarium was labeled with the family information. The fry were initially fed the Purina® AquaMax® powdered starter diet containing 50% protein until they reached 2.5cm in size. From 2.5-3.8 cm the fish were fed Purina® AquaMax® 100 diet containing 50% protein, from 3.8-5 cm they were fed Purina® AquaMax® 200 containing 50% protein, and from 5-7.6 cm Purina® AquaMax® 300 containing 50% protein. Fish were fed *ad libitum* daily. After 311 days of separate tank rearing in flow-through system, all fish were injected individually with a PIT tag (model MiniHPT8, 8.4mm, 132.2 kHz ISO FDX-B; Biomark, Boise, Idaho) into the mid-section of the abdomen.

For the next 245 days of rearing, 50% of the fish from each family were stocked and reared in a communal split-pond system with total area of 526 square-meter, depth of 1.5 meter, and volume of 789 cubic-meter. The remaining 50% of the fish from each family were kept in their original separate aquaria tank. The flow-through aquaria system was then converted into a recirculating aquaria system to allow additional 245 days rearing of fish in separate tanks. The fish in separate tanks were fed with Purina® AquaMax® 300 containing 50% protein while the fish in communal split-pond were fed *ad libitum* with 32% protein floating catfish pellets from Alabama Catfish Feedmill, LLC for 245 days.

Dissolved oxygen, ammonia, nitrite, pH, hardness, alkalinity and temperature were monitored and recorded throughout the two phases of the experiment period. Water quality parameters were maintained at their optimum levels, whereas, DO was >5mg/L, ammonia was <1 mg/L, nitrite was <0.05 mg/L, pH was between 6 and 7, hardness was between 40 and 70 mg/L, alkalinity was between 40 and 80 mg/L.

### *Natural infection from Aeromonas hydrophila*

A natural *Aeromonas hydrophila* infection occurred during the second month of the initial 311-day rearing in the flow-through system, and lasted for 20 days. During that infection period, mortality was observed across the hybrid families. The causative agent for this infection was confirmed to be the non-virulent strain (AL-01) of the *Aeromonas hydrophila* following PCR analysis of the putative *Aeromonas* isolates obtained from the moribund fish samples.

### *Data gathering and analyses*

After 311 days of separate tank rearing in flow-through system, data pertaining to early growth in terms of final body weight and body weight gain, coefficient of variation in size in terms of body weight, and survival from *A. hydrophila* natural infection were gathered and recorded. After 245 days of additional tank rearing in the recirculating system and the communal split-pond rearing, body weight, weight gain, and dressout percentage in the communal split-pond system were measured. All data were analyzed to estimate the general and specific combining ability for the early performance traits of the hybrids in three different intensive rearing systems.

The following formulas were used to calculate the performance traits:

a) Weight Gain (GW) = Final body weight ($W_f$) – initial body weight ($W_i$);

b) Specific Growth Rate (SGR) = [($LnW_f$ – $LnW_i$) / no. of days)] x 100

c) Coefficient of Variation (CV) = (Standard deviation of $W_f$ / mean $W_f$) x 100

(Note: The calculation of the CV in size was only possible for hybrid catfish families that were reared in separate tanks which served as replicate units in the flow-through and recirculating system and not for those hybrids reared in only one communal split-pond.)

d) Survival (%) = (Number of surviving fish / initial number of fish) x 100

e) Actual dressout percentage ($DrO_A$%) = (Dressout weight/Body weight) x 100

f) Corrected dressout percentage ($DrO_C$%) = $DrO_A$% - [(body weight – mean weight per family) x *b*-value between $DrO_A$% and body weight based on sex per family)]

(Note: The *b*-value mentioned above was calculated using LINEST function in Microsoft Excel 2016).

In this study, the dressout weight is the weight of the gutted fish without the head, fins, and tail. The early dressout percentage of the F1 C×B hybrid catfish was corrected for the effects of gender and family variability. Patterns of sexually dimorphic growth and carcass yield have been reported for hybrid catfish (Argue et al. 2003; Bosworth 2012), and channel catfish and blue catfish (Argue et al. 2003; Bosworth et al. 2004). The calculation of the *b*-value was done following the syntax for LINEST function in Microsoft Excel below:

*b*-value = LINEST (y_values, x_values)

Where, y_values is the dressout percentages of hybrids based on sex per family, x_values is the body weight of hybrids based on sex per family.

The statistical model I used as a genetic relationship matrix for the analysis of the early performance traits is stated below as suggested by Becker (1984) for factorial mating designs:

$$Y_{ijk} = \mu + S_i + D_j + (S \times D)_{ij} + e_{ijk}$$

Where, $Y_{ijk}$ is the trait value for the m$^{th}$ hybrid progeny, $\mu$ is the overall mean, $S_i$ is the random effect of the i$^{th}$ sire, $D_j$ is the random effect of the j$^{th}$ dam, $(S \times D)_{ij}$ is the random effect of the cross between the i$^{th}$ sire and j$^{th}$ dam, and $e_{ijk}$ is the random error.

The variance components are stated below following the genetic model II of Becker (1984):

$$\sigma^2_S = cov_{hs(S)}$$

$$\sigma^2_D = cov_{hs(D)}$$

$$\sigma^2_{SD} = cov_{fs} - (cov_{hs(S)} + cov_{hs(D)})$$

$$\sigma^2_e = \sigma^2_T - cov_{fs}$$

Where, the variance components of sire ($\sigma^2_S$) and dam ($\sigma^2_D$) are equal to the covariance of half sibs (hs) of the sire groups and dam groups, respectively. The dam component also contains the maternal effect. The component for the cross ($\sigma^2_{SD}$) is the covariance of the full sibs (fs) minus the sum of the half sibs covariance from dams and sires. The variance for random error ($\sigma^2_e$) contains the remainder of the genetic variance and environmental variance.

Given that this experiment had unbalanced data with missing values for some crosses, the Restricted Estimation of Maximum Likelihood (REML) was used as the standard procedure to estimate the genetic variance components for random effects of sire, dam, and cross and the associated variance-covariance matrix. The missing data were assumed to be random. The Best Linear Unbiased Predictors (BLUP) of individual sires, dams, and cross, and their standard errors were generated with Mixed Procedure of SAS (version 9.4, SAS, Cary, NC) to determine estimates of GCAs of sires, dams, and SCAs of crosses. All analyses were made at $P=0.05$.

The factorial mating design is an experiment that measures the variance of the male and female effects and the male x female interaction effects (Comstock and Robinson 1948). To evaluate the relative importance of the GCA and SCA effects, either of these effects must be significant ($P<0.05$). If both the GCA and SCA effects are not significant, then epistatic gene effects are responsible for the expression of the traits (Fehr 1993). According to Hallauer and Miranda (1988), male and female effects are equivalent to GCA effects for sire and dam, respectively, whereas, the male x female interaction effects are equivalent to SCA effects. For an unbalanced factorial mating design, the significance of these effects can be determined with the mean squares generated in the Type 3 Mixed Procedure of analyses of variance.

The estimate of combining ability using factorial mating design (NC II) determines the additive and non-additive components of genetic variance which are appropriate selection methods for selecting parents for efficient hybridization programs that can improve economically important quantitative characteristics. In this mating design, the GCA variances for sires and dams are equivalent to the sire and dam additive genetic variances, respectively; and the SCA variance is equivalent to the cross' dominant genetic variance (Cotterill et al. 1986). The highest variance component was considered the most important genetic effect as it determines the type of gene action involved in the control and expression of the traits.

When the values of GCA and SCA variances are relatively close, the method of Longin et al. (2013) can be used to determine the importance of the SCA. Whereas, if $\frac{\sigma^2 \mathrm{SCA}}{\sigma^2 \mathrm{GCAdam} + \sigma^2 \mathrm{GCAsire}} < 0.5$, the impact of SCA can be ignored.

Parents and/or cross from the more important genetic variance component were selected as best combiners based on their GCA and/or SCA estimates. The value of GCA or SCA estimates predicts the phenotypic deviation of the progeny to the overall population mean phenotype, whereas, the highest positive or negative estimates of GCAs or SCAs will most likely give the best or the worst performance traits. The strains of pooled parental sires, dams, or crosses from the more important genetic variance component were subjected to one-way analysis of variance using the GLM Procedure followed by Tukey-Kramer Test to compare their performance means. The Tukey-Kramer procedure has fared extremely well in Monte Carlo studies (Dunnett 1980). It is the modified version of Tukey's "Honestly Significant Difference Test (HSD)" that can be used for unequal sample sizes. Hayter (1989) describe Tukey-Kramer as a more powerful method than the Bonferroni, Sidak or Scheffé for pairwise comparison. The Scheffé Test is more flexible compared to the Tukey's HSD and can be also used for unequal sample size (Scheffé 1999). However, it has a low statistical power. This was only used as 2nd option next to Tukey-Kramer in this study to compare all possible pairs of means. The Scheffé Test was done for mean comparison with no significant difference result after Tukey-Kramer. Parental genotypes with best performance traits would be considered for selection.

# RESULTS

*Early Growth Performance Traits*

The population means and phenotypic standard deviations for the early growth performance traits of the 40 hybrid catfish families in three different intensive rearing systems at two ages are presented in Table 2.1.

Table 2. 1 The population means and phenotypic standard deviations (SD) for final body weight (Wt) and body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing, recirculating system for additional 245 days of separate tank rearing, and split-pond for additional 245 days of communal rearing.

| Rearing System | Age (days) | Trait | Population mean | Phenotypic SD |
|---|---|---|---|---|
| Flow-through system (initial 311-day separate tank rearing) | 311 | Final Body Wt (g) | 9.74 g | 3.19 |
| Recirculating system (additional 245-day separate tank rearing) | 556 | Final Body Wt (g) | 91.25 g | 36.21 |
| | | Body Wt Gain (g) | 80.26 g | 33.26 |
| Split-pond (additional 245-day communal rearing) | 556 | Final Body Wt (g) | 194.21 g | 94.07 |
| | | Body Wt Gain (g) | 184.21 g | 92.12 |

The early growth performance in terms of final average body weight and body weight gain were analyzed following REML/BLUP joint analyses based on the genetic relationship matrix to calculate the mean squares from the analyses of variance (Table 2.2), the variance components (Table 2.3) and the variance components ratio (Fig. 2.2, 2.5) and estimates for GCAs of sire and dam and/or SCAs of crosses (Fig. 2.3, 2.6, 2.7, 2.9, 2.10, 2.11). The mean comparison of parental strains after analyses of variance through GLM Procedure using Tukey-Kramer Test are presented in Figures 2.4 and 2.8.

Table 2. 2 Mean squares (MS) for the Type 3 Mixed Procedure analyses of variance of the factorial mating design component of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny test and error mean squares for final body weight (Wt) and body weight gain of channel catfish female × blue catfish male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing, recirculating system for additional 245 days of separate tank rearing, and split-pond for additional 245 days of communal rearing.

| Rearing System | Age (days) | Trait | Source of variation | | | |
|---|---|---|---|---|---|---|
| | | | Dam | Sire | Dam x Sire | Error MS |
| Flow-through system (initial 311-day separate tank rearing) | 311 | d.f. | 19 | 11 | 9 | 67 |
| | | Final Body Wt (g) | 14.70 $^{*}$ | 5.75 $^{ns}$ | 9.32 $^{ns}$ | 5.16 |
| Recirculating system (additional 245-day separate tank rearing) | 556 | d.f. | 19 | 11 | 8 | 677 |
| | | Final Body Wt (g) | 5059.56 $^{*}$ | 3028.11$^{*}$ | 908.11 $^{ns}$ | 1064.29 |
| | | Body Wt Gain (g) | 4087.45 $^{*}$ | 2463.53 $^{*}$ | 760.56 $^{ns}$ | 918.06 |
| Split-pond (additional 245-day communal rearing) | 556 | d.f. | 18 | 11 | 7 | 1480 |
| | | Final Body Wt (g) | 66867 $^{*}$ | 85175 $^{*}$ | 7699.88 $^{ns}$ | 7315.98 |
| | | Body Wt Gain (g) | 62384 $^{*}$ | 80256 $^{*}$ | 6579.16 $^{ns}$ | 7054.49 |

After ANOVA *F*-test: * = $p<0.05$, and $^{ns}$ = $p>0.05$
d.f. = degree of freedom.

Table 2. 3 Estimates of general combining ability variance for dam ($\sigma^2GCA_d$) and sire ($\sigma^2GCA_s$) and specific combining ability variance ($\sigma^2SCA$), error variance ($\sigma^2_E$) and corresponding standard errors for final body weight (Wt) and body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing, recirculating system for additional 245 days of separate tank rearing, and split-pond for additional 245 days of communal rearing.

| Rearing system | Age (days) | Trait | Genetic parameter estimates | | | |
|---|---|---|---|---|---|---|
| | | | $\sigma^2GCA_d$ (± SE) | $\sigma^2GCA_s$ (± SE) | $\sigma^2SCA$ (± SE) | $\sigma^2_E$ |
| Flow-through system (initial 311-day separate tank rearing) | 311 | Final Body Wt | 3.25 (2.30) | 0.91 (0.92) | 0.99 (1.28) | 5.13 |
| Recirculating system (additional 245-day separate tank rearing) | 556 | Final Body Wt | 222.83 (124.68) | 85.43 (68.21) | 20.7 (56.32) | 1060.16 |
| | | Body Wt Gain | 156.44 (99.42) | 60.69 (56.34) | 25.85 (54.75) | 914.56 |
| Split-pond (additional 245-day communal rearing) | 556 | Final Body Wt | 1463.21 (587.61) | 1388.25 (663.43) | 0 | 7322.73 |
| | | Body Wt Gain | 1320.19 (532.95) | 1293.47 (619.75) | 0 | 7056.66 |

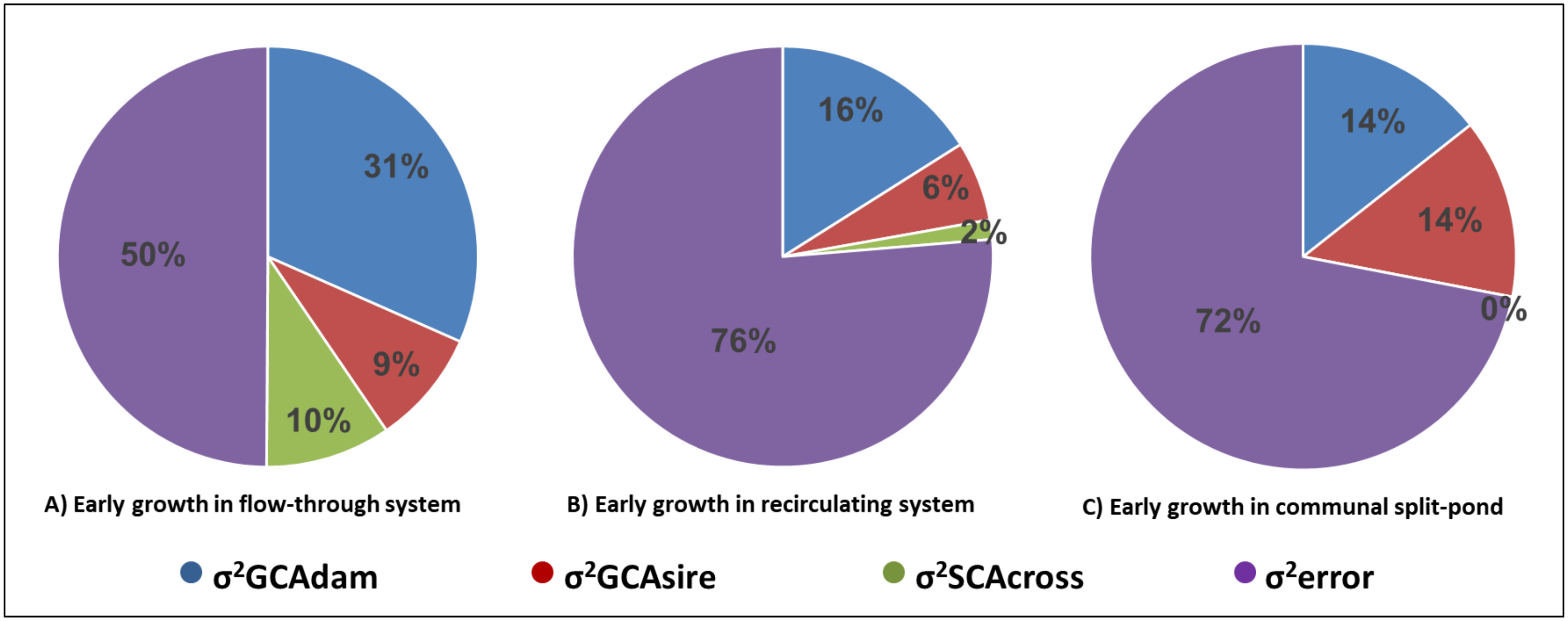


Figure 2. 2 Ratio of estimates of GCA variance components for dam and sire, SCA variance components for cross, and error variance components for early growth in terms of final body weight (Wt) of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing, recirculating system for additional 245 days of separate tank rearing, and split-pond for additional 245 days of communal rearing.

In all the three different intensive rearing systems, the mean squares of hybrid progeny showed significant differences ($P<0.05$, Table 2.2) for early growth in terms of final body weight and body weight gain in weight, indicating significant family effects, dam effects, sire effects and sometimes interactions. After the initial 311-day separate tank rearing of the hybrids in flow-through system, the mean square of GCA effect of the dam for final body weight was significant ($P<0.05$) indicating the importance of additive gene effects for this trait. The ratio of the combining ability variance components (Table 2.3, Fig. 2.2) also revealed that the largest component for the final body weight trait was the GCA variance for dam which is indicative of the dam effects having the most influence. The GCA effects of the dam revealed that the female parents 17 and 18 had the highest ($P<0.05$, Fig. 2.3) positive GCA estimates, 3.52 and 2.53, respectively, for early final average body weight, indicating that their progeny would most likely have a better early growth performance traits in terms of early final body weight when reared in separate tanks in flow-through system. Furthermore, the strains of the dam for the final body weight trait were found to be significantly different ($P<0.05$). Hybrid progeny of KxTh crossbred dams had the highest ($P<0.05$, Fig.2.4) mean body weight (17.95 g) compared to all other dam genotypes except Thompson strain that had the second highest (11.73 g) in the flow-through system during the initial 311-day separate tank rearing. The Thompson strain hybrids were not different ($P>0.05$) to all other dam type hybrids.

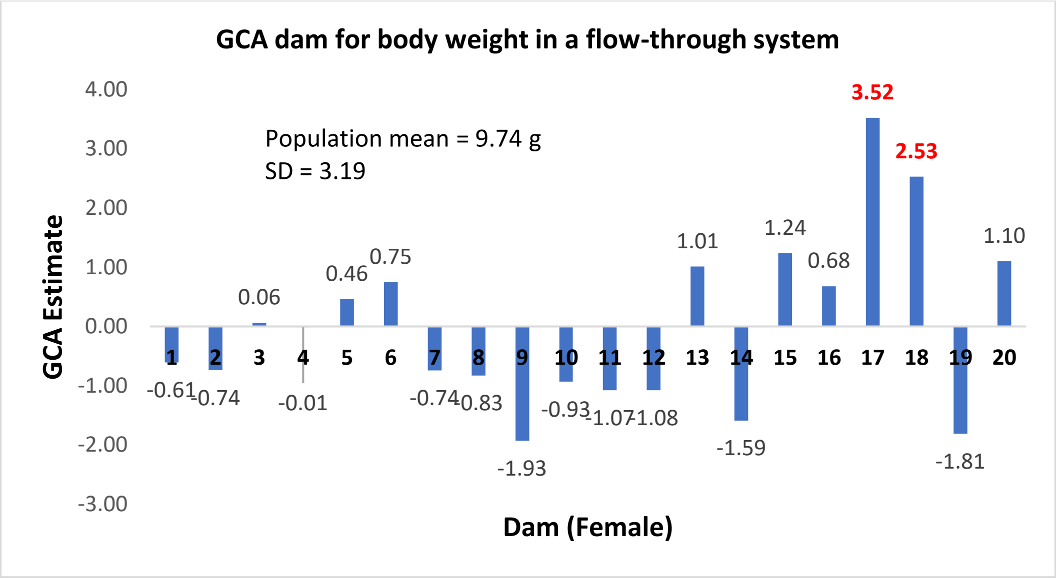


Figure 2. 3  The channel catfish (*Ictalurus punctatus*) female (dam) general combining ability estimates for final average body weight of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

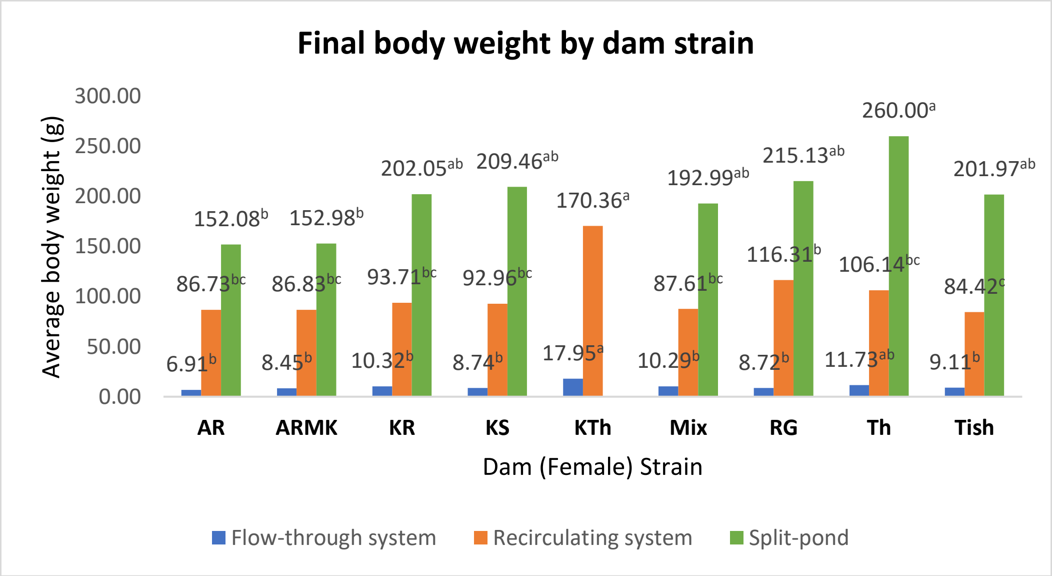


Figure 2. 4  Early growth in terms of final average body weight by parental dam strain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing, recirculating system for additional 245 days of separate tank rearing, and split-pond for additional 245 days of communal rearing. Hybrid genotypes in the same rearing system with the same superscript letter are not

significantly different (P>0.05, Tukey-Kramer Test). For genetic types in the communal split-pond, the mean comparison was done following Scheffe Test.

The mean squares of the final average body weight and body weight gain for the GCA effects of dam and sire parents were significant (P<0.05, Table 2.2) after the additional 245-day separate tank rearing in the recirculating system, indicating genetic variability contributed by the male and female parents. The ratio of the combining ability variance components (Table 2.3 showed that the largest component is the GCA variance for dam indicating that final average body weight (Fig. 2.2) and body weight gain (Fig. 2.5) traits were mostly controlled by the additive gene effects attributed to the dam parents. The GCA effects of the dam revealed that parent 17 gave the best (P<0.05, Fig. 2.6) estimate for final average body weight at 46.51 and body weight gain at 36.04 (Fig. 2.7), which would mean that its hybrid progeny would most likely gain better performance for these two traits compared to other parental dams. The dam parent 17 is a good combiner to produce hybrid catfish with better early growth performance in recirculating system. Hybrid progeny of KxTh crossbred dams strain had the highest (P<0.05, Fig. 2.4) final average body weight, 170.36 g, and highest body weight gain, 146.28 g, (P<0.05, Figure 2.8) followed by the RG hybrid type for these two traits. The RG hybrid type, however, was found not significantly different (P>0.05, Fig 2.4, 2.8) to all other parental dam strains for final average body weight and body weight gain.

