ANALYSES OF TEXTURE AND SENSORY TRAITS, CARCASS TRAITS, AND FILLET COLOR IN DIFFERENT GENETIC TYPES OF FARMED CATFISH: GENETIC APPROACHES TO ENHANCE CATFISH FILLETS

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 1 2021

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Abstract

Channel catfish (*Ictalurus punctatus*) and hybrid catfish (channel catfish ♀ × blue catfish (*Icatlurus furcatus*) ♂) aquaculture dominates the US aquaculture industry. These catfish genetic types have been heavily researched to improve aquaculture production traits, improve yield and the overall performance. Significant research has been devoted to the culture of catfish but not towards improving meat quality, an important consumer attribute. Multiple studies were conducted using channel catfish, blue catfish, and the hybrid catfish to evaluate their carcass, texture, sensory, and color traits of catfish fillets.

The first study conducted evaluated texture, sensory, and color traits of channel catfish, blue catfish, and hybrid catfish at three size classes: below market sized (<0.68 kilograms), market sized (0.68-0.92 kilograms) and above market sized (>0.92 kilograms). Results of this study revealed that with increasing size, hardness, chewiness, gumminess, and toughness attributes increased in channel catfish and hybrid catfish ($p<0.001$). This phenomenon was not observed in blue catfish. When market sized hybrid catfish and channel catfish are compared, the channel catfish had higher means for all texture traits, was observed to be more tough and fibrous than the hybrid catfish fillets ($p<0.05$). Hybrid catfish were observed to have a mushier fillet ($p <0.05$)

The second study evaluated fish quality parameters of commercial catfish fillets to imported Vietnamese swai fillets (*Pangasianodon hypophthalmus*) due to the impact imported swai fillets have on the domestic aquaculture market. This study revealed that control swai fillets were tougher, harder, and chewier than domestically farmed catfish ($p<0.05$). With a treatment

of sodium phosphate, these differences between US catfish and Vietnamese swai were nullified, and the resulting fillet was more mushy and less fibrous than controls of both fillet products.

Comparison of texture, sensory, and color traits of catfish fillets from 7 channel catfish strains revealed several strain and sex effects ($P<0.05$). Strain differences were observed for fillet %, redness of the fillet, hardness, cohesion, and all sensory traits evaluated except flavor.

Further analysis in a third study examined combining ability of channel catfish dams and blue catfish sires in their hybrid progeny and revealed that additive genetic variance was found in channel catfish dams for hardness, chewiness, and gumminess. Specific combining ability estimates revealed dominance and epistasis interactions for fillet yield, resilience, springiness, and yellowness of the fillets.

Lastly, a heritability study of channel catfish in a 50 x 50 cross-fostering design revealed additive genetic variance for fillet yield and redness of the fillet. Direct selection for sensory and texture traits was not feasible, however, heritability estimates revealed the potential to implement a genetic enhancement protocol for increasing fillet % and decreasing redness of channel catfish fillets. Increasing fillet % from the same sized channel catfish and decreasing redness in fillets would prove to be beneficial for the catfish industry and increase profits to channel catfish farmers and processors due to the detrimental effects red fillets have in the catfish market. Redness had a low but potentially significant genetic correlation with yellowness of the fillet, and selection against redness would also potentially decrease yellowness in channel catfish fillets.

Acknowledgments

I would like to give a massive thank you to the Poultry Science Department at Auburn University for letting us use their facilities to evaluate texture and sensory attributes of our fillets. Without the department's efforts and willingness to let us use their facilities, this project would not have been attainable. I would also like to thank everyone in the panel involved for consuming more catfish flesh than anyone I know, and for sitting through late nights to evaluate the properties of these fillets. Lastly, I would like to thank Dr. Rex Dunham for his assistance in the project and his great leadership that allowed us to get this massive project done in a short time, as well as Dr. Amit Morey for his knowledge, assistance in the study, and aiding in training the panel that made this study achievable.

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CHAPTER 1

TEXTURE AND SENSORY EVALUATION OF FILLETS FROM THREE SIZE CLASSES OF CHANNEL CATFISH (*Ictalurus punctatus*), BLUE CATFISH (*Ictalurus furcatus*) AND HYBRID CATFISH (CHANNEL CATFISH ♀ × BLUE CATFISH ♂)

ABSTRACT

Despite catfish being the dominant freshwater aquaculture product in the United States, catfish texture and sensory evaluation are understudied compared to other aquaculture species and very few studies have been conducted to evaluate these traits in catfish. This study was conducted to help bridge this gap of research within catfish. Mechanical texture, sensory, and color analyses was conducted for three sizes below market size (<0.68 kilograms) market size (0.68-0.92 kilograms) and above market size (>0.92 kilograms) of fillets for channel catfish (*Ictalurus punctatus*), blue catfish (*Ictalurus furcatus*) and hybrid catfish (channel catfish ♀ × blue catfish ♂). Toughness was evaluated to be different ($p < 0.05$) between every size class of channel catfish and hybrid fillet with toughness increasing with increased size, although this trend was not observed in blue catfish. This same trend was observed with an increase in hardness, chewiness, and gumminess in increasing size in channel catfish and hybrid catfish ($p = 0.001$). Mechanical texture showed blue catfish were significantly harder ($p = 0.0005$) at above market sized, but perceived increased toughness via sensory analyses was not observed. Across market sized hybrids and channel catfish, channel catfish were perceived to be more tough and hybrid fillets more fibrous, and every texture trait was significantly different between the two genetic types of market sized catfish. This study is the first large-scale analysis of texture and sensory traits within two catfish species and their interspecific hybrid at different harvest sizes. Market sized channel catfish was observed to be the best performing genetic type due to its less mushy fillet and though was perceived to be more fibrous than the blue and hybrid catfish, mushiness in the panel was evaluated to be unfavorable.

1. INTRODUCTION

Catfish is the leading aquaculture product in the United States and accounted for $335 million dollars of pond bank sales in 2018 (Hanson, 2018), as well as 75% of finfish and 50% of the total sales of United States food fish aquaculture in 2018 (USDA, 2019). Catfish aquaculture is of great importance in the southern United States especially in rural regions with poverty, unemployment, and food shortages (Kaliba and Engle, 2006). United States catfish production was on an almost constant rise from 1975-2003 (Hanson, 2018), but experienced a sharp decline from 2003-2013 due to many factors including increased input costs, a recession in the United States economy, and a large influx of low-priced imported catfish from overseas, primarily from China and Vietnam (Engle and Stone, 2013; Engle et al., 2018;). Catfish farmers are at risk and potentially susceptible to loss of profit and production again if the economy has a downturn in the future, or if there is a large increase in production costs (Dunham and Elaswad, 2017).

Catfish production has improved over time due to aeration techniques (Boyd et al., 2018), genetic improvement via selectively bred channel catfish *Ictalurus punctatus,* (Dunham and Elaswad, 2017), and improved pond management utilizing three techniques (intensively aerated ponds, split-pond systems, and in-pond raceway) (Kumar, Engle, Henson, et al., 2018). Arguably the most beneficial addition to catfish production is the introduction of the interspecific hybrid catfish (channel catfish ♀ × blue catfish (*Ictalurus furcatus)* ♂) which now accounts for 70% of United States catfish production (N. Chatakondi, US Department of Agriculture, personal communication).

Introduction of the hybrid catfish to the United States catfish aquaculture production was an essential contribution to improvement of catfish production due to their lower feed conversion ratio, improved disease resistance, improved fillet yield and dress out percentage, improved tolerance to low dissolved oxygen, faster growth compared to channel catfish, and increased seinability (Yant et al., 1976; Dunham et al., 1983; Dunham et al., 1987; Dunham and Argue, 1998; Bosworth et al., 2004; Dunham and Masser, 2012; Arias et al., 2012; Dunham et al., 2014). Although artificial fertilization techniques required to produce these hybrid catfish is labor intensive, recent improvements in artificial spawning have allowed for the hybrid catfish industry to expand (Boxrucker and Kuklinski, 2006; Dunham and Masser, 2012; Bosworth, et al., 2012; Su et al., 2013). Research into improvement of hybrid catfish typically focuses on production and comparatively few articles have investigated the resulting fillet quality and texture comparisons between channel and hybrid catfish (Bosworth et al., 2004; Li et al., 2020;).

Blue catfish aquaculture is rare in the United States compared to channel catfish and hybrid catfish production, largely in part to the longer time to reach maturation, poor feed conversion ratios, low levels of captive spawning success, and slower growth to harvest size compared to channel catfish (Graham, 1999). Due to the increased time to reach maturation and the increase in required feed and space resources, blue catfish aquaculture is not practiced nearly as much as channel and hybrid catfish aquaculture (Dunham, et al., 1994). Although blue catfish is not the primary farmed product, they are beneficial to farmers for producing channel catfish ♀ × blue catfish ♂ hybrids, as well as their higher tolerance to channel catfish virus disease and enteric septicemia of catfish (Wolters, et al., 1996; Silverstein, et al., 2008; Griffin, et al., 2010).

Texture of fish and meat products is of great importance to consumers and is one of the factors that drives the marketability of the product, which in turn drives the consumer demand and acceptance of the product (Coppes et al., 2002). The texture of the fish fillet, along with the flavor, contributes to the sensory factors of the fillet that the consumer will digest (Sawyer et al., 1984; 1988). Texture drives the consumer demand for a fish product and has shown to be one of the most important quality factors that drive demand (Koteng, 1992). Texture has been evaluated in various commonly farmed species such as Atlantic salmon (*Salmo salar*) (Kiessling, et al., 2004), Crisp grass carp (*Ctenopharyngodon idellus C.et V*) and grass carp (*Ctenopharyngodon idellus*) (Lin, et al., 2009), blackspot seabream (*Pagellus bogaraveo*) (Rincón, et al., 2016), and farmed Atlantic halibut (*Hippoglossus hippoglossus*) (Hagen, et al., 2007). With texture being such an important characteristic in consumer acceptance and demand for different meat and seafood products, it is important to thoroughly evaluate texture and sensory characteristics of channel catfish, blue catfish, and hybrid catfish to determine differences between the channel catfish, blue catfish, and hybrid catfish fillets for the best overall consumer product.

Texture analyses has been evaluated before for channel catfish (Hallier et al., 2008; Bland, et al., 2018; Bechtel et al., 2018; Li, et al., 2020) as well as various studies on sensory evaluation (Lovell et al., 1986; Johnson and Kelley, 1990; Silva and Ammerman, 1993; Bosworth, et al., 2004). Carcass properties and yields for hybrid catfish have been analyzed (Huang et al., 1994; Bosworth, et al., 2004), though a large study to determine texture and sensory differences between channel catfish and hybrid catfish has not been described. Blue catfish texture has not been analyzed, nor compared to channel catfish or hybrid catfish. In addition to mechanical texture evaluation using texture profile analyses (TPA) and sensory analyses using a semi-trained panel, a correlation between the two would be highly beneficial for correlating consumer evaluation of catfish fillets and TPA results for further insights of catfish fillet properties. Previous studies for correlation between TPA and sensory analyses have been evaluated for cooked sweet potatoes (Truong et al., 2002) as well as correlations between mechanical textures and sensory of frozen fish (Barroso et al., 1998). Muscle fiber diameter, composition, and density could be influencing texture differences among genetic types of catfish in the same sized fish (Johnston et al., 2000; Hyldig and Nielsen 2001; Listrat et al., 2016). Muscle composition of channel catfish as a result of stocking density, stress of transportation and hypoxic conditions, growth as a result of myostatin gene knockout, and muscle fiber density as a result of restricted feeding, analysis of muscle fiber composition, density, and diameter and their influence on texture is far behind that of other farmed species notably salmon (Kim and Lovell 1995; Ciaramella et al., 2016; Khalil et al., 2017; Refaey et al., 2018). With United States freshwater aquaculture being heavily dominated by catfish production and being the largest freshwater aquaculture product in the United States accounting for 60% of freshwater aquaculture product (FAO, 2019), it is key to evaluate texture and sensory attributes of the leading freshwater aquaculture product in the United States.

The objectives of this study were to determine differences within and among channel catfish, blue catfish, and hybrid catfish fillets regarding texture profile analyses and sensory evaluation for three size classes: below market (<0.68 kilograms), market size (0.68-0.92 kilograms) and above market size (>0.92 kilograms). Texture and sensory analyses of catfish fillets is under researched in the United States especially considering the economic impact catfish aquaculture has in the Southern United States. This is to our knowledge the first study to compare texture and sensory traits within different size classes of channel, blue, and hybrid catfish and evaluate key sensory and texture differences between market size channel and hybrid catfish. The results should provide guidance toward the direction of genetic enhancement programs as well as determining the effect of harvest size on flesh quality.

2. MATERIALS and METHODS

2.1 Experimental fish rearing

All experimental procedures used in this study were performed in accordance with guidelines of the Auburn University Institutional Animal Care and Use Committee for use and care of animals. Fish were reared and fed ad-libitum in 60L aquaria (150 individuals/aquarium) in a recirculating system at the EW Shell Fisheries Center at Auburn University in Auburn, AL. Upon reaching a mean of 30 grams, the experimental fish were PIT tagged and stocked into 0.04h earthen ponds at a rate of 14,000 fish/h. Fish were fed ad-libitum with 32% protein pelleted catfish feed seven days a week until they reached a mean weight of 1kg. Fish were then harvested, individually weighed, sexed, and species/genetic type determined prior to filleting.

2.2 Filleting of experimental fish

Individual fish were weighed live, then sacrificed with blunt force trauma to the head followed by pithing, following IACUC guidelines. After being sacrificed, individual fish were dissected to determine the genetic type of the fish by evaluation of the swim bladder. Channel catfish swim bladders have a one chamber swim bladder, blue catfish have a double chambered swim bladder, and hybrid catfish have a one chamber swim bladder with a nipple like protrusion on the end. Gonadal development and visceral body fat quantity were graded on a scale of 0.5-5 with 0.5 being least developed and 5 being the most developed. Fish were filleted in a uniform manner by making an incision on the head where the head meets the body of the fish and following the spine of the fish with a fillet knife. Flesh was cut away from the ribs resulting in a boneless shank fillet. After filleting, each fillet was skinned, individually weighed to determine shank fillet yield, and rinsed in a freshwater solution to remove blood and other particles. Fillets from each individual fish were vacuum sealed in a 15.24 cm x 30.48 cm Clarity 4-Mil vacuum pouch (Bunzl Processor; Koch Supplies, Riverside Missouri) and placed in a -10°C freezer.

2.3 Fillet processing for sensory evaluation and texture profile analyses

Prior to evaluation, fillets were placed in a 2 ± 2 °C refrigerator overnight for thawing. Once thawed, raw fillets were evaluated for color using a CR 300 Minolta Chromameter (Osaka, Japan) to evaluate lightness, redness, and yellowness of fillets, and weighed prior to and after cooking to evaluate cook loss. Individual fillets were wrapped in aluminum foil and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. The American Meat Science Association (AMSA) research guidelines (AMSA, 2015) were followed, and one fillet was served to a semi-trained sensory panel of 12 individuals (6 males and 6 females ranging from age 21-65) in clear plastic serving cups with lids. The other fillet was stored in a 2 ± 2 °C refrigerator overnight and raised to a temperature of ~72°F (22°C) before used for texture profile analyses.

2.4 Sensory evaluation of catfish fillets using a semi-trained panel

Following American Meat Science Association (AMSA) Research Guidelines for Cookery, Sensory Evaluation, and Instrumental Tenderness Measurements of Meat (2nd ed.) (AMSA, 2015) guidelines, a group of 12 individual panelists were trained to evaluate 5 different key attributes in catfish fillets; toughness, flakiness, mushiness, fibrousness, and flavor (Bland, et al., 2018). Each fillet sample was graded on a scale of 1-4, with 1 being the least and 4 being the most of each attribute, and each corresponding value was correlated with a food item to calibrate the panel to the attributes of the fillet (Table 1). Flakiness was graded on a 1-3 and flavor was graded on a scale of 1-10, with 1 being severe off flavor, a flavor of 5 had distinct off flavor, 7 mild to little off flavor, and 10 corresponding with no off flavor. Panelists were trained on five different occasions before the sensory evaluation of catfish fillets, with calibration sessions occurring each week of sensory evaluation. Panelists were served equal portions of a fillet (1.27 cm x 1.27 cm) in plastic 2 oz serving cups with a lid. Samples were portioned after being allowed to rest for 10 minutes after reaching an internal temperature of 74 °C 3 groups of 4 panelists were divided to ensure replication of each fillet and were given 12 blind samples with random numbers during each sensory session to reduce bias. Panelists scored their 5 attributes using a blind survey using Google Forms (Google, Mountain View CA, US, 2021) to prevent bias by observing other panelists scores. In between each sample, panelists drank a sip of room temperature water, took a bite of a saltine cracker, then drank another sip of water to cleanse the palate.

Table 1. Corresponding food items correlated to their score for each sensory attribute. This scale was used to calibrate the semi-trained panel in their evaluation of catfish fillet sensory attributes.

Attribute	1	2	3	4
Toughness Force required to bite through a fillet sample	Canned Dole Pineapple Chunk 1’ cube	Heritage Farm Chicken Hotdogs 2cm diameter piece	Hebrew National Beef Hotdog 2cm diameter piece	Starkist Solid White Albacore Canned Tuna in water 2 cm diameter serving
Mushiness How much a fillet sample dissipated after initial bite	Hebrew National Beef Hotdog 2 cm diameter piece	Raw White Mushroom Whole	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Simple Truth Organic Extra Firm Tofu 1’ cube
Flakiness Ease of which fillet samples were broken into individual muscle components	Cooked Wild Caught Pan Seared Sea Scallops ¼ scallop	Canned Dole Pineapple Chunk 1’ cube	Chicken of the Sea Canned Traditional Style Pink Salmon 2 cm diameter serving	N/A
Fibrousness Perception of amount of muscle tissue strands or filaments were left after chewing	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Canned Dole Pineapple Chunk 1’ cube	Raw Asparagus stem	Raw Asparagus base

2.5. Texture profile analyses of catfish fillets

Fillets were individually wrapped in aluminum foil, labeled, and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. After cooking, fillets were refrigerated at 2 ± 2 °C refrigerator overnight, then raised to room temperature ~72°F (22°C) prior to texture profile analyses. Each fillet was then sampled using TA-XT2i Texture Analyzer shear machine (Texture Technologies Corp., Scarsdale, NY) loaded with a 5 kg load cell with a ½'' diameter ball probe attachment (TA-18) (Bland et al., 2018). Seven attributes were evaluated for each fillet: gumminess, chewiness, springiness, hardness, cohesiveness resilience, and adhesiveness (Table 2). Each fillet was sampled in triplicate, with the mean average of each being used for statistical analyses.

Table 2. Texture profile attributes analyzed using a Texture Profile Analyzer, formula used to evaluate and determine each output, and the definition of each attribute analyzed.

Attribute	Formula	Description
Hardness	Force at anchor 1	Maximum force applied during the first compression
Gumminess	Hardness x Cohesiveness	Energy needed to disintegrate a semi solid food until it is ready to swallow
Chewiness	Hardness x Cohesiveness x Springiness	Energy needed to chew a solid food until ready to swallow
Springiness	Distance2/Distance 1	Rate at which a sample returns to its original size and shape
Adhesiveness	Area 3	Work required to overcome stickiness between the probe and the sample
Resilience	Area 2/ Area 1	How well a product returns to its original shape and size during the first probe
Cohesiveness	Area 4/ Area 1	How well a product returns to its original shape and size in the second probe relative to the first probe

2.6 Statistical Analyses

All data was analyzed using SAS statistical analysis software (v.9.4; SAS Institute Inc., Cary, NC, USA). One-way ANOVA using the proc mixed function was used to calculate differences in continuous texture attributes within blue catfish, channel catfish, and hybrid catfish at three different size or body weight groupings: below market size, market size (0.68 kg – 0.92 kg), and above market size. A Tukey’s post hoc test was conducted to evaluate differences among groups. Data was tested for normality using a Shapiro-Wilk test (Shapiro and Wilk 1965) and was considered non-normally distributed at an alpha =0.05. A non-parametric one-way ANOVA using a Kruskal Wallis test was used to evaluate differences in ordinal dependent categories (gonad development, visceral fat, and all sensory attributes) and non-normally distributed data. Statistical differences were assumed at an alpha of = 0.05.

3. RESULTS

3.1 Texture, sensory, and carcass traits of three channel catfish size classes

Means, standard deviations, and coefficient of variation of fillet %, cook loss, color, and texture attributes among the three size classes of channel catfish are found in Table 3. Hardness, gumminess, chewiness and yellowness (Y) of analyzed channel catfish fillets were significantly different ($P < 0.05$) among size classes. As the fish increased with size, the fillet became more hard, gummier, and chewier but became less yellow. Fillet %, cook loss %, lightness (L), and redness (R) were significantly different ($P < 0.05$) in the above market fish compared to the other two size classes with fillet yield % and lightness being the smallest means for above market sized channel catfish, and redness and cook loss being the largest among the three sizes for above market sized fish. Resilience was different ($P < 0.05$) between the market size fish and the other two size classes with market having the smallest mean. Cohesion and springiness were different ($P <0.05$) in below market and market sized channel catfish, with market having the smallest mean. Adhesiveness was not found to be significantly different among the three size classes of channel catfish.

Table 3.

Mean values for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness, ± standard deviation (SD) and coefficient of variation (CV) of three body weight size classes; below market size (<0.68 kilograms) market size (0.68-0.92 kilograms) and above market size (>0.92 kilograms) channel catfish (*Ictalurus punctatus).* An alpha =0.05 following a Tukey's post-hoc test is considered significant.

Size Class	Below Market Size	Market Size	Above Market Size	P Value
	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	
Trait	n=261	n=106	n=88	
Fillet %	25.99±3.26(.13)^{a}	25.30±2.74(.11)^{a}	23.18±4.84(.21)^{b}	<0.0001
Cook Loss %	23.22±4.94(.22)^{a}	23.94±6.00(.25)^{a}	25.78±6.14(.24)^{b}	<0.0001
L	55.99±3.72(.07)^{a}	55.92±3.68(.07)^{a}	54.47±4.48(.08)^{b}	0.002
R	2.34±2.22(.95)^{b}	1.98±1.70(.87)^{b}	3.53±2.88(.81)^{a}	0.0001
Y	9.02±3.26(.36)^{a}	7.20±3.03(.42)^{b}	6.21±4.40(.71)^{c}	0.02
Hardness	594.63±192.43(.32)^{a}	736.46±224.04(.30)^{b}	1005.08±352.78(.35)^{c}	<0.0001
Adhesiveness	-3.93±13.2(3.36)	-2.94±1.65(.56)	-3.00±2.32(.77)	N/S
Resilience	23.79±3.69(.16)^{a}	22.66±3.54(.16)^{b}	24.10±5.20(.22)^{a}	0.049
Cohesion	0.56±.05(.09)^{a}	0.55±.05(.09)^{b}	0.56±.07(.13)^{ab}	0.03
Springiness	74.39±5.68(.08)^{a}	72.07±5.62(.08)^{b}	73.80±6.59(.09)^{ab}	0.02
Gumminess	336.19±122.89(.37)^{a}	406.72±144.48(.36)^{b}	572.94±245.63(.43)^{c}	<0.0001
Chewiness	251.33±98.26(.39)^{a}	295.28±113.31(.38)^{b}	429.61±203.99(.48)^{c}	0.0001

Significant P values following a Turkeys Post Hoc test are listed in the last column. Means followed by the same letter in a row are not significantly different (P > 0.05).

Means, standard deviations, and coefficient of variation of evaluated ordinal data of sensory attributes, gonadal development, and visceral fat development for three size classes of channel catfish are presented in Table 4. Table 4 also indicates differences between the three channel catfish size classes based on the results of a Kruskal Wallis test. Gonadal development, toughness, and mushiness were significantly different ($P<0.05$) across all three size classes, with the above market size channel catfish having the highest gonadal development and toughest flesh, and below market sized having the mushiest flesh. Evaluation of fat, flavor, and fibrousness were significantly different ($P<0.05$) between above market size fish and the other two size classes with above market having the highest visceral fat content, most fibrous flesh, and the highest evaluation of off flavor. Flakiness was significantly less ($P<0.05$) in below market size fish then above and market sized channel catfish.

Table 4.

Mean values ± standard deviation coefficient of variation (CV) for sensory attributes toughness, mushiness, flakiness, fibrousness, flavor, gonadal development (gonad), and visceral fat deposition (fat) evaluated on an ordinal scale in three body weight size classes (below market size (<0.68 kilograms) market size (0.68-0.92 kilograms) and above market size (>0.92 kilograms)) channel catfish (*Ictalurus punctatus*). Significant differences in evaluated ordinal data based on the results of a Kruskal Wallis test between the three channel catfish size classes are denoted by letter values in each row. The highest significant P value between the size classes is shown in the last column. An alpha =0.05 is considered significant.

Attribute	Below Market Size	Market Size	Above Market Size	P Value
	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	
	n=261	n=106	n=88	
Gonad	1.22±.66(.54)^{a}	1.92±.85(.44)^{b}	2.99±1.32(.44)^{c}	<0.0001
Fat	0.82±.41(.50)^{b}	0.88±.58(.66)^{b}	1.02±.55(.54)^{a}	0.022
Toughness	2.20±.49(.22)^{a}	2.33±.56(.23)^{b}	2.55±.59(.47)^{c}	0.015
Mushiness	2.06±.51(.25)^{a}	1.88±.62(.33)^{b}	1.69±.54(.32)^{c}	0.034
Flakiness	2.24±.30(.13)^{b}	2.37±.39(.16)^{a}	2.37±.37(.16)^{a}	0.0031
Fibrousness	1.75±.37(.21)^{b}	1.84±.36(.20)^{b}	2.04±.38(.19)^{a}	0.0007
Flavor	7.34±.68(.09)^{a}	7.47±.63(.08)^{a}	7.17±.77(.11)^{b}	0.03

Significant P values from a Kruskal-Wallis are reported. Means followed by a different letter value in each row are significantly (P <0.05) different.

3.2 Texture, sensory, and carcass traits of three blue catfish size classes

Means, standard deviations, and coefficient of variation of evaluated texture, color, cook loss % and fillet yield% among three size classes of blue catfish are found in Table 5. Fillet %, redness (R), resilience, cohesion, springiness, and chewiness were significantly different ($P<0.05$) between the below and above market size classes, but not significantly different to the market sized blue catfish. Fillet %, resilience, cohesion, and springiness were highest in the below market sized blue catfish while chewiness and redness of the fillet were highest in above market blue catfish. Hardness and gumminess in above market size class blue catfish were harder and gummier ($P <0.05$) than the other two size classes. No other statistical differences were observed

Table 5.

Mean values for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness, ± standard deviation (SD) and coefficient of variation (CV) of three size classes of live body weight blue catfish (*Ictalurus furcatus*) below market size (<0.68 kilograms) market size (0.68-0.92 kilograms) and above market size (>0.92 kilograms). An alpha =0.05 following a Tukey's post-hoc test is considered significant.

Size Class	Below Market Size	Market Size	Above Market Size	P Value
	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	
Trait	n=28	n=14	n=36	
Fillet %	26.06±2.71(.10)^{a}	24.46±3.20(.13)^{ab}	23.25±6.15(.26)^{b}	<0.0001
Cook Loss %	27.96±5.30(.19)	24.49±10.50(.43)	25.97±7.89(.30)	N/S
L	57.06±3.80(.07)	55.83±3.85(.07)	55.98±4.97(.09)	N/S
R	3.95±2.05(.52)^{b}	4.22±2.81(.67)^{ab}	6.05±4.13(.68)^{a}	0.0001
Y	7.44±1.66(.22)	8.08±3.28(.41)	7.87±6.09(.77)	N/S
Hardness	412.75±135.76(.33)^{b}	447.25±125.78(.28)^{b}	659.56±260.54(.40)^{a}	<0.0001
Adhesiveness	-3.16±2.20(.70)	-3.55±1.74(.49)	-5.78±6.86(1.19)	N/S
Resilience	23.79±3.69(.16)^{a}	20.14±3.94(.20)^{ab}	18.88±3.96(.21)^{b}	0.049
Cohesion	0.53±.05(.09)^{a}	0.51±.06(.11)^{ab}	0.49±.06(.13)^{b}	0.032
Springiness	76.11±4.92(.06)^{a}	74.13±6.63(.09)^{ab}	70.60±5.82(.08)^{b}	0.001
Gumminess	219.88±76.99(.35)^{a}	228.65±67.46(.30)^{a}	329.65±162.02(.49)^{b}	<.0001
Chewiness	168.53±63.35(.38)^{b}	172.34±61.73(.36)^{ab}	236.03±124.15(.53)^{a}	0.0001

Significant P values following a Turkeys Post Hoc test are listed in the last column. Means followed by the same letter in a row are not significantly different (P > 0.05).

Means, standard deviations, and coefficient of variation among three size classes of hybrid catfish for sensory attributes, gonadal, and visceral fat development are found in Table 6. Visceral fat deposits were significantly more ($P < 0.05$) in above market sized blue catfish compared to the other two size classes, and fibrousness was less than in below market sized than the other two size classes. No other significant differences ($P > 0.05$) were observed among size classes.

Table 6.

Mean values ± standard deviation and coefficient of variation (CV) for sensory attributes toughness, mushiness, flakiness, fibrousness, flavor, gonadal development (gonad), and visceral fat deposition (fat) evaluated on an ordinal scale in three body weight size classes (below market size (<0.68 kilograms) market size (0.68-0.92 kilograms) and above market size (>0.92 kilograms)) blue catfish (*Ictalurus furcatus*). Significant differences in evaluated ordinal data based on the results of a Kruskal Wallis test between the blue catfish size classes are denoted by letter values in each row. The highest significant P value between the size classes is shown in the last column. An alpha = 0.05 is considered significant

Size Class	Below Market Size $\bar{X}$ ± SD (CV)	Market Size $\bar{X}$ ± SD (CV)	Above Market Size $\bar{X}$ ± SD (CV)	P Value
Attribute	n=28	n=14	n=36	
Gonad	1.09±.68(.63)	1.18±.89(.76)	1.68±1.36(.81)	N/S
Fat	1.43±1.00(.70)^{b}	1.71±.96(.56)^{b}	2.42±.84(.35)^{a}	0.02
Toughness	1.90±.43(.23)	1.96±.54(.28)	2.11±.60(.29)	N/S
Mushiness	2.38±.53(.22)	2.29±.64(.28)	2.11±.63(.30)	N/S
Flakiness	2.34±.34(.15)	2.39±.46(.19)	2.49±.25(.10)	N/S
Fibrousness	1.54±.26(.17)^{b}	1.63±.42(.26)^{a}	1.85±.48(.26)^{a}	0.04
Flavor	7.36±.66(.09)	7.33±.97(.13)	7.40±.93(.13)	N/S

Significant P values from a Kruskal-Wallis are reported in Table 6. Means with different letter values in each row are considered significant (P<0.05).

3.3 Texture, sensory, and carcass traits of three hybrid catfish size classes

Means, standard deviations, and coefficient of variation among three size classes of hybrid catfish are reported in Table 7. Hardness, chewiness, and gumminess were significantly different ($P < 0.05$) between each size class and mean values increased with increasing size. Fillet % was significantly higher ($P < 0.05$) in market sized hybrids then above market sized hybrids but was not significantly different to the below market size class. Lightness (L) was significantly higher ($P < 0.05$) in below market sized hybrids than above market sized hybrids. Redness (R) of the fillet was the lowest ($P < 0.05$) in the below market sized hybrid catfish. No other statistical differences were observed.

Table 7.

Mean values for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness, ± standard deviation (SD) and coefficient of variation (CV) of three size classes: below market size (<0.68 kilograms) market size (0.68-0.92 kilograms) and above market size (>0.92 kilograms) of live body weight hybrid catfish (Channel catfish (*Ictalurus punctatus)* ♀ × Blue catfish (*Ictalurus furcatus)* ♂*)*. An alpha =0.05 is considered significant following a Tukey's post-hoc test.

Size Class	Below Market Size	Market Size	Above Market Size	P Value
	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	
Trait	n=48	n=63	n=85	
Fillet %	26.69±5.11(.19)^{ab}	27.04±3.19(.12)^{a}	25.13±3.70(.15)^{b}	0.001
Cook Loss %	23.74±3.99(.17)	23.71±5.28(.22)	23.35±4.65(.20)	N/S
L	55.79±3.92(.17)^{a}	54.70±3.25(.06)^{ab}	53.83±4.21(.08)^{b}	0.02
R	1.98±1.69(.86)^{b}	3.05±2.37(.78)^{a}	4.17±3.95(.95)^{a}	0.03
Y	8.88±3.94(.44)	7.55±3.71(.49)	7.91±4.94(.62)	N/S
Hardness	479.33±136.45(.28)^{c}	595.76±138.17(.23)^{b}	711.11±206.97(.29)^{a}	0.0005
Adhesiveness	-5.22±4.33(.82)	-5.18±3.67(.71)	-6.22±5.09(.82)	N/S
Resilience	19.77±4.78(.24)	19.24±4.31(.22)	19.20±4.18(.22)	N/S
Cohesion	0.50±.06(.12)	0.49±.06(.13)	0.49±.06(.12)	N/S
Springiness	71.25±6.76(.09)	69.72±5.55(.08)	70.77±5.26(.07)	N/S
Gumminess	241.45±73.30(.30)^{c}	294.22±79.77(.27)^{b}	354.29±117.53(.33)^{a}	0.001
Chewiness	173.09±59.80(.35)^{c}	206.44±61.75(.30)^{b}	252.05±89.96(.36)^{a}	0.0007

Significant P values following a Turkeys Post Hoc test are listed in the last column. Means followed by the same letter in a row are not significantly different (P > 0.05).

Means, standard deviations, and coefficient of variation of sensory attributes, gonadal development, and visceral fat deposition among three size classes of hybrid catfish are reported in Table 8. Toughness of hybrid fillets was significantly different ($P < 0.05$) between all three size groups and increased with increasing size class. Visceral fat deposition and perceived fibrousness were highest ($P < 0.05$) in above market sized hybrid catfish. Gonadal development was significantly different ($P < 0.05$) between market sized fish and above market sized fish, but no other differences between size classes were observed. Mushiness was the highest ($P < 0.05$) and flakiness the least ($P < 0.05$) in below market sized hybrid catfish. Flavor had no observable differences between the three size groups.

Table 8.

Mean values ± standard deviation (SD) and coefficient of variation (CV) for sensory attributes toughness, mushiness, flakiness, fibrousness, flavor, gonadal (gonad), and visceral fat deposition (fat) evaluated on an ordinal scale in three size classes of live weight (below market size (<0.68 kilograms) market size (0.68-0.92 kilograms) and above market size (>0.92 kilograms) hybrid catfish (Channel catfish (*Ictalurus punctatus)* ♀ × Blue catfish (*Ictalurus furcatus)* ♂) significant differences in evaluated ordinal data based on the results of a Kruskal Wallis test between the three hybrid catfish size classes are denoted by letter values. The highest significant p value between the size classes is shown in the last column. An alpha =0.05 is considered significant.

	Below Market Size $\bar{X}$ ± SD (CV)	Market Size $\bar{X}$ ± SD (CV)	Above Market Size $\bar{X}$ ± SD (CV)	P Value
Attribute	n=48	n=63	n=85	
Gonad	1.23±.88(.72)^{ab}	1.44±.83(.58)^{a}	1.16±.66(.57)^{b}	0.02
Fat	1.81±.62(.34)^{b}	1.97±.72(.37)^{b}	2.47±.90(.36)^{a}	0.0004
Toughness	1.83±.48(.26)^{c}	2.04±.41(.20)^{b}	2.19±.50(.23)^{a}	0.02
Mushiness	2.45±.57(.23)^{a}	2.10±.58(.28)^{b}	1.96±.62(.31)^{b}	0.002
Flakiness	2.31±.29(.13)^{b}	2.45±.35(.14)^{a}	2.54±.35(.20)^{a}	0.04
Fibrousness	1.60±.34(.21)^{b}	1.59±.26(.17)^{b}	1.77±.35(.20)^{a}	0.005
Flavor	7.42±.79(.11)	7.41±.96(.13)	7.44±.83(.11)	N/S

Significant P values from a Kruskal-Wallis are reported in Table 8. Mean values with the same letter value in each row are not significant (P > 0.05).

3.4 Differences in texture, carcass, sensory, and fillet color attributes between three catfish genetic types at three size classes

Means, standard deviations, and coefficient of variation for carcass, texture, and fillet color traits among three genetic types of catfish below 0.68 kg in body weight are reported in Table 9. Cohesion was significantly different ($P < 0.05$) across all three genetic types. Channel catfish had the most cohesive fillet, hybrid catfish had the least cohesive, and blue catfish cohesiveness between the two other genetic types. Blue catfish had higher ($P < 0.05$) cook loss and red colored fillets than the other two genetic types. Blue catfish had the least yellow fillets ($P < 0.05$) compared to the other two genetic types of catfish. Channel catfish had harder, gummier, chewier, and more resilient fillets among the three catfish genetic types ($P < 0.05$). Hybrid catfish had the least ($P < 0.05$) springy fillets among the three genetic types.

Table 9.

Mean values for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness, ± standard deviation (SD) and coefficient of variation (CV) of three genetic types of catfish : Channel catfish (*Ictalurus punctatus*), blue catfish (*Ictalurus furcatus)* and the hybrid catfish (Channel catfish ♀ × Blue catfish ♂*)* at below market size (<0.68 kilograms). An alpha =0.05 was considered a significant difference following a Tukey's post-hoc test.

Genetic Type	Channel Catfish $\bar{X}$ ± SD (CV)	Blue Catfish $\bar{X}$ ± SD (CV)	Hybrid Catfish $\bar{X}$ ± SD (CV)	P Value
Trait	n=261	n=28	n=48	
Fillet %	25.99±3.26(.13)	26.06±2.71(.10)	26.69±5.11(.19)	N/S
Cook Loss %	23.22±4.94(.22)^{b}	27.96±5.30(.19)^{a}	23.74±3.99(.17)^{b}	0.0009
L	55.99±3.72(.07)	57.06±3.80(.07)	55.79±3.92(.07)	N/S
R	2.34±2.22(.95)^{b}	3.95±2.05(.52)^{a}	1.98±1.69(.86)^{b}	0.0005
Y	9.02±3.26(.36)^{a}	7.44±1.66(.22)^{b}	8.88±3.94(.44)^{ab}	0.02
Hardness	594.63±192.43(.32)^{a}	412.75±135.76(.33)^{b}	479.33±136.45(.28)^{b}	0.0002
Adhesiveness	-3.93±13.2(3.36)	-3.16±2.20(.70)	-5.22±4.33(.82)	N/S
Resilience	23.79±3.69(.16)^{a}	21.91±3.58(.16)^{b}	19.77±4.78(.24)^{b}	0.04
Cohesion	0.56±.05(.09)^{a}	0.53±.05(.09)^{b}	0.50±.06(.12)^{c}	0.04
Springiness	74.39±5.68(.08)^{a}	76.11±4.92(.06)^{a}	71.25±6.76(.09)^{b}	0.002
Gumminess	336.19±122.89(.37)^{a}	219.88±76.99(.35)^{b}	241.45±73.30(.30)^{b}	<0.0001
Chewiness	251.33±98.26(.39)^{a}	168.53±63.35(.38)^{b}	173.09±59.80(.35)^{b}	0.0007

Significant P values following a Turkeys Post Hoc test are listed in the last column. Means followed by the same letter in a row are not significantly different (P > 0.05).