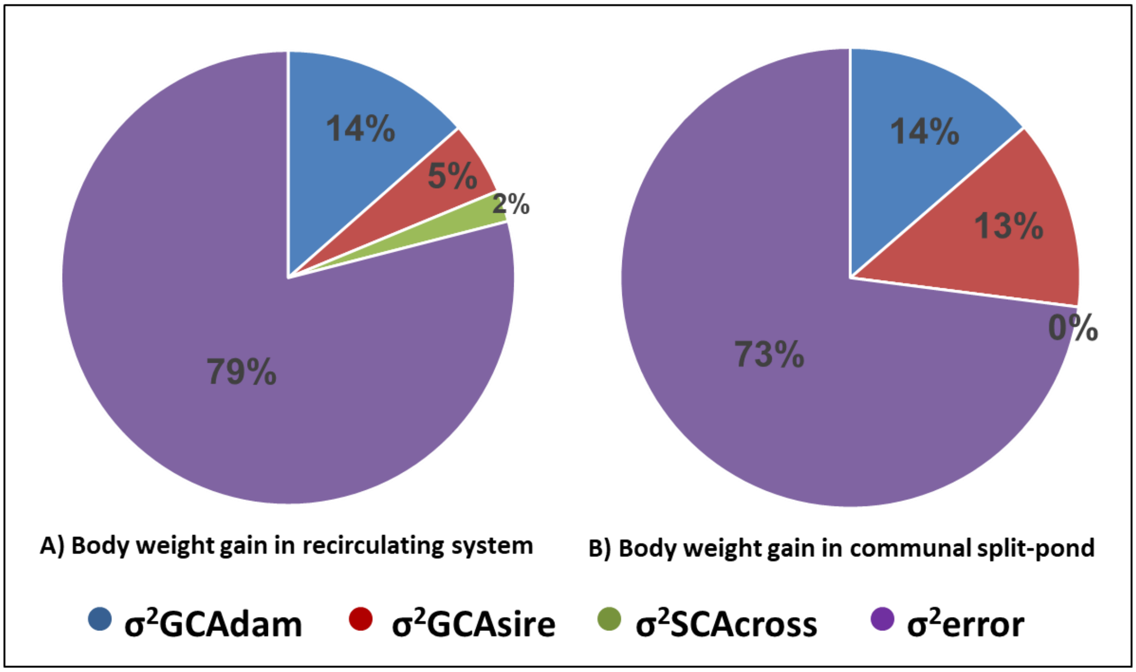


Figure 2. 5 Ratio of estimates of GCA variance components for dam and sire, SCA variance components for cross, and error variance components for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing, and split-pond for additional 245 days of communal rearing.

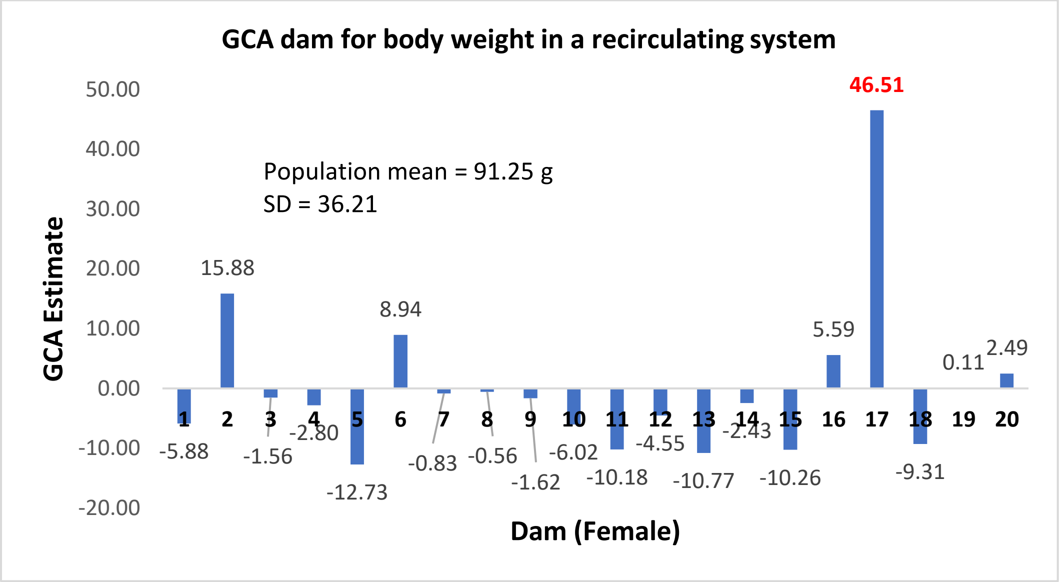


Figure 2. 6 The channel catfish (*Ictalurus punctatus*) female (dam) general combining ability estimates for final average body weight of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

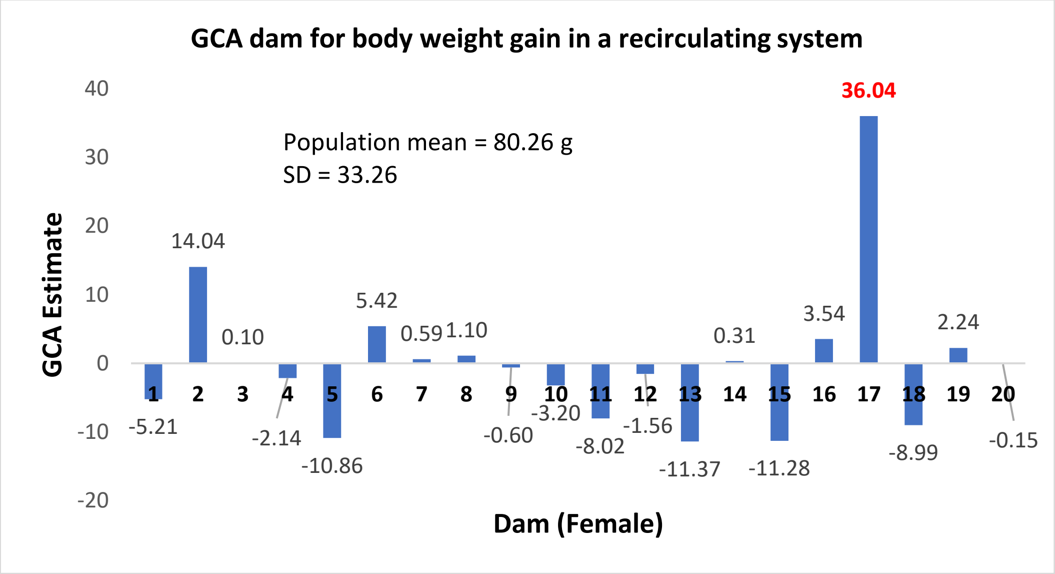


Figure 2. 7 The channel catfish (*Ictalurus punctatus*) female (dam) general combining ability estimates for body weight gain of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

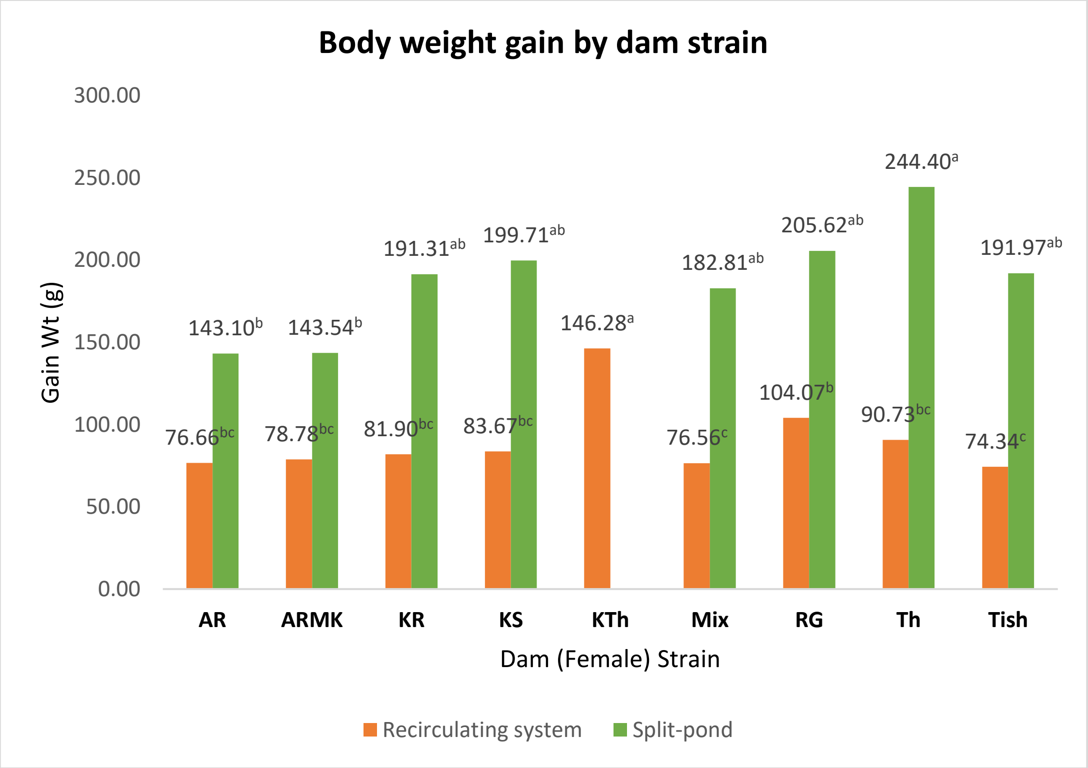
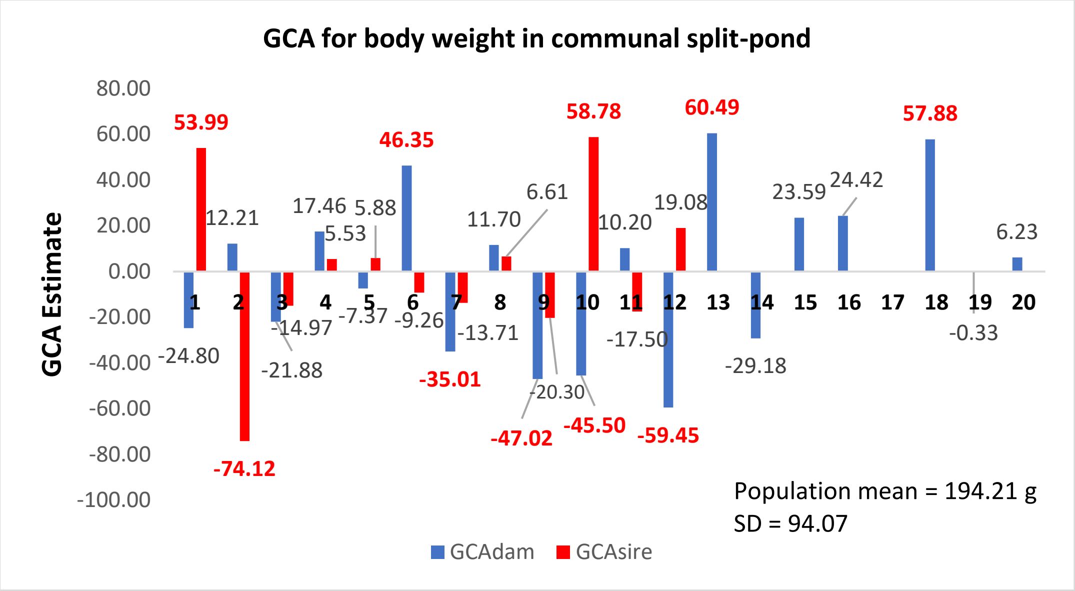


Figure 2. 8 Early growth in terms of body weight gain by parental dam strain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating

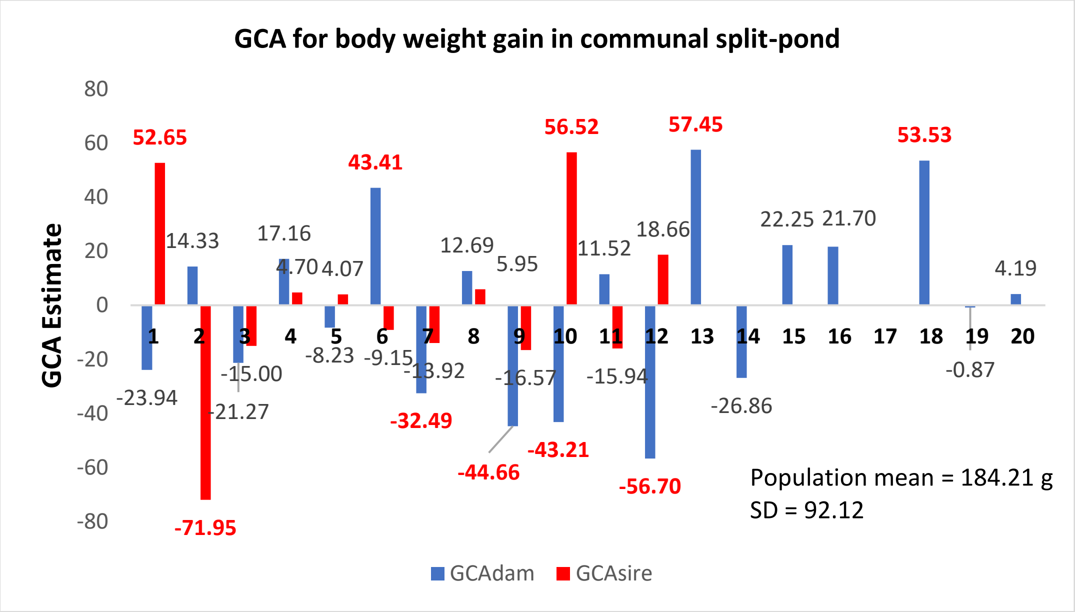
system for additional 245 days of separate tank rearing, and split-pond for additional 245 days of communal rearing. Hybrid genotypes in the recirculating system with the same superscript letter are not significantly different (P>0.05, Tukey-Kramer Test). For genetic types in the communal split-pond, the mean comparison was done following Scheffe Test.

The mean squares for final average body weight and body weight gain after the additional 245-day rearing of hybrid catfish in the communal split-pond were significant (P<0.05, Table 2.2) for the GCA effects of the male and female parents, indicating that the additive gene effects were contributed by the male and female parents. The combining ability variance components ratio (Table 2.3, Fig. 2.2, 2.5) revealed that the largest additive gene effects controlling the two traits were attributed almost equally to both the dam and sire parents. The dam parents 13, 18, and 6 had the best (P<0.05) positive GCA estimates for final average body weight at 60.49, 57.88, and 46.35, respectively (Fig. 2.9) and for body weight gain at 57.45, 53.53, and 43.41, respectively (Fig. 2.10). The sire parents 10 and 1 had the best (P<0.05) positive GCA estimates for final average body weight at 58.78 and 53.99, respectively (Fig. 2.9) and for body weight gain at 56.52 and 52.65, respectively (Fig. 2.10). The hybrid progeny of these dams and sires should have better early growth traits. Hybrids from Thompson dams had the highest observed early final average body weight (260.00 g, Fig. 2.4) and body weight gain (244.40 g, Fig. 2.8), while AR and ARMK hybrids had the lowest values. Hybrid progeny of KxTh crossbred dams strain was not included in the analyses for final average body weight and body weight gain of F1 hybrid catfish in communal split-pond because this group was not stocked in the pond. Hybrids from DR crossbred sires had the highest observed final average body weight (242.61 g, Fig. 2.11) and body weight gain (244.40 g, Fig. 2.11), followed by the RG hybrids. The TBB and DB hybrids gave the lowest final body weight and body weight gain in communal split-pond.


GCA for body weight in communal split-pond

Population mean = 194.21 g
SD = 94.07

Figure 2. 9 The channel catfish (*Ictalurus punctatus*) female (dam) and blue catfish (*I. furcatus*) male (sire) general combining ability estimates for final mean body weight of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).


GCA for body weight gain in communal split-pond

Population mean = 184.21 g
SD = 92.12

Figure 2. 10 The channel catfish (*Ictalurus punctatus*) female (dam) and blue catfish (*I. furcatus*) male (sire) general combining ability estimates for body weight gain of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

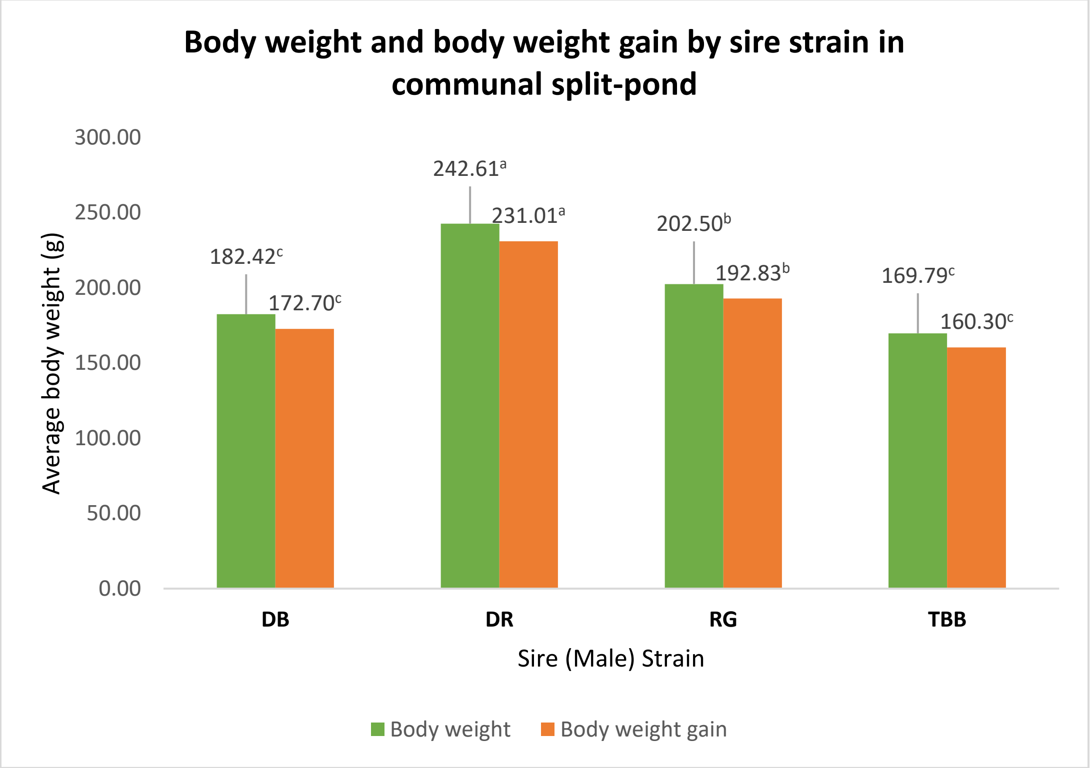


Figure 2. 11 Early growth in terms of body weight and body weight gain by parental sire strain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing. Hybrid genotypes in the same rearing system with the same superscript letter are not significantly different (P>0.05, Tukey-Kramer Test). For genetic types in the communal split-pond, the mean comparison was done following Scheffe Test.

### *Coefficient of Variation in Size*

The population means and phenotypic standard deviations for CV in size in terms of body weight of the 40 hybrid catfish families reared in separate tanks in flow-through and recirculating system are shown in Table 2.4.

The coefficients of variation in body weight were analyzed following REML/BLUP joint analyses based on the genetic relationship matrix to calculate for the mean squares from the analyses of variance (Table 2.5), the variance components (Table 2.6), the variance components ratio (Fig. 2.12) and estimates for GCAs of sire and dam and/or SCAs of crosses (Figures 2.13, 2.15). The mean comparison of parental strains after analysis of variance through GLM Procedure using Tukey-Kramer Test are presented in Figures 2.14 and 2.16.

Table 2. 4 The population means and phenotypic standard deviations (SD) for coefficient of variation (CV) in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing and recirculating system for additional 245 days of separate tank rearing.

| Rearing System | Age (days) | Population mean | Phenotypic SD |
|---|---|---|---|
| Flow-through system (initial 311-day separate tank rearing) | 311 | 28.24 | 8.96 |
| Recirculating system (additional 245-day separate tank rearing) | 556 | 30.05 | 14.69 |

Table 2. 5 Mean squares (MS) for the Type 3 Mixed Procedure analyses of variance of the factorial mating design component of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny test and error mean squares for coefficient of variation (CV) in body weight of channel catfish female × blue catfish male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing and recirculating system for additional 245 days of separate tank rearing.

| Rearing System | Age (days) | | Source of variation | | | |
|---|---|---|---|---|---|---|
| | | | Dam | Sire | Dam x Sire | Error |
| Flow-through system (initial 311-day separate tank rearing) | 311 | d.f. | 19 | 11 | 8 | 66 |
| | | MS | 230.54$^{*}$ | 31.07$^{ns}$ | 34.5$^{ns}$ | 22.81 |
| Recirculating system (additional 245-day separate tank rearing) | 556 | d.f. | 19 | 11 | 7 | 41 |
| | | MS | 401.36$^{*}$ | 365.56$^{*}$ | 380.68$^{*}$ | 126.04 |

After ANOVA *F*-test: * = $p<0.05$, and $^{ns}$ = $p>0.05$ d.f. = degree of freedom.

Table 2. 6 Estimates of general combining ability variance for dam ($\sigma^2GCA_d$) and sire ($\sigma^2GCA_s$) and specific combining ability variance ($\sigma^2SCA$), error variance ($\sigma^2_E$) and corresponding standard errors for coefficient of variation (CV) in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing and recirculating system for additional 245 days of separate tank rearing.

| Rearing system | Age (days) | Genetic parameter estimates | | | |
|---|---|---|---|---|---|
| | | $\sigma^2GCA_d$ (± SE) | $\sigma^2GCA_s$ (± SE) | $\sigma^2SCA$ (± SE) | $\sigma^2_E$ |
| Flow-through system (initial 311-day separate tank rearing) | 311 | 83.83 (31.08) | 1.79 (3.35) | 2.65 (4.56) | 22.46 |
| Recirculating system (additional 245-day separate tank rearing) | 556 | 21.18 (37.27) | 0 | 46.65 (56.74) | 159.10 |

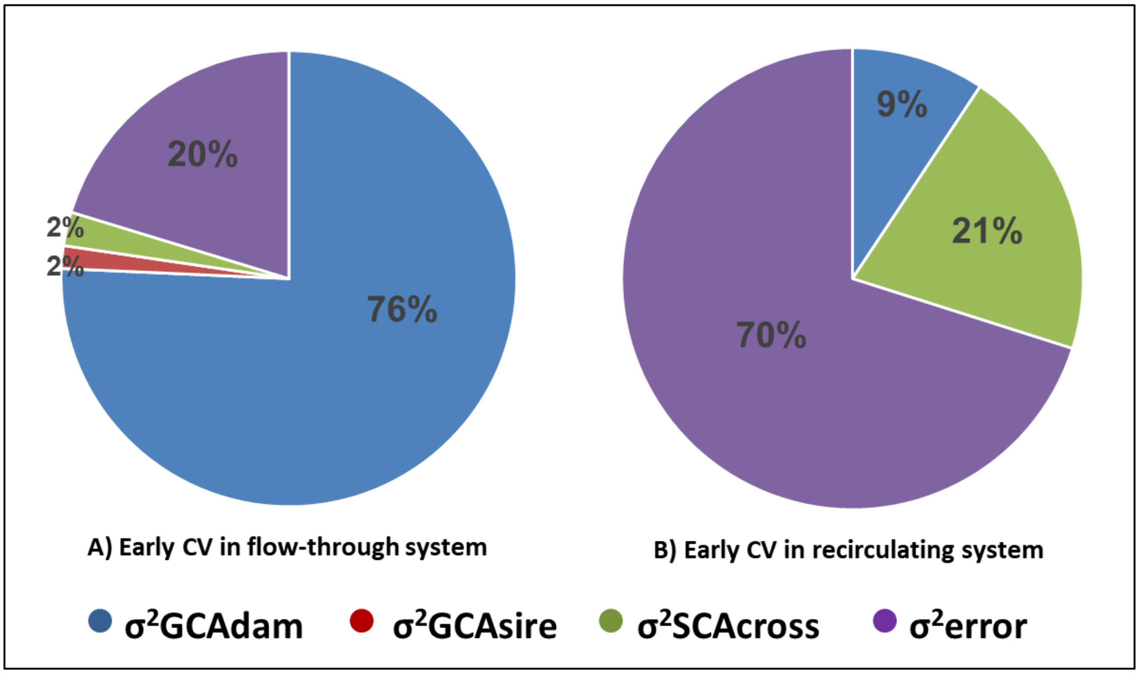


Figure 2. 12 Ratio of estimates of GCA variance components for dam and sire, SCA variance components for cross, and error variance components for coefficient of variance (CV) in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid

progeny in flow-through system for 311 days of separate tank rearing and recirculating system for additional 245 days of separate tank rearing.

The mean squares of coefficient of variation in body weight was significant (P<0.05) only for the GCA effects of the dam for the hybrid catfish after the initial 311-day separate tank rearing in flow-through system (Table 2.5), indicating importance of additive gene effects of the female parent. The combining ability variance components ratio (Fig. 2.12) revealed that the CV in body weight trait of the hybrid progeny reared in separate tanks in flow-through system was controlled by the additive gene effects attributed to the dam parents. For CV, the best GCA estimate would be the lowest negative value if one were selecting for uniformity. Parental dam 9 had the best or most negative (P<0.05, Fig. 2.13) GCA estimate. The hybrid progeny of this dam would likely have a very low coefficient of variation in body weight. Hybrid progeny of KxTh crossbred dams had the highest (P<0.05) variation in body weight compared to hybrids from other dam types (Fig. 2.14). The parental dam strain with the lowest CV (0.20) was AR strain. However, the AR strain was not significantly different from other dam genotypes except KxTh.