Means, standard deviations, and coefficient of variations of sensory attributes, gonadal development, and visceral fat deposition among three genetic types of catfish at below market size (body weight <0.68 kg) is reported in Table 10. Visceral fat deposition was significantly different ($P < 0.05$) between all three size classes with hybrid catfish having the highest fat deposition, and channel catfish the least. Channel catfish were more tough and fibrous than the other two genetic types of catfish and was also significantly less mushy ($P < 0.05$).

Table 10.

Mean values ± standard deviation (SD) and coefficient of variation (CV) for sensory attributes toughness, mushiness, flakiness, fibrousness, flavor, gonadal (gonad), and visceral fat deposition (fat) evaluated on an ordinal scale in three genetic types of catfish: Channel catfish (*Ictalurus punctatus*) Blue catfish (*Ictalurus furcatus*) and hybrid catfish (Channel catfish ♀ × Blue catfish ♂) at a body weight below 0.68 kg. The highest significant p value between the size classes is shown in the last column. An alpha =0.05 is considered a significant difference following analyses using Kruskal-Wallis test.

Genetic Type	Channel Catfish $\bar{X} \pm SD\ (CV)$	Blue Catfish $\bar{X} \pm SD\ (CV)$	Hybrid Catfish $\bar{X} \pm SD\ (CV)$	P value
Attribute	n=261	n=28	n=48	
Gonad	1.22±.66(.54)	1.09±.68(.63)	1.23±.88(.72)	N/S
Fat	0.82±.41(.50)^{c}	1.43±1.00(.70)^{b}	1.81±.62(.34)^{a}	0.004
Toughness	2.20±.49(.22)^{a}	1.90±.43(.23)^{b}	1.83±.48(.26)^{b}	0.004
Mushiness	2.06±.51(.25)^{b}	2.38±.53(.22)^{a}	2.45±.57(.23)^{a}	0.004
Flakiness	2.24±.30(.13)	2.34±.34(.15)	2.31±.29(.13)	N/S
Fibrousness	1.75±.37(.21)^{a}	1.54±.26(.17)^{b}	1.60±.34(.21)^{b}	0.003
Flavor	7.34±.68(.09)	7.36±.66(.09)	7.42±.79(.11)	N/S

Significant P values from a Kruskal-Wallis are reported in Table 10. Mean values with the same letter value in each row are not significant between genetic catfish types (P > 0.05).

Means, standard deviations, and coefficient of variation for carcass, texture, and fillet color traits among three genetic types of catfish at market size (0.68-0.92 kg) is listed in Table 11. Hardness was significantly different ($P < 0.05$) among all catfish genetic types, with channel catfish being the hardest, hybrid catfish the medium hardness, and blue catfish the least hard. Fillet % was the highest ($P < 0.05$) for hybrid catfish compared to the other two genetic types. Fillet redness was less ($P < 0.05$) in channel catfish then the other two catfish genetic types. Adhesiveness, resilience, and cohesion were found to be significantly different ($P < 0.05$) between channel and hybrid catfish with channel catfish having the higher mean, but neither genetic type was significantly different to blue catfish ($P > 0.05$). Hybrid catfish were less ($P < 0.05$) springy then the other two genetic types, and channel catfish were more ($P < 0.05$) gummy and chewy than the other two catfish genetic types. No significant differences were observed for cook loss, lightness and yellowness of the fillets.

Table 11.

Mean values ± standard deviation (SD) and coefficient of variation (CV) for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness of three genetic types of catfish: Channel catfish (*Ictalurus punctatus*), Blue catfish (*Ictalurus furcatus)* and the hybrid catfish (Channel catfish ♀ × Blue catfish ♂*)* at market size (0.68-0.92 kilograms). An alpha =.05 is considered significant following a Tukey's post-hoc test.

Genetic Type	Channel Catfish $\bar{X}$ ± SD (CV)	Blue Catfish $\bar{X}$ ± SD (CV)	Hybrid Catfish $\bar{X}$ ± SD (CV)	P Value
Trait	n=106	n=14	n=63	
Fillet %	25.30±2.74(.11)^{b}	24.46±3.20(.13)^{b}	27.04±3.19(.12)^{a}	0.01
Cook Loss %	23.94±6.00(.25)	24.49±10.50(.43)	23.71±5.28(.22)	N/S
L	55.92±3.68(.07)	55.83±3.85(.07)	54.70±3.25(.06)	N/S
R	1.98±1.70(.87)^{b}	4.22±2.81(.67)^{a}	3.05±2.37(.78)^{a}	0.003
Y	7.20±3.03(.42)	8.08±3.28(.41)	7.55±3.71(.49)	N/S
Hardness	736.46±224.04(.30)^{a}	447.25±125.78(.28)^{c}	595.76±138.17(.23)^{b}	0.02
Adhesiveness	-2.94±1.65(.56)^{a}	-3.55±1.74(.49)^{ab}	-5.18±3.67(.71)^{b}	0.002
Resilience	22.66±3.54(.16)^{a}	20.14±3.94(.20)^{ab}	19.24±4.31(.22)^{b}	<0.0001
Cohesion	0.55±.05(.09)^{a}	0.51±.06(.11)^{ab}	0.49±.06(.13)^{b}	<0.0001
Springiness	72.07±5.62(.08)^{a}	74.13±6.63(.09)^{a}	69.72±5.55(.08)^{b}	0.03
Gumminess	406.72±144.48(.36)^{a}	228.65±67.46(.30)^{b}	294.22±79.77(.27)^{b}	<0.0001
Chewiness	295.28±113.31(.38)^{a}	172.34±61.73(.36)^{b}	206.44±61.75(.30)^{b}	<0.0001

Significant P values following a Turkeys Post Hoc test are listed in the last column. Means followed by the same letter in a row are not significantly different (P > 0.05).

Means, standard deviations, and coefficient of variations of gonadal development, visceral fat content, and sensory attributes among three catfish genetic types at market size (0.68-0.92 kg) in Table 12. Channel catfish had higher ($P < 0.05$) gonadal development and toughness among the three catfish genetic types. Channel catfish had the least visceral fat content and had the least mushy flesh ($P < 0.05$) among the three genetic types. Fibrousness was different ($P < 0.05$) between channel catfish and hybrid catfish but was not different in blue catfish among all three genetic types. No significant differences were observed for flakiness and flavor.

Table 12.

Mean values ± standard deviation (SD) and coefficient of variation (CV) for sensory attributes toughness, mushiness, flakiness, fibrousness, flavor, gonadal (gonad), and visceral fat deposition (fat) evaluated on an ordinal scale in three size genetic types of catfish: Channel catfish (*Ictalurus punctatus*) Blue catfish (*Ictalurus furcatus*) and hybrid catfish (Channel catfish ♀ × Blue catfish ♂*)* at market size (body weight 0.68-0.92 kg). The highest significant p value between the size classes is shown in the last column. An alpha =0.05 is considered significant following evaluation using a Kruskal-Wallis test.

Genetic Type	Channel Catfish $\bar{X}$ ± SD (CV)	Blue Catfish $\bar{X}$ ± SD (CV)	Hybrid Catfish $\bar{X}$ ± SD (CV)	P value
Attribute	n=106	n=14	n=63	
Gonad	1.92±.85(.44)^{a}	1.18±.89(.76)^{b}	1.44±.83(.58)^{b}	0.002
Fat	0.88±.58(.66)^{b}	1.71±.96(.56)^{a}	1.97±.72(.37)^{a}	0.0002
Toughness	2.33±.56(.23)^{a}	1.96±.54(.28)^{b}	2.04±.41(.20)^{b}	0.02
Mushiness	1.88±.62(.33)^{b}	2.29±.64(.28)^{a}	2.10±.58(.28)^{a}	0.04
Flakiness	2.37±.39(.16)	2.39±.46(.19)	2.45±.35(.14)	N/S
Fibrousness	1.84±.36(.20)^{a}	1.63±.42(.26)^{ab}	1.59±.26(.17)^{b}	0.003
Flavor	7.47±.63(.08)	7.33±.97(.13)	7.41±.96(.13)	N/S

Significant P values from a Kruskal-Wallis are reported in Table 12. Mean values with the same letter value in each row are not significant between catfish genetic types (P > 0.05).

Means, standard deviations, and coefficient of variation for texture, carcass, and fillet color traits among three catfish genetic types at above market size (>0.98 kg) are presented in Table 13. Channel catfish had a more ($P < 0.05$) hard, resilient, cohesive, springy, gummy, and chewier fillets than the other two genetic types. Fillet % was significantly higher ($P < 0.05$) in hybrid catfish than channel catfish, but no differences between blue catfish and the other two genetic types were observed. Cook loss was higher ($P < 0.05$) in channel catfish than hybrid catfish with no significant differences between blue catfish and the other two catfish genetic types. Lightness of the fillet was higher ($P < 0.05$) in blue catfish compared to hybrid catfish, but channel catfish was not significantly different from the other two genetic types. Blue catfish had the reddest fillet ($P < 0.05$) of all genetic types. No significant differences were observed for yellowness of the fillet.

Table 13.

Mean values for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness, ± standard deviation (SD) and coefficient of variation (CV) of three genetic types of catfish : Channel catfish (*Ictalurus punctatus*), blue catfish (*Ictalurus furcatus)* and the hybrid catfish (Channel catfish ♀ × Blue catfish ♂*)* at above market size (>0.92 kilograms). An alpha =.05 is considered significant difference following a Tukey's post-hoc test.

Genetic Type	Channel Catfish	Blue Catfish	Hybrid Catfish	P Value
	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	$\bar{X}$ ± SD (CV)	
Trait	n=88	n=36	n=85	
Fillet %	23.18±4.84(.21)^{b}	23.25±6.15(.26)^{ab}	25.13±3.70(.15)^{a}	0.003
Cook Loss %	25.78±6.14(.24)^{a}	25.97±7.89(.30)^{ab}	23.35±4.65(20)^{b}	0.02
L	54.47±4.48(.08)^{ab}	55.98±4.97(.09)^{a}	53.83±4.21(.08)^{b}	0.04
R	3.53±2.88(.81)^{b}	6.05±4.13(.68)^{a}	4.17±3.95(.95)^{b}	0.02
Y	6.21±4.40(.71)	7.87±6.09(.77)	7.91±4.94(.62)	N/S
Hardness	1005.08±352.78(.35)^{a}	659.56±260.54(.40)^{b}	711.11±206.97(.29)^{b}	<0.0001
Adhesiveness	-3.00±2.32(.77)^{a}	-5.78±6.86(1.19)^{ab}	-6.22±5.09(.82)^{b}	0.002
Resilience	24.10±5.20(.22)^{a}	18.88±3.96(.21)^{b}	19.20±4.18(.22)^{b}	<0.0001
Cohesion	0.56±.07(.13)^{a}	0.49±.06(.13)^{b}	0.49±.06(.12)^{b}	<0.0001
Springiness	73.80±6.59(.09)^{a}	70.60±5.82(.08)^{b}	70.77±5.26(.07)^{b}	0.02
Gumminess	572.94±245.63(.43)^{a}	329.65±162.02(.49)^{b}	354.29±117.53(.33)^{b}	<0.0001
Chewiness	429.61±203.99(.48)^{a}	236.03±124.15(.53)^{b}	252.05±89.96(.36)^{b}	<0.0001

Significant P values following a Turkeys Post Hoc test are listed in the last column. Means followed by the same letter in a row are not significantly different (P > 0.05).

Means, standard deviations, and coefficient of variations of gonadal development, visceral fat content, and sensory attributes among three catfish genetic types in above market sized (>0.92 kg) are presented in Table 14. Channel catfish had the greatest ($P < 0.05$) gonadal development among genetic types of catfish evaluated and less ($P < 0.05$) visceral fat content. Channel catfish also had the most tough, most fibrous, and least mushy fillets evaluated by the sensory panel ($P < 0.05$) among catfish genetic types. Hybrid catfish had a more ($P < 0.05$) flakey fillet with less off flavor compared to channel catfish, but blue catfish had no significant differences between the two other genetic types.

Table 14.

Mean values ± standard deviation (SD) and coefficient of variation (CV) for sensory attributes toughness, mushiness, flakiness, fibrousness, flavor, gonadal (gonad), and visceral fat deposition (fat) evaluated on an ordinal scale in three size genetic types of catfish: Channel catfish (*Ictalurus punctatus*) Blue catfish (*Ictalurus furcatus*) and hybrid catfish (Channel catfish ♀ × Blue catfish ♂) at above market size (> 0.92 kg). The highest significant p value between the size classes is shown in the last column. An alpha =0.05 is considered a significant difference following a Kruskal-Wallis test.

Genetic Type	Channel Catfish $\bar{X}$ ± SD (CV)	Blue Catfish $\bar{X}$ ± SD (CV)	Hybrid Catfish $\bar{X}$ ± SD (CV)	P value
Attribute	n=88	n=36	n=85	
Gonad	$2.99\pm1.32(.44)^{a}$	$1.68\pm1.36(.81)^{b}$	$1.16\pm.66(.57)^{b}$	<0.0001
Fat	$1.02\pm.55(.54)^{b}$	$2.42\pm.84(.35)^{a}$	$2.47\pm.90(.36)^{a}$	<0.0001
Toughness	$2.55\pm.59(.47)^{a}$	$2.11\pm.60(.29)^{b}$	$2.19\pm.50(.23)^{b}$	0.0006
Mushiness	$1.69\pm.54(.32)^{b}$	$2.11\pm.63(.30)^{a}$	$1.96\pm.62(.31)^{a}$	0.003
Flakiness	$2.37\pm.37(.16)^{b}$	$2.49\pm.25(.10)^{ab}$	$2.54\pm.35(.20)^{a}$	0.01
Fibrousness	$2.04\pm.38(.19)^{a}$	$1.85\pm.48(.26)^{b}$	$1.77\pm.35(.20)^{b}$	0.03
Flavor	$7.17\pm.77(.11)^{b}$	$7.40\pm.93(.13)^{ab}$	$7.44\pm.83(.11)^{a}$	0.01

Significant P values from a Kruskal-Wallis are reported in Table 12. Mean values with the same letter value in each row are not significant between catfish genetic types (P > 0.05).

4. DISCUSSION

4.1 Evaluation of texture, sensory, and color attributes in three size classes of channel catfish

Fillet hardness, gumminess, chewiness and toughness all increased with increasing size classes while yellowness of the fillet decreased. A potential explanation that would influence the increase in hardness is the increase in muscle fiber size with the increase of fish size which has a direct influence on texture analyses, which could also potentially explain the increased observed toughness and fibrousness observed in larger channel catfish compared to market and below market sized classes (Hyldig and Nielsen 2001; Listrat et al., 2016). Gumminess and chewiness are calculated using hardness in their equation which would also influence their difference in all size classes however “chewiness” and “firmness” observed by a sensory panel examining Atlantic salmon fillets found an increase in chewiness with an increase in muscle fiber density (Johnston et al., 2000). The decrease in observed mushiness with an increasing size correlates with toughness increase due to their attributes being almost opposite and observing an increase in toughness and decrease in mushiness due to either muscle composition, fillet thickness, size, age, or other phenotypic attributes would make sense as these are fundamental influences on fish texture and sensory observations (Cheng et al., 2014). Further studies should be conducted to evaluate muscle fiber thickness at different sizes of channel catfish and their influence on mechanical and sensory texture profile analyses.

Yellowness of channel catfish fillets was observed to decrease with increasing size, redness was more prominent in larger fish than the other two size classes, and lightness decreased in above market sized channel catfish. This phenomenon with yellow discoloration is a hinderance to the commercial market and is typically found on the dorsal area of the fillet

(Lovell 1984). Carotenoids have been shown to have a direct influence on yellowness of catfish fillets (Li et al., 2007) and because animals cannot produce carotenoids they must be taken in from their feed (Shahidi and Brown 1998). It has been shown that three major carotenoids (lutein, zeaxanthin, and alloxanthin) have a strong relationship with yellowness of fillets and should be examined in future studies to reduce yellowness of market channel catfish (Li et al., 2013). These carotenoids make the fillet more nutritious to consumers and a potential strategy to decrease market losses would be to promote and market a “superior golden fillet”.

Redness in channel catfish fillets cause an estimated $443,000 dollar loss for farmers and $683,000 for processors (Allred et al., 2019). The same study showed that rejected fillets from catfish processing plants had a high prevalence of *Aeromonas sobria* in rejected red fillets (68%) and could be a contributing factor in our analyses. Potentially the increased redness in larger fish could be due to insufficient washing of larger fillets in a freshwater bath compared to the smaller fish or a combination of bacteria, insufficient washing, or potential diseases that potentially influence redness (Allred et al., 2019).

Fillet % decreasing in larger channel catfish is a phenomenon that has been explained previously by the impact of the relatively larger head size compared to body size, resulting in a decreased fillet % (Rutten et al., 2005; Geng et al., 2016).

4.2 Evaluation of texture, sensory, and color attributes in three size classes of blue catfish

Differences in texture, sensory, and color attributes in three sizes of blue catfish were much less severe than observed in channel catfish. This lack of differences observed in blue catfish compared to channel catfish size classifications could be attributed to less samples of blues at each size class being sampled, or morphological differences between the two Ictalurid species. Within size classes of blue catfish fillet yield % was significantly less in above market size compared to below, but neither was significantly different to market size blue catfish. Hardness of blue catfish fillets were significantly different of above market sized between the other two size classes and resilience, chewiness, springiness, and cohesiveness were significantly different between above and below market size, but neither was significantly different to market sized blues. Gumminess was significantly different in above market sized blue catfish to the other two size classes. Visceral fat was significantly more in above market size blues then the other two size classes, and fibrousness was higher in market and above market size blues then below market sized fish. Fillet yield% being lower in the larger blue catfish can be explained by the larger head in larger mature blue catfish resulting in lower fillet yield overall (Rutten et al, 2005) Lightness and yellowness of blue catfish fillets were not significantly different between the three size classes but redness significantly more in the above market to below market sized blues. This could potentially be due accumulation of bacteria as potentially explained by the Allred study (Allred et al., 2019) or improper washing of larger fillets. Differences in texture attributes analyzed showed no significant differences between all three size classes but was significantly different in all attributes between above and below market sizes except adhesiveness which showed no significant differences. This difference between large and smaller blue catfish can potentially be attributed to fillet thickness, muscle fiber diameter and size similar to channel catfish (Hyldig and Nielsen 2001; Listrat et al., 2016; Li et al., 2017). The lack of significant difference in hardness between the medium sized market blues and the smaller below market size blue catfish that were observed in channel catfishcould be contributed to the slower growth of blue catfish, although strain effects have been observed where blue catfish grow faster (Dunham et al., 1994). Muscle fiber size and quantity is key in texture attributes (Fauconneau

1993) and muscle fiber quantity recruited to reach a certain size varies between strains and species (Weatherly et al., 1979) which can be a key phenotypic attribute in analyzing texture and sensory differences across species and why these differences in size classes are found. The only sensory attribute significantly different between the three size classes of blue catfish was fibrousness, which was less fibrous in below market sized blues compared to the other two size classes. This observation in the fibrousness being less in smaller blue catfish can be potentially attributed to muscle fiber diameter and quantity being potentially less compared to the larger two size classes. This observation could potentially be indicative of muscle fiber size through the growth of blue catfish, though quantification of muscle fiber density and diameter is needed, and evaluation of these traits is key in understanding texture differences between Ictalurid species and within species.

4.3 Evaluation of texture, sensory, and color attributes in three size classes of hybrid catfish

Hardness, gumminess, chewiness, and toughness were all observed to increase with increasing size of hybrid catfish and was significantly different between all three size classes. What is intriguing with these results is the difference in perceived toughness in each size class, but the inverse of mushiness was not significantly different between market size and above market sized hybrids. These differences in texture attributes could potentially be explained by fillet thickness between each size class which is shown to influence texture analyses of catfish and other fish species (Veland and Torrissen 1999; Li et al., 2017). However, these differences can also potentially be attributed to muscle density and composition that can vary between fish sizes (Johnston et al., 2000; Hyldig and Nielsen 2001; Listrat et al., 2016). Fibrousness being significantly more in the larger above market sized hybrids compared to the two smaller size classes could also be attributed to these muscle composition differences. Toughness of the fillets being attributed to thickness of the fillet isn't the likely answer as the fillets were cut to uniform sizes following AMSA guidelines (American Meat Science Association 2015). Lightness (L) was significantly higher in below market compared to above market size hybrids, and redness (A) was significantly less in below compared to market and above market size hybrids and neither. Lightness (L) differences in fish fillets have been attributed to higher water deposits on the surface of the fillet (Hernández et al., 2009) and while cook loss was not significantly different across all size classes due to drip loss, direct moisture content was not evaluated in our fillets via proximate analyses. Redness differences could potentially be attributed to *Aeromonas sobria* accumulation as seen in rejected channel catfish fillets (Allred et al., 2019) as well as carotenoid contents within fillets that were not measured (Shahidi and Brown 1998) that have been shown to influence fillet color attributes. Increased flakiness observed between market sized and above market sized hybrids to the smaller below market sized hybrids is an intriguing result as channel catfish had increasing flakiness observed in the same size comparisons and blue catfish had no significant differences observed. Flakiness observations in fish sensory would be to the uniqueness of fish muscle anatomy that allows for the "flaking" sensation to be much more pronounced compared to terrestrial farmed species (Chambers and Robel 1993). This flakiness of the muscle fibers coming apart during oral chewing has not been as studied as other sensory attributes but is likely linked to muscle composition and fiber density and cohesion.

4.4 Comparison of the channel catfish, blue catfish, and channel catfish female X blue catfish male hybrid

Comparison of three genetic types of farmed catfish for texture and sensory traits at three different harvest size class yielded results that are insightful to evaluate texture and sensory differences across farmed catfish genetic types. At all three size classes channel catfish had a harder, gummier, chewier texture and the most tough fillet ($P < 0.05$) of the three genetic types of catfish. This evaluation is a key finding in evaluating catfish texture as we can conclude that channel catfish have a harder, gummier, chewier, and tougher fillet at all life stages. This difference in observed texture and sensory differences at all body sizes evaluated can likely be attributed to muscle composition differences that channel catfish have that lead to these evaluated differences. It is likely that an increased muscle fiber number, density, size, and thickness, that can contribute to these observed differences (Fauconneau 1993; Nielsen 2001; Listrat et al., 2016). At market size, hybrid catfish had the highest fillet yield %, and yielded more flesh than channel catfish at above market size classes ($P < 0.05$), however no significant differences in fillet yield was observed at below market size. These results are logical due to the relationship between fillet yield and body morphology. At the smallest size class, the fish had not reached sexual maturity and their bodies were more likely to be uniformly shaped amongst the genetic types, then after reaching market size and larger channel catfish were reaching maturity and their heads became larger to the body resulting in a decrease fillet yield compared to hybrids and blues (Rutten et al, 2005). A study conducted in evaluating fillet yield in four genetic types of catfish showed that hybrid catfish (.83 kg) had a higher fillet yield then channel catfish (.56 kg) and blue catfish (.36 kg) (Argue et al., 2003). At these weights evaluated in the previous study when compared to our study, the results are similar across genetic types. Hybrid catfish had higher visceral fat deposition than channel catfish at every size class evaluated ($P < 0.05$) and higher visceral fat deposition than blue catfish in the below market size class ($P < 0.05$). This evaluation of higher visceral fat deposition in hybrid catfish compared to channel catfish has been observed in other studies (Yant et al., 1976; Bosworth et al., 2004). It is possible the high visceral fat deposition is due to inheritance from the blue sire in hybrid progeny, as blue catfish had higher visceral fat deposition than channel catfish at every size class in our study (P <0.05). This could be longer time to reach sexual maturity in blue catfish than channel catfish, which allows for more energy to be diverted to fat deposition in blue catfish (Dunham and Smitherman 1987). This is confirmed in our study as well with blue catfish having lower gonadal development than channel catfish in market and above market size classes (P <0.05).

4.5 Evaluation of texture, sensory, and color attributes in market size channel catfish and hybrid catfish

With up to 70% of catfish aquaculture in the United States being based around the production of hybrid catfish (N. Chatakondi, US Department of Agriculture, personal communication) it is imperative to evaluate the texture and sensory attributes of hybrid and channel catfish. Evaluation of blue catfish properties in our study serves multiple purposes. if they had showed superior carcass traits, it might justify increased use of this species in catfish aquaculture. Evaluation of blue catfish texture, sensory, and fillet color traits helps elucidate genetics of the texture traits and understanding blue catfish phenotype and genetics would be useful in backcrossing programs. Channel catfish and blue catfish fillet % decreased with size and the above market hybrid catfish had a lower fillet % than the two smaller size classes. Relative head size was likely increasing for all genetic types resulting in this observed trend of decreased fillet % in larger fish. Fillet % of hybrid catfish at all sizes was better than blue and channel catfish, likely due to their smaller head size as similar results were found in various studies (Argue et al., 2003; Bosworth 2012; Dunham and Masser 2012), but cannot sum up total differences among genetic types of catfish as blue catfish have the smallest head size of genetic types (Dunham et al., 1984).

Redness of the fillet also increased with size in all three genetic types. In general, blue catfish had the reddest fillet at all sizes. For market sized fish the redness of hybrid catfish fillets was greater than channel catfish. Differences in redness can be explained by moisture content in filets which was not measured in our study (Hernández et al., 2009). Several factors can lead to redness in the fillet including catfish being subjected to high temperatures, potential internal hemorrhaging that leads to blotchy red coloration on the fillet, small spots of redness are believed to be from spining by other catfish, and stress events from the environment, harvest, and transportation is shown to reduce fillet quality and potentially lead to increased redness. (Desai et al., 2014; Ciaramella et al., 2016; Refaey et al., 2017; Allred et al., 2019).

Lightness of the fillet decreased in channel catfish and hybrid catfish with increasing size. Among genetic types, above market size blue catfish had the lightest fillet followed by channel catfish and then hybrid catfish being the least light. Yellowness of the fillet did not show much variability across size or genetic types but did decrease with increasing size of channel catfish.

Most other mechanical texture and sensory attributes were higher in channel catfish including hardness, resilience, adhesiveness, cohesiveness, gumminess, chewiness, toughness, and fibrousness. Hardness of the fillet increased with size in all genetic types. In below and market sized fish, hybrid catfish were intermediate for hardness. Resilience was more complicated as it decreased with size in blue catfish, the below and above market sized channel catfish had the highest values, and no relationship was observed in hybrid catfish. Below market and market sized blue catfish were intermediate for cohesiveness compared to channel catfish and hybrid catfish. The same genetic relationship existed for adhesiveness, except only market sized as below and above market size blue and hybrid catfish were not different. Cohesiveness decreased with increasing blue catfish size. Gumminess, chewiness, toughness, and fibrousness all increased with size across the three genetic types of catfish.

Springiness was less straightforward to interpret as below market and market sized channel and blue catfish had higher values than the hybrid catfish, and in above market size fish channel catfish had the highest mean. Within genetic types, above market and below market channel catfish had the highest springiness, blue catfish springiness decreased with size and no differences were observed in hybrids among size groups.

Evaluating mushiness among genetic types, blue catfish and hybrid catfish were mushier than channel catfish and mushiness decreased with increasing size across all genetic types of catfish. Mushiness is a key attribute that at least one catfish processor has concern with when comparing the “mushy” hybrid fillet to the imported pangasius fillets (*Pangasianodon hypopthalmus).* This concern needs to be further studied to evaluate the extent of these differences on consumer preference and determine if a consumer preference exists.

Flakiness was similar among all genetic types except for the above market size hybrid catfish which had the highest flakiness, followed by blue catfish and then channel catfish was the least flakey. Flakiness increased with size with increasing size among all three genetic types of catfish.

Differences observed in cook loss were small among and within all three genetic types. Blue catfish had the highest loss in the below market size class, and hybrid catfish had the least cook loss in the above market size class. Cook loss in channel catfish increased with increasing size.

Gonadal development among genetic types of catfish was greatest in market and above market channel catfish and increased with body weight in blue catfish and channel catfish. The opposite trend was observed in hybrid catfish, genetics of sexual maturation and relation to size could potentially be different in hybrid catfish and potentially sexual maturation slowed growth of the hybrid catfish.

Visceral fat was different among genetic types of catfish. At below market size, hybrids had the most visceral fat followed by blue catfish, and channel catfish had the least visceral fat deposition. At market size and above market size blue catfish and hybrid catfish had the most visceral fat content and channel catfish had the least. Channel catfish had the least visceral fat content at all size classes, and fat was shown to increase with increasing size in all genetic types. Visceral fat in rainbow trout (*Oncorhynchus mykiss*) was shown to have a negative correlation with shear force texture analyses which could potentially influence hybrid texture hardness, and in turn sensory evaluation (Aussanasuwannakul et al., 2011).

Overall, channel catfish had the most distinctive flesh and pattern of texture attributes and the most tough and fibrous flesh among genetic types. Blue catfish and hybrid catfish had a more variable pattern compared to channel catfish and were more similar to each other than to channel catfish. This could be an example of paternal predominance in hybrid catfish (Dunham et al., 1982). Distinct genetic effects on texture were observed in the current experiment, which is contrast to an earlier study that found no different in texture of cooked channel catfish and hybrid catfish fillets (Huang et al., 1994).

Bosworth et al., (2004) found that fillet yield in hybrid catfish was higher than channel catfish showing similar results to our study. The study also found that Kramer shear force in texture analyses was higher in one channel catfish strain than a second channel catfish strain and the hybrid catfish. The sensory evaluation in their study found no difference between channel catfish and hybrid catfish for “firmness”, “flakiness”, or “flavor” which shows slightly different results compared to our study as our sensory panel found higher “toughness” in channel catfish than hybrid catfish. Flakiness and flavor was higher in above market size hybrid catfish in our study but not different in the smaller fish. Bosworth et al., (2004) used what would classify as market size catfish and below market size catfish in their study, so the flakiness and flavor results are the same across our studies. A more recent study (Bosworth 2012) showed similar results with hybrid catfish having a higher shank fillet yield than channel and blue catfish, and hybrid catfish and blue catfish having higher fat content than channel catfish.

5. CONCLUSION

The results of this study show distinctive channel catfish texture and sensory traits at all size classes. Blue catfish and hybrid catfish are more similar to each other than to channel catfish, and due to the production benefits the hybrid catfish provides, a blue catfish aquaculture for enhanced texture or sensory is not needed. A key finding in this study is the higher toughness of channel catfish fillets and the mushier flesh of the hybrid catfish. Consumer evaluation of these two products needs to be conducted before confirming the "best fillet" and to see consumer preference between the two fillets. We have found differences between the two genetic types in this study, but before confirmation and guidance of industry for best fillet properties, a consumer preference survey or study on fillet properties needs to be evaluated. Further studies are needed that evaluate muscle fiber density, size, and muscle composition to correlate these traits to potentially explain differences in texture between market size hybrid and channel catfish.

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CHAPTER 2

TEXTURE, SENSORY, COLOR, AND CARCASS TRAITS OF SEVEN STRAINS OF CHANNEL CATFISH (*ICTALURUS PUNCTATUS*) FILLETS

ABSTRACT

Five genetic strains of channel catfish (*Ictalurus punctatus)* were analyzed for texture, sensory, body carcass, and color traits to evaluate potential differences between strains that could be indicative of underlying genetic variation for these traits that could be utilized to enhance these important traits. These strains of Kansas Mix (Kmix) Kansas Select (103KS) Kansas Random (KR) Tishomingo x ARMK (TARMk), Kansas x Thompson (KTH), Late Spawn Strain, and an unknown M6 strain were found to have differences across certain strains in fillet yield %, cook loss, redness, hardness, cohesion, visceral fat content and all sensory traits analyzed except flavor. These traits play a key role in aquaculture production and acceptance of fillets by a consumer directly impacting the marketability of the fillet product and profitability to catfish farmers and processors. Kmix had the second highest fillet yield, lowest cook loss, the lowest hardness, and least tough and most mushy strain while KR had the lowest fillet yield, highest cook loss, highest hardness, and the most tough and less mushy strain. Despite similar origins, these strain differences could be due to underlying genetic differences between the strains contributing to these observed texture, sensory, and body carcass differences. This study shows the influence a genetic strain has on these traits and is indicative of underlying genetic contributions to these traits that can be utilized to enhance catfish aquaculture

1. INTRODUCTION

Catfish farming worldwide was responsible for 5.06 million metric tonnes of production in 2016, primarily using *Clarias, Icatlurus, and Pangasius* catfish and was the fourth largest taxonomic grouping of farmed aquatic species (Tacon, 2018). Worldwide, aquaculture employs 56.7 million people and provides rural areas with an opportunity for valuable income, providing the ability to diverse job opportunities in these communities (Allison, 2005; FAO, 2012; Phillips, et al., 2016). More than half (53%) of all fish consumed worldwide is from farmed species with a projection of 60% in 2030 (FAO, 2018). With such a high demand for seafood and aquaculture products, improvement in production of species worldwide is needed to meet these future demands and to ensure a continued reliable source of seafood production (Verdegem and Bosma, 2009; Nayolor et al., 2009; Houston et al., 2019).

In the United States aquaculture is dominated by catfish production making up 75% of total finfish production and 50% of total sales of US aquaculture food fish production (FAO, 2019). This large production of catfish is dominated by channel catfish (*Ictaulrus punctatus*) and hybrid catfish (channel catfish ♀ × blue catfish (*Icatulurus furcatus* ♂)) grossing a total of $335 million dollars of pond bank sales in 2018 (Hanson, 2018). With such high volume of production and contribution to overall market value, catfish production is responsible for 50% US food fish production and 31% of food-sized farmed seafood (Vilsack and Reilly, 2013). To aid in furthering the production and to enhance the catfish aquaculture industry, genetic enhancement efforts have been researched to aid in overall genetic improvement of channel catfish and increase various economically important traits such as carcass yield, growth, reproductive performance, and seinability (Dunham and Elaswad, 2017; Bosworth et al., 2020).

Without a proper genetic management plan, aquaculture farmers and commercial hatcheries run the potential of loss of production and risk inbreeding in their stocks (Nguyen, 2016). Genetic enhancement protocols and management plans have been established in a wide variety of farmed species, with each genetic enhancement project aimed at improving different traits important to aquaculture production (Dunham et al., 2000). Genetic management plans range greatly focusing on specific traits to enhance and range from carcass yield, growth, early spawning, disease resistance, and feed conversion ratio (Gall 2004; Yáñez et al., 2014; Kause et al., 2016; Bosworth el al., 2020). Even with the importance genetics plays for improving aquaculture production there is still a large genetic potential that has yet to be achieved that can bolster future production (FAO 2019). There is a lack of recognized stocks and strains especially when compared to other agriculture practices and has limited adaptation to different culture conditions (FAO 2019).

Even with the increased emphasis in genetic programs in aquaculture species, the sector is significantly behind that of other agriculture programs (Rye et al., 2010; FAO 2019). Despite the various genetic management plans in aquaculture species to improve production very little research has been done in the genetic management of flesh quality, specifically texture attributes. Aquaculture food production was responsible for $232 billion dollars (USD) in 2016, with more than half of that market production being reliant on the farming of fin fish (FAO 2019). While it is important to have genetic enhancement protocols to increase overall production and meet an increasing demand in farmed fish products, the flesh product from the fish is the main commercial product purchased by consumers and people are eating more fish today than ever before (FAO 2019). Research into genetic contribution to these flesh products need to be more thoroughly researched.

Some research has investigated the genetic contribution of various carcass quality traits, though it is not nearly as studied for other traits in aquaculture production. Astaxanthin level, canthaxanthin content, color, fat and moisture all were heritable (0.10-0.20) in Atlantic salmon (*Salmo salar),* along with positive genetic correlations of carotenoid pigmentation, moisture, and fat with body weight (Quinton et al., 2005). Earlier studies were also conducted addressing heritability and genetic correlations of dress out % and fat % in channel catfish males and females (El-Ibiary and Joyce 1978), dressing %, fat %, carcass quality score, flesh color score, protein % in rainbow trout (*Oncorhynchus mykiss*) (Gjerde and Gjedrem 1984; Gjerde 1989) as well as dressing %, carcass quality score and flesh color score in Atlantic salmon (Gjerde and Gjedrem 1984).

Genetic research into texture attributes has been conducted for various cultured species. Muscle texture in farmed European whitefish (*Coregonus lavaretus*) had moderate heritability score (0.30 ± 0.09) and was correlated with lipid deposition (-0.32) (Kause et al., 2009). Fillet hardness in Gilthead seabream (*Sparus aurata)* was found to have lower heritability than European whitefish (..21 +-.06) when measured on the back of a whole fish and was negatively correlated with weight (García-Celdrán et al., 2015). Texture of flesh using a penetrometer in Coho salmon (*Oncorhynchus kisutch)* was found to have low heritability (.06-.09) in two different populations (Neira et al., 2004).

Strain and sex effects on texture have been evaluated for different species commercially farmed fish. A study on three different strains of farmed turbot (*Scophthalmus maximus*) showed variations within strains for softness of the fillet, however, this could be contributed to environmental influences as each strain was harvested in different times of the year and it is unclear if differences were a result of strain or environmental influences (Roth et al., 2010). A similar study was conducted with five different strains of rainbow trout grown in partial water reuse systems, and minimal effect of strain on flesh texture attributes were found (Crouse et al., 2018). More than 3000 coho salmon were sampled, but no sex effect was observed for texture (Neira et al., 2004).

There is a lack of strain and sex effect information on channel catfish considering that catfish play such a key role in US aquaculture production (Hanson 2018). One study on only two strains of channel catfish found no differences in texture and sensory attributes, except a minor but significant effect on firmness in frozen-thawed fillets (Bosworth et al., 2004). However, these fish were grown in different ponds which could have led to environmental influence on texture and sensory outputs. In the current study, the objectives were to determine fillet properties, texture and sensory attributes, and sex effects on these traits in 7 strains of channel catfish.

2. MATERIALS and METHODS

2.1 Strain origins of experimental fish

A total of seven different strains of channel catfish were used for this study to evaluate strain differences in texture, sensory, fillet yield %, and color of channel catfish fillets. Three strains used in this study have origins from the same river system and are derived from the same original stock 6-8 pairings brought to Auburn University in 1976 (Dunham and Smitherman 1984). 103KS is a mixed line from Kansas Select and NWAC 103. NWAC 103 was the Uvalde strain that was derived from Studdard Fish Farm, Moore, Texas. (Dunham and Smitherman 1984). USDA conducted two generations of selection for body weight leading to the NWAC 103 strain derived from original Uvalde strain. KS is derived from Kansas Random (KR), but KS had been selected for growth for 8 generations. Kansas Random (KR) originate from the same population brought to Auburn University and are propagated through random mating, are resistant to disease. Kansas Mix (Kmix) are a mix of KS and KR strains that were crossbred, then selected for 2 generations for body weight and growth. Kansas x Thompson (KTH) is an F3 strain developed from the crossbreeding of these Kansas origin catfish that were crossed with Thompson-Anderson farm stock channel catfish that are derived from the Yazoo River in Mississippi (Dunham and Smitherman 1984). Tishomingo x ARMK (TARMk) is a strain derived from the cross breeding of Tishomingo hatchery stock channel catfish and ARMK strain channel catfish. ARMK strain channel catfish are derived from Auburn strain females mated with Rio channel males and were propagated via mass selection for body weight where the largest 10% in the F_2 were used as broodstock. Females from this mass selection were later crossed with Kansas males forming ARMK strain channel catfish that were propagated with the largest 10% of fingerlings of 33 crosses used as future stock (Dunham and Smitherman 1984). Tishomingo strain channel catfish are from the Blue River in Oklahoma in the 1930’s, the Washita River, Oklahoma; the Grand River, Fort Gibson, Oklahoma; Red River in the 1950’s. These Tishomingo strain have an unknown broodstock origin that could be from these different locations (Dunham and Smitherman 1984). ARMK starin was crossed with this Tishomingo strain to form TARMk strain that is propagated today at Auburn University. Late Spawn strain is a new strain of channel catfish created at Auburn University that have been selected for their ability to spawn late in the traditional spawning season and is derived from AR and ARMK strains. M6 strain is an unknown strain of channel catfish at Auburn University that are derived from the same pond but have unknown origins.