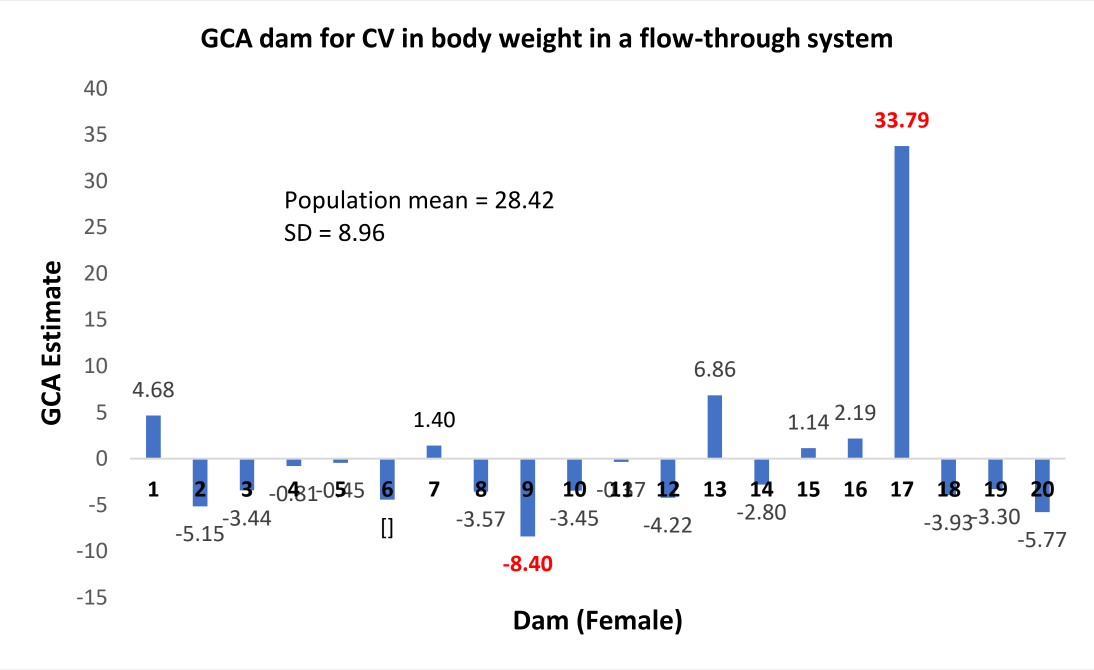


Figure 2. 13 The channel catfish (*Ictalurus punctatus*) female (dam) general combining ability estimates for coefficient of variance (CV) in body weight of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

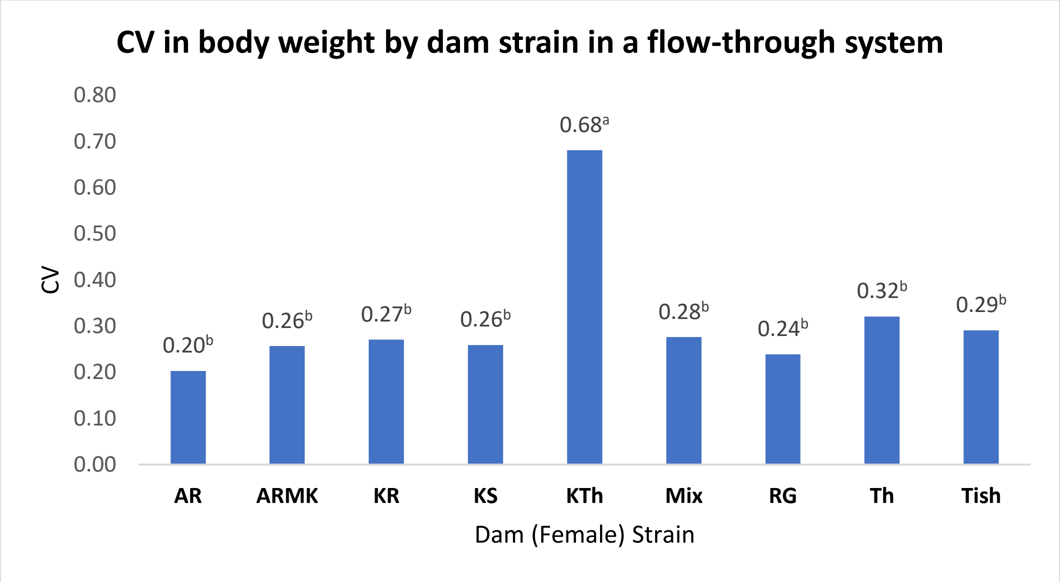


Figure 2. 14 Coefficient of variance (CV) in body weight by parental dam strain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing. Hybrid genotypes in the same rearing

system with the same superscript letter are not significantly different (P>0.05, Tukey-Kramer Test).

For CV in body weight of the hybrids reared for an additional 245 days in separate tanks in recirculating system, significant differences (P<0.05, Table 2.5) were found on the mean squares of CV in body weight for the GCA effects of the dam, sire, and dam-sire cross suggesting the variability in the genetic materials of this trait. The largest variance component ratio (Fig. 2.12) was found for the SCA which suggests the presence of heterosis and the importance of dominance and epistatic gene effects from the cross in controlling this trait. The SCA effects revealed that the crosses 15x6, 2x3, and 18x1 had the best SCA estimates at -4.72, -4.52, and -4.40, respectively (Fig. 2.15). The hybrid progeny of these crosses will have very low variation in terms of body weight. The cross RGxDB gave the lowest CV of 13.69 which was not different (P>0.05) to all other crosses except to ARMKxDB (Fig. 2.16).

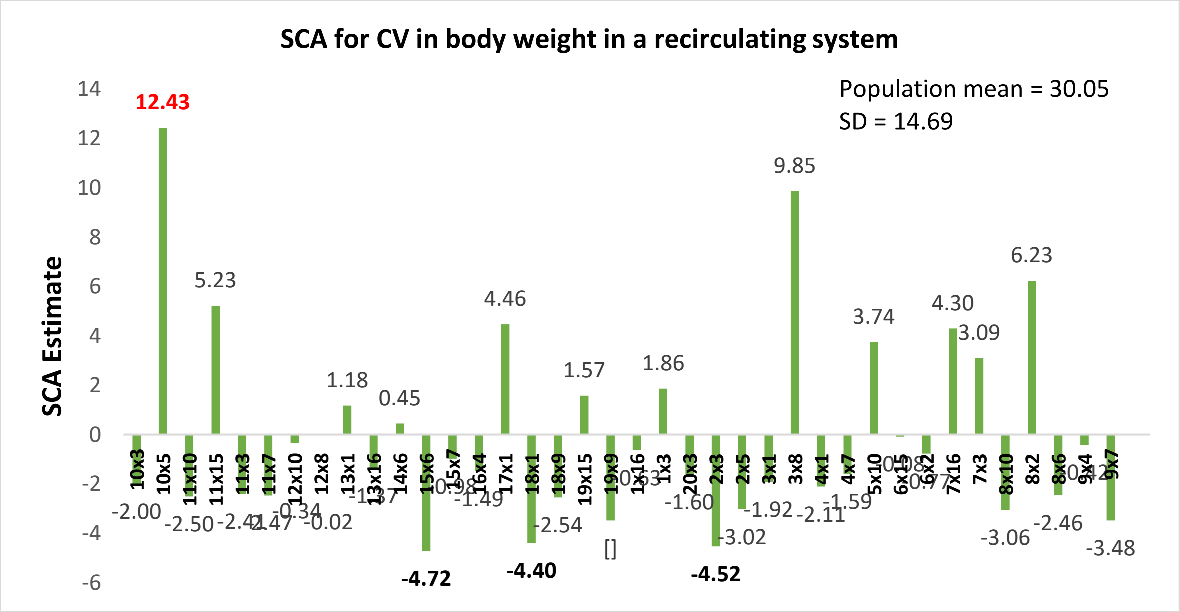


Figure 2. 15 The channel catfish (*Ictalurus punctatus*) female (dam) x blue catfish (*I. furcatus*) male (sire) specific combining ability estimates for coefficient of variance (CV) in body weight of channel catfish female × blue catfish male F1 hybrid progeny in recirculating system for

additional 245 days of separate tank rearing. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

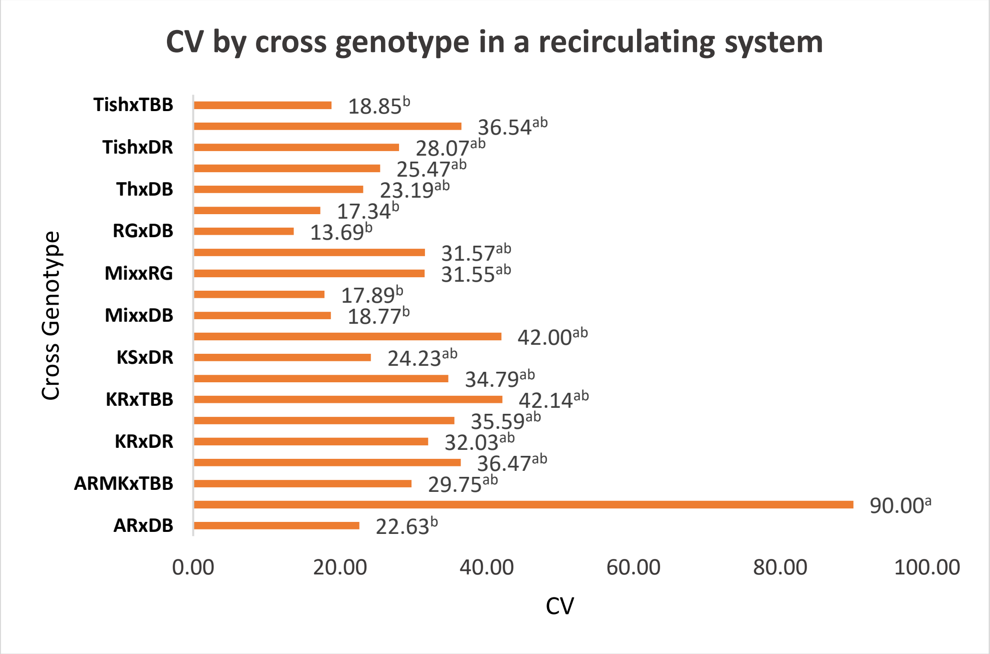


Figure 2. 16 Coefficient of variance (CV) in body weight by parental cross genotype of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing. Hybrid genotypes in the same rearing system with the same superscript letter are not significantly different (P>0.05, Tukey-Kramer Test).

### *Early Resistance to Aeromonas hydrophila Infection*

During the initial 311 days of rearing of the 40 hybrid catfish families in separate tanks in the flow-through system, mortality was observed due to natural *Aeromonas hydrophila* infection. The population mean and phenotypic standard deviation for the survival rate of hybrid catfish after *A. hydrophila* infection are presented in Table 2.7. The survival rates of the hybrids were analyzed following REML/BLUP joint analyses based on the genetic relationship matrix to calculate for the mean squares from the analysis of variance (Table 2.7), the variance components (Table 2.8) and the variance components ratio and estimates for GCAs of sire and dam and/or SCAs of crosses

(Fig. 2.17, 2.18, 2.20). The mean comparison of parental strains after analysis of variance through GLM Procedure using Tukey-Kramer Test are presented in Figures (2.19, 2.21).

Table 2. 7 The population mean, phenotypic standard deviation (SD), and mean squares (MS) for the Type 3 Mixed Procedure analysis of variance of the factorial mating design component of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny test and error mean squares for the survival rate of channel catfish female × blue catfish male hybrid catfish after a natural *Aeromonas hydrophila* infection.

| Trait | Population mean (%) | Phenotypic SD | | Source of Variation | | | |
|---|---|---|---|---|---|---|---|
| | | | | dam | sire | dam x sire | Error |
| Survival rate from natural *Aeromonas hydrophila* infection | 83.67% | 22.76 | | | | | |
| | | | d.f. | 19 | 11 | 9 | 67 |
| | | | MS | $670.19^{*}$ | $915.12^{*}$ | $527.96^{ns}$ | 314.11 |

After ANOVA *F*-test: * = $p<0.05$, and $^{ns}$ = $p>0.05$
d.f. = degree of freedom.

Table 2. 8 Estimates of general combining ability variance for dam ($\sigma^2GCA_d$) and sire ($\sigma^2GCA_s$) and specific combining ability variance ($\sigma^2SCA$), error variance ($\sigma^2_E$) and corresponding standard errors for the survival rate of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny after a natural *Aeromonas hydrophila* infection.

| Trait | Genetic parameter estimates | | | |
|---|---|---|---|---|
| | $\sigma^2GCA_d$ (± SE) | $\sigma^2GCA_s$ (± SE) | $\sigma^2SCA$ (± SE) | $\sigma^2_E$ |
| Survival rate from natural *Aeromonas hydrophila* infection | 63.76 (53.55) | 109.08 (64.65) | 0 | 335.28 |

The mean squares of the survival rate of hybrid catfish from natural *A. hydrophila* infection was significant (P<0.05, Table 2.7) for the GCA effects of the dam and sire parents indicating the importance of additive gene effects. The combining ability variance components ratio (Table 2.8, Fig. 2.17) revealed that the early resistance of hybrids to natural *A. hydrophila* infection is controlled largely (almost double) by the additive gene effects attributed to the sire parent. Parental sire 7 had the best highest positive GCA estimate of 7.29 (Fig. 2.18), which suggests that its hybrid progeny will likely have better early resistance to *A. hydrophila*. The hybrid progeny of TBB, DB, and RG sires had the highest survival rates ($P<0.05$, Fig. 2.19) after natural *Aeromonas* infection at 90.89, 90.81, and 86.43%, respectively. The hybrid progeny from DxR crossbred sires had the lowest survival rate at 64.08%.

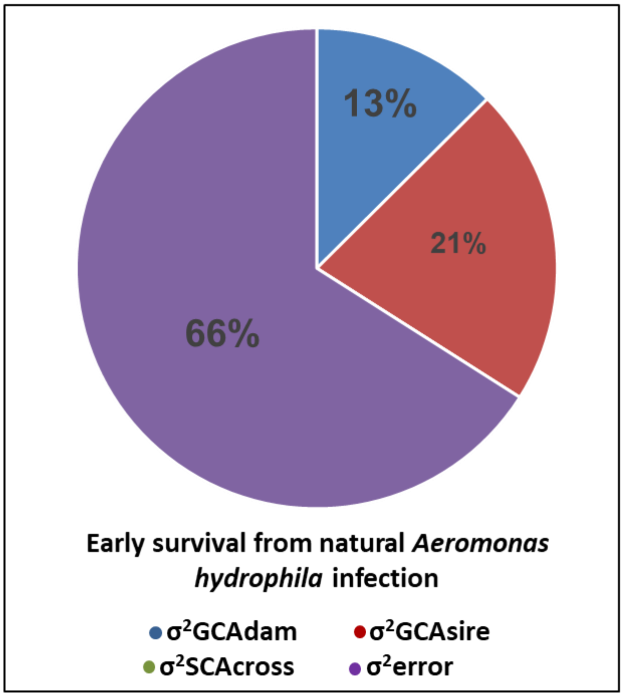


Figure 2. 17 Ratio of estimates of GCA variance components for dam and sire, SCA variance components for cross, and error variance components for the early survival of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny from natural *Aeromonas hydrophila* infection.

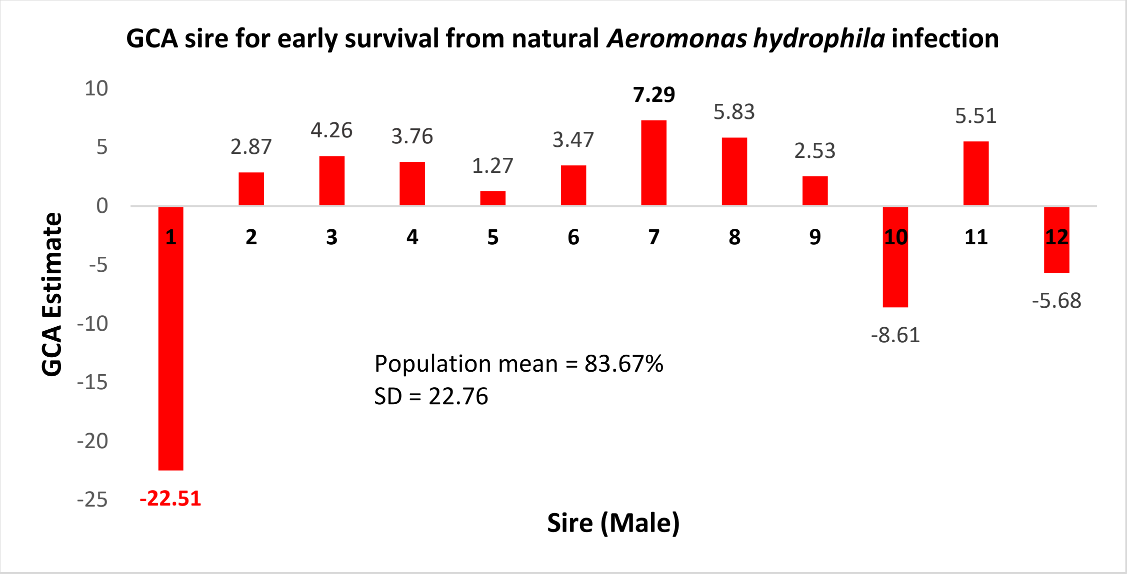


Figure 2. 18 The blue catfish (*Ictalurus furcatus*) male (sire) general combining ability estimates for the early survival of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny from natural *Aeromonas hydrophila* infection. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

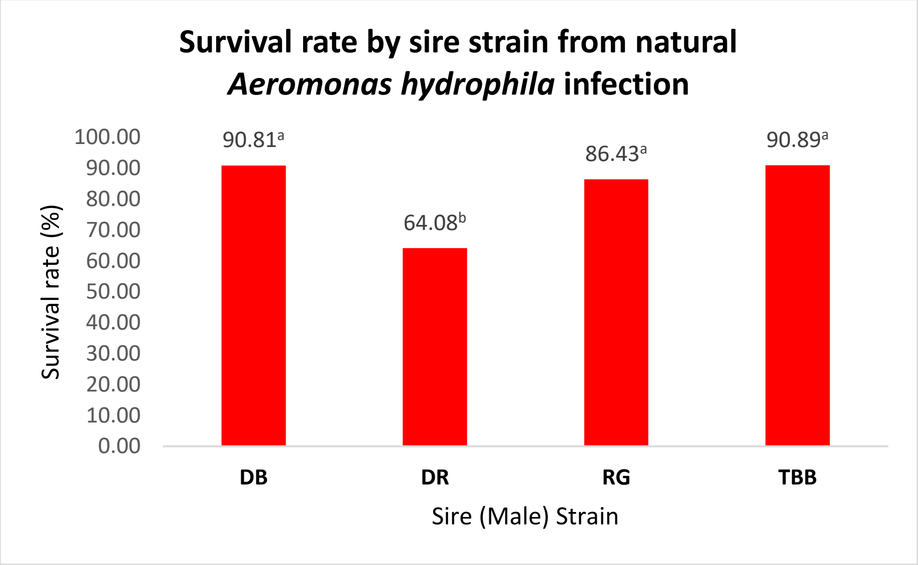


Figure 2. 19 Early resistance of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny to natural *Aeromonas hydrophila* infection in terms of survival rate by parental sire strain of hybrid catfish. Hybrid genotypes in the same rearing system with the same superscript letter are not significantly different (P>0.05, Tukey-Kramer Test).

Since the GCA effects of the dam were also significant (P<0.05, Table 2.7) as revealed by the mean squares for the survival rate of hybrid catfish from natural *A. hydrophila* infection, the additive genetic effects of the dam cannot be ignored. In terms of GCA estimates for this trait, parental dam 3 had the best highest positive GCA estimate of 5.64 (Fig. 2.20), suggesting that its hybrid progeny will have better resistance to *A. hydrophila* infection. The survival rate of hybrid progenies of all nine dam genotypes did not differ significantly for *A. hydrophila* infection except for KxTh crossbred dams.

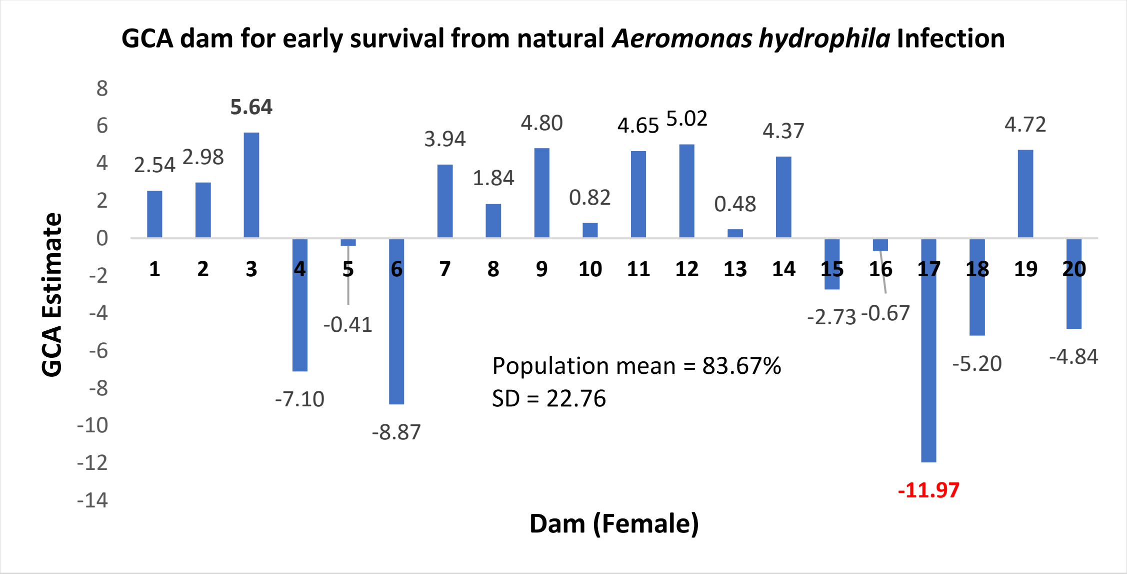


Figure 2. 20 The channel catfish (*Ictalurus punctatus*) female (dam) general combining ability estimates for the early survival of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny from natural *Aeromonas hydrophila* infection. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

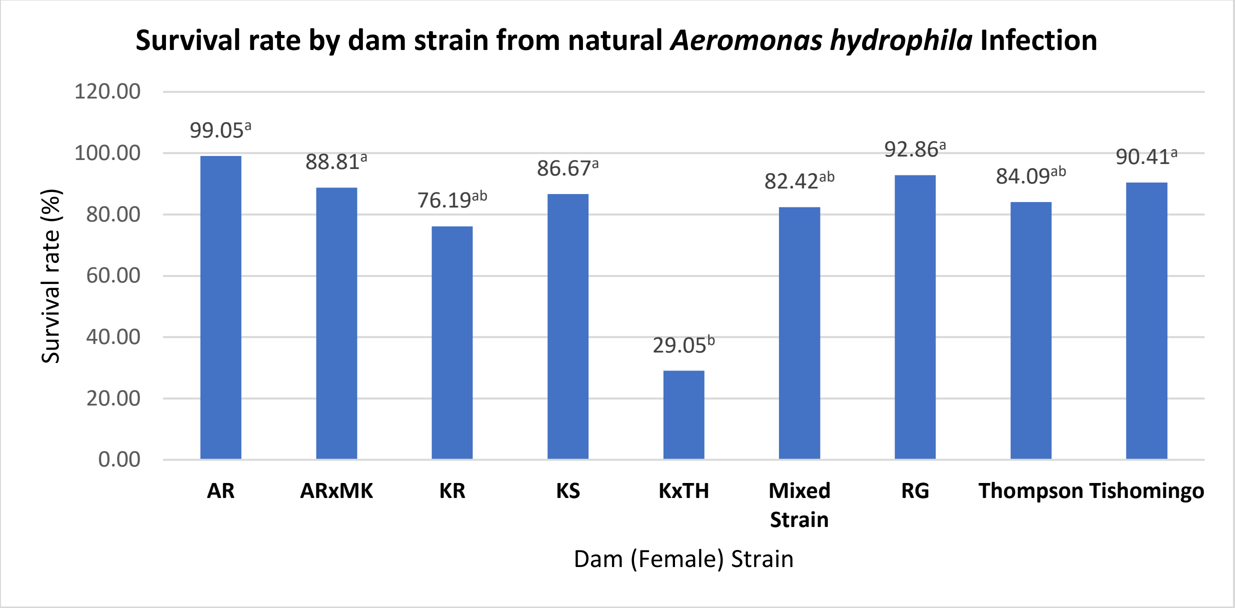


Figure 2. 21 Early resistance of channel catfish (*I. punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny to natural *Aeromonas hydrophila* infection in terms of survival rate by parental dam strain of hybrid catfish. Hybrid genotypes in the same rearing system with the same superscript letter are not significantly different ($P>0.05$, Tukey-Kramer Test).

### *Dressout Percentage*

The dressout percentage of the hybrid catfish was determined after the additional 245-day communal rearing in split-pond. The population mean and phenotypic standard deviation for the dressout percentage of the hybrid catfish are presented in Table 2.9. The mean squares from the analysis of variance (Table 2.9), the variance components (Table 2.10), the variance components ratio and estimates for GCAs of sire and dam and/or SCAs of crosses (Figures 2.22, 2.23). The mean comparison of the cross genotypes after analysis of variance through GLM Procedure using Tukey-Kramer Test is presented in Figures (2.24).