2.2 Rearing of experimental fish

All experimental procedures used in this study were performed in accordance with guidelines of the Auburn University Institutional Animal Care and Use Committee for use and care of animals. Fish were reared and fed ad-libitum in 60L aquaria (150 individuals/aquarium) in a recirculating system at the EW Shell Fisheries Center at Auburn University in Auburn, AL. Upon reaching a mean of 30 grams, the experimental fish were PIT tagged and stocked into 0.04h earthen ponds at a rate of 14,000 fish/ha. Fish were fed ad-libitum with 32% protein pelleted catfish feed seven days a week until they reached a mean weight of 1kg. Fish were then harvested, individually weighed, sexed, and species/genetic type determined prior to filleting.

2.3 Filleting of experimental fish

Individual fish were weighed live, then sacrificed with blunt force trauma to the head followed by pithing, following IACUC guidelines. Channel catfish swim bladders have a one chamber swim bladder and evaluation of the swim bladder was used to confirm the species evaluated. Gonadal development and visceral body fat quantity were graded on a scale of 0.5-5 with 0.5 being least developed and 5 being the most developed. Fish were filleted in a uniform manner by making an incision on the head where the head meets the body of the fish and following the spine of the fish with a fillet knife. Flesh was cut away from the ribs resulting in a boneless shank fillet. After filleting, each fillet was skinned, individually weighed to determine shank fillet yield, and rinsed in a freshwater solution to remove blood and other particles. Fillets from each individual fish were vacuum sealed in a 15.24 cm x 30.48 cm Clarity 4-Mil vacuum pouch (Bunzl Processor; Koch Supplies, Riverside Missouri) and placed in a -10°C freezer.

2.4 Fillet processing for sensory evaluation and texture profile analyses

Prior to evaluation, fillets were placed in a 2 ± 2 °C refrigerator overnight for thawing. Once thawed, raw fillets were evaluated for color using a CR 300 Minolta Chromameter (Osaka, Japan) to evaluate lightness, redness, and yellowness of fillets, and weighed prior to and after cooking to evaluate cook loss. Individual fillets were wrapped in aluminum foil and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. The American Meat Science Association (AMSA) research guidelines (AMSA, 2015) were followed, and one fillet was served to a semi-trained sensory panel of 12 individuals (6 males and 6 females ranging from age 21-65) in clear plastic serving cups with lids. The other fillet was stored in a 2 ± 2 °C refrigerator overnight and raised to a temperature of ~72°F (22°C) before used for texture profile analyses.

2.5 Sensory evaluation of catfish fillets using a semi-trained panel

Following American Meat Science Association (AMSA) Research Guidelines for Cookery, Sensory Evaluation, and Instrumental Tenderness Measurements of Meat (2nd ed.) (AMSA, 2015) guidelines, a group of 12 individual panelists were trained to evaluate 5 different key attributes in catfish fillets; toughness, flakiness, mushiness, fibrousness, and flavor (Bland, et al., 2018). Each fillet sample was graded on a scale of 1-4, with 1 being the least and 4 being the most of each attribute, and each corresponding value was correlated with a food item to calibrate the panel to the attributes of the fillet (Table 15). Flakiness was graded on a 1-3 and flavor was graded on a scale of 1-10, with 1 being severe off flavor, a flavor of 5 had distinct off flavor, 7 mild to little off flavor, and 10 corresponding with no off flavor. Panelists were trained on five different occasions before the sensory evaluation of catfish fillets, with calibration sessions occurring each week of sensory evaluation. Panelists were served equal portions of a fillet (1.27 cm x 1.27 cm) in plastic 2 oz serving cups with a lid. Samples were portioned after being allowed to rest for 10 minutes after reaching an internal temperature of 74 °C 3 groups of 4 panelists were divided to ensure replication of each fillet and were given 12 blind samples with random numbers during each sensory session to reduce bias. Panelists scored their 5 attributes using a blind survey using Google Forms (Google, Mountain View CA, US, 2021) to prevent bias by observing other panelists scores. In between each sample, panelists drank a sip of room temperature water, took a bite of a saltine cracker, then drank another sip of water to cleanse the palate.

Table 15. Corresponding food items correlated to their score for each sensory attribute. This scale was used to calibrate the semi-trained panel in their evaluation of catfish fillet sensory attributes.

Attribute	1	2	3	4
Toughness Force required to bite through a fillet sample	Canned Dole Pineapple Chunk 1’ cube	Heritage Farm Chicken Hotdogs 2 cm diameter piece	Hebrew National Beef Hotdog 2 cm diameter piece	Starkist Solid White Albacore Canned Tuna in water 2 cm diameter serving
Mushiness How much a fillet sample dissipated after initial bite	Hebrew National Beef Hotdog 2 cm diameter piece	Raw White Mushroom Whole	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Simple Truth Organic Extra Firm Tofu 1’ cube
Flakiness Ease of which fillet samples were broken into individual muscle components	Cooked Wild Caught Pan Seared Sea Scallops ¼ scallop	Canned Dole Pineapple Chunk 1’ cube	Chicken of the Sea Canned Traditional Style Pink Salmon 2 cm diameter serving	N/A
Fibrousness Perception of amount of muscle tissue strands or filaments were left after chewing	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Canned Dole Pineapple Chunk 1’ cube	Raw Asparagus stem	Raw Asparagus base

2.6 Texture profile analyses of catfish fillets

Fillets were individually wrapped in aluminum foil, labeled, and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. After cooking, fillets were refrigerated at 2 ± 2 °C refrigerator overnight, then raised to room temperature ~72°F (22°C) prior to texture profile analyses. Each fillet was then sampled using TA-XT2i Texture Analyzer shear machine (Texture Technologies Corp., Scarsdale, NY) loaded with a 5 kg load cell with a ½' diameter ball probe attachment (TA-18) (Bland et al., 2018). Seven attributes were evaluated for each fillet: gumminess, chewiness, springiness, hardness, cohesiveness resilience, and adhesiveness (Table 16). Each fillet was sampled in triplicate, with the mean average of each being used for statistical analyses.

Table 16.

Texture profile attributes analyzed, formula used for each output, and the definition of each attribute analyzed.

Attribute	Formula	Description
Hardness	Force at anchor 1	Maximum force applied during the first compression
Gumminess	Hardness x Cohesiveness	Energy needed to disintegrate a semi solid food until it is ready to swallow
Chewiness	Hardness x Cohesiveness x Springiness	Energy needed to chew a solid food until ready to swallow
Springiness	Distance2/Distance 1	Rate at which a sample returns to its original size and shape
Adhesiveness	Area 3	Work required to overcome stickiness between the probe and the sample
Resilience	Area 2/ Area 1	How well a product returns to its original shape and size during the first probe
Cohesiveness	Area 4/ Area 1	How well a product returns to its original shape and size in the second probe relative to the first probe

2.6 Statistical Analyses

All data was analyzed using SAS statistical analysis software (v.9.4; SAS Institute Inc., Cary, NC, USA). Data was tested for normality using a Shapiro-Wilk test (Shapiro and Wilk 1965) and was considered non normally distributed at an alpha =0.05. A non-parametric one-way ANOVA using a Kruskal Wallis test was used to evaluate differences in ordinal dependent categories (gonad development, visceral fat development, and all sensory attributes) and texture attributes that were not normally distributed. Statistical differences were assumed at an alpha of = 0.05. When a significant effect of size on a texture, sensory, carcass, or fillet color trait was detected using a linear regression analyses, we adjusted for these differences using the formula $Y_A = Y - b_{xy} (X_i - X_p)$ where Y_A is the adjusted attribute, Y is the actual attribute value, b_{xy} is the regression coefficient, X_i is the mean replicate weight, and X_p is the mean weight of all replicates. Differences in texture, fillet yield %, cook loss %, and color were evaluated using a one-way ANOVA with a Tukey post hoc conducted to determine differences between groups. An alpha of =0.05 was considered statistically different between strains.

3. RESULTS

3.1 Effect of Size on Fillet %, Texture Properties, and Fillet Color

Body weight of channel catfish evaluated in the current study had a significant impact on redness of the fillet (P=0.01), as well as hardness, gumminess, chewiness, yellowness of the fillet, and fillet % (P <0.0001). Fillet yield and yellowness of the fillet decreased with increasing body weight, while redness of the fillet, hardness, gumminess, and chewiness all increased with increasing body weight. Regression equations for each trait are presented in Table 17. No other significant impacts for body weight on traits evaluated were found in the current study.

Table 17

Regression equations for significant impact on body weight for redness and yellowness of the fillet, fillet % (total fillet weight / live body weight of the fish), hardness, chewiness (hardness x springiness x cohesion), and gumminess (hardness x cohesion) in channel catfish (*Icatlurus punctatus)*.

Trait	Regression Equation	R^2	P value
Fillet %	$y= -0.06x + 0.51$	0.1	<0.0001
Redness	$y= 0.04x + 1.10$	0.01	0.01
Yellowness	$y= -0.15x + 4.55$	0.12	<0.0001
Hardness	$y= 0.44x+ 2.90$	0.36	<0.0001
Gumminess	$y= 0.44x + 2.64$	0.29	<0.0001
Chewiness	$y= 0.43x + 2.51$	0.26	<0.0001

3.2 Strain differences for fillet %, texture Properties, and fillet color

Means, standard deviations, and coefficient of variation for texture, carcass, and fillet color attributes for 7 strains of channel catfish are reported in Table 18. Fillet % was higher ($P<0.05$) in M6 strain among all other strains except Tishomingo x ARMK (TARMk). M6 and KR had more cook loss than Kmix ($P <0.05$) but no other differences among strains were observed for cook loss. M6 strain had a redder fillet than all other strains ($P<0.05$) except for TARMk. Kansas-Thompson (KTH) was less red than 103KS ($P <0.05$). KR fillets were harder ($P<0.05$) than Kmix, KTH, and 103KS strains. Kmix was the least hard and less hard ($P<0.05$) than Late Spawn, TARMk, and KR strains. M6 unknown strains were the least cohesive ($P<0.05$) and less cohesive than all strains except Late Spawn and 103KS. No differences were observed in lightness (L), yellowness (Y), adhesiveness, resilience, springiness, gumminess, and chewiness.

Table 18.

Means for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness, adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness, ± standard deviation (SD) and coefficient of variation (CV) of seven strains of channel catfish (*Ictalurus punctatus*). The strains evaluated are Kansas Mix (Kmix), Kansas Random (Kr), Late Spawn, Kansas x Thompson (KTH), Tishomingo x ARMK (TARMk), M6, NWAC 103 x Kansas Select (103KS). An alpha = 0.05 is considered significant following a Tukey's post hoc test.

Strain	Kmix	Kr	Late Spawn	KTH	TARMk	M6	103KS	P Value$_1$
Trait	n=352	n=24	n=19	n=17	n=5	n=22	n=15	
Fillet %	25.87± 3.28 (.13)^{b}	20.04± 5.25 (.26)^{c}	23.42±3.50 (.15)^{bc}	22.56±4.31 (.19)^{c}	21.81± 3.56 (.16)^{abc}	26.54± 5.32 (.20)^{a}	24.34± 3.06 (.13)^{b}	0.02
Cook Loss %	23.06± 4.92 (.21)^{b}	27.47± 10.07 (.37)^{a}	25.58±4.42 (.17)^{ab}	23.05± 5.82 (.25)^{ab}	27.33±6.57 (.24)^{ab}	27.40± 3.89(.14)^{a}	24.61±3.34 (.14)^{ab}	0.02
L	55.68± 4.57 (.08)	52.98± 5.19 (.10)	58.24± 7.26 (.12)	55.75± 2.65 (.05)	55.10± 6.34 (.12)	51.35± 10.24 (.20)	55.21± 2.22 (.04)	N/S
R	2.33± 2.20 (.94)^{bc}	3.24± 2.34 (.72)^{bc}	2.48±2.05 (.83)^{bc}	1.08± 1.32 (1.22)^{c}	5.21± 3.82 (.73)^{bc}	5.44±3.08 (.57)^{a}	2.87± 2.60 (.91)^{b}	0.03
Y	8.37± 3.41 (.40)	6.17± 4.83 (.78)	7.11± 3.22 (.45)	8.75± 3.50 (.40)	8.59± 4.03 (.47)	6.64± 5.57 (.84)	8.71±4.00 (.46)	N/S
Hardness	647.48 ± 229.68(.35)^{c}	1052.51± 420.66(.40)^{a}	869.17± 275.10(.32)^{ab}	702.62± 206.45(.29)^{bc}	1070.45± 290.32(.27)^{ab}	921.79± 306.09 (.33)^{ab}	718.65± 353.66 (.49)^{bc}	0.008
Adhesiveness	-2.99± 2.32 (.78)	-1.93 ±1.43 (.73)	-2.50±1.45 (.58)	-3.08 ± 2.24 (.73)	-1.82 ±.74 (.40)	-3.24±3.49 (1.08)	-3.23± 2.15 (.67)	N/S
Resilience	23.67± 3.82 (.16)	25.49± 6.03 (.24)	22.43±3.69 (.16)	26.33± 4.19 (.16)	27.98± 5.12 (.18)	22.38± 5.81 (.26)	23.78± 4.74 (.20)	N/S
Cohesion	0.56±.05 (.09)^{a}	0.58±.08 (.13)^{a}	0.55±.05 (.09)^{ab}	.59±.03 (.05)^{a}	.62±.07 (.11)^{a}	.52±.09 (.17)^{b}	.55±.07 (.13)^{ab}	0.02
Springiness	73.81± 5.87 (.08)	76.27± 8.37 (.11)	71.85±5.65 (.08)	76.64± 6.24 (.08)	76.15± 6.53(.09)	71.69± 6.50 (.09)	73.31± 7.74 (.11)	N/S
Gumminess	363.93± 142.71 (.39)	622.92± 309.79 (.50)	479.95± 167.08(.35)	414.69± 130.69 (.32)	670.16± 200.19(.30)	500.31± 221.25 (.44)	406.79± 216.33(.53)	N/S
Chewiness	269.96± 111.65 (.41)	478.80± 267.62 (.56)	348.95± 131.65(.38)	316.98± 104.29 (.33)	518.51± 167.05(.32)	371.27± 185.14 (.50)	300.30± 163.00 (.54)	N/S

Significant P values among groups following a Tukeys Post Hoc test is reported in the last column. Different letter superscripts in the same row denote significance between groups ($P<0.05$).

Means, standard deviations, and coefficient of variation for seven strains of channel catfish are presented in Table 19. Kmix had a less tough and more mushy flesh (P<0.05) than M6, Kr, and Late Spawn strains, and 103KS was more mushy than Late Spawn strain (P<0.05). Kmix was less fibrous than Kr, TARMk, Late Spawn and M6 channel catfish (P <0.05) but no other differences were found among groups. KTH and Kmix fillets had less flakey flesh (P<0.05) than Late Spawn, but no other significant differences between groups was observed. TARMk and KR had higher gonadal development then all other strains (P<0.05). M6 and Late Spawn had more gonadal development than Kmix (P<0.05), but no statistical differences were observed among Kmix, KTH, and 103KS. No differences were observed among strains for flavor.

Table 19.

Means ± standard deviation (SD) and coefficient of variation (CV) of sensory attributes toughness (tough), mushiness (mushy), flakiness (flakey), fibrousness (fibrous), flavor, gonadal development (gonad), and visceral fat content (fat) in seven strains of channel catfish (*Ictalurus punctatus*) that were graded on an ordinal scale. An alpha =0.05 after analyses using a Kruskal Wallis test was considered significant.

Strain	Kmix	Kr	Late Spawn	KTH	TARMk	M6	103KS	P Value$_1$
	n=352	n=24	n=19	n=17	n=5	n=22	n=15	
Gonad	1.50±.89(.59)^{c}	3.67±1.09(.30)^{a}	2.37±1.48(.62)^{b}	1.35±.61(.45)^{bc}	3.9±.65 (.17)^{a}	1.98±.85(.43)^{b}	2.1±1.54(.73)^{bc}	0.017
Fat	.84±.43 (.51)^{b}	.90±.47 (.52)^{ab}	1.21±1.03(.85)^{ab}	.82±.43 (.52)^{ab}	.70±.45(.64)^{ab}	1.11±.60(.54)^{a}	.87±.44 (.51)^{ab}	0.012
Tough	2.23±.51(.23)^{b}	2.71±.75 (.28)^{a}	2.52±.40 (.16)^{a}	2.42±.51(.21)^{ab}	2.47±.67(.27)^{ab}	2.60±.57(.22)^{a}	2.29±.45(.20)^{ab}	0.006
Mushy	2.00±.56(.29)^{a}	1.64±.50 (.30)^{bc}	1.68±.44 (.26)^{c}	1.96±.61(.31)^{ac}	1.61±.56(.35)^{ac}	1.68±.64(.38)^{bc}	1.96±.47(.24)^{ab}	0.04
Flakey	2.28±.31(.14)^{b}	2.51±.60 (.24)^{ab}	2.43±.38 (.16)^{a}	2.17±.33(.17)^{b}	2.17±.25(.11)^{ab}	2.33±.30(.13)^{ab}	2.30±.37(.16)^{ab}	0.04
Fibrous	1.78±.38(.21)^{b}	2.01±.42 (.21)^{a}	1.93±.36 (.19)^{a}	1.89±.33(.17)^{ab}	2.07±.26(.12)^{a}	2.12±.39(.18)^{a}	1.92±.29(.15)^{ab}	0.008
Flavor	7.36±.68(.09)	7.19±.89 (.12)	7.49±.46 (.06)	7.28±.57(.08)	6.9±.55 (.08)	7.33±.86(.12)	7.16±.77(.11)	N/S

1. Highest significant P values following a Kruskal Walis test are listed in the last column. Different letter superscripts in the same row denotes significance between groups. An alpha =0.05 is considered significant

3.2 Sex differences in carcass, texture, and fillet color traits in channel catfish

Means, standard deviations, and coefficient of variation for male and female channel catfish for carcass traits, texture traits, and fillet color traits are reported in Table 20. Females had a higher fillet % (P=0.0002) while males had a more hard, gummy, and chewier fillet (P <0.05). Although not statistically significant (P= 0.054), a potential biological significance of females having a more yellow fillet is observable in the results. No other differences were observed.

Table 20.

Means ± standard deviation (SD) and coefficient of variation (CV) for fillet yield % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness, between male and female channel catfish (*Ictalurus punctatus).* P values after a Tukey's Post Hoc Test are listed in the last column, an alpha =0.05 is considered significant.

Attribute	Male n=238	Female n=216	P value
Fillet %	24.45± 3.66(.15)	26.34±3.73(.14)	0.002
Cook Loss %	23.74±5.38(.23)	23.50±5.37(.23)	0.26 (N/S)
L	55.85±4.75(.09)	55.02±5.47(.23)	0.48 (N/S)
R	2.56±2.52(.98)	2.43±2.16(.89)	0.68 (N/S)
Y	8.06±3.41(.42)	8.30±3.89(.47)	0.054 (N/S)
Hardness	717.00±293.73(.41)	664.64±240.70(.36)	0.03
Adhesiveness	-2.97±2.42(.82)	-2.90±2.18(.75)	0.59 (N/S)
Resilience	23.78±4.38(.18)	23.81±3.87(.16)	0.79 (N/S)
Cohesion	0.56±.06(.10)	0.56±.05(.09)	0.73 (N/S)
Springiness	73.86±6.03(.08)	73.87±6.28(.08)	0.99 (N/S)
Gumminess	405.40±186.35(.46)	374.96±154.72(.41)	0.003
Chewiness	301.81±147.10(.49)	278.95±125.87(.45)	0.006

Means, standard deviations, and coefficient of variations for sensory traits, gonadal development, and visceral fat content between channel catfish sexes are presented in Table 21. Evaluation of these traits that were graded on an ordinal scale and compared using a Kruskal Wallis test showed no differences between sexes for any traits at an alpha significance of 0.05. At an alpha equal to 0.10, males have higher gonadal development than females in the current study.

Table 21.

Means ± standard deviation (SD) and coefficient of variation (CV) between male and female channel catfish (*Ictalurus punctatus)* for sensory attributes toughness, mushiness, flakiness, fibrousness, flavor, and gonadal, visceral fat development rated on an ordinal scale. An alpha =0.10 after analyses using a Kruskal Wallis test was considered significant.

Species	Male	Female	P value
Attribute	n=238	n=216	
Gonad	1.81±1.17(.65)	1.61±1.01(.62)	0.08
Fat	.92±.55(.60)	0.82±.41(.50)	0.13 N/S
Toughness	2.32±.56(.24)	2.27±.52(.23)	0.20 N/S
Mushiness	1.92±.59(.30)	1.97±.53(.27)	0.23 N/S
Flakiness	2.29±.35(.15)	2.31±.33(.14)	0.69 N/S
Fibrousness	1.86±.39(.21)	1.80±.38(.21)	0.14 N/S
Flavor	7.36±.68(.09)	7.32±.71(.10)	0.58 N/S

4. DISCUSSION

Seven strains of channel catfish were compared for carcass traits, fillet color, and fillet texture. Strain differences were observed for fillet %, gonadal development, and visceral fat deposition. Sex effects were also noticeable for these traits. Strain effects were present for cook loss, but no sex effects were observed. Strain affected redness of the fillet, trended toward affecting yellowness, but did not affect lightness. Sex effects were not statistically significant for yellowness of the fillet, but a biological significance was observed. Male channel catfish had a harder, gummier, and chewier fillet than female channel catfish. There were strain effects for all sensory traits generated by the human palate, toughness, mushiness, fibrousness, and flakiness. However, only fibrousness trended toward significance between sexes with males trending toward having a more fibrous fillet. There were no strain or sex effects for flavor.

The Kansas derived strains had the lowest fillet %. KR along with KTH had the lowest fillet %, Kmix and 103KS had a medium fillet yield, and M6 strain had the highest fillet yield. Fillet % was different among strains in previous studies (Dunham et al., 1983), and consistent with the current study, a Kansas derived strain had a lower fillet yield than Rio Grande derived strain. Kmix was selected for increased growth rate and exhibited a positive correlated response to selection for carcass yield, which is consistent with the results of Rezk (1993), as KS, ancestor to Kmix, also had a positive correlated response to selection for carcass yield when body was selected when compared to their control strain. These differences in fillet yield could be related to morphology, and this relationship should be thoroughly studied in the future.

Sexual development, gonadal development, and fat deposits could also influence carcass yield. The gonad score was negatively correlated with fillet %. As gonad development increased among strains, the fillet % decreased. Likely, increased ovarian development and increase head size associated with gonadal development reduces fillet percentage. This also is indicitave of the importance of obtaining rapid growth to enable harvest before sexual maturation and effective harvest to prevent fish from reaching sexual maturity prior to marketing. Large fat deposits could also have an adverse effect on carcass yield but were not observed in the current study.

Sex effects were observed for fillet yield % with females having a higher fillet % compared to males Fillet yield is related to body morphology, and large head size will will influence fillet yield negatively. Channel catfish exhibit sexual dimorphism, and the male head is larger than that of the female (El-Ibiary et al., 1976), which is the likely cause of the sex effect in the current study. Other studies have shown little to no sex effect on fillet % in channel catfish (El-Ibiary and Joyce 1978; Dunham et al., 1985) while a more recent study showed sex differences in fillet yield in one strain, no observed sex differences in fillet yield in a second strain (Bosworth et al., 2004).

Strain impacted redness and trended toward affecting yellowness in channel catfish fillets. Choice of strain could assist in alleviating problems in the market with red and yellow fillet coloration. Additionally, initiation selection programs with strains with the most desirable color characteristics might be considered. Sex effects were near significant for yellowness with females having fillets that were more yellow than those of males. Perhaps, females are more prone to depositing carotenoids in their flash due to the importance carotenoids play in egg development (Lubzens et al., 2003).

Hardness was among the traits for which differences among strains were observed. Fillet hardness was the highest in M6, KR, and Late spawn and lowest in the Kmix channel catfish.

With hardness being the force required by the TPA machine during first compression of the fillet, it makes logical sense that perceived toughness through sensory analysis was highest in these three strains and lowest in Kmix. Strains with the highest hardness also tended to have the highest cohesiveness of fillets. Hardness of fillets is directly correlated to myofibrillar structure and composition, as well as enzyme activity, stretching and aggregation of protein, and dissolution of myosin and structural protein (Hyldig & Nielsen, 2001; Andersen, Andersen, & Baron, 2007). A potential explanation for observed strain differences observed here outside of fillet thickness is a potential genetic component that is influencing structural proteins, enzyme activity, stretching of protein, and overall myofibrillar structure.

In chapter 3, only dam effects for sensory traits were observed in a heritability study (Chapter 3), this hardness differences could be linked to sex related genes in channel catfish. Sex effects were observed when the 7 strains in this study were pooled for hardness with males having a harder, gummier, and chewier fillet that might be explained by differential expression of sex related genes influencing muscle structure. Sex effect was noted in our study for hardness with males having a harder, gummier, and chewier fillet that could be explained by these sex-linked genes influencing muscle structure.

Strain effects were observed for sensory traits with KR, Late Spawn, and M6 strain being more tough and less mushy than Kmix strain. Late spawn was more flakey than Kmix and KTH, and Kmix was less fibrous than all strains except KTH and 103KS. No differences between sexes were found for all sensory traits, which indicates from a flesh quality standpoint, there are no advantages to mixed sex or monosex culture in the future. Few studies have been conducted to evaluate sensory components of channel catfish fillets, and studies that have been done examined other explanations for sensory differences such as strain differences of channel catfish (Bosworth et al., 2004), evaluation of off flavors due to geosmin (Lovell et al., 1986), consumer preference int terms of flavor of channel catfish fed different feeds (Faukner et al., 2013), sensory evaluation for texture and flavor of channel catfish fed different feeds and stored using different methods (Huang et al., 1992), as well as impact of storage techniques on sensory evaluation (Bland et al., 2018). None of these studies focused specifically on sex effects in channel catfish for sensory evaluation.

5. CONCLUSION

In this study we found sex differences in channel catfish for fillet yield, hardness, chewiness, and gumminess as well as strain differences between 6 different strains for various important texture and sensory attributes. Strain differences were observed for fillet %, which were in some cases influenced by gonadal development. Strain affected color, mechanical, and sensory texture. These strain differences should be considered when initiating a genetic enhancement effort and might be considered if the catfish industry wants to develop a higher quality product. Male channel catfish had a harder, chewier, and gummier flesh than female channel catfish. Genetically based strain differences exist for these carcass quality traits. The characteristics that are most desired by consumers have not been defined or related to these numbers. This next step needs to be conducted to fully determine which care the best genetic types for carcass quality.

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CHAPTER 3

HERITABILITY FOR TEXTURE, SENSORY, AND COLOR OF FILLETS AND CARCASS TRAITS IN CHANNEL CATFISH (*Ictalurus punctatus*)

Abstract

50 females and 50 male channel catfish (*Icatlurus punctatus*) were mated in a cross-fostering design resulting in 100 half sibling and full sibling families that were used to determine heritability and genetic correlations for texture, sensory, fillet color, and carcass traits. Texture traits, sensory, and fillet color are especially understudied in channel catfish compared to other aquaculture species and utilization of a selective breeding program for these traits could prove to be essential in improving the fillet product sold to consumers. The results of this study showed a moderate heritability for fillet % (0.17±.01) and redness (0.21±0.02), but low or near zero heritability for all other traits. Redness in catfish fillets is an undesirable trait and causes significant loss to catfish farmers and producers annually. As a result of this study, a family selection program can be implemented to select against redness of fillets. This could potentially result in a line of channel catfish with a more uniform texture and sensory sensation perceived by the consumer. Due to the financial impact red pigmentation has on the channel catfish industry, this line of channel catfish could result in increased profits for catfish farmers and processors. A second family selective breeding program can also be implemented to increase fillet % in channel catfish resulting in a higher flesh yield for the same sized fish increasing profits for catfish processors and farmers alike.

1. INTRODUCTION

Commercial aquaculture in the United States is dominated by the farming of channel catfish (*Icatulrus punctatus*) and the interspecific hybrid of a channel catfish ♀ × blue catfish (*Icttalurus furcatus*) ♂ and in total is responsible for 74 % of total finfish production, 29% of total volume of aquaculture production, and was responsible for $335 million of pond bank sales in 2018 (Hanson 2018; FAO 2019). Despite this heavy dominance on the US aquaculture production Ictalurid catfish production in the United States saw a 50% decrease in overall processed volume between 2003 and 2013, but has seen a small but steady rise in production volume since 2013 (Hanson, 2018). Various aquaculture innovations have been credited to the US catfish sector including improved aeration techniques (Boyd et al., 2018), genetic management, production systems, and formulation of improved balance in feeds (Dunham and Elaswad, 2017; Engle et al., 2018). Hybrid catfish production is a key aspect in US catfish production and constitutes a majority of annual US freshwater aquaculture (Torrans and Ott, 2018). Research to genetically improve channel catfish as well as hybrid catfish is of key importance and continues to impact profitability of catfish aquaculture (Dunham and Elaswad, 2017).

Catfish production worldwide is a major contributor to overall volume, 5 million metric tons, in aquaculture, resulting in the fourth largest taxonomic aquatic farmed species between three major catfish taxonomic groups: *Ictalurus*, *Clarias*, and *Pangasianodon* (Tacon, 2018). Key economic phenotypic attributes have been evaluated in channel catfish including selection for body size in different strains, growth rate in various strains, heritability of carcass weight and weight in various life stages, and disease resistance (Padi, 1995; Rezk et al., 2003; Bilodeau-Bourgeois et al., 2007; Bosworth et al., 2020).

Narrow sense heritability estimates are based on proportion of additive genetic variance in the population and play a significant role in evolution and breeding and differ from population to population and strain to strain (Vischer et al., 2008; Dunham, 2011). Texture traits should be of importance for marketability of fish products. There is not a great deal of research addressing this for aquaculture species. Gilthead seabream (*Sparus aurata*) texture on a whole fish was found to have a medium heritability for hardness (0.21 ± 0.06), muscular fat (0.31 ± 0.08), and moisture (0.24 ± 0.07) indicating the capability to alter this trait with selection (García-Celdrán et al., 2015). Farmed European whitefish (*Coregonus lavaretus*) heritabilites for texture and carcass qualities also had a moderate heritability in muscle texture (force to cut fillet/surface area of fillet) (0.30 ± 0.09), fillet lipid % (0.37 ± 0.10), fillet lightness (0.16 ± 0.07) and a low heritability for fillet protein % (0.04 ± 0.06) (Kause et al., 2011). Induced triploidy in shi drum (*Umbrina cirrosa*) resulted in a more tender cooked fillet and increased lightness in raw fillets when compared to diploids (Segato et al., 2007).

Genetic research into salmonid carcass and texture qualities is much more advanced than other farmed aquatic species. A moderate heritability was found for muscle fiber number (0.33 ± 0.05) and had a strong genetic correlation between fat % (-.85) and fibre density (.60) in Atlantic salmon (Vieira et al., 2007). Heritability values in two different populations of coho salmon (*Oncorhynchus kisutch*) were low for texture of flesh (0.06-0.09) but was higher in other significant body carcass traits such as fillet weight (0.18), fillet percentage (0.11), and fat content of the filleted flesh (0.17). (Neira et al., 2004). Within these populations sex did not affect the texture of the fillet. Atlantic salmon heritability for body carcass traits were low for gutted weight %, fillet %, de-headed weight %, and fillet % (0.01-0.04), but a heritability for waste weight % was moderate (0.3) (Powell et al., 2008). Atlantic salmon genetic research into fillet properties has progressed further by conducting a genome wide association study (GWAS) which found that quantitative trait loci (QTL) for fat content on chromosomes 9 and 10 and fillet firmness in chromosomes 3 and 11, providing a promising outlook on enhancing these phenotypic traits via marker assisted selection (Sodeland et al., 2013).

Very little research has been conducted into genetic contribution of fillet qualities in channel catfish. (Bosworth et al., 2004) found that there was variability between two strains of channel catfish in terms of texture attributes and found that yellowness of raw fillets was significantly different between two strains, as well as significant differences in texture attributes in Krammer shear force in baked fillets. However, there were genotype-environment interactions between fresh, thawed, and cooked fillets due to the fish being raised in different ponds. An earlier study was done to compare carcass traits between channel and hybrid catfish grown in the same pond which found no difference in texture and flavor of cooked fillets (Huang et al., 1994).

Texture of meat plays a key role in consumer acceptance of a product and is affected by post-mortem treatment, harvesting and slaughter processes, and biological properties (Dunajski, 1980; Haard, 1992; and Gjedrem, 1997). With flesh color, texture, and carcass quality traits having a direct influence on yield and consumer acceptance, it is key to determine genetic influence on these parameters to increase marketability and aquaculture production profits in farmed species (Neira et al., 2004). With US catfish production plummeting half its total production volume in a 10-year span while still leading the US finfish production comprising 74% of total finfish production (Hanson, 2018; FAO, 2019), it is key to determine heritability of channel catfish carcass, texture, ands sensory traits. Our objectives were to determine heritability and genetic correlations of texture, sensory, and carcass yield attributes to predict the potential effectiveness of selective breeding programs to improve channel catfish fillets.

2. MATERIALS METHODS

2.1 Experimental fish rearing

All experimental procedures used in this study were performed in accordance with guidelines of the Auburn University Institutional Animal Care and Use Committee for use and care of animals. Fish were reared and fed ad-libitum in 60L aquaria (150 individuals/aquarium) in a recirculating system at the EW Shell Fisheries Center at Auburn University in Auburn, AL. Fifty channel catfish females were mated in a cross-fostering design with 50 channel catfish males. Each male was mated with 2 females and each female was mated with 2 males resulting in 100 full-sib and half-sib families to determine heritability, genetic correlation, and estimate additive, dominance, and epistatic effects (Becker 1984). Upon reaching a mean of 30 grams, the experimental fish were PIT tagged and stocked into 0.04-ha earthen ponds at a rate of 14,000 fish/ha. Fish were fed ad-libitum with 32% protein pelleted catfish feed seven days a week until they reached a mean weight of 1kg. Fish were then harvested, individually weighed, sexed, and family determined prior to filleting. Three males and three females were analyzed from each family with sufficient numbers of males and females. Families without three males and females were sampled six times total with extra males or females being used to even out sampling totals. All fish from families with less than six samples were used. A total of 82 full sibling families and 105 half sibling families were evaluated for heritability estimates.

2.2 Filleting of experimental fish

Individual fish were weighed live, then sacrificed with blunt force trauma to the head followed by pithing, following IACUC guidelines. After being sacrificed, individual fish were dissected to determine the genetic type of the fish by evaluation of the swim bladder. Channel catfish swim bladders have a one chamber swim bladder and evaluation of the swim bladder was used to confirm the species evaluated. Gonadal development and visceral body fat quantity were graded on a scale of 0.5-5 with 0.5 being least developed and 5 being the most developed. Fish were filleted in a uniform manner by making an incision on the head where the head meets the body of the fish and following the spine of the fish with a fillet knife. Flesh was cut away from the ribs resulting in a boneless shank fillet. After filleting, each fillet was skinned, individually weighed to determine shank fillet yield, and rinsed in a freshwater solution to remove blood and other particles. Fillets from each individual fish were vacuum sealed in a 15.24 cm x 30.48 cm Clarity 4-Mil vacuum pouch (Bunzl Processor; Koch Supplies, Riverside Missouri) and placed in a -10°C freezer.

2.3 Fillet processing for sensory and texture profile analyses

Prior to evaluation, fillets were placed in a 2 ± 2 °C refrigerator overnight for thawing. Once thawed, raw fillets were evaluated for color using a CR 300 Minolta Chromameter (Osaka, Japan) to evaluate lightness, redness, and yellowness of fillets, and weighed prior to and after cooking to evaluate cook loss. Individual fillets were wrapped in aluminum foil and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. The American Meat Science Association (AMSA) research guidelines (AMSA, 2015) were followed, and one fillet was served to a semi-trained sensory panel of 12 individuals (6 males and 6 females ranging from age 21-65) in clear plastic serving cups with lids. The other fillet was stored in a 2 ± 2 °C refrigerator overnight and raised to a temperature of ~72°F (22°C) before used for texture profile analyses.

2.4 Sensory evaluation of catfish fillets using a semi-trained panel

Following American Meat Science Association (AMSA) Research Guidelines for Cookery, Sensory Evaluation, and Instrumental Tenderness Measurements of Meat (2nd ed.) (AMSA, 2015) guidelines, a group of 12 individual panelists were trained to evaluate 5 different key attributes in catfish fillets; toughness, flakiness, mushiness, fibrousness, and flavor (Bland, et al., 2018). Each fillet sample was graded on a scale of 1-4, with 1 being the least and 4 being the most of each attribute, and each corresponding value was correlated with a food item to calibrate the panel to the attributes of the fillet (Table 22). Flakiness was graded on a 1-3 and flavor was graded on a scale of 1-10, with 1 being severe off flavor, a flavor of 5 had distinct off flavor, 7 mild to little off flavor, and 10 corresponding with no off flavor. Panelists were trained on five separate occasions before the sensory evaluation of catfish fillets, with calibration sessions occurring each week of sensory evaluation. Panelists were served equal portions of a fillet (1.27 cm x 1.27 cm) in plastic 2 oz serving cups with a lid. Samples were portioned after being allowed to rest for 10 minutes after reaching an internal temperature of 74 °C 3 groups of 4 panelists were divided to ensure replication of each fillet and were given 12 blind samples with random numbers during each sensory session to reduce bias. Panelists scored their 5 attributes using a blind survey using Google Forms (Google, Mountain View CA, 2021) to prevent bias by observing other panelists scores. In between each sample, panelists drank a sip of room temperature water, took a bite of a saltine cracker, then drank another sip of water to cleanse the palate.

Table 22.

Corresponding food items correlated to their score for each sensory attribute. This scale was used to calibrate the semi-trained panel in their evaluation of catfish fillet sensory attributes.