Table 2. 9 The population mean, phenotypic standard deviation (SD), and mean squares (MS) for the Type 3 Mixed Procedure analysis of variance of the factorial mating design component of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny test and error mean squares for the dressout percentage of channel catfish female × blue catfish male hybrid catfish after additional 245-day communal rearing in split-pond.

| | Population mean (%) | Phenotypic SD | | Source of Variation | | | |
|---|---|---|---|---|---|---|---|
| | | | | dam | sire | dam x sire | error |
| Dressout Percentage | 58.90% | 2.73 | | | | | |
| | | | d.f. | 15 | 10 | 4 | 262 |
| | | | MS | $26.09^{*}$ | $30.51^{*}$ | $5.72^{ns}$ | 5.66 |

After ANOVA *F*-test: * = $p<0.05$, and $^{ns}$ = $p>0.05$
d.f. = degree of freedom.

Table 2. 10 Estimates of general combining ability variance for dam ($\sigma^2GCA_d$) and sire ($\sigma^2GCA_s$) and specific combining ability variance ($\sigma^2SCA$), error variance ($\sigma^2_E$) and corresponding standard errors for the dressout percentage of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny after additional 245-day communal rearing in split-pond.

| Trait | Genetic parameter estimates | | | |
|---|---|---|---|---|
| | $\sigma^2GCA_d$ (± SE) | $\sigma^2GCA_s$ (± SE) | $\sigma^2SCA$ (± SE) | $\sigma^2_E$ |
| Dressout Percentage | 0.12 (0.70) | 0.41 (0.48) | 1.32 (0.92) | 5.67 |

The mean squares of the dressout percentage of the hybrid catfish was found significant (P<0.05, Table 2.9) for the GCA effects of the dam and sire parents. However, the combining ability variance components ratio (Table 2.10, Fig. 2.22) revealed that the most important component that controls this trait is the SCA variance indicating presence of heterosis and dominance and epistatic gene effects of the cross. The cross 11x10 had the best SCA estimate, 1.76 (P<0.05, Fig. 2.23). The other crosses that also had high SCA estimates were 4x7 and 2x5.

These three crosses involved parents that are good combiners (i.e., good GCA x good GCA), indicating the concentration of positive alleles, additive x additive gene action, and interaction of favorable genes from both parents in each cross. The hybrid progeny of these three crosses with their high SCA estimates will likely have better dressout percentage. The cross RGxDB gave the highest mean, 61.57%, which was significantly better (P<0.05, Fig. 2.24) than the 3 crosses with the lowest means. TishxDR, 60.87%, and KSxDR, 60.44%, had the next highest means.

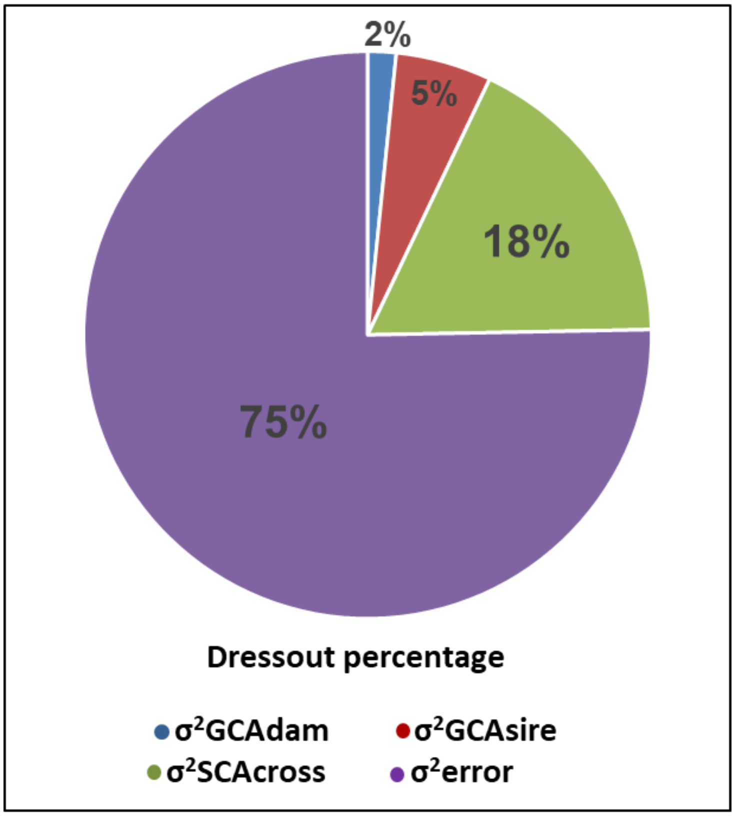


Figure 2. 22 Ratio of estimates of GCA variance components for dam and sire, SCA variance components for cross, and error variance components for the dressout percentage of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny after additional 245-day communal rearing in split-pond.

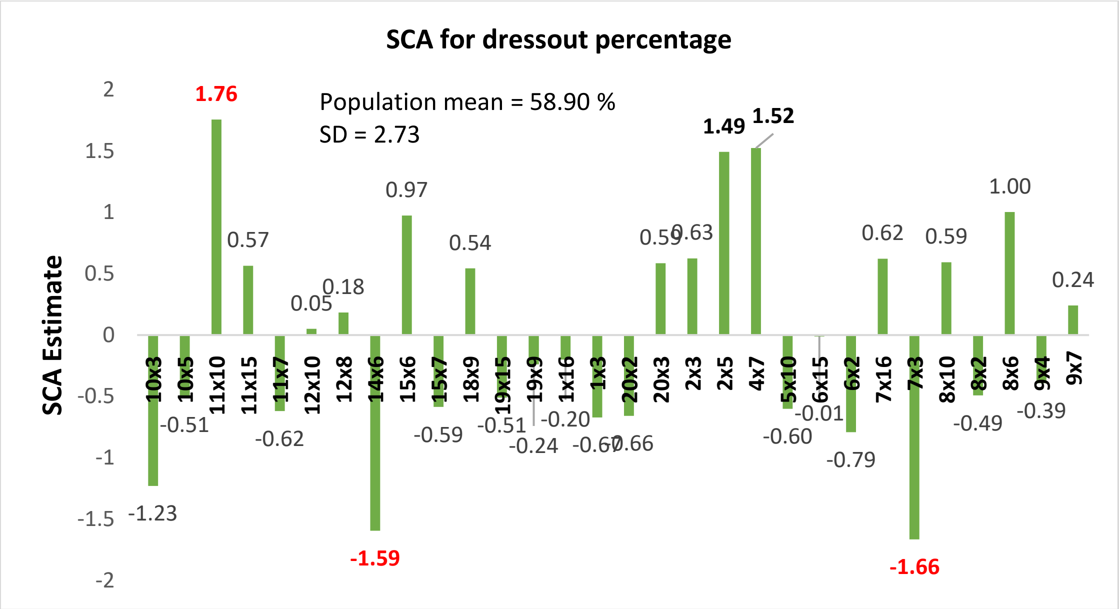


Figure 2. 23 The channel catfish (*Ictalurus punctatus*) female (dam) x blue catfish (*I. furcatus*) male (sire) specific combining ability estimates for the dressout percentage of channel catfish female × blue catfish male F1 hybrid progeny after additional 245-day communal rearing in split-pond. GCA estimates in red font are significantly different among others (P<0.05, *t*-test).

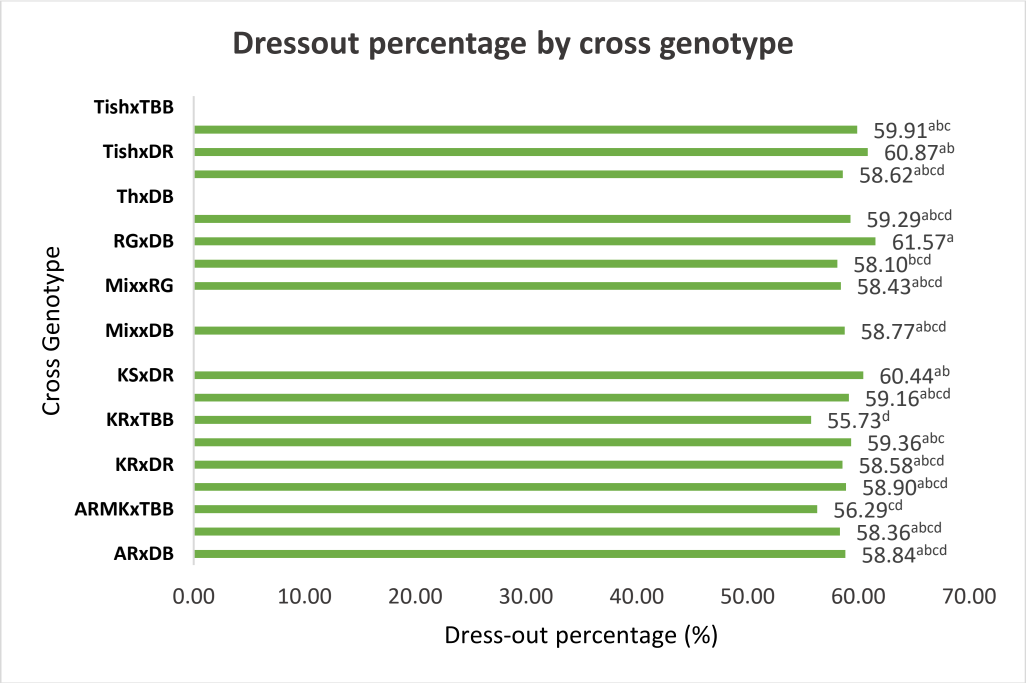


Figure 2. 24 Dressout percentage by parental cross genotype of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny after additional 245-day communal rearing in split-pond. Hybrid genotypes in the same rearing system with the same superscript letter are not significantly different (P>0.05, Tukey-Kramer Test).

## Discussion

Application of hybrid catfish is increasingly prevalent due to their faster growth rate, better survival rate, disease resistance, tolerance of low oxygen, carcass yield and seinability. However, hybrid catfish performance could be further improved through reciprocal recurrent selection if GCA and/or SCA are of sufficient magnitude. In the current study, dam GCA had the strongest influence on early growth (body weight) in aquaria. Over time the percentage of variance due to genetics decreased, and after the hybrid progeny were transferred to ponds, the dam and sire GCAs equalized. Similar results were obtained when growth rate was measured as weight gain. Coefficient of variation for body weight was most strongly influenced by dam GCA in the flow-through system, and shifted more to control by SCA as the fish continued to grow in the recirculating system. Sire GCA followed by dam GCA had the strongest genetic influence on hybrid fry resistance to *Aeromonas hydrophila.* SCA was the strongest genetic component for dressout percentage.

Bosworth and Waldbieser (2014) estimated the GCA and SCA variances for growth and carcass yield in hybrid catfish of market-size. The dam GCA for body weight was the strongest factor, however, when maternal effects are accounted for dam and sire GCAs were likely equivalent. In the current study, dam GCA had the strongest influence on early growth (body weight) in aquaria, especially at the initial stage in the flow-through system. SCA was detectable at this time. Over time the percentage of variance due to genetics decreased, and after the hybrid progeny were transferred to ponds, the dam and sire GCAs equalized. The relative influence of dam additive gene effects, sire additive gene effects and dominance shifted in the 3 environments or times evaluated indicative of either genotype-environment interactions or genotype-age interactions. The pond result, the environment used by Bosworth and Waldbieser (2014), with fish more similar in size to that experiment, resulted in almost identical results, equivalency of sire and dam GCA. However, one difference may be more maternal effects in the study of Bosworth and Waldbieser (2014).

The similarity in the results for body weight between the current study and that of Bosworth and Waldbieser (2014) is significant as they utilized different strains than the current study, suggesting that the genetics of variable hybrid performance are similar across different strains and lines of channel catfish and blue catfish. Thus, a standard breeding program to improve growth rate of hybrid catfish should be applicable industry wide, just as selection for increased body weight of channel catfish was effective in all strains of channel catfish evaluated (Dunham 2011).

Our results and those of Bosworth and Waldbieser (2014) indicate that when hybrid progeny are grown in ponds, selection for channel catfish female and blue catfish male body weight should result in faster growing hybrid progeny. That prediction was not accurate after four generations of selection for body weight in Kansas strain channel catfish (Jeppsen 1995), as hybrids from control females grew at the same rate as hybrids from selected females. However, it was accurate after eight generations of selection for body weight in Kansas strain as hybrid fingerlings from selected females grew faster than hybrids from control females (Makhubu 2014; Alsaqufi 2015). The explanation for the change over a 4-generation period is not clear, however, allele frequency changes would be expected between generations, and this could explain the variable results. The dam GCA suggests that the selection of channel catfish females for body weight should result in faster growing hybrids, and this will need to be verified in multiple populations to determine the generality of this prediction.

The relative importance of the GCAs and SCA were similar when growth rate was measured as body weight or weight gain. Although the type of gene action was changing over time or by environment, this suggests that genetic ranking was staying the same and genotype-environment interactions were minimal. However, this conclusion is not correct. If the dam GCA of individual females is examined, the females with the highest GCA changes for different environments and as the hybrid progeny increase in size. Thus, strong genotype-environment or genotype-age interactions occurred or both.

Size variation of hybrid catfish grown in the catfish industry at high density has become a problem. At low density, the hybrid is a very uniform growing fish (Dunham et al. 1982), however, at high density there is great increase in body weight variability (Ramboux 1990). The coefficient of variation for body weight of hybrid catfish, in regard to combining ability variance differed between the two aquaria rearing systems. The GCA variance for dam was more predominant compared to SCA during the initial 311 days in the flow-through system indicating additive gene effects controlling this trait, whereas the SCA variance became twice as large as dam GCA when hybrids were reared for an additional 245 days in the recirculating system indicating dominance gene effects having greater influence for this trait. Hybrids produced by the KxTh crossbred dams had the largest CV for body weight. This is not surprising as the crossbred females should have a high level of heterozygosity, and should produce a large variety of gametes from a genetic standpoint. Additionally, linkage disequilibrium could contribute to the variability (Christiansen 1989; Slatkin 2008) of hybrid offspring from these crossbred females.

Can channel catfish dams be selected to produce hybrid progeny that grow faster and exhibit more uniform growth. The results from the fry growth in flow through aquaria indicate that this would be difficult. Dams with the highest GCA for body weight tended to have also have high GCA for CV, and those with low GCA for body weight also had low GCA for CV, indicating selection of fast growing hybrid fingerlings would also increase variability, and selection for uniform growth would also decrease growth.

The top three crosses with desirable negative SCA estimates for CV in body weight were 15x6 (Tishomingo x DB), 2x3 (RG x TBB), and 18x1 (Mix strains x DR). These top 3 crosses all belonged to different strains, thus there were no dramatic strain effects for SCA of CV. However, crosses from dam strains containing the greatest lineage of RG strain tended to have the most uniform growth. The SCA effects of the three desirable crosses, influenced by both additive and dominance genetic variation (Eisen et al. 1983), suggests the potential for improving CV through selection for specific pairs.

In the case of early resistance of F1 hybrid catfish to *Aeromonas hydrophila* natural infection, the sire GCA had more impact than the dam GCA, and the SCA was zero, indicating that additive gene effects were important, but not dominance. Although the GCA values among individual sires were not statistically different, nine sires had positive GCA estimates for this trait, and three sires had relatively low negative GCA estimates. The hybrid progeny from the sire strains DB, TBB, and RG, had the best survival, approximately 90%. The hybrid progeny from the DxR crossbred sires had the poorest survival rate, 64%. Similar to what was observed with F1 KxTh crossbred dams, hybrids from the F1 crossbred males had poor survival related performance. One expectation would be that there might be positive maternal effects from crossbred dams, but the opposite was true. Perhaps, linkage disequilibrium (Christiansen 1989; Slatkin 2008) resulted in lowered overall fitness in the hybrid progeny from these intraspecific F1 parents. It should be beneficial to combine the best alleles from multiple strains or lines, but the results from the current study suggest that multiple generations may be needed for potential negative effects from linkage disequilibrium dissipate before beneficial effects from selecting in the more diverse genetic background be realized.

Parental sires with best GCA values among the better performing strains can likely be used to improve the early resistance trait of hybrid catfish to *Aeromonas hydrophila* infection through selection. Future studies that would employ controlled disease challenges on the hybrid catfish (at different ages) that are generated from a full factorial mating design would be very informative in exploring the genetic components responsible for the expression of this trait. Combining abilities for measurable parameters in the immune system that are genetically correlated with disease resistance may also be conducted to allow indirect selection for improved disease resistance of hybrid catfish.

The family variability could be attributed to the combination effect of strain differences. The largest genetic variance component for dressout percentage was the SCA variance which indicates the presence of heterosis and dominance gene effects of the specific cross. Bosworth and Waldbieser (2014) found the opposite result with maternal effects and dam GCA being much more influential than SCA. There are many potential explanations as there were several differences in the two studies. Different strains were used, and processing technology was different. In the current study, the fish were much smaller and the dressout percentage much smaller. Thus, many factors, genetic, environmental and genotype-environment interactions are possible explanations of the opposite results of the two studies.

Based on the SCA values, the cross 11x10 had the best significant positive SCA estimate for dressout. The other crosses that also gave relatively high and positive SCA estimates are 4x7 and 2x5. These three crosses involved parents with good x good GCA parental combinations indicating the concentration of positive alleles and interaction of favorable genes from both parents in each cross. The high SCA effects of these crosses with both parents that are good general combiners also suggest additive x additive gene action (Dey et al. 2014; Verma and Srivastava 2004). The results in this study were consistent with the conclusion of Cotterill et al. (1986), where crossing parents with best GCA estimates would usually produce outstanding progeny, even when dominance variance equals additive variance. Sire strain effects were also evident for dressout percentage. When paired comparisons are made with the same dam strain, but varying sire strain, hybrids from the TBB blue catfish consistently had the lowest dressout percentage and those from RG blue catfish had the highest. Combining parental lines with desirable high GCA values and cross genotypes would likely result in inheritable genetic gains for improving the dressout percentage of hybrid catfish. Additionally, cross genotypes that exhibit heterosis for dressout can also be selected as in common beans, heterosis and SCA are highly correlated (de Fátima Machado et al. 2002). Future research can be conducted on catfish to confirm this correlation. Future research should also determine the relationship of the early dressout percentage of F1 hybrid catfish to the dressout percentage of hybrids at the more typical market-size. If valid, selection and prediction of hybrids with better dressout done at the early age would save time and money. The current data is also relevant from the standpoint that there are a few markets that prefer small fish.

For most traits assessed in this study, the GCA variance of the parental dams were relatively larger compared to the GCA variance of the parental sires and the SCA. Several studies on fish species such as hybrid catfish (Bosworth and Walbieser 2014; Drescher 2017), hybrid striped bass (*Morone chrysops* × *Morone saxatilis*) (Wang et al. 2006), sea bass (*Dicentrarchus labrax L.*) (Saillant et al. 2006), and carp (*Cyprinus carpio L.*) (Vandeputte et al. 2004), after analyses of their factorial matings also revealed greater degrees of additive variance (GCA) than the dominance variance (SCA).  Bosworth and Waldbieser (2014) reported a confounding effect to genetic variance resulting to greater magnitude of additive variance due to greater genetic variation in the channel catfish females, which was supported by microsatellite data that showed high polymorphism in the channel catfish females used and low level of polymorphism in the blue catfish used in their study. The females used in their study were a mixture of fish from different strains from commercial farms with large breeding populations and therefore expected to be more polymorphic. The blue catfish they used in their study were from a single strain of fish obtained from a commercial farm and therefore expected to be of low level of polymorphism.  Hence, the magnitude of additive variance in their study was greater in favor of channel catfish females than the blue catfish males. This is assuming that the quantity of additive variation is correlated with the quantity of microsatellite variation. However, alternative explanations exist as the microsatellites do not distinguish between additive and dominance genes and expression. The use of a population made from many strains could also result in a large amount of dominance effects, raising the impact of SCA. Also, significant additive variation can exist even in highly inbred lines (Chan 1971), thus GCA could be of great importance even in the case of limited microsatellite variability.

In the current study, the genetic variance could not be ascribed to such partitioning of the relative importance of the genetic components because of the explanation above, but also because the effects of high polymorphism were expected to be present in both male and female catfish parents used. The female parents used in this study were a mixture of lines and a crossbreed of channel catfish, indicating that the overall female population could be highly polymorphic. On one hand, the male blue catfish were composed of three strains and a crossbreed, which could also result in high polymorphism. Thus, the polymorphism of the male and female catfish parents in this study could possibly contribute to the magnitude of additive genetic variance.

In the current study, GCA was the strongest genetic component explaining the genetic variation for most of the traits evaluated. According to Griffing (1956), parents with the highest GCA estimates should generate a population with a higher mean yield. GCA estimates close to zero indicate that the progeny’s performance does not differ from the general mean of all crosses. On the other hand, positive or negative estimates indicate that the parent is better or worse than the other parents included in the mating design, as compared to the mean yield of the crosses (Griffing 1956). In this study, the GCA estimates obtained correspond to the frequency of desirable or undesirable alleles of the parents with additive effects for the early growth performance traits of the F1 hybrid catfish. Consequently, parents with higher GCA estimates should generate progeny with the highest mean yield, from which elite parental lines can be selected. However, in the process of choosing elite parents, the highest GCA estimate alone is not sufficient enough if the parents are genetically similar because the population will present a restricted variability thereby reducing the chances to select improved lines. On the other hand, SCA measures the degree of allelic complementation. In this study, the magnitude of SCA variance was greater than the GCA variance for the CV in body weight of hybrids reared in the recirculating system and the dressout percentage of hybrids reared in communal split-pond. This result therefore suggests that selecting the cross from those with desirable SCA estimates along with parents with the highest magnitudes of GCA estimates would be feasible and result in the most effective selective breeding program.

For traits where GCA variances are larger than SCA variances, selection of parents that are good combiners is efficient because the value of the parents can be examined at the F1 generation of its hybrid progeny based from the GCA estimates (Melchinger et al. 1998; Smith et al. 2008). Selected parents of hybrids with good GCA estimates can be reproduced to develop parental lines that are good combiners in producing improved hybrids. The GCA performance of these parental lines can be predicted from the GCAs of their parents because the GCA is controlled by the additive gene effects which are heritable from the parents and can be passed onto the progeny. (Lv et al. 2012). Hence, improvement of the hybrid catfish becomes effective and less costly due to the less time taken to release F1 hybrids with low amount of materials needed in the breeding programs. In the case where SCA variance is more important over GCA variance for some traits, selection of parents/cross for hybrids can be done in later generation of the parental lines until the target traits are improved. (Bao et al. 2009; Ertiro et al. 2013).

As this study was conducted on young, small hybrid catfish, future research should confirm that there is a relationship between the genetic mechanisms at this time point, and that of food size hybrid catfish to ensure that the research has practical application not only to fingerling producers, but also food fish producers and processors. Genotype-environment interactions should also be further explored. Future research could also involve integrating molecular aspects of combining ability. Linkage analysis revealed the contribution of several QTLs to GCA effects and heterosis of agronomic traits in rice and maize which provided the information for dissecting the genetic bases of combining ability (Lv et al. 2012; Qi 2013; Qu 2012; Liu et al. 2015; Zhou et al. 2017). Linkage analysis on both the GCA and SCA effects for each trait could also be conducted to explore and unveil the QTLs of combining abilities for important traits and evaluate how they contribute to the overall performance of hybrid catfish.

## Conclusion

The early growth traits of the F1 hybrid catfish were found to be controlled by the additive gene effects attributed to the parental channel catfish females when hybrids were reared in aquaria. However, the additive gene effects from both parental channel catfish females and blue catfish males equalized when hybrids were reared in pond. Alternatively, this could be a size effect as the fish were not reared to equal sizes in the two environments. Additive gene effects of the dam controlling coefficient of variation in body weight declined and dominance gene effects of the cross increased as the fish grew. The early resistance of the F1 hybrid catfish to *Aeromonas hydrophila* natural infection was found to be controlled by the additive gene effects attributed to parental blue catfish males, suggesting the importance of selecting blue catfish males with better GCA estimates to generate hybrid catfish with improved resistance to *Aeromonas*. The importance of dominance gene effects of the cross in controlling the dressout percentage of the F1 hybrid catfish was revealed. Cross genotypes exhibiting the highest SCA estimates which involved both parents having high x high GCA estimates would generate F1 hybrid catfish with better dressout percentage.

A breeding plan can be developed to improve the early growth, body weight variation, disease resistance and dressout percentage of F1 channel-blue hybrid catfish utilizing GCA and SCA information from this study. Using the GCA/SCA estimates obtained from the combining ability analyses, elite parental and/or cross genotypes capable of producing superior hybrid catfish were identified and performance of hybrid catfish progeny can be predicted. The genetic mechanisms observed should allow reciprocal recurrent selection of channel catfish and blue catfish to develop high yielding parental lines and hybrids that would be beneficial to the catfish industry.