Attribute	1	2	3	4
Toughness Force required to bite through a fillet sample	Canned Dole Pineapple Chunk 1’ cube	Heritage Farm Chicken Hotdogs 2cm diameter piece	Hebrew National Beef Hotdog 2cm diameter piece	Starkist Solid White Albacore Canned Tuna in water 2 cm diameter serving
Mushiness How much a fillet sample dissipated after initial bite	Hebrew National Beef Hotdog 2 cm diameter piece	Raw White Mushroom Whole	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Simple Truth Organic Extra Firm Tofu 1’ cube
Flakiness Ease of which fillet samples were broken into individual muscle components	Cooked Wild Caught Pan Seared Sea Scallops ¼ scallop	Canned Dole Pineapple Chunk 1’ cube	Chicken of the Sea Canned Traditional Style Pink Salmon 2 cm diameter serving	N/A
Fibrousness Perception of amount of muscle tissue strands or filaments were left after chewing	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Canned Dole Pineapple Chunk 1’ cube	Raw Asparagus stem	Raw Asparagus base

2.5 Texture profile analyses of catfish fillets

Fillets were individually wrapped in aluminum foil, labeled, and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. After cooking, fillets were refrigerated at 2 ± 2 °C refrigerator overnight, then raised to room temperature ~72°F (22°C) prior to texture profile analyses. Each fillet was then sampled using TA-XT2i Texture Analyzer shear machine (Texture Technologies Corp., Scarsdale, NY) loaded with a 5 kg load cell with a ½' diameter ball probe attachment (TA-18) (Bland et al., 2018). Seven attributes were evaluated for each fillet: gumminess, chewiness, springiness, hardness, cohesiveness resilience, and adhesiveness (Table 23). Each fillet was sampled in triplicate, with the mean average of each being used for statistical analyses.

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Table 23.

Texture profile attributes analyzed, formula used for each output, and the definition of each attribute analyzed.

Attribute	Formula	Description
Hardness	Force at anchor 1	Maximum force applied during the first compression
Gumminess	Hardness x Cohesiveness	Energy needed to disintegrate a semi solid food until it is ready to swallow
Chewiness	Hardness x Cohesiveness x Springiness	Energy needed to chew a solid food until ready to swallow
Springiness	Distance2/Distance 1	Rate at which a sample returns to its original size and shape
Adhesiveness	Area 3	Work required to overcome stickiness between the probe and the sample
Resilience	Area 2/ Area 1	How well a product returns to its original shape and size during the first probe
Cohesiveness	Area 4/ Area 1	How well a product returns to its original shape and size in the second probe relative to the first probe

2.6 Statistical analyses

All data was analyzed using SAS statistical analysis software (v.9.4; SAS Institute Inc., Cary, NC, USA). Narrow sense heritability estimates were calculated using the equation $h^2_d= 4(\sigma^2_d)/(\sigma^2_d+ \sigma^2_s+ \sigma^2_{s*d}+ \sigma^2_e)$ where σ^2_d is equal to dam variance, σ^2_s is sire variance, σ^2_{s*d} is sire x dam variance, and σ^2_e is the variance in error. $h^2_s= 4(\sigma^2_s)/ (\sigma^2_d+ \sigma^2_s+ \sigma^2_{s*d}+ \sigma^2_e)$ was used to calculate sire heritability, and $h^2_{d*s}= 2(\sigma^2_d+ \sigma^2_s)/(\sigma^2_d+ \sigma^2_s+ \sigma^2_{s*d}+ \sigma^2_e)$ was used to calculate heritability of sire x dam. Standard error for heritability estimates is equal to the square root of the variance (Grossman and Norton 1981). To evaluate heritability of sensory data graded on a discrete ordinal scale, sensory evaluation values were divided by the largest score possible and then multiplied by 100 resulting in a 0-100 scale for each sensory trait with 0 correlating with the lowest and 100 correlating with the highest for each trait (Lien et al., 2015). Genetic correlations were estimated using the equation Cov S+D/σ^2_s (x) σ^2_s(y) σ^2_d (x) σ^2_d(y) where COV S+D is the covariance between traits for the sire and dam, /σ^2_s (x) is the variance for the sire for trait x, σ^2_s(y) is the variance for the sire for trait y, and σ^2_d (x) is the dam variance for trait x σ^2_d(y) is the dam variance for trait y. Proc mixed with a restricted estimation of likelihood was used to calculate variance of sire, dam, sire x dam interactions, and error with Proc Varcomp used to verify the variance estimates.

3. RESULTS

Means, standard deviations, and coefficient of variations for males and females used in heritability estimations are shown in Table 24. Fillet % was higher in female progeny than male progeny (P <0.001). No other significant sex effects were found in this study.

Table 24.

Mean values for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight) lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness ± standard deviation (SD) and coefficient of variation (CV) of male and female channel catfish (*Ictalurus punctatus)* used in this study.

	Female $\bar{X}$ ± SD (CV)	Male $\bar{X}$ ± SD (CV)
Trait	n=188	n=195
Fillet %[1]	26.59±3.01(.11)	24.88±3.32(.13)
Cook Loss %	23.22±4.21(.18)	23.56±4.97(.21)
L	55.88±2.14(.06)	55.92±3.68(.07)
R	2.14±1.99(.92)	2.17±1.94(.90)
Y	8.40±3.53(.42)	8.24±3.08(.37)
Hardness	635.82±200.22(.31)	660.54±238.48(.36)
Adhesiveness	-2.97±1.90(.64)	-2.91±1.7(.59)
Resilience	23.53±3.37(.14)	23.54±3.92(.17)
Cohesion	0.55±.05(.08)	0.56±.05(.09)
Springiness	73.76±5.50(.07)	73.76±5.88(.08)
Gumminess	357.18±125.27(.35)	371.36±149.66(.40)
Chewiness	264.38±98.57(.37)	275.16±116.24(.42)
Toughness	2.23±.50(.22)	2.26±.52(.23)
Mushiness	2.00±.53(.26)	1.99±.59(.30)
Flakiness	2.28±.29(.13)	2.26±.33(.15)
Fibrousness	1.78±.38(.21)	1.80±.37(.21)
Flavor	7.35±.69(.09)	7.37±.66(.09)

1. Fillet % is significantly different between sexes (P<0.001) after a Tukey's post hoc test was conducted.

Dam general combining ability (GCA) was small for all traits, but largest, 10%, for fillet % which was observed higher than sire general combining ability, 4%, and specific combining ability (SCA) which was zero for fillet % (Table 25). Although relatively small, 2-6%, dam GCA was higher than sire GCA and SCA for sensory traits. Sire GCA was the highest combining ability for only redness (10%) and adhesiveness (9%). Dam GCA and SCA were equivalent (4%) for lightness. Sire GCA and SCA were equivalent (4%) for hardness. SCA had the highest values, up to 22%, for yellowness (22%), resilience (15%), chewiness (11%), gumminess (8%), springiness (9%), and cohesiveness (14%).

Table 25.

Variance components and their ratio of total variance for sire, dam, and sire x dam interactions in channel catfish (*Ictalurus punctatus)* for traits fillet % (total fillet weight / live body weight) cook loss % (cooked fillet weight divided by raw fillet weight), lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, chewiness, and sensory evaluated traits toughness, mushiness, flakiness, fibrousness, and flavor.

	σ^2 dam		σ^2 sire		σ^2 sire x dam		σ^2 error	
	Ratio	Variance	Ratio	Variance	Ratio	Variance	Ratio	Variance
Fillet %	0.10	0.00014	0.04	0.000060	0.00	0.00	0.86	0.0012
Cook Loss %	0.00	0.00	0.00	0.00	0.01	0.000022	0.99	0.0029
L	0.04	0.000024	0.002	0.00000010	0.04	0.000029	0.91	0.00059
R	0.05	0.00023	0.10	0.00044	0.03	0.00014	0.82	0.0036
Y	0.02	0.00014	0.06	0.00037	0.22	0.0014	0.70	0.0045
Hardness	0.00	0.00	0.04	0.00064	0.04	0.00058	0.92	0.014
Adhesiveness	0.00	0.00	0.09	0.0000061	0.01	0.00000052	0.90	0.00006
Cohesion	0.00	0.00	0.00	0.00	0.14	.00021	0.86	0.0013
Resilience	0.02	0.000042	0.00	0.00	0.15	0.00028	0.83	0.0015
Springiness	0.00	0.00	0.01	0.000039	0.09	0.00040	0.90	0.0039
Gumminess	0.00	0.00	0.02	0.00035	0.08	0.0017	0.90	0.019
Chewiness	0.00	0.00	0.002	0.00006	0.11	0.0027	0.89	0.021
Toughness	0.06	9.10	0.00	0.00	0.00	0.00	0.94	140.60
Mushiness	0.02	4.04	0.00	0.00	0.00	0.00	0.98	176.35
Flakiness	0.04	7.83	0.00	0.00	0.00	0.00	0.96	196.50
Fibrousness	0.04	3.12	0.00	0.00	0.01	0.92	0.95	84.83
Flavor	0.00	0.00	0.00	0.00	0.00	0.00	1.0	0.45

Sire and dam heritability estimates were zero for cook loss and cohesion indicating no additive genetic variation for these traits in channel catfish (Table 26). Sire estimates of heritability (Table 28) were moderate for hardness and adhesiveness, but low for springiness, gumminess, and chewiness with dam estimates of heritability of these traits equal to zero. Genetic correlations for these traits were all zero. Dam estimates for heritability (Table 27) for resilience, toughness, mushiness, fibrousness, and flakiness were moderate but sire estimates are zero for these traits. Genetic correlations of the dam between sensory traits were high, ranging from .56-.93. Overall genetic correlations for these traits were all zero.

Heritability estimates for redness (0.21), yellowness (0.16) and fillet % (0.17) are the only traits with moderate additive genetic variance found in both the sire and dam, indicating the potential to enhance these traits with selection. Fillet % had low genetic correlations with color traits and genetic correlations of 0 with all other traits. Lightness had a moderate negative correlation with redness of the fillet (-0.29) and a low genetic correlation with yellowness of the fillet (0.03). However, yellowness of the fillet had a moderate genetic correlation with redness (0.32) and an extremely high dam genetic correlation with lightness (0.99).

Table 26.

Estimates of sirexdam heritability are bold in diagonal in channel catfish (*Ictalurus punctatus)* ± standard error (SE) for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight), lightness (L), redness (R), yellowness (Y), hardness (N) (hard), adhesiveness (adhes.), resilience (res.), cohesion (cohe.), springiness (spring.), gumminess (Gummy), chewiness (Chew.) and sensory evaluated traits toughness (tough), mushiness (mush), flakiness (flakey), fibrousness (fibrous), and flavor. Genetic correlations between traits are above the diagonal.

Trait	FY	CL	L	R	Y	Hard.	Adhes.	Res.	Cohe.	Spring.	Gummy.	Chew.	Tough	Mush	Flakey	Fibrous	Flavor
Fillet %	**0.28±0.01**	0.00	0.02	-0.06	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cook Loss		**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L			**0.01±0.01**	-0.29	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
R				**0.31±0.03**	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Y					**0.16±0.04**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hardness						**0.08±0.02**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Adhesiveness							**0.18±0.001**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Resilience								**0.09±0.01**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cohesion									**0.01±0.01**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Springiness										**0.03±0.04**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gumminess											**0.03±0.04**	0.00	0.00	0.00	0.00	0.00	0.00
Chewiness												**0.01±0.01**	0.00	0.00	0.00	0.00	0.00
Toughness													**0.12±0.09**	0.00	0.00	0.00	0.00

Mushiness	**0.04±0.01**	0.00	0.00	0.00
Flakiness		**0.07±0.01**	0.00	0.00
Fibrousness			**0.08±0.01**	0.00
Flavor				**0.00**

Table 27.

Estimates of dam heritability are bold in diagonal in channel catfish (*Ictalurus punctatus)* ± standard error (SE) for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight), lightness (L), redness (R), yellowness (Y), hardness (N) (hard), adhesiveness (adhes.), resilience (res.), cohesion (cohe.), springiness (spring.), gumminess, chewiness, and sensory evaluated traits toughness (tough), mushiness (mush), flakiness (flakey), fibrousness (fibrous), and flavor. Dam genetic correlations between traits are above the diagonal.

Trait	FY	CL	L	R	Y	Hard.	Adhes.	Res.	Cohe.	Spring	Gummy	Chew	Tough	Mush	Flakey	Fibrous	Flavor
Fillet %	**0.39±0.01**	0.00	0.34	-0.78	0.65	0.00	0.00	-0.003	0.00	0.00	0.00	0.00	-0.003	-0.001	-0.002	0.01	0.00
Cook Loss		**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L			**0.15±0.01**	-0.002	0.99	0.00	0.00	-0.001	0.00	0.00	0.00	0.00	-0.01	0.01	0.01	0.001	0.00
R				**0.21±0.02**	0.001	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	-0.05	0.01	0.01	-0.05	0.00
Y					**0.09±0.01**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hardness						**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Adhesiveness							**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Resilience								**0.09±.006**	0.00	0.00	0.00	0.00	0.06	-0.12	-0.20	-0.02	0.00
Cohesion									**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Springiness										**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gumminess											**0.00**	0.00	0.00	0.00	0.00	0.00	0.00
Chewiness												**0.00**	0.00	0.00	0.00	0.00	0.00
Toughness													**0.24±0.17**	-0.84	-0.79	0.56	0.00
Mushiness														**0.09±0.01**	0.93	-0.53	0.00

Flakiness	**0.14±0.01**	-0.58	0.00
Fibrousness		**0.15±0.03**	0.00
Flavor			**0.00**

Table 28

Estimates of sire heritability are bold in diagonal in channel catfish (*Ictalurus punctatus)* ± standard error (SE) for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight), lightness (L), redness (R), yellowness (Y), hardness (N) (hard), adhesiveness (adhes.), resilience (res.), cohesion (cohe.), springiness (spring.), gumminess (Gummy), chewiness (Chew) and sensory evaluated traits toughness (tough), mushiness (mush), flakiness (flakey), fibrousness (fibrous), and flavor. Sire genetic correlations between traits are above the diagonal.

Trait	FY	CL	L	R	Y	Hard.	Adhes.	Res.	Cohe.	Spring	Gummy	Chew	Tough	Mush	Flakey	Fibrous	Flavor
Fillet %	**0.17±0.01**	0.00	$2.57e^{-6}$	-0.0004	0.0003	0.003	$-1.1e^{-5}$	0.00	0.00	-0.0005	0.001	0.0001	0.00	0.00	0.00	0.00	0.00
Cook Loss		**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L			**0.01±001**	-0.03	0.003	-0.04	$8.63e^{-6}$	0.00	0.00	$3.14e^{-6}$	-0.001	-0.001	0.00	0.00	0.00	0.00	0.00
R				**0.40±0.20**	0.002	-0.002	$-4.73e^{-6}$	0.00	0.00	$6.00e^{-5}$	0.001	0.004	0.00	0.00	0.00	0.00	0.00
Y					**0.23±0.16**	0.001	$5.10e^{-6}$	0.00	0.00	$8.30e^{-5}$	0.001	0.0004	0.00	0.00	0.00	0.00	0.00
Hardness						**0.16±0.03**	$6.92e^{-5}$	0.00	0.00	$8.29e^{-5}$	0.01	0.005	0.00	0.00	0.00	0.00	0.00
Adhesiveness							**0.37±0.20**	0.00	0.00	0.003	0.003	0.001	0.00	0.00	0.00	0.00	0.00
Resilience								**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cohesion									**0.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Springiness										**0.04±0.01**	0.006	0.005	0.00	0.00	0.00	0.00	0.00
Gumminess											**0.07±0.02**	0.009	0.00	0.00	0.00	0.00	0.00
Chewiness												**0.01±0.01**	0.00	0.00	0.00	0.00	0.00
Toughness													**0.00**	0.00	0.00	0.00	0.00
Mushiness														**0.00**	0.00	0.00	0.00

Flakiness	**0.00**	0.00	0.00
Fibrousness		**0.00**	0.00
Flavor			**0.00**

4. DISCUSSION

This is the first report of heritability estimates and genetic correlations for texture traits of channel catfish. Fillet % and redness had moderately low heritability, approximately 0.20. Our results for estimated heritability showed that direct selection for texture and sensory traits is not feasible. Estimates of heritability for hardness, adhesiveness, springiness, gumminess, and chewiness showed a dam heritability of zero or near zero and significant sire estimates for heritability of gumminess, springiness and chewiness indicative of dominant gene action on these traits. The opposite was true for yellowness, resilience, and all sensory traits as dam heritabilities were above zero and sire heritabilites were near or at zero indicative of genetic maternal effects at this late life stage. No genetic basis was obvious for cook loss, cohesion, and flavor. Most genetic correlations were zero, near zero, or minimal. Lightness had a low negative genetic correlation with redness, and redness had a low genetic correlation with yellowness of the fillet.

Heritability estimates for fillet % were high in dam estimates (0.39±0.01) and moderate in sire estimates (0.17±0.01) indicating additive genetic variance as well as maternal effects. Thus, family selection for increased yield in channel catfish should be successful. The combining ability results support the conclusion that there was no dominance genetic variation for fillet %, but additive and maternal effects were genetic components for this trial. The fillet heritability results were similar to the heritability obtained for corrected carcass weight, 0.32, in channel catfish from a multi generation experiment (Bosworth et al., 2020). Earlier studies found significant differences in fillet % among different strains of channel catfish due to morphological differences among strains of channel catfish and was indicative of morphology effecting fillet yield (Dunham et al., 1983).

The channel catfish estimates of heritability for fillet % are almost identical to that of striped catfish (*Pangasianodon hypophthalmus*) (0.17±0.04) from Vietnam (Vu et al., 2019; Muhammad et al., 2010). Fillet yield heritability has been measured in other aquaculture species and varies considerably. Atlantic salmon have been found to have almost no heritability 0.01-0.04, for fillet % (Powell et al., 2008; Tsai et al., 2015). Coversely, GIFT strain Nile tilapia (*Oreochromis niloticus*) (0.25±0.07), common carp (*Cyprinus carpio*) (0.38±0.09 with skin and .21±.07 without skin), and gilthead seabream (0.31±0.07 for dressing percentage and 0.12 ± 0.03 for fillet percentage) have significant additive genetic variation for fillet % (Kocour et al., 2007; Navarro et al., 2009; Nguyen et al., 2010).

Sex effects for carcass traits in catfish can be quite variable. Fillet yield in channel catfish has the potential for a sex effect as well with females having a larger fillet yield due to the smaller head size when compared to males (El-Ibiary et al., 1976), however, another study found that male channel catfish had a higher dress out % than female channel catfish (Bondari et al., 1985). Other studies have found no sex effects on dress out % for channel catfish and (Dunham et al., 1985) and hybrid catfish had no sex effect for dress out % but had a higher fillet % of progeny from a Rio sire strain (Ramboux 1991). In the current study, females had a higher fillet %, however, this could be due the age of the fish (2.5 years old) with some males having larger heads due to sexual maturity resulting in decreased fillet yield compared to females. Conversely, females might have greater visceral fat % due to ovarian development balancing the effect of head size from the males (Dunham et al., 1985), but was note seen in in the current study. Studies conducted to evaluate fillet mass and fillet yield % in channel catfish based on body morphology characteristics, indicated that potential differences in fillet yield between males and females could be due to sexual dimorphisms in body characteristics between males and females (Bosworth et al., 2001).

In regard to texture values, no sex effects were observed. In another study, (Dunham unpublished) found that 2-3 kg male channel catfish brood stock had tough flesh after cooking compared to flaky and tender flesh of females at the beginning of spawning season. Thus, sex effects could become important if size preferences of future markets change or new products are developed, warranting of more thorough evaluation of catfish of different size, ages, and at different times of the year.

Genetic enhancement of fillet yield and other carcass traits, including texture might result from genomic approaches. A genome wide association study in backcross catfish (female channel catfish x male F_1 hybrid catfish) (Geng et al., 2016), and a similar QTL mapping study found linkage groups and associated genes that associate with head length, head width, as well as other body characteristics found linkage groups and associated genes that associate with head length and width (Hutson et al., 2014). This could lead to future marker assisted selection or selection indices to improve fillet yield. Since the heritabilities for texture traits was low or zero, GWAS studies maybe beneficial for these traits to accelerate genetic enhancement.