# References

Alsaqufi, A.S. 2015. Approaches to improve production and performance of channel catfish (*Ictalurus punctatus*) female x blue catfish (*I. furcatus*) male hybrid catfish. Doctoral Dissertation. Auburn University, Auburn, Alabama.

Argue, B.J., Z. Liu, and R.A. Dunham. 2003. Dress-out and fillet yields of Channel Catfish, *Ictalurus punctatus,* Blue Catfish, *I. furcatus,* and their F1, F2 and backcross hybrids. Aquaculture 228:81–90.

Arias, C.R., W. Cai, E.J. Peatman, and S.A. Bullard. 2012. Catfish hybrid *Ictalurus punctatus* × *I. furcatus* exhibits higher resistance to columnaris disease than the parental species. Diseases of Aquatic Organisms 100:77–81.

Bao, Y., S. Wang, X. Wang, Y. Wang, X. Li, et al. 2009. Heterosis and combining ability for major yield traits of a new wheat germplasm Shannong 0095 derived from *Thinopyrum intermedium*. Agricultural Sciences in China 8(6):753-760.

Becker, W.A. 1984. Manual of Quantitative Genetics. Academic Enterprises, Pullman, Washington.

Beecham, R.V., M.J. Griffin, S.B. LaBarre, D.J. Wise, M. J. Mauel, L.M.W. Pote, and C. D. Minchew. 2011. The effects of proliferative gill disease on the blood physiology of channel catfish, blue catfish, and channel x blue catfish hybrid fingerlings. North American Journal of Aquaculture 72:213-218.

Bosworth, B.G. 2012. Effects of winter feeding on growth, body composition, and processing traits of co-cultured blue catfish (*Ictalurus furcatus*), channel catfish (*I. punctatus*) and channel catfish × blue catfish hybrids. National American Journal of Aquaculture 74:553–559.

Bosworth, B.G., and G. Waldbieser. 2014. General and specific combining ability of male blue catfish (*Ictalurus furcatus*) and female channel catfish (*Ictalurus punctatus*) for growth and carcass yield of their F1 hybrid progeny. Aquaculture 420–421:147–153.

Bosworth, B.G., W.R. Wolters, D.J. Wise, and M.H. Li. 1998. Growth, feed conversion, fillet proximate composition and resistance to *Edwardsiella ictaluri* of channel catfish, *Ictalurus punctatus* (Rafinesque), blue catfish, *Ictalurus furcatus* (Lesueur), and their reciprocal Fl hybrids fed 25% and 45% protein diets. Aquaculture Research 29:251-257.

Bosworth, B.G., W.R. Wolters, J.L. Silva, R.S. Chamul, and S. Park. 2004. Comparison of production, meat yield, and meat quality traits of NWAC 103 line channel catfish (*Ictalurus punctatu*s), Norris line channel catfish, and channel catfish female × blue catfish male (*I. furcatus*) F1 hybrids. National American Journal of Aquaculture 66:177–183.

Brooks, M.J., R.O. Smitherman, J.A. Chappell, and R.A. Dunham. 1982a. Sex-weight relations in Blue, Channel, and White catfishes: implications for brood stock selection. Progressive Fish-Culturist 44:105–106.

Brooks, M.J., R.O. Smitherman, J.A. Chappell, J.C. Williams, and R.A. Dunham. 1982b. Length variation in species and hybrid populations of Blue, Channel and White catfishes. Proceedings of the South East Association of the Fish and Game Commission 36:190–195.

Brown, T.W., J.A. Chappell, and C.E. Boyd. 2011. A commercial-scale, in pond raceway system for ictalurid catfish production. Aquaculture Engineering 44:72–79.

Chan, M.T. 1971. Experience with the determination of realized heritability in the tilapia (*Tilapia mossambica*). Genetica 7:53-59.

Chappell, J.A. 1979. An evaluation of twelve genetic groups of catfish for suitability in commercial production. Doctoral Dissertation. Auburn University, Auburn, Alabama.

Christiansen, F.B. 1989. Linkage equilibrium in multi-locus genotypic frequencies with mixed selfing and random mating. Theoretical Population Biology 35:307-336.

Comstock, R.E., and H.F. Robinson. 1948. The components of genetic variance in populations of biparental progenies and their use in estimating the average degree of dominance. Biometrics 4:254–266.

Cotterill, P.P., C.A. Dean, and G. Van Wyk. 1986. Additive and dominance genetic effects in *Pinus pinaster, P. radiata* and *P. elliottii* and some implications for breeding strategy. Silvae Genetica 36:221–231.

de Fátima Machado, C., J. B. dos Santos, G. H. de Sousa Nunes, and M. A. Patto Ramalho. 2002. Choice of common bean parents based on combining ability estimates. Genetics and Molecular Biology 25(2):179–183.

Dey, S.S., N. Singh, R. Bhaatia, C. Parkash, and C. Chandel. 2014. Genetic combining ability and heterosisfor important vitamins and antioxidant pigments in cauliflower (*Brassica oleracea var. botrytis L.*). Euphytica 195(2):169-181.

Drescher, D. 2017. Combining ability of channel catfish (*Ictalurus punctatus*) females and blue catfish (*I. furcatus*) males for tolerance of low oxygen. Master's Thesis. Auburn University, Auburn, Alabama.

Dunham, R. A. 2011. Aquaculture and Fisheries Biotechnology: Genetic Approaches, 2nd edition. CAB International, Cambridge, MA, USA.

Dunham, R.A., A.C.R. Ramboux, and D.A. Perera. 2014a. Effect of strain on the growth, survival and sexual dimorphism of channel × blue catfish hybrids grown in earthen ponds. Aquaculture 420–421, S20–S24.

Dunham, R.A., A.C.R. Ramboux, and D.A. Perera. 2014b. Effect of strain on tolerance of low dissolved oxygen of channel × blue catfish hybrids. Aquaculture 420–421, S25–S28.

Dunham, R.A., and B.J. Argue. 1998. Seinability of Channel Catfish, Blue Catfish, and F1, F2, F3 and backcross hybrids in earthen ponds. Progressive Fish-Culturist 60:214–220.

Dunham, R.A., and M. Masser. 2012. Production of Hybrid Catfish. Southern Regional Aquaculture Center Publication Number, 190.

Dunham, R.A., and R.E. Brummett. 1999. Response of two generations of selection to increased body weight in Channel Catfish, *Ictalurus punctatus* compared to hybridization with Blue Catfish *I. furcatus*. Journal of Applied Aquaculture 3:211–222.

Dunham, R. A., and R. O. Smitherman. 1984. Ancestry and breeding of channel catfish in the United States. Circular 273. Alabama Agricultural Experiment Station, Auburn University, AL.

Dunham, R.A., G.M. Umali, R. Beam, A.H. Kristanto, and M. Trask. 2008. Comparison of production traits of NWAC103 Channel Catfish, NWAC103 Channel Catfish × Blue Catfish hybrids, Kansas select 21 Channel Catfish, and Blue Catfish grown at commercial densities and exposed to natural bacterial epizootics. North American Journal of Aquaculture 70:98–106.

Dunham, R.A., R.E. Brummett, M.O. Ella, and R.O. Smitherman. 1990. Genotype-environment interactions for growth of Blue, Channel, and hybrid catfish in ponds and cages at varying densities. Aquaculture 85:143–151.

Dunham, R.A., R.O. Smitherman, and C. Webber. 1983. Relative tolerance of Channel × Blue hybrid and Channel catfish to low oxygen concentrations. Progressive Fish-Culturist 45:55–56.

Dunham, R.A., R.O. Smitherman, and R.K. Goodman. 1987. Comparison of mass selection, crossbreeding, and hybridization for improving growth of Channel Catfish. Progressive Fish-Culturist 49:293–296.

Dunham, R.A., R.O. Smitherman, M.J. Brooks, M. Benchakan, and J.A. Chappell. 1982. Paternal predominance in reciprocal Channel-Blue hybrid catfish. Aquaculture 29:389–396.

Dunham, R.A., R.O. Smitherman, R.K. Goodman, and P. Kemp. 1986. Comparison of strains, crossbreeds, and hybrids of Channel Catfish for vulnerability to angling. Aquaculture 57:193–201.

Dunnett, C.W. 1980. Pairwise multiple comparisons in the unequal variance case. Journal of the American Statistical Association 75:796-800.

Eisen, E.J., G. Horstgen-Schwark, A.M. Saxton, and T.R. Bandy. 1983. Genetic interpretation and analysis of diallel crosses with animals. Theoretical and Applied Genetics 65:17-23.

Ella, M.O. 1984. Genotype-environment interactions for growth rate of Blue, Channel, and hybrid catfish grown at varying stocking densities. Master's Thesis. Auburn University, Auburn, Alabama.

Ertiro, B.T., H. Zeleke, D. Friesen, M. Blummel, and A.S. Twumasi. 2013. Relationship between the performance of parental inbred lines and hybrids for food-feed traits in maize (*Zea mays L*.) in Ethiopia. Field Crops Research 153:86-93.

Falconer, D.S. 1989. Introduction to quantitative genetics. 3rd edition. Oliver & Boyd. London.

Fehr, W.R. 1993. Principles of cultivar development: development of hybrid cultivars. Macmillan Publishing Company, New York, USA.

Giudice, J.J. 1966. Growth of Blue × Channel catfish hybrid as compared to its parent species. Progressive Fish-Culturist 28:142–145.

Griffin, M.J., S.R. Reichley, L.H. Khoo, T.E. Greenway, C.C. Mischke, and D.J. Wise. 2014. Comparative susceptibility of Channel Catfish, Blue Catfish, and their hybrid cross to experimental challenge with *Bolbophorus damnificus* (Digenea: Bolbophoridae) cercariae. Journal of Aquatic Animal Health 2:96-9.

Griffing, B .1956. Concept of general and specific combining ability in relation to diallel crossing system. Australian Journal of Biological Science 9:463-493.

Hallauer, A.R., and J.B. Miranda. 1988. Quantitative genetics in maize breeding, 2nd edition. Iowa State University Press, Ames, IA, USA.

Hayter, A.J. 1989. Pairwise comparisons of generally correlated means. Journal of the American Statistical Association 84:208-213.

Huang, Y.W., R.T. Lowell, and R.A. Dunham. 1994. Carcass characteristics of Channel and hybrid catfish, and quality changes during refrigerated storage. Journal of Food Sciences 59:64–66.

Jeppsen, T. 1995. Comparison of performance of channel catfish, *Ictalurus punctatus*, female x blue catfish, *I. furcatus*, male hybrids from Kansas select and Kansas random dams. Master's Thesis, Auburn University, Auburn, Alabama.

Li, M.H., E.H. Robinson, B.B. Manning, D.R. Yant, N.G. Chatakondi, B.G. Bosworth, and W.R. Wolters. 2004. Comparison of the Channel Catfish, *Ictalurus punctatus*, (NWAC103 strain) and the Channel × Blue catfish, *I. punctatus* × *I. furcatus*, F1 hybrid for growth, feed efficiency, processing yield, and body composition. Journal of Applied Aquaculture 15:63–71.

Liu, C., G. Song, Y. Zhou, X. Qu, Z. Guo, Z. Liu, D. Jiang, and D. Yang. 2015. OsPRR37 and Ghd7 are the major genes for general combining ability of DTH, PH and SPP in rice. Scientific Reports 5:12803.

Longin, C. F. H., M. Gowda, J. Mühleisen, E. Ebmeyer, E. Kazman, R. Schachschneider, J. Schacht, M. Kirchhoff, Y. Zhao, and J. C. Reif. 2013. Hybrid wheat: Quantitative genetic parameters and consequences for the design of breeding programs. Theoretical and Applied Genetics 126(11):2791–2801.

Luo, W., C. Zeng, S. Yi, N. Robinson, W. Wang, and Z. Gao. 2014. Heterosis and combining ability evaluation for growth traits of blunt snout bream (*Megalobrama amblycephala*) when crossbreeding three strains. China Science Bulletin 59(9):857-864.

Lutz, C.G., A.M. Armas-Rosales, and A.M. Saxton. 2010. Genetic effect influencing in six varieties of tilapia (*Oreochromis*) and their reciprocal crosses. Aquaculture Research 41(11):e770-e780.

Lv, A.Z., H. Zhang, Z. Zhang, Y. Tao, B. Yue, et al. 2012. Conversion of the statistical combining ability into a genetic concept. Journal of Integrative Agriculture 11:43-52.

Makhubu, N.P. 2014. Genotype-environment interactions for growth, survival, sexual dimorphism and seinability for different genetic types of channel catfish (*Ictalurus punctatus*) ♀ x blue catfish (*I. furcatus*) ♂ cultured in three environments. Master's Thesis. Auburn University, Auburn, Alabama.

Melchinger, A., W. Schmit, and H.H. Geiger. 1998. Comparison of testcrosses from F2 and first backcross populations in maize. Crop Science 28(5):743-749.

Pomerleau, S., and C.R. Engle. 2005. An economic comparison of producing catfish, (*Ictalurus punctatus*), stockers with either 9-, 11-, or 13-cm fingerlings. Journal of Applied Aquaculture 17:61-73.

Qi, H. 2013. Identification of combining ability loci for five yield-related traits in maize using a set of testcrosses with introgression lines. Theoretical and Applied Genetics 126:369–377.

Qu, Z. 2012. QTL mapping of combining ability and heterosis of agronomic traits in rice backcross recombinant inbred lines and hybrid crosses. Public Library of Science One 7:e28463.

Ramboux, A. 1990. Evaluation of four genetic groups of channel-blue catfish hybrids grown in earthen ponds. Doctoral Dissertation, Auburn University, Alabama.

Saillant, E., M. Dupont-Nivet, P. Haffray, and B. Chatain. 2006. Estimates of heritability and genotype–environment interactions for bodyweight in sea bass (*Dicentrarchus labrax L.*) raised under communal rearing conditions. Aquaculture 254:139–147.

Salem A.H., and M.A. Ali. 2012. Combining ability for sunflower yield contributing characters and oil content over different water supply environments. Journal of American Science 8:227-233.

SAS 9.4, SAS Institute Inc. NC, USA.

Scheffé, H. 1999. The analysis of variance. Wiley, New York, USA.

Silverstein, P.S., B.G. Bosworth, and P.S. Gaunt. 2008. Differential susceptibility of blue catfish, *Ictalurus furcatus* (Valenciennes), channel catfish, *I. punctatus* (Rafinesque), and blue×channel catfish hybrids to channel catfish virus. Journal of Fish Diseases 31:77–79.

Slatkin, M. 2008. Linkage disequilibrium – understanding the evolutionary past and mapping the medical future. Nature Reviews Genetics 9(6):477-485.

Smith, J.S.C., T. Hussain, E.S. Jones, G. Graham, D. Podlich, et al. 2008. Use of doubled haploids in maize breeding: implications for intellectual property protection and genetic diversity in hybrid crops. Molecular Breeding 22(1):51-59.

Sprague, G.F., and L.A. Tatum 1942. General vs. specific combining ability in single crosses of corn. Journal of American Society of Agronomy 34:923–932.

Su, B., D.A. Perera, Y. Zohar, E. Abraham, J. Stubblefield, M. Fobes, R. Beam, B. Argue, C. Ligeon, J. Padi, P. Waters, G. Umali-Maceina, N. Chatakondi, A. Kristanto, A. Hutson, C. Templeton, J. Ballenger, A. Chaimongkol, A. Gima, M. Gima, A. Zuberi, D.M. Lambert, S. Kim, M. Mandour, and R.A. Dunham. 2013. Relative effectiveness of carp pituitary extract, luteinizing hormone releasing hormone analog (LHRHa) injections and LHRHa implants for producing hybrid catfish fry. Aquaculture 372-375: 133–136.

Su, S., P. Xu, and X. Yuan. 2013a. Estimates of combining ability and heterosis for growth traits in a full diallel cross of three strains of common carp , *Cyprinus carpio L*. African Journal of Biotechnology 12(22):3514–3521.

Tave, D., A. McGinty, J. A. Chappell, and R. O. Smitherman. 1981. Relative harvestability by angling of Blue Catfish, Channel Catfish, and their reciprocal hybrids. North American Journal of Aquaculture 1:73–76.

Tucker, C.S., and E.H. Robinson. 1990. Channel Catfish Farming Handbook. Van Nostrand Reinhold, New York, New York, USA.

USDA, National Agricultural Statistic Service. 2013. Catfish Production Report.

Vandeputte, M.K., S. Mauger, M. Dupont-Nivet, D. De Guerry, M. Rodina, D. Gela, D. Vallod, B. Chevassus, and O. Linhart. 2004. Heritability estimates for growth-related traits using microsatellite parentage assignment in juvenile common carp (*Cyprinus carpio L*.). Aquaculture 235:223–236.

Verma, O.P., and H.K. Srivastava. 2004. Genetic component and combining ability analyses in relation to heterosis for yield and associated traits using three diverse rice-growing ecosystems. Field Crops Research 88:91-102.

Wang, X., K.E. Ross, E. Saillant, D.M. Gatlin III, and J.R. Gold. 2006. Quantitative genetics and heritability of growth-related traits in hybrid striped bass (*Morone chrysops* × *Morone saxatilis*). Aquaculture 261:535–545.

Wolters, W. R., and M. R. Johnson. 1995. Analysis of a diallel cross to estimate effects of crossing on resistance to enteric septicemia in channel catfish, *Ictalurus punctatus*. Aquaculture 137(1–4):263–269.

Wolters, W.R., D.J. Wise, and P.H. Klesius. 1996. Survival and antibody response of Channel Catfish, Blue Catfish and Channel Catfish female × Blue Catfish male hybrids after exposure to *Edwardsiella ictaluri*. Journal of Aquatic Animal Health 8:249–254.

Yant, D.1975. Production of hybrid blue *Ictalurus furcatus* (Lesueur) male, channel *I. punctatus* (Rafinesque) female catfish and channel catfish in earthen ponds. Master's Thesis, Auburn University, Alabama.

Yant, D.R., R.O. Smitherman, and O.L. Green. 1976. Production of hybrid (Blue × Channel) catfish and Channel Catfish in ponds. Proceedings of the Southeast Association of the Fish and Game Commission 29:82–86.

Zhou, H., D. Xia, J. Zeng, G. Jiang, and Y. He. 2017. Dissecting combining ability effect in a rice NCII-III population provides insights into heterosis in *indica-japonica* cross. Rice 10:39. DOI 10.1186/s12284-017-0179-9.

# APPENDIX

Appendix Table 1 The Type 3 Mixed Procedure of analysis of variance for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| Type 3 Analysis of Variance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **Dam** | 19 | 279.28982 | 14.699464 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 67 | 2.85 | 0.0008 |
| **Sire** | 11 | 63.226235 | 5.747840 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 67 | 1.11 | 0.3643 |
| **dam*sire** | 9 | 83.893658 | 9.321518 | Var(Residual) + Q(dam*sire) | MS(Residual) | 67 | 1.81 | 0.0830 |
| **Residual** | 67 | 345.57193 | 5.157790 | Var(Residual) | . | . | . | . |

Appendix Table 2 REML estimation of variance components for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| Covariance Parameter Estimates | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **Dam** | 0.6336 | 3.2529 | 2.2970 | 1.42 | 0.0784 |
| **Sire** | 0.1765 | 0.9061 | 0.9232 | 0.98 | 0.1632 |
| **Cross** | 0.1928 | 0.9896 | 1.2827 | 0.77 | 0.2202 |
| **Residual** | 1.0000 | 5.1337 | 0.8795 | 5.84 | <.0001 |

Appendix Table 3 GCA/SCA estimates with corresponding T-test (P=0.05) for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| **Estimates** | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 1** | -0.6084 | 1.0893 | 67 | -0.56 | 0.5783 |
| **DAM 10** | -0.9338 | 1.0948 | 67 | -0.85 | 0.3967 |
| **DAM 11** | -1.0748 | 0.9205 | 67 | -1.17 | 0.2471 |
| **DAM 12** | -1.0783 | 1.0994 | 67 | -0.98 | 0.3302 |
| **DAM 13** | 1.0104 | 1.3024 | 67 | 0.78 | 0.4406 |
| **DAM 14** | -1.5882 | 1.3041 | 67 | -1.22 | 0.2275 |
| **DAM 15** | 1.2365 | 1.0891 | 67 | 1.14 | 0.2603 |
| **DAM 16** | 0.6755 | 1.4950 | 67 | 0.45 | 0.6528 |
| **DAM 17** | 3.5208 | 1.2905 | 67 | 2.73 | 0.0081 |
| **DAM 18** | 2.5287 | 1.0937 | 67 | 2.31 | 0.0239 |
| **DAM 19** | -1.8133 | 1.1041 | 67 | -1.64 | 0.1052 |
| **DAM 2** | -0.7383 | 1.0948 | 67 | -0.67 | 0.5024 |
| **DAM 20** | 1.1038 | 1.1146 | 67 | 0.99 | 0.3256 |
| **DAM 3** | 0.06081 | 1.1760 | 67 | 0.05 | 0.9589 |
| **DAM 4** | -0.01384 | 1.0794 | 67 | -0.01 | 0.9898 |
| **DAM 5** | 0.4615 | 1.2904 | 67 | 0.36 | 0.7217 |
| **DAM 6** | 0.7492 | 1.0299 | 67 | 0.73 | 0.4695 |
| **DAM 7** | -0.7404 | 1.0893 | 67 | -0.68 | 0.4991 |
| **DAM 8** | -0.8300 | 0.9708 | 67 | -0.85 | 0.3956 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 9** | -1.9278 | 1.1013 | 67 | -1.75 | 0.0846 |
| **SIRE 1** | 1.6254 | 0.7222 | 67 | 2.25 | 0.0277 |
| **SIRE 10** | 0.4315 | 0.6981 | 67 | 0.62 | 0.5386 |
| **SIRE 11** | -0.3219 | 0.7448 | 67 | -0.43 | 0.6669 |
| **SIRE 12** | 0.3077 | 0.7840 | 67 | 0.39 | 0.6960 |
| **SIRE 2** | -0.6001 | 0.7543 | 67 | -0.80 | 0.4291 |
| **SIRE 3** | -0.3063 | 0.6766 | 67 | -0.45 | 0.6522 |
| **SIRE 4** | -0.09421 | 0.8387 | 67 | -0.11 | 0.9109 |
| **SIRE 5** | 0.08529 | 0.8094 | 67 | 0.11 | 0.9164 |
| **SIRE 6** | -0.06679 | 0.7656 | 67 | -0.09 | 0.9307 |
| **SIRE 7** | -0.3870 | 0.7116 | 67 | -0.54 | 0.5883 |
| **SIRE 8** | -0.3471 | 0.8311 | 67 | -0.42 | 0.6776 |
| **SIRE 9** | -0.3265 | 0.8061 | 67 | -0.40 | 0.6868 |
| **10x3** | -0.7634 | 0.8870 | 67 | -0.86 | 0.3925 |
| **10x5** | 0.4793 | 0.8931 | 67 | 0.54 | 0.5932 |
| **11x10** | 0.2686 | 0.8686 | 67 | 0.31 | 0.7582 |
| **11x11** | -0.8844 | 0.8723 | 67 | -1.01 | 0.3143 |
| **11x3** | 0.4580 | 0.9259 | 67 | 0.49 | 0.6224 |
| **11x7** | -0.1692 | 0.8701 | 67 | -0.19 | 0.8464 |
| **12x10** | 0.06707 | 0.8896 | 67 | 0.08 | 0.9401 |
| **12x8** | -0.3951 | 0.8958 | 67 | -0.44 | 0.6606 |

**Estimates**

| Parents/ Cross | Estimate | Standard Error | DF | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| **13x1** | 0.4634 | 0.9379 | 67 | 0.49 | 0.6229 |
| **13x12** | -0.1560 | 0.9389 | 67 | -0.17 | 0.8686 |
| **14x6** | -0.4832 | 0.9198 | 67 | -0.53 | 0.6011 |
| **15x6** | 0.4739 | 0.8917 | 67 | 0.53 | 0.5969 |
| **15x7** | -0.09767 | 0.8897 | 67 | -0.11 | 0.9129 |
| **16x4** | 0.2055 | 0.9463 | 67 | 0.22 | 0.8287 |
| **17x1** | 1.0712 | 0.9180 | 67 | 1.17 | 0.2474 |
| **18x1** | 0.3648 | 0.8897 | 67 | 0.41 | 0.6831 |
| **18x9** | 0.4046 | 0.8947 | 67 | 0.45 | 0.6526 |
| **19x11** | 0.2094 | 0.8920 | 67 | 0.23 | 0.8151 |
| **19x9** | -0.7611 | 0.8945 | 67 | -0.85 | 0.3978 |
| **1x12** | 0.005037 | 0.8914 | 67 | 0.01 | 0.9955 |
| **1x3** | -0.1901 | 0.8868 | 67 | -0.21 | 0.8309 |
| **20x2** | -0.3758 | 0.9069 | 67 | -0.41 | 0.6799 |
| **20x3** | 0.7116 | 0.8919 | 67 | 0.80 | 0.4277 |
| **2x3** | 0.1616 | 0.8870 | 67 | 0.18 | 0.8560 |
| **2x5** | -0.3862 | 0.8931 | 67 | -0.43 | 0.6668 |
| **3x1** | 0.002459 | 0.9011 | 67 | 0.00 | 0.9978 |
| **3x8** | 0.01604 | 0.9358 | 67 | 0.02 | 0.9864 |
| **4x1** | -0.1265 | 0.8888 | 67 | -0.14 | 0.8872 |
| **4x7** | 0.1223 | 0.8895 | 67 | 0.14 | 0.8910 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **5x10** | 0.1404 | 0.9180 | 67 | 0.15 | 0.8789 |
| **6x10** | -0.3326 | 0.9286 | 67 | -0.36 | 0.7214 |
| **6x11** | 0.3233 | 0.8833 | 67 | 0.37 | 0.7155 |
| **6x2** | 0.2372 | 0.8837 | 67 | 0.27 | 0.7892 |
| **7x12** | 0.4870 | 0.8914 | 67 | 0.55 | 0.5867 |
| **7x3** | -0.7122 | 0.8868 | 67 | -0.80 | 0.4248 |
| **8x10** | 0.3278 | 0.8738 | 67 | 0.38 | 0.7087 |
| **8x2** | -0.5167 | 0.8776 | 67 | -0.59 | 0.5580 |
| **8x6** | -0.06361 | 0.8782 | 67 | -0.07 | 0.9425 |
| **9x4** | -0.3084 | 0.8960 | 67 | -0.34 | 0.7318 |
| **9x7** | -0.2781 | 0.8904 | 67 | -0.31 | 0.7558 |

Appendix Table 4 ANOVA for mean performance by parental strains following GLM Procedure for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| **Model** | 8 | 305.583505 | 38.197938 | 4.98 | <.0001 |
| **Error** | 98 | 751.570970 | 7.669092 | | |
| **Corrected Total** | 106 | 1057.154475 | | | |

Appendix Table 5 Mean comparison of performance by parental strains using Tukey-Kramer Test for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| **Tukey-Kramer Comparison Lines for Least Squares Means of dam** | | | | |
|---|---|---|---|---|
| **LS-means with the same letter are not significantly different.** | | | | |
| | | **wt LSMEAN** | **dam** | **LSMEAN Number** |
| | A | 17.946667 | **5** | 5 |
| | A | | | |
| B | A | 11.730000 | **8** | 8 |
| B | | | | |
| B | | 10.318462 | **3** | 3 |
| B | | | | |
| B | | 10.285217 | **6** | 6 |
| B | | | | |
| B | | 9.110741 | **9** | 9 |
| B | | | | |
| B | | 8.738889 | **4** | 4 |
| B | | | | |
| B | | 8.721667 | **7** | 7 |
| B | | | | |
| B | | 8.445000 | **2** | 2 |
| B | | | | |
| B | | 6.908333 | **1** | 1 |

Note: Dam strain 1 – AR; 2 – ARMK; 3 – KR; 4 – KS; 5 – KTh; 6 – Mix; 7 RG; 8 – Thompson; 9 - Tishomingo

Appendix Table 6 The Type 3 Mixed Procedure of analysis of variance for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| Type 3 Analysis of Variance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **dam** | 19 | 96132 | 5059.559486 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 677 | 4.75 | <.0001 |
| **sire** | 11 | 33309 | 3028.113423 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 677 | 2.85 | 0.0012 |
| **dam*sire** | 8 | 7264.878620 | 908.109828 | Var(Residual) + Q(dam*sire) | MS(Residual) | 677 | 0.85 | 0.5560 |
| **Residual** | 677 | 720521 | 1064.285618 | Var(Residual) | . | . | . | . |

Appendix Table 7 REML estimation of variance components for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| Covariance Parameter Estimates | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **dam** | 0.2102 | 222.83 | 124.68 | 1.79 | 0.0370 |
| **sire** | 0.0805 | 85.4252 | 68.2055 | 1.25 | 0.1052 |
| **cross** | 0.0195 | 20.6986 | 56.3180 | 0.37 | 0.3566 |
| **Residual** | 1.0000 | 1060.16 | 57.3733 | 18.48 | <.0001 |

Appendix Table 8 GCA/SCA estimates with corresponding T-test (P=0.05) for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| **Estimates** | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 1** | -5.8803 | 7.5527 | 677 | -0.78 | 0.4365 |
| **DAM 10** | -6.0247 | 8.2881 | 677 | -0.73 | 0.4675 |
| **DAM 11** | -10.1791 | 5.5604 | 677 | -1.83 | 0.0676 |
| **DAM 12** | -4.5508 | 6.5838 | 677 | -0.69 | 0.4897 |
| **DAM 13** | -10.7686 | 7.7604 | 677 | -1.39 | 0.1657 |
| **DAM 14** | -2.4328 | 9.9062 | 677 | -0.25 | 0.8061 |
| **DAM 15** | -10.2612 | 7.3960 | 677 | -1.39 | 0.1658 |
| **DAM 16** | 5.5880 | 10.3220 | 677 | 0.54 | 0.5884 |
| **DAM 17** | 46.5104 | 8.7521 | 677 | 5.31 | <.0001 |
| **DAM 18** | -9.3132 | 7.1152 | 677 | -1.31 | 0.1910 |
| **DAM 19** | 0.1124 | 7.6187 | 677 | 0.01 | 0.9882 |
| **DAM 2** | 15.8794 | 8.2216 | 677 | 1.93 | 0.0538 |
| **DAM 20** | 2.4863 | 8.3499 | 677 | 0.30 | 0.7660 |
| **DAM 3** | -1.5614 | 7.4637 | 677 | -0.21 | 0.8344 |
| **DAM 4** | -2.7999 | 7.3786 | 677 | -0.38 | 0.7045 |
| **DAM 5** | -12.7271 | 7.9134 | 677 | -1.61 | 0.1082 |
| **DAM 6** | 8.9377 | 7.6978 | 677 | 1.16 | 0.2460 |
| **DAM 7** | -0.8289 | 7.5527 | 677 | -0.11 | 0.9126 |
| **DAM 8** | -0.5627 | 6.4654 | 677 | -0.09 | 0.9307 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 9** | -1.6237 | 8.1159 | 677 | -0.20 | 0.8415 |
| **SIRE 1** | 13.9749 | 5.4988 | 677 | 2.54 | 0.0113 |
| **SIRE 10** | 5.0489 | 5.1000 | 677 | 0.99 | 0.3225 |
| **SIRE 11** | -11.1101 | 5.5812 | 677 | -1.99 | 0.0469 |
| **SIRE 12** | -2.9743 | 6.3798 | 677 | -0.47 | 0.6412 |
| **SIRE 2** | -3.1889 | 6.1763 | 677 | -0.52 | 0.6058 |
| **SIRE 3** | 2.1881 | 5.3719 | 677 | 0.41 | 0.6839 |
| **SIRE 4** | 4.3505 | 7.6694 | 677 | 0.57 | 0.5707 |
| **SIRE 5** | 0.4893 | 7.9336 | 677 | 0.06 | 0.9508 |
| **SIRE 6** | -2.7782 | 6.4419 | 677 | -0.43 | 0.6664 |
| **SIRE 7** | -5.9728 | 5.3763 | 677 | -1.11 | 0.2670 |
| **SIRE 8** | 7.8346 | 6.4767 | 677 | 1.21 | 0.2268 |
| **SIRE 9** | -7.8621 | 6.4893 | 677 | -1.21 | 0.2261 |
| **10x3** | -1.1834 | 4.3637 | 677 | -0.27 | 0.7863 |
| **10x5** | 0.6238 | 4.4582 | 677 | 0.14 | 0.8888 |
| **11x10** | 0.6036 | 4.1365 | 677 | 0.15 | 0.8840 |
| **11x11** | -4.1875 | 4.1574 | 677 | -1.01 | 0.3142 |
| **11x3** | 1.1967 | 4.3002 | 677 | 0.28 | 0.7809 |
| **11x7** | 1.4418 | 4.1407 | 677 | 0.35 | 0.7278 |
| **12x10** | -1.0314 | 4.2062 | 677 | -0.25 | 0.8064 |
| **12x8** | 0.6087 | 4.2714 | 677 | 0.14 | 0.8867 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **13x1** | -0.3765 | 4.3349 | 677 | -0.09 | 0.9308 |
| **13x12** | -0.6238 | 4.3621 | 677 | -0.14 | 0.8863 |
| **14x6** | -0.2260 | 4.4297 | 677 | -0.05 | 0.9593 |
| **15x6** | 0.5316 | 4.4076 | 677 | 0.12 | 0.9040 |
| **15x7** | -1.4848 | 4.3141 | 677 | -0.34 | 0.7308 |
| **16x4** | 0.5191 | 4.4379 | 677 | 0.12 | 0.9069 |
| **17x1** | 4.3204 | 4.4087 | 677 | 0.98 | 0.3275 |
| **18x1** | 0.4187 | 4.2762 | 677 | 0.10 | 0.9220 |
| **18x9** | -1.2838 | 4.3098 | 677 | -0.30 | 0.7659 |
| **19x11** | 0.6317 | 4.3281 | 677 | 0.15 | 0.8840 |
| **19x9** | -0.6212 | 4.3240 | 677 | -0.14 | 0.8858 |
| **1x12** | -0.2247 | 4.3405 | 677 | -0.05 | 0.9587 |
| **1x3** | -0.3215 | 4.3027 | 677 | -0.07 | 0.9405 |
| **20x2** | 1.1679 | 4.4530 | 677 | 0.26 | 0.7932 |
| **20x3** | -0.9370 | 4.3688 | 677 | -0.21 | 0.8302 |
| **2x3** | 1.9803 | 4.3612 | 677 | 0.45 | 0.6499 |
| **2x5** | -0.5052 | 4.4580 | 677 | -0.11 | 0.9098 |
| **3x1** | -1.4346 | 4.3143 | 677 | -0.33 | 0.7396 |
| **3x8** | 1.2896 | 4.3953 | 677 | 0.29 | 0.7693 |
| **4x1** | 0.4582 | 4.3169 | 677 | 0.11 | 0.9155 |
| **4x7** | -0.7183 | 4.3173 | 677 | -0.17 | 0.8679 |

**Estimates**

| Parents/ Cross | Estimate | Standard Error | DF | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| **5x10** | -1.1822 | 4.3950 | 677 | -0.27 | 0.7880 |
| **6x11** | 0.8639 | 4.3217 | 677 | 0.20 | 0.8416 |
| **6x2** | -0.03365 | 4.3423 | 677 | -0.01 | 0.9938 |
| **7x12** | 0.1279 | 4.3405 | 677 | 0.03 | 0.9765 |
| **7x3** | -0.2048 | 4.3027 | 677 | -0.05 | 0.9620 |
| **8x10** | 2.8334 | 4.2132 | 677 | 0.67 | 0.5015 |
| **8x2** | -1.9069 | 4.2623 | 677 | -0.45 | 0.6547 |
| **8x6** | -0.9788 | 4.2949 | 677 | -0.23 | 0.8198 |
| **9x4** | 0.5351 | 4.4387 | 677 | 0.12 | 0.9041 |
| **9x7** | -0.6859 | 4.3554 | 677 | -0.16 | 0.8749 |

Appendix Table 9 ANOVA for mean performance by parental strains following GLM Procedure for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| **Model** | 8 | 145211.943 | 18151.4928 | 16.20 | <.0001 |
| **Error** | 707 | 792052.295 | 1120.3003 | | |
| **Corrected Total** | 715 | 937264.237 | | | |

Appendix Table 10 Mean comparison of performance by parental strains using Tukey-Kramer Test for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

**Tukey-Kramer Comparison Lines for Least Squares Means of dam**

**LS-means with the same letter are not significantly different.**

| | | **wt LSMEAN** | **dam** | **LSMEAN Number** |
|---|---|---|---|---|
| | A | 170.3611 | **5** | 5 |
| | | | | |
| | B | 116.3095 | **7** | 7 |
| | B | | | |
| C | B | 106.1364 | **8** | 8 |
| C | B | | | |
| C | B | 93.7065 | **3** | 3 |
| C | B | | | |
| C | B | 92.9576 | **4** | 4 |
| C | B | | | |
| C | B | 87.6129 | **6** | 6 |
| C | B | | | |
| C | B | 86.8250 | **2** | 2 |
| C | B | | | |
| C | B | 86.7273 | **1** | 1 |
| C | | | | |
| C | | 84.4196 | **9** | 9 |

**The LINES display does not reflect all significant comparisons. The following additional pairs are significantly different: (7,6)**

Note: Dam strain 1 – AR; 2 – ARMK; 3 – KR; 4 – KS; 5 – KTh; 6 – Mix; 7 RG; 8 – Thompson; 9 - Tishomingo

Appendix Table 11 The Type 3 Mixed Procedure of analysis of variance for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| **Type 3 Analysis of Variance** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **dam** | 19 | 77662 | 4087.453408 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 677 | 4.45 | <.0001 |
| **sire** | 11 | 27099 | 2463.530809 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 677 | 2.68 | 0.0022 |
| **dam*sire** | 8 | 6084.486762 | 760.560845 | Var(Residual) + Q(dam*sire) | MS(Residual) | 677 | 0.83 | 0.5776 |
| **Residual** | 677 | 621526 | 918.059091 | Var(Residual) | . | . | . | . |

Appendix Table 12 REML estimation of variance components for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| **Covariance Parameter Estimates** | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **dam** | 0.1711 | 156.44 | 99.4165 | 1.57 | 0.0578 |
| **sire** | 0.0664 | 60.6901 | 56.3441 | 1.08 | 0.1407 |
| **cross** | 0.0283 | 25.8533 | 54.7523 | 0.47 | 0.3184 |
| **Residual** | 1.0000 | 914.56 | 49.5005 | 18.48 | <.0001 |

Appendix Table 13 GCA/SCA estimates with corresponding T-test (P=0.05) for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 1** | -5.2105 | 6.8687 | 677 | -0.76 | 0.4484 |
| **DAM 10** | -3.2010 | 7.5143 | 677 | -0.43 | 0.6702 |
| **DAM 11** | -8.0232 | 5.1024 | 677 | -1.57 | 0.1163 |
| **DAM 12** | -1.5576 | 6.0759 | 677 | -0.26 | 0.7977 |
| **DAM 13** | -11.3735 | 7.0551 | 677 | -1.61 | 0.1074 |
| **DAM 14** | 0.3124 | 8.8226 | 677 | 0.04 | 0.9718 |
| **DAM 15** | -11.2753 | 6.8081 | 677 | -1.66 | 0.0982 |
| **DAM 16** | 3.5377 | 9.0714 | 677 | 0.39 | 0.6967 |
| **DAM 17** | 36.0375* | 7.9547 | 677 | 4.53 | <.0001 |
| **DAM 18** | -8.9922 | 6.5014 | 677 | -1.38 | 0.1671 |
| **DAM 19** | 2.2359 | 6.9241 | 677 | 0.32 | 0.7469 |
| **DAM 2** | 14.0387 | 7.4621 | 677 | 1.88 | 0.0604 |
| **DAM 20** | -0.1454 | 7.5726 | 677 | -0.02 | 0.9847 |
| **DAM 3** | 0.1025 | 6.8400 | 677 | 0.01 | 0.9880 |
| **DAM 4** | -2.1393 | 6.7517 | 677 | -0.32 | 0.7515 |
| **DAM 5** | -10.8634 | 7.3213 | 677 | -1.48 | 0.1383 |
| **DAM 6** | 5.4239 | 7.0063 | 677 | 0.77 | 0.4391 |
| **DAM 7** | 0.5919 | 6.8687 | 677 | 0.09 | 0.9313 |
| **DAM 8** | 1.0981 | 5.8969 | 677 | 0.19 | 0.8523 |

**Estimates**

| Parents/ Cross | Estimate | Standard Error | DF | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| **DAM 9** | -0.5973 | 7.3830 | 677 | -0.08 | 0.9355 |
| **SIRE 1** | 10.6884 | 4.9066 | 677 | 2.18 | 0.0297 |
| **SIRE 10** | 3.7095 | 4.6289 | 677 | 0.80 | 0.4232 |
| **SIRE 11** | -8.7648 | 5.0658 | 677 | -1.73 | 0.0841 |
| **SIRE 12** | -2.6356 | 5.6573 | 677 | -0.47 | 0.6414 |
| **SIRE 2** | -1.7333 | 5.5326 | 677 | -0.31 | 0.7542 |
| **SIRE 3** | 2.1749 | 4.7785 | 677 | 0.46 | 0.6491 |
| **SIRE 4** | 2.8325 | 6.6075 | 677 | 0.43 | 0.6683 |
| **SIRE 5** | 0.9457 | 6.8522 | 677 | 0.14 | 0.8903 |
| **SIRE 6** | -2.1950 | 5.7094 | 677 | -0.38 | 0.7008 |
| **SIRE 7** | -5.5191 | 4.8563 | 677 | -1.14 | 0.2562 |
| **SIRE 8** | 7.1018 | 5.8130 | 677 | 1.22 | 0.2222 |
| **SIRE 9** | -6.6050 | 5.7753 | 677 | -1.14 | 0.2532 |
| **10x3** | -1.2740 | 4.7665 | 677 | -0.27 | 0.7893 |
| **10x5** | 0.7450 | 4.9355 | 677 | 0.15 | 0.8801 |
| **11x10** | 1.1408 | 4.4483 | 677 | 0.26 | 0.7977 |
| **11x11** | -5.2384 | 4.4702 | 677 | -1.17 | 0.2417 |
| **11x3** | 1.2756 | 4.6915 | 677 | 0.27 | 0.7858 |
| **11x7** | 1.4961 | 4.4474 | 677 | 0.34 | 0.7367 |
| **12x10** | -1.3269 | 4.5290 | 677 | -0.29 | 0.7696 |
| **12x8** | 1.0695 | 4.6359 | 677 | 0.23 | 0.8176 |

**Estimates**

| Parents/ Cross | Estimate | Standard Error | DF | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| **13x1** | -1.4866 | 4.7328 | 677 | -0.31 | 0.7535 |
| **13x12** | -0.3930 | 4.7799 | 677 | -0.08 | 0.9345 |
| **14x6** | 0.05162 | 4.8689 | 677 | 0.01 | 0.9915 |
| **15x6** | 0.1335 | 4.8575 | 677 | 0.03 | 0.9781 |
| **15x7** | -1.9968 | 4.6899 | 677 | -0.43 | 0.6704 |
| **16x4** | 0.5846 | 4.8814 | 677 | 0.12 | 0.9047 |
| **17x1** | 5.9555 | 4.8279 | 677 | 1.23 | 0.2178 |
| **18x1** | 1.2470 | 4.6396 | 677 | 0.27 | 0.7882 |
| **18x9** | -2.7330 | 4.6956 | 677 | -0.58 | 0.5607 |
| **19x11** | 0.4501 | 4.7281 | 677 | 0.10 | 0.9242 |
| **19x9** | -0.08063 | 4.7155 | 677 | -0.02 | 0.9864 |
| **1x12** | -0.6471 | 4.7510 | 677 | -0.14 | 0.8917 |
| **1x3** | -0.2140 | 4.6854 | 677 | -0.05 | 0.9636 |
| **20x2** | 1.6797 | 4.9289 | 677 | 0.34 | 0.7334 |
| **20x3** | -1.7038 | 4.7767 | 677 | -0.36 | 0.7214 |
| **2x3** | 2.6622 | 4.7619 | 677 | 0.56 | 0.5763 |
| **2x5** | -0.3422 | 4.9351 | 677 | -0.07 | 0.9447 |
| **3x1** | -1.9388 | 4.6912 | 677 | -0.41 | 0.6795 |
| **3x8** | 1.9558 | 4.8377 | 677 | 0.40 | 0.6861 |
| **4x1** | 0.7761 | 4.7108 | 677 | 0.16 | 0.8692 |
| **4x7** | -1.1296 | 4.7126 | 677 | -0.24 | 0.8106 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **5x10** | -1.7953 | 4.8005 | 677 | -0.37 | 0.7085 |
| **6x11** | 1.0546 | 4.7170 | 677 | 0.22 | 0.8232 |
| **6x2** | -0.1582 | 4.7514 | 677 | -0.03 | 0.9734 |
| **7x12** | -0.08269 | 4.7510 | 677 | -0.02 | 0.9861 |
| **7x3** | 0.1805 | 4.6854 | 677 | 0.04 | 0.9693 |
| **8x10** | 3.5615 | 4.5568 | 677 | 0.78 | 0.4347 |
| **8x2** | -2.2599 | 4.6243 | 677 | -0.49 | 0.6252 |
| **8x6** | -1.1202 | 4.6725 | 677 | -0.24 | 0.8106 |
| **9x4** | 0.6220 | 4.9027 | 677 | 0.13 | 0.8991 |
| **9x7** | -0.7207 | 4.7553 | 677 | -0.15 | 0.8796 |

Appendix Table 14 ANOVA for mean performance by parental strains following GLM Procedure for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Model** | 8 | 104729.284 | 13091.1604 | 13.49 | <.0001 |
| **Error** | 707 | 686109.444 | 970.4518 | | |
| **Corrected Total** | 715 | 790838.728 | | | |

Appendix Table 15 Mean comparison of performance by parental strains using Tukey-Kramer Test for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| Tukey-Kramer Comparison Lines for Least Squares Means of dam | | | | |
|---|---|---|---|---|
| LS-means with the same letter are not significantly different. | | | | |
| | | gw LSMEAN | dam | LSMEAN Number |
| | A | 146.2778 | **5** | 5 |
| | | | | |
| | B | 104.0714 | **7** | 7 |
| | B | | | |
| C | B | 90.7273 | **8** | 8 |
| C | B | | | |
| C | B | 83.6695 | **4** | 4 |
| C | B | | | |
| C | B | 81.9000 | **3** | 3 |
| C | B | | | |
| C | B | 78.7750 | **2** | 2 |
| C | B | | | |
| C | B | 76.6591 | **1** | 1 |
| C | | | | |
| C | | 76.5605 | **6** | 6 |
| C | | | | |
| C | | 74.3357 | **9** | 9 |

Note: Dam strain 1 – AR; 2 – ARMK; 3 – KR; 4 – KS; 5 – KTh; 6 – Mix; 7 RG; 8 – Thompson; 9 - Tishomingo

Appendix Table 16 The Type 3 Mixed Procedure of analysis of variance for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| Type 3 Analysis of Variance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **dam** | 18 | 1203607 | 66867 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 1480 | 9.14 | <.0001 |
| **sire** | 11 | 936922 | 85175 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 1480 | 11.64 | <.0001 |
| **dam*sire** | 7 | 53899 | 7699.882732 | Var(Residual) + Q(dam*sire) | MS(Residual) | 1480 | 1.05 | 0.3922 |
| **Residual** | 1480 | 10827647 | 7315.977758 | Var(Residual) | . | . | . | . |

Appendix Table 17 REML estimation of variance components for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| Covariance Parameter Estimates | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **Dam** | 0.1998 | 1463.21 | 587.61 | 2.49 | 0.0064 |
| **Sire** | 0.1896 | 1388.25 | 663.43 | 2.09 | 0.0182 |
| **Cross** | 0 | 0 | . | . | . |
| **Residual** | 1.0000 | 7322.73 | 268.69 | 27.25 | <.0001 |

Appendix Table 18 GCA/SCA estimates with corresponding T-test (P=0.05) for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| **Estimates** | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 1** | -24.7995 | 15.2140 | 1480 | -1.63 | 0.1033 |
| **DAM 10** | -45.4955 | 15.2412 | 1480 | -2.99 | 0.0029 |
| **DAM 11** | 10.2043 | 12.1881 | 1480 | 0.84 | 0.4026 |
| **DAM 12** | -59.4547 | 14.5064 | 1480 | -4.10 | <.0001 |
| **DAM 13** | 60.4941 | 21.2309 | 1480 | 2.85 | 0.0044 |
| **DAM 14** | -29.1778 | 17.1418 | 1480 | -1.70 | 0.0889 |
| **DAM 15** | 23.5872 | 14.4909 | 1480 | 1.63 | 0.1038 |
| **DAM 16** | 24.4196 | 28.3809 | 1480 | 0.86 | 0.3897 |
| **DAM 18** | 57.8824 | 17.7588 | 1480 | 3.26 | 0.0011 |
| **DAM 19** | -0.3281 | 14.5993 | 1480 | -0.02 | 0.9821 |
| **DAM 2** | 12.2091 | 15.9535 | 1480 | 0.77 | 0.4442 |
| **DAM 20** | 6.2279 | 15.2221 | 1480 | 0.41 | 0.6825 |
| **DAM 3** | -21.8796 | 25.8394 | 1480 | -0.85 | 0.3973 |
| **DAM 4** | 17.4613 | 16.8679 | 1480 | 1.04 | 0.3008 |
| **DAM 5** | -7.3654 | 18.6712 | 1480 | -0.39 | 0.6933 |
| **DAM 6** | 46.3458 | 14.6558 | 1480 | 3.16 | 0.0016 |
| **DAM 7** | -35.0115 | 15.0933 | 1480 | -2.32 | 0.0205 |
| **DAM 8** | 11.6990 | 12.9791 | 1480 | 0.90 | 0.3675 |
| **DAM 9** | -47.0187 | 14.8313 | 1480 | -3.17 | 0.0016 |

**Estimates**

| Parents/ Cross | Estimate | Standard Error | DF | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| **SIRE 1** | 53.9887 | 19.4715 | 1480 | 2.77 | 0.0056 |
| **SIRE 10** | 58.7832 | 14.2127 | 1480 | 4.14 | <.0001 |
| **SIRE 11** | -17.5024 | 14.0829 | 1480 | -1.24 | 0.2141 |
| **SIRE 12** | 19.0782 | 16.7352 | 1480 | 1.14 | 0.2545 |
| **SIRE 2** | -74.1187 | 14.7094 | 1480 | -5.04 | <.0001 |
| **SIRE 3** | -14.9721 | 14.5224 | 1480 | -1.03 | 0.3027 |
| **SIRE 4** | 5.5255 | 17.8006 | 1480 | 0.31 | 0.7563 |
| **SIRE 5** | 5.8792 | 17.1939 | 1480 | 0.34 | 0.7324 |
| **SIRE 6** | -9.2582 | 15.1569 | 1480 | -0.61 | 0.5414 |
| **SIRE 7** | -13.7118 | 13.9885 | 1480 | -0.98 | 0.3271 |
| **SIRE 8** | 6.6053 | 17.4065 | 1480 | 0.38 | 0.7044 |
| **SIRE 9** | -20.2970 | 16.6829 | 1480 | -1.22 | 0.2239 |
| **10x3** | 0 | . | . | . | . |
| **10x5** | 0 | . | . | . | . |
| **11x10** | 0 | . | . | . | . |
| **11x11** | 0 | . | . | . | . |
| **11x3** | 0 | . | . | . | . |
| **11x7** | 0 | . | . | . | . |
| **12x10** | 0 | . | . | . | . |
| **12x8** | 0 | . | . | . | . |
| **13x1** | 0 | . | . | . | . |
| **13x12** | 0 | . | . | . | . |
| **14x6** | 0 | . | . | . | . |
| **15x6** | 0 | . | . | . | . |
| **15x7** | 0 | . | . | . | . |
| **16x4** | 0 | . | . | . | . |
| **18x1** | 0 | . | . | . | . |
| **18x9** | 0 | . | . | . | . |
| **19x11** | 0 | . | . | . | . |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **19x9** | 0 | . | . | . | . |
| **1x12** | 0 | . | . | . | . |
| **1x3** | 0 | . | . | . | . |
| **20x2** | 0 | . | . | . | . |
| **20x3** | 0 | . | . | . | . |
| **2x3** | 0 | . | . | . | . |
| **2x5** | 0 | . | . | . | . |
| **3x1** | 0 | . | . | . | . |
| **4x1** | 0 | . | . | . | . |
| **4x7** | 0 | . | . | . | . |
| **5x10** | 0 | . | . | . | . |
| **6x11** | 0 | . | . | . | . |
| **6x2** | 0 | . | . | . | . |
| **7x12** | 0 | . | . | . | . |
| **7x3** | 0 | . | . | . | . |
| **8x10** | 0 | . | . | . | . |
| **8x2** | 0 | . | . | . | . |
| **8x6** | 0 | . | . | . | . |
| **9x4** | 0 | . | . | . | . |
| **9x7** | 0 | . | . | . | . |

Appendix Table 19 ANOVA for mean performance by parental strains following GLM Procedure for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| **Model** | 7 | 533951.04 | 76278.72 | 8.94 | <.0001 |
| **Error** | 1509 | 12880632.61 | 8535.87 | | |
| **Corrected Total** | 1516 | 13414583.65 | | | |

Appendix Table 20 Mean comparison of performance by parental strains using Scheffe Test for final body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| **Means with the same letter are not significantly different.** | | | | |
|---|---|---|---|---|
| **Scheffe Grouping** | | **Mean** | **N** | **dam** |
| | A | 260.00 | 5 | 8 |
| | A | | | |
| B | A | 215.13 | 78 | 7 |
| B | A | | | |
| B | A | 209.46 | 148 | 4 |
| B | A | | | |
| B | A | 202.05 | 239 | 3 |
| B | A | | | |
| B | A | 201.97 | 497 | 9 |
| B | A | | | |
| B | A | 192.99 | 321 | 6 |
| B | | | | |
| B | | 152.98 | 104 | 2 |
| B | | | | |
| B | | 152.08 | 125 | 1 |

Note: Dam strain 1 – AR; 2 – ARMK; 3 – KR; 4 – KS; 5 – KTh; 6 – Mix; 7 RG; 8 – Thompson; 9 - Tishomingo

Appendix Table 21 The Type 3 Mixed Procedure of analysis of variance for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| Type 3 Analysis of Variance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **dam** | 18 | 1122919 | 62384 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 1480 | 8.84 | <.0001 |
| **sire** | 11 | 882814 | 80256 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 1480 | 11.38 | <.0001 |
| **dam*sire** | 7 | 46054 | 6579.159764 | Var(Residual) + Q(dam*sire) | MS(Residual) | 1480 | 0.93 | 0.4800 |
| **Residual** | 1480 | 10440639 | 7054.486114 | Var(Residual) | . | . | . | . |

Appendix Table 22 REML estimation of variance components for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| Covariance Parameter Estimates | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **Dam** | 0.1871 | 1320.19 | 532.95 | 2.48 | 0.0066 |
| **Sire** | 0.1833 | 1293.47 | 619.75 | 2.09 | 0.0184 |
| **Cross** | 0 | 0 | . | . | . |
| **Residual** | 1.0000 | 7056.66 | 258.91 | 27.26 | <.0001 |

Appendix Table 23 GCA/SCA estimates with corresponding T-test (P=0.05) for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 1** | -23.9430 | 14.6870 | 1480 | -1.63 | 0.1033 |
| **DAM 10** | -43.2113 | 14.7060 | 1480 | -2.94 | 0.0034 |
| **DAM 11** | 11.5210 | 11.7401 | 1480 | 0.98 | 0.3266 |
| **DAM 12** | -56.7031 | 14.0044 | 1480 | -4.05 | <.0001 |
| **DAM 13** | 57.4523* | 20.5523 | 1480 | 2.80 | 0.0053 |
| **DAM 14** | -26.8623 | 16.5961 | 1480 | -1.62 | 0.1057 |
| **DAM 15** | 22.2547 | 14.0060 | 1480 | 1.59 | 0.1123 |
| **DAM 16** | 21.7013 | 27.3263 | 1480 | 0.79 | 0.4272 |
| **DAM 18** | 53.5325 | 17.1902 | 1480 | 3.11 | 0.0019 |
| **DAM 19** | -0.8690 | 14.1011 | 1480 | -0.06 | 0.9509 |
| **DAM 2** | 14.3252 | 15.4061 | 1480 | 0.93 | 0.3526 |
| **DAM 20** | 4.1863 | 14.7245 | 1480 | 0.28 | 0.7762 |
| **DAM 3** | -21.2656 | 24.9317 | 1480 | -0.85 | 0.3938 |
| **DAM 4** | 17.1634 | 16.3409 | 1480 | 1.05 | 0.2937 |
| **DAM 5** | -8.2298 | 18.0817 | 1480 | -0.46 | 0.6491 |
| **DAM 6** | 43.4050 | 14.1753 | 1480 | 3.06 | 0.0022 |
| **DAM 7** | -32.4871 | 14.5680 | 1480 | -2.23 | 0.0259 |
| **DAM 8** | 12.6917 | 12.5112 | 1480 | 1.01 | 0.3105 |
| **DAM 9** | -44.6623 | 14.3326 | 1480 | -3.12 | 0.0019 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **SIRE 1** | 52.6480 | 18.9098 | 1480 | 2.78 | 0.0054 |
| **SIRE 10** | 56.5157 | 13.7779 | 1480 | 4.10 | <.0001 |
| **SIRE 11** | -15.9389 | 13.6651 | 1480 | -1.17 | 0.2436 |
| **SIRE 12** | 18.6552 | 16.2407 | 1480 | 1.15 | 0.2509 |
| **SIRE 2** | -71.9454 | 14.2898 | 1480 | -5.03 | <.0001 |
| **SIRE 3** | -14.9984 | 14.0598 | 1480 | -1.07 | 0.2863 |
| **SIRE 4** | 4.6961 | 17.2947 | 1480 | 0.27 | 0.7860 |
| **SIRE 5** | 4.0668 | 16.6793 | 1480 | 0.24 | 0.8074 |
| **SIRE 6** | -9.1548 | 14.7101 | 1480 | -0.62 | 0.5338 |
| **SIRE 7** | -13.9157 | 13.5653 | 1480 | -1.03 | 0.3051 |
| **SIRE 8** | 5.9452 | 16.9186 | 1480 | 0.35 | 0.7253 |
| **SIRE 9** | -16.5737 | 16.1963 | 1480 | -1.02 | 0.3063 |
| **10x3** | 0 | . | . | . | . |
| **10x5** | 0 | . | . | . | . |
| **11x10** | 0 | . | . | . | . |
| **11x11** | 0 | . | . | . | . |
| **11x3** | 0 | . | . | . | . |
| **11x7** | 0 | . | . | . | . |
| **12x10** | 0 | . | . | . | . |
| **12x8** | 0 | . | . | . | . |
| **13x1** | 0 | . | . | . | . |
| **13x12** | 0 | . | . | . | . |
| **14x6** | 0 | . | . | . | . |
| **15x6** | 0 | . | . | . | . |
| **15x7** | 0 | . | . | . | . |
| **16x4** | 0 | . | . | . | . |
| **18x1** | 0 | . | . | . | . |
| **18x9** | 0 | . | . | . | . |
| **19x11** | 0 | . | . | . | . |

**Estimates**

| Parents/ Cross | Estimate | Standard Error | DF | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| **19x9** | 0 | . | . | . | . |
| **1x12** | 0 | . | . | . | . |
| **1x3** | 0 | . | . | . | . |
| **20x2** | 0 | . | . | . | . |
| **20x3** | 0 | . | . | . | . |
| **2x3** | 0 | . | . | . | . |
| **2x5** | 0 | . | . | . | . |
| **3x1** | 0 | . | . | . | . |
| **4x1** | 0 | . | . | . | . |
| **4x7** | 0 | . | . | . | . |
| **5x10** | 0 | . | . | . | . |
| **6x11** | 0 | . | . | . | . |
| **6x2** | 0 | . | . | . | . |
| **7x12** | 0 | . | . | . | . |
| **7x3** | 0 | . | . | . | . |
| **8x10** | 0 | . | . | . | . |
| **8x2** | 0 | . | . | . | . |
| **8x6** | 0 | . | . | . | . |
| **9x4** | 0 | . | . | . | . |
| **9x7** | 0 | . | . | . | . |

Appendix Table 24 ANOVA for mean performance by parental strains following GLM Procedure for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| **Model** | 7 | 515345.82 | 73620.83 | 9.00 | <.0001 |
| **Error** | 1509 | 12350203.01 | 8184.36 | | |
| **Corrected Total** | 1516 | 12865548.83 | | | |

Appendix Table 25 Mean comparison of performance by parental strains using Scheffe Test for body weight gain of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in split-pond for additional 245 days of communal rearing.

| **Means with the same letter are not significantly different.** | | | | |
|---|---|---|---|---|
| **Scheffe Grouping** | | **Mean** | **N** | **dam** |
| | A | 244.40 | 5 | 8 |
| | A | | | |
| B | A | 205.62 | 78 | 7 |
| B | A | | | |
| B | A | 199.71 | 148 | 4 |
| B | A | | | |
| B | A | 191.97 | 497 | 9 |
| B | A | | | |
| B | A | 191.31 | 239 | 3 |
| B | A | | | |
| B | A | 182.81 | 321 | 6 |
| B | | | | |
| B | | 143.54 | 104 | 2 |
| B | | | | |
| B | | 143.10 | 125 | 1 |

Note: Dam strain 1 – AR; 2 – ARMK; 3 – KR; 4 – KS; 5 – KTh; 6 – Mix; 7 RG; 8 – Thompson; 9 - Tishomingo

Appendix Table 26 The Type 3 Mixed Procedure of analysis of variance for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| Type 3 Analysis of Variance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **dam** | 19 | 4380.200908 | 230.536890 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 66 | 10.11 | <.0001 |
| **sire** | 11 | 341.735121 | 31.066829 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 66 | 1.36 | 0.2121 |
| **dam*sire** | 8 | 276.019249 | 34.502406 | Var(Residual) + Q(dam*sire) | MS(Residual) | 66 | 1.51 | 0.1699 |
| **Residual** | 66 | 1505.60 | 22.812053 | Var(Residual) | . | . | . | . |

Appendix Table 27 REML estimation of variance components for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| Covariance Parameter Estimates | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **dam** | 3.7327 | 83.8272 | 31.0813 | 2.70 | 0.0035 |
| **sire** | 0.07975 | 1.7910 | 3.3471 | 0.54 | 0.2963 |
| **cross** | 0.1178 | 2.6454 | 4.5594 | 0.58 | 0.2809 |
| **Residual** | 1.0000 | 22.4578 | 3.8466 | 5.84 | <.0001 |

Appendix Table 28 GCA/SCA estimates with corresponding T-test (P=0.05) for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| **Estimates** | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 1** | 4.6814 | 3.0538 | 66 | 1.53 | 0.1301 |
| **DAM 10** | -3.4484 | 3.0614 | 66 | -1.13 | 0.2641 |
| **DAM 11** | -0.3669 | 2.7089 | 66 | -0.14 | 0.8927 |
| **DAM 12** | -4.2204 | 3.0698 | 66 | -1.37 | 0.1738 |
| **DAM 13** | 6.8620 | 3.8395 | 66 | 1.79 | 0.0785 |
| **DAM 14** | -2.7981 | 3.7015 | 66 | -0.76 | 0.4524 |
| **DAM 15** | 1.1446 | 3.0548 | 66 | 0.37 | 0.7091 |
| **DAM 16** | 2.1887 | 4.7876 | 66 | 0.46 | 0.6491 |
| **DAM 17** | 33.7885 | 3.6748 | 66 | 9.19 | <.0001 |
| **DAM 18** | -3.9315 | 3.0570 | 66 | -1.29 | 0.2029 |
| **DAM 19** | -3.2957 | 3.0744 | 66 | -1.07 | 0.2876 |
| **DAM 2** | -5.1492 | 3.0614 | 66 | -1.68 | 0.0973 |
| **DAM 20** | -5.7670 | 3.3130 | 66 | -1.74 | 0.0864 |
| **DAM 3** | -3.4358 | 3.3209 | 66 | -1.03 | 0.3046 |
| **DAM 4** | -0.8147 | 3.0391 | 66 | -0.27 | 0.7895 |
| **DAM 5** | -0.4491 | 3.6843 | 66 | -0.12 | 0.9034 |
| **DAM 6** | -4.4154 | 3.0695 | 66 | -1.44 | 0.1550 |
| **DAM 7** | 1.3993 | 3.0538 | 66 | 0.46 | 0.6483 |
| **DAM 8** | -3.5701 | 2.7928 | 66 | -1.28 | 0.2056 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 9** | -8.4022 | 3.0661 | 66 | -2.74 | 0.0079 |
| **SIRE 1** | 0.6935 | 1.1823 | 66 | 0.59 | 0.5595 |
| **SIRE 10** | 1.4358 | 1.1577 | 66 | 1.24 | 0.2193 |
| **SIRE 11** | 0.2093 | 1.1763 | 66 | 0.18 | 0.8594 |
| **SIRE 12** | 0.5552 | 1.2198 | 66 | 0.46 | 0.6505 |
| **SIRE 2** | -0.7100 | 1.1965 | 66 | -0.59 | 0.5550 |
| **SIRE 3** | -0.2080 | 1.1164 | 66 | -0.19 | 0.8528 |
| **SIRE 4** | -0.2640 | 1.2745 | 66 | -0.21 | 0.8366 |
| **SIRE 5** | -0.1649 | 1.2394 | 66 | -0.13 | 0.8946 |
| **SIRE 6** | -0.3717 | 1.2129 | 66 | -0.31 | 0.7602 |
| **SIRE 7** | -0.2955 | 1.1398 | 66 | -0.26 | 0.7962 |
| **SIRE 8** | -0.3317 | 1.2546 | 66 | -0.26 | 0.7923 |
| **SIRE 9** | -0.5481 | 1.2350 | 66 | -0.44 | 0.6587 |
| **10x3** | -0.3494 | 1.5238 | 66 | -0.23 | 0.8193 |
| **10x5** | 0.2406 | 1.5244 | 66 | 0.16 | 0.8751 |
| **11x10** | 0.7460 | 1.4869 | 66 | 0.50 | 0.6175 |
| **11x11** | 0.03531 | 1.4874 | 66 | 0.02 | 0.9811 |
| **11x3** | -0.2893 | 1.5533 | 66 | -0.19 | 0.8528 |
| **11x7** | -0.5036 | 1.4866 | 66 | -0.34 | 0.7359 |
| **12x10** | 0.3011 | 1.5254 | 66 | 0.20 | 0.8442 |
| **12x8** | -0.4343 | 1.5260 | 66 | -0.28 | 0.7769 |

**Estimates**

| Parents/ Cross | Estimate | Standard Error | DF | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| **13x1** | -0.2300 | 1.5800 | 66 | -0.15 | 0.8847 |
| **13x12** | 0.4465 | 1.5801 | 66 | 0.28 | 0.7784 |
| **14x6** | -0.08830 | 1.6049 | 66 | -0.06 | 0.9563 |
| **15x6** | 0.6002 | 1.5251 | 66 | 0.39 | 0.6952 |
| **15x7** | -0.5640 | 1.5248 | 66 | -0.37 | 0.7126 |
| **16x4** | 0.06907 | 1.6077 | 66 | 0.04 | 0.9659 |
| **17x1** | 1.0663 | 1.6048 | 66 | 0.66 | 0.5087 |
| **18x1** | 0.7037 | 1.5255 | 66 | 0.46 | 0.6461 |
| **18x9** | -0.8278 | 1.5260 | 66 | -0.54 | 0.5893 |
| **19x11** | -0.1223 | 1.5256 | 66 | -0.08 | 0.9364 |
| **19x9** | 0.01826 | 1.5258 | 66 | 0.01 | 0.9905 |
| **1x12** | -0.5820 | 1.5241 | 66 | -0.38 | 0.7038 |
| **1x3** | 0.7297 | 1.5236 | 66 | 0.48 | 0.6336 |
| **20x2** | -0.3736 | 1.5668 | 66 | -0.24 | 0.8123 |
| **20x3** | 0.1916 | 1.5574 | 66 | 0.12 | 0.9025 |
| **2x3** | 0.3217 | 1.5238 | 66 | 0.21 | 0.8335 |
| **2x5** | -0.4842 | 1.5244 | 66 | -0.32 | 0.7518 |
| **3x1** | -0.05267 | 1.5579 | 66 | -0.03 | 0.9731 |
| **3x8** | -0.05576 | 1.5673 | 66 | -0.04 | 0.9717 |
| **4x1** | -0.4630 | 1.5245 | 66 | -0.30 | 0.7623 |
| **4x7** | 0.4373 | 1.5246 | 66 | 0.29 | 0.7752 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **5x10** | -0.01417 | 1.6048 | 66 | -0.01 | 0.9930 |
| **6x11** | 0.3960 | 1.5251 | 66 | 0.26 | 0.7959 |
| **6x2** | -0.5354 | 1.5252 | 66 | -0.35 | 0.7267 |
| **7x12** | 0.9556 | 1.5241 | 66 | 0.63 | 0.5328 |
| **7x3** | -0.9114 | 1.5236 | 66 | -0.60 | 0.5518 |
| **8x10** | 1.0879 | 1.4952 | 66 | 0.73 | 0.4694 |
| **8x2** | -0.1398 | 1.4960 | 66 | -0.09 | 0.9258 |
| **8x6** | -1.0608 | 1.4962 | 66 | -0.71 | 0.4808 |
| **9x4** | -0.4590 | 1.5260 | 66 | -0.30 | 0.7645 |
| **9x7** | 0.1938 | 1.5255 | 66 | 0.13 | 0.8993 |

Appendix Table 29 ANOVA for mean performance by parental strains following GLM Procedure for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| **Model** | 8 | 0.53794931 | 0.06724366 | 21.72 | <.0001 |
| **Error** | 96 | 0.29726650 | 0.00309653 | | |
| **Corrected Total** | 104 | 0.83521581 | | | |

Appendix Table 30 Mean comparison of performance by parental strains using Tukey-Kramer Test for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in flow-through system for 311 days of separate tank rearing.

| **Tukey-Kramer Comparison Lines for Least Squares Means of dam** | | | |
|---|---|---|---|
| **LS-means with the same letter are not significantly different.** | | | |
| | **cv LSMEAN** | **dam** | **LSMEAN Number** |
| A | 0.68062432 | **5** | 5 |
| | | | |
| B | 0.32076927 | **8** | 8 |
| B | | | |
| B | 0.29084218 | **9** | 9 |
| B | | | |
| B | 0.28137894 | **3** | 3 |
| B | | | |
| B | 0.27611228 | **6** | 6 |
| B | | | |
| B | 0.25900928 | **4** | 4 |
| B | | | |
| B | 0.25653502 | **2** | 2 |
| B | | | |
| B | 0.23849914 | **7** | 7 |
| B | | | |
| B | 0.20307101 | **1** | 1 |
| **The LINES display does not reflect all significant comparisons.<br>The following additional pairs are significantly different: (9,1)** | | | |

Note: Dam strain 1 – AR; 2 – ARMK; 3 – KR; 4 – KS; 5 – KTh; 6 – Mix; 7 RG; 8 – Thompson; 9 - Tishomingo

Appendix Table 31 The Type 3 Mixed Procedure of analysis of variance for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| **Type 3 Analysis of Variance** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **dam** | 19 | 7625.773812 | 401.356516 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 41 | 3.18 | 0.0009 |
| **sire** | 11 | 4021.114628 | 365.555875 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 41 | 2.90 | 0.0065 |
| **dam*sire** | 7 | 2664.769003 | 380.681286 | Var(Residual) + Q(dam*sire) | MS(Residual) | 41 | 3.02 | 0.0118 |
| **Residual** | 41 | 5167.79 | 126.043691 | Var(Residual) | . | . | . | . |

Appendix Table 32 REML estimation of variance components for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| **Covariance Parameter Estimates** | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **dam** | 0.1331 | 21.1784 | 37.2660 | 0.57 | 0.2849 |
| **sire** | 0 | 0 | . | . | . |
| **cross** | 0.2932 | 46.6488 | 56.7361 | 0.82 | 0.2055 |
| **Residual** | 1.0000 | 159.10 | 44.1313 | 3.61 | 0.0002 |

Appendix Table 33 GCA/SCA estimates with corresponding T-test (P=0.05) for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

**Estimates**

| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
|---|---|---|---|---|---|
| **DAM 1** | 0.5588 | 4.0186 | 41 | 0.14 | 0.8901 |
| **DAM 10** | 4.7344 | 4.1081 | 41 | 1.15 | 0.2558 |
| **DAM 11** | -0.9771 | 3.6067 | 41 | -0.27 | 0.7878 |
| **DAM 12** | -0.1630 | 3.9083 | 41 | -0.04 | 0.9669 |
| **DAM 13** | -0.08875 | 4.2069 | 41 | -0.02 | 0.9833 |
| **DAM 14** | 0.2030 | 4.3866 | 41 | 0.05 | 0.9633 |
| **DAM 15** | -2.5861 | 4.0456 | 41 | -0.64 | 0.5262 |
| **DAM 16** | -0.6762 | 4.3866 | 41 | -0.15 | 0.8782 |
| **DAM 17** | 2.0262 | 4.1964 | 41 | 0.48 | 0.6318 |
| **DAM 18** | -3.1508 | 4.0456 | 41 | -0.78 | 0.4405 |
| **DAM 19** | -0.8703 | 4.0186 | 41 | -0.22 | 0.8296 |
| **DAM 2** | -3.4252 | 4.0456 | 41 | -0.85 | 0.4021 |
| **DAM 20** | -0.7279 | 4.3866 | 41 | -0.17 | 0.8690 |
| **DAM 3** | 3.6011 | 4.0456 | 41 | 0.89 | 0.3786 |
| **DAM 4** | -1.6795 | 4.0186 | 41 | -0.42 | 0.6782 |
| **DAM 5** | 1.6985 | 4.1964 | 41 | 0.40 | 0.6878 |
| **DAM 6** | -0.3871 | 3.9617 | 41 | -0.10 | 0.9226 |
| **DAM 7** | 3.3553 | 4.1081 | 41 | 0.82 | 0.4188 |
| **DAM 8** | 0.3246 | 3.6928 | 41 | 0.09 | 0.9304 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 9** | -1.7700 | 4.0456 | 41 | -0.44 | 0.6640 |
| **SIRE 1** | 0 | . | . | . | . |
| **SIRE 10** | 0 | . | . | . | . |
| **SIRE 11** | 0 | . | . | . | . |
| **SIRE 12** | 0 | . | . | . | . |
| **SIRE 2** | 0 | . | . | . | . |
| **SIRE 3** | 0 | . | . | . | . |
| **SIRE 4** | 0 | . | . | . | . |
| **SIRE 5** | 0 | . | . | . | . |
| **SIRE 6** | 0 | . | . | . | . |
| **SIRE 7** | 0 | . | . | . | . |
| **SIRE 8** | 0 | . | . | . | . |
| **SIRE 9** | 0 | . | . | . | . |
| **10x3** | -2.0029 | 5.6634 | 41 | -0.35 | 0.7254 |
| **10x5** | 12.4312 | 6.0890 | 41 | 2.04 | 0.0477 |
| **11x10** | -2.5028 | 5.2743 | 41 | -0.47 | 0.6376 |
| **11x11** | 5.2250 | 5.2743 | 41 | 0.99 | 0.3277 |
| **11x3** | -2.4054 | 6.0643 | 41 | -0.40 | 0.6937 |
| **11x7** | -2.4691 | 5.2743 | 41 | -0.47 | 0.6422 |
| **12x10** | -0.3384 | 5.3454 | 41 | -0.06 | 0.9498 |
| **12x8** | -0.02065 | 5.3454 | 41 | -0.00 | 0.9969 |
| **13x1** | 1.1776 | 6.0942 | 41 | 0.19 | 0.8477 |
| **13x12** | -1.3731 | 6.0942 | 41 | -0.23 | 0.8229 |
| **14x6** | 0.4471 | 6.1037 | 41 | 0.07 | 0.9420 |
| **15x6** | -4.7154 | 6.0858 | 41 | -0.77 | 0.4429 |
| **15x7** | -0.9808 | 5.3787 | 41 | -0.18 | 0.8562 |
| **16x4** | -1.4894 | 6.1037 | 41 | -0.24 | 0.8084 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **17x1** | 4.4630 | 5.4161 | 41 | 0.82 | 0.4147 |
| **18x1** | -4.3958 | 5.3787 | 41 | -0.82 | 0.4185 |
| **18x9** | -2.5444 | 6.0858 | 41 | -0.42 | 0.6781 |
| **19x11** | 1.5697 | 5.6504 | 41 | 0.28 | 0.7826 |
| **19x9** | -3.4866 | 5.6504 | 41 | -0.62 | 0.5406 |
| **1x12** | -0.6326 | 5.6504 | 41 | -0.11 | 0.9114 |
| **1x3** | 1.8635 | 5.6504 | 41 | 0.33 | 0.7432 |
| **20x2** | -1.6033 | 6.1037 | 41 | -0.26 | 0.7941 |
| **20x3** | -4.5245 | 5.3787 | 41 | -0.84 | 0.4051 |
| **2x3** | -3.0200 | 6.0858 | 41 | -0.50 | 0.6224 |
| **2x5** | -1.9224 | 5.3787 | 41 | -0.36 | 0.7226 |
| **3x1** | 9.8543 | 6.0858 | 41 | 1.62 | 0.1131 |
| **3x8** | -2.1103 | 5.6504 | 41 | -0.37 | 0.7107 |
| **4x1** | -1.5890 | 5.6504 | 41 | -0.28 | 0.7799 |
| **4x7** | 3.7413 | 5.4161 | 41 | 0.69 | 0.4936 |
| **5x10** | -0.08137 | 5.3583 | 41 | -0.02 | 0.9880 |
| **6x11** | -0.7713 | 5.6422 | 41 | -0.14 | 0.8919 |
| **6x2** | 4.3020 | 6.0890 | 41 | 0.71 | 0.4839 |
| **7x12** | 3.0886 | 5.6634 | 41 | 0.55 | 0.5885 |
| **7x3** | -3.0572 | 5.2943 | 41 | -0.58 | 0.5668 |
| **8x10** | 6.2275 | 5.2943 | 41 | 1.18 | 0.2463 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **8x2** | -2.4553 | 5.2943 | 41 | -0.46 | 0.6453 |
| **8x6** | -0.4198 | 6.0858 | 41 | -0.07 | 0.9453 |
| **9x4** | -3.4790 | 5.3787 | 41 | -0.65 | 0.5214 |

Appendix Table 34 ANOVA for mean performance by parental cross following GLM Procedure for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| **Model** | 20 | 7324.18037 | 366.20902 | 2.23 | 0.0092 |
| **Error** | 58 | 9512.73205 | 164.01262 | | |
| **Corrected Total** | 78 | 16836.91242 | | | |

Appendix Table 35 Mean comparison of performance by parental cross using Tukey-Kramer Test for coefficient of variation in body weight of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny in recirculating system for additional 245 days of separate tank rearing.

| **Tukey-Kramer Comparison Lines for Least Squares Means of Parental Cross** | | | | |
|---|---|---|---|---|
| **LS-means with the same letter are not significantly different.** | | | | |
| | | **cv LSMEAN** | **Cross** | **LSMEAN Number** |
| | A | 89.99541 | **ARMKxDB** | 12 |
| | A | | | |
| B | A | 42.14426 | **KRxTBB** | 19 |
| B | A | | | |
| B | A | 41.99625 | **KThxDR** | 2 |
| B | A | | | |
| B | A | 36.53805 | **TishxRG** | 13 |
| B | A | | | |

**Tukey-Kramer Comparison Lines for Least Squares Means of Parental Cross**

**LS-means with the same letter are not significantly different.**

| | | **cv LSMEAN** | **Cross** | **LSMEAN Number** |
|---|---|---|---|---|
| B | A | 36.46542 | **KRxDB** | 16 |
| B | A | | | |
| B | A | 35.59495 | **KRxRG** | 18 |
| B | A | | | |
| B | A | 34.78819 | **KSxDB** | 20 |
| B | A | | | |
| B | A | 32.03125 | **KRxDR** | 17 |
| B | A | | | |
| B | A | 31.56692 | **MixxTBB** | 6 |
| B | A | | | |
| B | A | 31.54520 | **MixxRG** | 5 |
| B | A | | | |
| B | A | 29.74938 | **ARMKxTBB** | 15 |
| B | A | | | |
| B | A | 28.07211 | **TishxDR** | 11 |
| B | A | | | |
| B | A | 25.46654 | **TishxDB** | 10 |
| B | A | | | |
| B | A | 24.22536 | **KSxDR** | 21 |
| B | A | | | |
| B | A | 23.18816 | **ThxDB** | 9 |
| B | | | | |
| B | | 22.62508 | **ARxDB** | 1 |
| B | | | | |
| B | | 18.84733 | **TishxTBB** | 14 |
| B | | | | |
| B | | 18.77399 | **MixxDB** | 3 |
| B | | | | |
| B | | 17.88942 | **MixxDR** | 4 |
| B | | | | |
| B | | 17.34018 | **RGxTBB** | 8 |
| B | | | | |
| B | | 13.68837 | **RGxDB** | 7 |

**The LINES display does not reflect all significant comparisons. The following additional pairs are significantly different: (12,16) (12,18) (12,20) (12,17) (12,6) (12,5) (12,15) (12,11) (12,10) (12,21)**

Appendix Table 36 The Type 3 Mixed Procedure of analysis of variance for survival rate of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny from natural *Aeromonas hydrophila* infection.

| Type 3 Analysis of Variance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **dam** | 19 | 12734 | 670.185319 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 67 | 2.13 | 0.0122 |
| **sire** | 11 | 10066 | 915.116399 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 67 | 2.91 | 0.0034 |
| **dam*sire** | 9 | 4751.611118 | 527.956791 | Var(Residual) + Q(dam*sire) | MS(Residual) | 67 | 1.68 | 0.1110 |
| **Residual** | 67 | 21045 | 314.106132 | Var(Residual) | . | . | . | . |

Appendix Table 37 REML estimation of variance components for survival rate of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny from natural *Aeromonas hydrophila* infection.

| Covariance Parameter Estimates | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **dam** | 0.1902 | 63.7632 | 53.5457 | 1.19 | 0.1169 |
| **sire** | 0.3253 | 109.08 | 64.6532 | 1.69 | 0.0458 |
| **cross** | 0 | 0 | . | . | . |
| **Residual** | 1.0000 | 335.28 | 53.0717 | 6.32 | <.0001 |

Appendix Table 38 GCA/SCA estimates with corresponding T-test (P=0.05) for survival rate of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny from natural *Aeromonas hydrophila* infection.

**Estimates**

| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
|---|---|---|---|---|---|
| **DAM 1** | 2.5436 | 5.9755 | 67 | 0.43 | 0.6717 |
| **DAM 10** | 0.8185 | 6.0172 | 67 | 0.14 | 0.8922 |
| **DAM 11** | 4.6496 | 5.2101 | 67 | 0.89 | 0.3754 |
| **DAM 12** | 5.0202 | 6.0903 | 67 | 0.82 | 0.4127 |
| **DAM 13** | 0.4764 | 6.9063 | 67 | 0.07 | 0.9452 |
| **DAM 14** | 4.3685 | 6.7570 | 67 | 0.65 | 0.5202 |
| **DAM 15** | -2.7308 | 5.9508 | 67 | -0.46 | 0.6478 |
| **DAM 16** | -0.6678 | 7.4238 | 67 | -0.09 | 0.9286 |
| **DAM 17** | -11.9721 | 6.6694 | 67 | -1.80 | 0.0772 |
| **DAM 18** | -5.2013 | 6.0152 | 67 | -0.86 | 0.3903 |
| **DAM 19** | 4.7178 | 6.0835 | 67 | 0.78 | 0.4408 |
| **DAM 2** | 2.9751 | 6.0172 | 67 | 0.49 | 0.6226 |
| **DAM 20** | -4.8381 | 6.0697 | 67 | -0.80 | 0.4282 |
| **DAM 3** | 5.6405 | 6.3495 | 67 | 0.89 | 0.3775 |
| **DAM 4** | -7.1048 | 5.8837 | 67 | -1.21 | 0.2315 |
| **DAM 5** | -0.4136 | 6.6661 | 67 | -0.06 | 0.9507 |
| **DAM 6** | -8.8653 | 5.7783 | 67 | -1.53 | 0.1297 |
| **DAM 7** | 3.9399 | 5.9755 | 67 | 0.66 | 0.5119 |
| **DAM 8** | 1.8398 | 5.4473 | 67 | 0.34 | 0.7366 |

**Estimates**

| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
|---|---|---|---|---|---|
| **DAM 9** | 4.8039 | 6.1049 | 67 | 0.79 | 0.4341 |
| **SIRE 1** | -22.5061 | 5.9158 | 67 | -3.80 | 0.0003 |
| **SIRE 10** | -8.6100 | 5.7534 | 67 | -1.50 | 0.1392 |
| **SIRE 11** | 5.5067 | 6.2921 | 67 | 0.88 | 0.3846 |
| **SIRE 12** | -5.6789 | 6.7959 | 67 | -0.84 | 0.4063 |
| **SIRE 2** | 2.8739 | 6.4566 | 67 | 0.45 | 0.6577 |
| **SIRE 3** | 4.2565 | 5.5364 | 67 | 0.77 | 0.4447 |
| **SIRE 4** | 3.7607 | 7.6520 | 67 | 0.49 | 0.6247 |
| **SIRE 5** | 1.2749 | 7.0887 | 67 | 0.18 | 0.8578 |
| **SIRE 6** | 3.4663 | 6.4253 | 67 | 0.54 | 0.5914 |
| **SIRE 7** | 7.2911 | 5.8804 | 67 | 1.24 | 0.2193 |
| **SIRE 8** | 5.8336 | 7.6141 | 67 | 0.77 | 0.4463 |
| **SIRE 9** | 2.5314 | 7.0516 | 67 | 0.36 | 0.7207 |
| **10x3** | 0 | . | . | . | . |
| **10x5** | 0 | . | . | . | . |
| **11x10** | 0 | . | . | . | . |
| **11x11** | 0 | . | . | . | . |
| **11x3** | 0 | . | . | . | . |
| **11x7** | 0 | . | . | . | . |
| **12x10** | 0 | . | . | . | . |
| **12x8** | 0 | . | . | . | . |
| **13x1** | 0 | . | . | . | . |
| **13x12** | 0 | . | . | . | . |
| **14x6** | 0 | . | . | . | . |
| **15x6** | 0 | . | . | . | . |
| **15x7** | 0 | . | . | . | . |
| **16x4** | 0 | . | . | . | . |
| **17x1** | 0 | . | . | . | . |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Parents/ Cross** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **18x1** | 0 | . | . | . | . |
| **18x9** | 0 | . | . | . | . |
| **19x11** | 0 | . | . | . | . |
| **19x9** | 0 | . | . | . | . |
| **1x12** | 0 | . | . | . | . |
| **1x3** | 0 | . | . | . | . |
| **20x2** | 0 | . | . | . | . |
| **20x3** | 0 | . | . | . | . |
| **2x3** | 0 | . | . | . | . |
| **2x5** | 0 | . | . | . | . |
| **3x1** | 0 | . | . | . | . |
| **3x8** | 0 | . | . | . | . |
| **4x1** | 0 | . | . | . | . |
| **4x7** | 0 | . | . | . | . |
| **5x10** | 0 | . | . | . | . |
| **6x10** | 0 | . | . | . | . |
| **6x11** | 0 | . | . | . | . |
| **6x2** | 0 | . | . | . | . |
| **7x12** | 0 | . | . | . | . |
| **7x3** | 0 | . | . | . | . |
| **8x10** | 0 | . | . | . | . |
| **8x2** | 0 | . | . | . | . |
| **8x6** | 0 | . | . | . | . |
| **9x4** | 0 | . | . | . | . |
| **9x7** | 0 | . | . | . | . |

Appendix Table 39 ANOVA for mean performance by parental strains following GLM Procedure for survival rate of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny from natural *Aeromonas hydrophila* infection.

| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| **Model** | 3 | 13434.96016 | 4478.32005 | 11.12 | <.0001 |
| **Error** | 103 | 41468.88548 | 402.61054 | | |
| **Corrected Total** | 106 | 54903.84564 | | | |

Appendix Table 40 Mean comparison of performance by parental strains using Tukey-Kramer Test for survival rate of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny from natural *Aeromonas hydrophila* infection.

| **Tukey-Kramer Comparison Lines for Least Squares Means of Sire** | | | |
|---|---|---|---|
| **LS-means with the same letter are not significantly different.** | | | |
| | **aer LSMEAN** | **Sire** | **LSMEAN Number** |
| A | 90.89312 | **4** | 4 |
| A | | | |
| A | 90.81245 | **1** | 1 |
| A | | | |
| A | 86.42813 | **3** | 3 |
| | | | |
| B | 64.07923 | **2** | 2 |

Note: Sire strain 1 – DB; 2 – DR; 3 – RG; 4 – TBB

Appendix Table 41 The Type 3 Mixed Procedure of analysis of variance for dressout percentage of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny.

| Type 3 Analysis of Variance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **Expected Mean Square** | **Error Term** | **Error DF** | **F Value** | **Pr > F** |
| **dam** | 15 | 391.322448 | 26.088163 | Var(Residual) + Q(dam,dam*sire) | MS(Residual) | 262 | 4.61 | <.0001 |
| **sire** | 10 | 305.088231 | 30.508823 | Var(Residual) + Q(sire,dam*sire) | MS(Residual) | 262 | 5.39 | <.0001 |
| **dam*sire** | 4 | 22.861745 | 5.715436 | Var(Residual) + Q(dam*sire) | MS(Residual) | 262 | 1.01 | 0.4028 |
| **Residual** | 262 | 1482.90 | 5.659907 | Var(Residual) | . | . | . | . |

Appendix Table 42 REML estimation of variance components for dressout percentage of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny.

| Covariance Parameter Estimates | | | | | |
|---|---|---|---|---|---|
| **Cov Parm** | **Ratio** | **Estimate** | **Standard Error** | **Z Value** | **Pr > Z** |
| **dam** | 0.02144 | 0.1215 | 0.6955 | 0.17 | 0.4307 |
| **sire** | 0.07248 | 0.4108 | 0.4763 | 0.86 | 0.1942 |
| **cross** | 0.2337 | 1.3244 | 0.9241 | 1.43 | 0.0759 |
| **Residual** | 1.0000 | 5.6669 | 0.4956 | 11.43 | <.0001 |

Appendix Table 43 GCA/SCA estimates with corresponding T-test (P=0.05) for dressout percentage of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny.

| **Estimates** | | | | | |
|---|---|---|---|---|---|
| **Label** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **DAM 1** | -0.07989 | 0.3315 | 262 | -0.24 | 0.8097 |
| **DAM 10** | -0.1592 | 0.3315 | 262 | -0.48 | 0.6315 |
| **DAM 11** | 0.1562 | 0.3241 | 262 | 0.48 | 0.6302 |
| **DAM 12** | 0.02149 | 0.3321 | 262 | 0.06 | 0.9484 |
| **DAM 14** | -0.1463 | 0.3395 | 262 | -0.43 | 0.6670 |
| **DAM 15** | 0.03570 | 0.3314 | 262 | 0.11 | 0.9143 |
| **DAM 18** | 0.04995 | 0.3398 | 262 | 0.15 | 0.8832 |
| **DAM 19** | -0.06872 | 0.3319 | 262 | -0.21 | 0.8361 |
| **DAM 2** | 0.1943 | 0.3315 | 262 | 0.59 | 0.5582 |
| **DAM 20** | -0.00668 | 0.3323 | 262 | -0.02 | 0.9840 |
| **DAM 4** | 0.1398 | 0.3406 | 262 | 0.41 | 0.6819 |
| **DAM 5** | -0.05502 | 0.3393 | 262 | -0.16 | 0.8713 |
| **DAM 6** | -0.07372 | 0.3316 | 262 | -0.22 | 0.8242 |
| **DAM 7** | -0.09561 | 0.3315 | 262 | -0.29 | 0.7732 |
| **DAM 8** | 0.1013 | 0.3243 | 262 | 0.31 | 0.7551 |
| **DAM 9** | -0.01368 | 0.3321 | 262 | -0.04 | 0.9672 |
| **SIRE 10** | 0.5586 | 0.4968 | 262 | 1.12 | 0.2619 |
| **SIRE 11** | 0.01382 | 0.5190 | 262 | 0.03 | 0.9788 |
| **SIRE 12** | 0.1308 | 0.5482 | 262 | 0.24 | 0.8116 |

**Estimates**

| **Label** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
|---|---|---|---|---|---|
| **SIRE 2** | -0.6028 | 0.5231 | 262 | -1.15 | 0.2502 |
| **SIRE 3** | -0.7293 | 0.4795 | 262 | -1.52 | 0.1295 |
| **SIRE 4** | -0.1214 | 0.5865 | 262 | -0.21 | 0.8362 |
| **SIRE 5** | 0.3059 | 0.5482 | 262 | 0.56 | 0.5773 |
| **SIRE 6** | 0.1187 | 0.5195 | 262 | 0.23 | 0.8194 |
| **SIRE 7** | 0.1739 | 0.5003 | 262 | 0.35 | 0.7284 |
| **SIRE 8** | 0.05690 | 0.5865 | 262 | 0.10 | 0.9228 |
| **SIRE 9** | 0.09479 | 0.5485 | 262 | 0.17 | 0.8629 |
| **10x3** | -1.2289 | 0.7414 | 262 | -1.66 | 0.0986 |
| **10x5** | -0.5059 | 0.7749 | 262 | -0.65 | 0.5144 |
| **11x10** | 1.7558 | 0.7478 | 262 | 2.35 | 0.0196 |
| **11x11** | 0.5659 | 0.7586 | 262 | 0.75 | 0.4564 |
| **11x7** | -0.6189 | 0.7492 | 262 | -0.83 | 0.4095 |
| **12x10** | 0.05080 | 0.7497 | 262 | 0.07 | 0.9460 |
| **12x8** | 0.1835 | 0.7942 | 262 | 0.23 | 0.8175 |
| **14x6** | -1.5941 | 0.7635 | 262 | -2.09 | 0.0378 |
| **15x6** | 0.9749 | 0.7608 | 262 | 1.28 | 0.2012 |
| **15x7** | -0.5858 | 0.7515 | 262 | -0.78 | 0.4364 |
| **18x9** | 0.5444 | 0.7775 | 262 | 0.70 | 0.4844 |
| **19x11** | -0.5102 | 0.7607 | 262 | -0.67 | 0.5030 |
| **19x9** | -0.2388 | 0.7746 | 262 | -0.31 | 0.7581 |

| Estimates | | | | | |
|---|---|---|---|---|---|
| **Label** | **Estimate** | **Standard Error** | **DF** | **t Value** | **Pr > \|t\|** |
| **1x12** | -0.2003 | 0.7749 | 262 | -0.26 | 0.7962 |
| **1x3** | -0.6704 | 0.7414 | 262 | -0.90 | 0.3667 |
| **20x2** | -0.6591 | 0.8260 | 262 | -0.80 | 0.4256 |
| **20x3** | 0.5862 | 0.7419 | 262 | 0.79 | 0.4302 |
| **2x3** | 0.6259 | 0.7414 | 262 | 0.84 | 0.3993 |
| **2x5** | 1.4922 | 0.7749 | 262 | 1.93 | 0.0552 |
| **4x7** | 1.5233 | 0.8203 | 262 | 1.86 | 0.0644 |
| **5x10** | -0.5997 | 0.7529 | 262 | -0.80 | 0.4265 |
| **6x11** | -0.01109 | 0.7608 | 262 | -0.01 | 0.9884 |
| **6x2** | -0.7924 | 0.7628 | 262 | -1.04 | 0.2998 |
| **7x12** | 0.6221 | 0.7749 | 262 | 0.80 | 0.4229 |
| **7x3** | -1.6642 | 0.7414 | 262 | -2.24 | 0.0256 |
| **8x10** | 0.5941 | 0.7477 | 262 | 0.79 | 0.4275 |
| **8x2** | -0.4922 | 0.7604 | 262 | -0.65 | 0.5180 |
| **8x6** | 1.0021 | 0.7583 | 262 | 1.32 | 0.1875 |
| **9x4** | -0.3913 | 0.7941 | 262 | -0.49 | 0.6226 |
| **9x7** | 0.2422 | 0.7512 | 262 | 0.32 | 0.7474 |

Appendix Table 44 ANOVA for mean performance by parental cross following GLM Procedure for dressout percentage of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny.

| **Source** | **DF** | **Sum of Squares** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| **Model** | 16 | 384.033369 | 24.002086 | 3.71 | <.0001 |
| **Error** | 275 | 1778.674549 | 6.467907 | | |
| **Corrected Total** | 291 | 2162.707917 | | | |

Appendix Table 45 Mean comparison of performance by parental cross using Tukey-Kramer Test for dressout percentage of channel catfish (*Ictalurus punctatus*) female × blue catfish (*I. furcatus*) male F1 hybrid progeny.

| **Tukey-Kramer Comparison Lines for Least Squares Means of Parental Cross** | | | | | | |
|---|---|---|---|---|---|---|
| **LS-means with the same letter are not significantly different.** | | | | | | |
| | | | | **dress LSMEAN** | **Cross** | **LSMEAN Number** |
| | | A | | 61.56575 | **RGxDB** | 5 |
| | | A | | | | |
| B | | A | | 60.87204 | **TishxDR** | 8 |
| B | | A | | | | |
| B | | A | | 60.44303 | **KSxDR** | 17 |
| B | | A | | | | |
| B | | A | C | 59.91281 | **TishxRG** | 10 |
| B | | A | C | | | |
| B | | A | C | 59.35864 | **KRxRG** | 14 |
| B | | A | C | | | |
| B | D | A | C | 59.29353 | **RGxTBB** | 6 |
| B | D | A | C | | | |
| B | D | A | C | 59.15804 | **KSxDB** | 16 |
| B | D | A | C | | | |
| B | D | A | C | 58.90101 | **KRxDB** | 12 |
| B | D | A | C | | | |
| B | D | A | C | 58.84092 | **ARxDB** | 1 |
| B | D | A | C | | | |
| B | D | A | C | 58.76714 | **MixxDB** | 2 |
| B | D | A | C | | | |
| B | D | A | C | 58.61534 | **TishxDB** | 7 |
| B | D | A | C | | | |
| B | D | A | C | 58.58214 | **KRxDR** | 13 |

| **Tukey-Kramer Comparison Lines for Least Squares Means of Parental Cross** | | | | | | |
|---|---|---|---|---|---|---|
| **LS-means with the same letter are not significantly different.** | | | | | | |
| | | | | **dress LSMEAN** | **Cross** | **LSMEAN Number** |
| B | D | A | C | | | |
| B | D | A | C | 58.42555 | **MixxRG** | 3 |
| B | D | A | C | | | |
| B | D | A | C | 58.35914 | **ARMKxDB** | 9 |
| B | D | | C | | | |
| B | D | | C | 58.10218 | **MixxTBB** | 4 |
| | D | | C | | | |
| | D | | C | 56.29161 | **ARMKxTBB** | 11 |
| | D | | | | | |
| | D | | | 55.73371 | **KRxTBB** | 15 |