Based on the difference between dam and sire heritability estimates, hardness, adhesiveness, springiness, gumminess, and chewiness appear to be controlled primarily by dominance gene action rather than additive gene action. Thus, interspecific crossbreeding or other genetic manipulations would likely be more successful in improving these traits than selection. One option would be reciprocal recurrent selection within the population, but that strategy would be somewhat complex. SCA was the only combining ability above zero for springiness, gumminess, and chewiness, thus, reciprocal recurrent selection would be the best intrapopulation program to alter these traits. Based on the SCA and sire GCA both at 4%, reciprocal recurrent selection for hardness as well as selection for male performance could result in genetic gains for this trait. However, with SCA near zero, selection for males for adhesiveness might improve this trait.

In the case of resilience, toughness, mushiness, flakiness, and fibrousness, dam heritability was above zero and sire heritability was near or at zero indicative of maternal effects at this late life stage. Genetic maternal effects are heritable, and in theory, can affect selection response positively or negatively (Kirkpatrick and Lande 1989, Räsänen and Kruuk 2007, Charmantier et al. 2013, White and Wilson 2019). Family selection based on female performance may be a mechanism to genetically alter and improve sensory traits and resilience in channel catfish, and the observed dam GCA being above zero for the sensory traits while sire GCA and SCA were zero supports this hypothesis. However, the SCA was much higher than dam GCA for resilience, suggesting that reciprocal recurrent selection might be the best approach for this trait.

Cook loss and flavor did not appear to have any genetic basis. If considered a high priority, these traits would need to be improved via indirect selection, genomic selection, interspecific hybridization, or genetic biotechnology such as gene editing, genetic engineering, or polyploidy. Cohesion had no heritability; thus, the biotechnological approaches could be an alternative, but the SCA was 14% suggesting that reciprocal recurrent selection would result in progress for cohesion.

Very little data exists for genetics of texture of other species. However, compared to channel catfish, texture traits such as hardness inn Gilthead seabream was different by having low to moderate levels of additive genetic variation (García-Celdrán et al., 2015). Farmed European whitefish heritability for muscle texture had moderate levels of additive genetic varation (Kause et al., 2011), again dissimilar from the current study, although this trait was not exactly analgous to any of the traits measured in channel catfish, but similar to hardness. Coho salmon texture was more similar to channel catfish results in the current study as heritability for flesh texture was 0.06-0.09, which again was measured differently than for channel catfish, butanalagous to hardness and toughness (Vieira et al., 2014). No sex effects were observed in coho salmon populations evaluated for texture of the fillet (Vieira et al., 2014).

For color traits, lightness has a dam heritability of 0.15±.01 with sire heritability being near zero, indicating maternal effects had the greatest genetic influences, and family selection for female performance would be the best quantitative genetics path for improvement. Yellowness was partially controlled by additive genetics as dam heritability was also low and sire heritability was moderate, suggesting selection has some potential response, but a combination of selection and crossbreeding may be a better approach for genetic alteration of yellowness.

Dam heritability for redness was moderate (0.21±0.02) and high for the sire estimate (0.40±0.02). Redness should respond to selection. Redness in fillets presents a unique set of problems and solutions. Redness in channel catfish fillets is detrimental in the channel catfish market, and is responsible for an estimated annual loss of $443,000 for catfish farmers and $683,000 for catfish processors (Allred et al., 2019). *Aeromonas sobria* incidence was higher in red fillets than acceptable fillets showing that environmental factors also play a role in redness of fillets and it is not purely a genetic trait. Potentially, there could be a genetic correlation that explains resistance to bacteria, retention of the pigment from carotenoids, and perception of redness. Different gene expressions might impact the ability to overcome bacteria and retention of these pigments. With redness being detrimental to the channel catfish industry and causing a massive loss in profitability to farmers and processors, it is feasible to implement a family selection program to select against this redness that would have significant economic impact if effective.

Heritability estimates for color of raw fillets have been evaluated in other aquaculture species with European white fish having a zero heritability estimate of fillet lightness (0.02 ± 0.1) (Kause et al., 2011). Fillet color of Atlantic salmon assessed visually using a Roche SalmoFan scale was found to have a low but significant heritability (0.14±0.03) in one study (Tsai et al., 2015) and was much higher for redness in a second study (0.43 ± 0.06) (Ødegård et al., 2014). A third study examining Atlantic salmon color heritability revealed a moderate heritability for redness (0.20±0.02) using a Minolta chromameter using a similar procedure and had similar results to the present study for heritability, and found low genetic correlation (.41±.08) between the observed color using the chromameter and carotenoid pigment content suggesting that perceived color and retention of pigment are likely not controlled by the same genes (Norris and Cunningham 2004). This wide range of heritability for flesh color across species and even within species shows the importance of estimating heritability for each population, strain, or species as additive genetic variance can vary population to population (Dunham 2011). In two different populations of coho salmon (*Oncorhynchus kisutch*) heritability estimates for prefereable red-orange color fillets were 0.04 ± 0.01 in one population and 0.08 ± 0.02 in another population (Dufflocq et al., 2017). These wide range of heritability for flesh color across species and even within species shows the importance of estimating heritability for each population as additive genetic variance will vary population to population (Dunham 2011).

Our research is to develop the best catfish product for catfish farmers and processors using our genetic understanding of these greatly important aquaculture species to enhance the catfish aquaculture sector. With these results we believe that a selective breeding program could be implemented to select against redness of catfish fillets, which if successful, will increase profits to both catfish farmers and processors.

Our results for estimated heritability showed that direct selection for texture and sensory traits is not feasible.

5. Conclusion

This lack of captured genetic contribution could be due to an overall very low genetic contribution that we were not able to estimate, or that these traits are purely controlled by environmental factors or outside influences that are not genetic. Strong dominance and epistatic effects in the texture traits is an interesting finding, showing that either multiple genes are influencing these traits through muscle development or dominance in a few alleles is a main contributor to this phenomenon. The results of this study indicate the potential to capture additive genetic variance in channel catfish to implement two selective breeding programs using family selection. One selection program would be to implement a breeding program to enhance fillet %, while the other would be a family selection program to select against redness of the fillet. While only moderate in effect, being able to implement a selective breeding program for these traits would increase profits to farmers by increasing the flesh from the same sized fish and selecting against redness.

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CHAPTER 4

COMBINING ABILITY OF CHANNEL CATFISH (*Ictalurus punctatus*) FEMALES AND BLUE CATFISH (*Ictalurus furcatus)* MALES FOR SENSORY AND TEXTURE ATTRIBUTES, FILLET COLOR, AND CARCASS TRAITS

ABSTRACT

The channel catfish (*Ictalurus puncatatus*) x blue catfish (*Ictalurus furcatus*) hybrid is a commonly farmed fish and has multiple improved traits compared to its parent species including increased disease resistance, low dissolved oxygen resistance, increased tolerance for crowding, and greater growth and feed conversion. However, research addressing sensory and texture traits as well as color of fillets has not been studied for potential genetic enhancement of this hybrid. This study was conducted to evaluate general and specific combining ability (GCA and SCA, respectively) using a 6 x 6 full factorial design to evaluate sensory and texture traits as well as fillet color. There was a significant GCA in the channel catfish dams for lightness of the fillet, hardness, gumminess, and chewiness indicative of additive genetic variance in the channel catfish that could be captured to enhance these traits through a selective breeding program. Fillet %, cook loss, and yellowness of the fillets had significant SCA indicative of potential dominance and epistasis interactions contributing to different families performing better or worse for these traits. No significant GCAs were found for the sire, highlighting the lack of additive genetic variance from the blue catfish males found in the hybrid progeny. The results of this study indicate there is potential to genetically enhance hardness, gumminess, chewiness, and lightness of the fillet in channel catfish, and to implement a reciprocal recurrent selection for improved fillet %, less cook loss, and decreased yellowness in the hybrid fillets.

1. INTRODUCTION

Catfish production in the United States dominates aquaculture finfish production summing up to 74% of total finish production (Hanson, 2018). Within the catfish aquaculture sector channel catfish (*Icatlurus punctatus*) and hybrid catfish (channel catfish ♀ × blue catfish (*I. furcatus*) ♂) are the two commercially grown products with hybrid catfish dominating commercial production. Total estimations of overall hybrid catfish production vary, with conservative estimates placing hybrid catfish production at 30-40 % of total catfish production, and larger estimates totaling up to 70 % of total catfish production (Bosworth and Waldbieser, 2014; Torrans and Ott, 2018). Even with the lowest estimate of hybrid catfish production at 30% of total catfish production, this would result in over $100 million dollars of total hybrid catfish pond bank sales in 2018 compared to the total catfish production of $335 million dollars of pond bank sales (FAO, 2019). If this low estimate of hybrid catfish production was taken into consideration as its own individual farmed product, it would rank as the third most valuable aquaculture product behind channel catfish and marine mollusk production (FAO, 2019; Yang et al., 2020). Hybrid catfish are primarily cultured in the Southern states of Mississippi, Alabama, Arkansas, and Texas with Mississippi being responsible for over 50% of catfish production in the United States in 2012 (USDA 2014, Surathkal and Dey, 2020). Hybrid catfish make up the majority of the US freshwater aquaculture production (Torrans and Ott 2018) largely due to the hybrid catfish being superior to channel catfish in many different key aquaculture key attributes including better growth, feed conversion, higher tolerance to crowding, higher resistance to enteric septicemia of catfish (ESC), and a higher tolerance to low dissolved oxygen conditions (Wolters et al., 1996; Dunham et al., 2000; Li et al., 2004; Kumar and Engle 2010; Bosworth et al., 2015; Torrans and Ott 2018). Although the hybrid catfish is superior to the channel catfish in many attributes one obstacle to overcome for commercial producers is the extra feed resources, space resources, and the longer time for blue catfish males to reach sexual maturity to harvest milt (Dunham et al., 1994; Su et al., 2013; Perera et al., 2017). Research is ongoing to overcome this problem has been applied by looking at cryopreservation of valuable blue spermatogonia stem cells to enhance genetic management practices and xenogenesis technology (Abualreesh et al., 2020).

Being able to identify the genetic basis of important production traits and to develop genetic management plans to enhance production traits is critical for aquaculture production due to their direct impact on economic value and profitability to the farmer (Gjedrem 1983; Perry et al., 2004). Variation in production traits has been observed in channel catfish with differences in growth rates, feed intake, survival when exposed to ESC, and survival in low dissolved oxygen environments (Silverstein et al., 1999; Dunham et al., 2008; Dunham et al., 2014). Heritability and selection response to key production traits of carcass weight and growth has recently been reviewed in a strain of channel catfish (Delta Select) that was developed by the United States Department of Agriculture (USDA) to enhance channel catfish production (Bosworth et al., 2020).

Although hybrid catfish have better production traits than channel catfish, different genetic types of hybrids vary in performance and can be further improved genetically. To determine the best approach to genetically enhance interspecific hybrids, the general combining ability and specific combining ability must be evaluated. Combining ability is influenced by additive effects of two alleles at a locus independently and deviation due to dominance effects and potential interactions between the two alleles (Lynch and Walsh 1998). Quantifying these additive effects in an interspecific hybrid is key to evaluate the potential best crosses, or the use of selection in a parent species to enhance the interspecific hybrid.

General combining ability (GCA) has been defined as the average performance in a line of hybrid crosses while specific combining ability (SCA) is the deviation of certain crosses in the line from their expectation based on the average performance (Sprague and Tatum 1942). Evaluation of important commercial production traits of growth and carcass yield in hybrid catfish for combining ability determined that selection within blue male lines and channel catfish female lines would be effective for increasing performance in the F1 interspecific channel catfish female x blue catfish male hybrid (Bosworth and Waldbieser 2014). Evaluation in GCA of hybrid striped bass for growth related traits showed significant differences in GCA for growth rate among sires and dams, but a non-significant difference in SCA among sire x dam crosses (Wang et al., 2006).

Texture and sensory attributes of flesh play an important role in consumer acceptance of a product and can be significantly impacted by harvesting, slaughter, post-mortem treatment, and biological properties (Haard, 1992; Dunajski, 1980; and Gjedrem, 1997). Sensory sensations are influenced by texture properties of the flesh, and texture attributes are one of the main drivers in consumer demand and acceptance of a product which in turn directly impacts the marketability of a product (Coppes, Pavlisko, and De Vecchi, 2002; Sawyer et al., 1984; 1988). Texture traits are impacted by muscle structure, muscle fiber density, muscle fiber quantity and other muscle attributes (Weatherley et al., 1979; Fauconneau 1993). Very little research has been conducted for evaluating hybrid catfish texture and sensory attributes. An early study found no significant differences in cooked hybrid catfish and channel catfish from the same pond, however genetic type and strain was not evaluated (Huang et al., 1994). Comparisons between market traits and texture analyses between two strains of channel catfish and one genetic type of hybrid catfish has been evaluated with significant differences being observed between channel catfish and hybrid catfish for overall acceptability in baked fillets and color in frozen-thawed fillets (Bosworth et al., 2004).

Texture and sensory evaluation in catfish fillet qualities are significantly behind that of other species including salmonids, gilthead seabream (*Sparus aurata),* and European whitefish (*Coregonus lavaretus*) (Gjerde and Gjedrem, 1984; Gjerde, 1989; Quinton, et al., 2005; García-Celdrán et al., 2015; Kause et al., 2015). There is a lack of research into the genetics of catfish texture compared to that of other species, although texture and sensory attributes have been evaluated in catfish fillets without genetic components being considered in the study (Bland et al., 2018). To aid in bridging this gap our objective was to determine genetic contributions to texture and sensory attributes in hybrid catfish by determining GCA and SCA in the channel catfish female and blue catfish male parents of hybrid catfish for key market, texture, and sensory attributes.

2. MATERIALS and METHODS

2.1 Rearing of experimental fish

All experimental procedures used in this study were performed in accordance with guidelines of the Auburn University Institutional Animal Care and Use Committee for use and care of animals. Six blue males were sacrificed via blunt force trauma to the head followed by pithing, testes extracted, and used to individually fertilize egg masses from 6 female channel catfish. Blue catfish strains used in this study were Auburn-Rio (AR), D&B, DR, probable AR, and an unknown strain (Unk) (Dunham and Smitherman, 1984). Strains of Kansas ancestry were used in this study including Kansas Random (KR), Kansas Mix (KMix), and a probable Kmix female (PKMix) (Dunham and Smitherman 1984). This resulted in 36 families of hybrid catfish progeny that were used to evaluate texture and sensory traits. The hybrid progeny were reared and fed ad-libitum in 60L aquaria (150 individuals/aquarium) in a recirculating system at the EW Shell Fisheries Center at Auburn University in Auburn, AL. Upon reaching a mean of 30 grams, the experimental fish were PIT tagged and stocked into 0.04-ha earthen ponds at a rate of 14,000 fish/ha. Fish were fed ad-libitum with 32% protein pelleted catfish feed seven days a week until they reached a mean weight of 1kg. Fish were then harvested at an age of 40 months, individually weighed, sexed, and family determined prior to filleting.

2.2 Filleting of experimental fish

Individual fish were weighed live, then sacrificed with blunt force trauma to the head followed by pithing, following IACUC guidelines. After being sacrificed, individual fish were dissected to determine the genetic type of the fish by evaluation of the swim bladder. Channel catfish swim bladders have a one chamber swim bladder, blue catfish have a double chambered swim bladder, and hybrid catfish have a one chamber swim bladder with a nipple like protrusion on the end. Gonadal development and visceral body fat quantity were graded on a scale of 0.5-5 with 0.5 being least developed and 5 being the most developed. Fish were filleted in a uniform manner by making an incision on the head where the head meets the body of the fish and following the spine of the fish with a fillet knife. Flesh was cut away from the ribs resulting in a boneless shank fillet. After filleting, each fillet was skinned, individually weighed to determine shank fillet yield, and rinsed in a freshwater solution to remove blood and other particles. Fillets from each individual fish were vacuum sealed in a 15.24 cm x 30.48 cm Clarity 4-Mil vacuum pouch (Bunzl Processor; Koch Supplies, Riverside Missouri) and placed in a -10°C freezer.

2.3 Fillet processing for texture profile analyses and sensory analyses

Prior to evaluation, fillets were placed in a 2 ± 2 °C refrigerator overnight for thawing. Once thawed, raw fillets were evaluated for color using a CR 300 Minolta Chromameter (Osaka, Japan) to evaluate lightness, redness, and yellowness of fillets, and weighed prior to and after cooking to evaluate cook loss. Individual fillets were wrapped in aluminum foil and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. The American Meat Science Association (AMSA) research guidelines (AMSA, 2015) were followed, and one fillet was served to a semi-trained sensory panel of 12 individuals (6 males and 6 females ranging from age 21-65) in clear plastic serving cups with lids. The other fillet was stored in a 2 ± 2 °C refrigerator overnight and raised to a temperature of ~72°F (22°C) before used for texture profile analyses.

2.4 Development of a semi-trained sensory panel

Following American Meat Science Association (AMSA) Research Guidelines for Cookery, Sensory Evaluation, and Instrumental Tenderness Measurements of Meat (2nd ed.) (AMSA, 2015) guidelines, a group of 12 individual panelists were trained to evaluate 5 different key attributes in catfish fillets; toughness, flakiness, mushiness, fibrousness, and flavor (Bland, et al., 2018). Each fillet sample was graded on a scale of 1-4, with 1 being the least and 4 being the most of each attribute, and each corresponding value was correlated with a food item to calibrate the panel to the attributes of the fillet (Table 29). Flakiness was graded on a 1-3 and flavor was graded on a scale of 1-10, with 1 being severe off flavor, a flavor of 5 had distinct off flavor, 7 mild to little off flavor, and 10 corresponding with no off flavor. Panelists were trained on five different occasions before the sensory evaluation of catfish fillets, with calibration sessions occurring each week of sensory evaluation. Panelists were served equal portions of a fillet (1.27 cm x 1.27 cm) in plastic 2 oz serving cups with a lid. Samples were portioned after being allowed to rest for 10 minutes after reaching an internal temperature of 74 °C 3 groups of 4 panelists were divided to ensure replication of each fillet and were given 12 blind samples with random numbers during each sensory session to reduce bias. Panelists scored their 5 attributes using a blind survey using Google Forms (Google, Mountain View CA, US, 2021) to prevent bias by observing other panelists scores. In between each sample, panelists drank a sip of room temperature water, took a bite of a saltine cracker, then drank another sip of water to cleanse the palate.

Table 29.

Corresponding food items correlated to their score for each sensory attribute. This scale was used to calibrate the semi-trained panel in their evaluation of catfish fillet sensory attributes.

Attribute	1	2	3	4
Toughness Force required to bite through a fillet sample	Canned Dole Pineapple Chunk 1’ cube	Heritage Farm Chicken Hotdogs 2cm diameter piece	Hebrew National Beef Hotdog 2cm diameter piece	Starkist Solid White Albacore Canned Tuna in water 2 cm diameter serving
Mushiness How much a fillet sample dissipated after initial bite	Hebrew National Beef Hotdog 2 cm diameter piece	Raw White Mushroom Whole	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Simple Truth Organic Extra Firm Tofu 1’ cube
Flakiness Ease of which fillet samples were broken into individual muscle components	Cooked Wild Caught Pan Seared Sea Scallops ¼ scallop	Canned Dole Pineapple Chunk 1’ cube	Chicken of the Sea Canned Traditional Style Pink Salmon 2 cm diameter serving	N/A
Fibrousness Perception of amount of muscle tissue strands or filaments were left after chewing	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Canned Dole Pineapple Chunk 1’ cube	Raw Asparagus stem	Raw Asparagus base

2.5 Texture profile analyses of catfish fillets

Fillets were individually wrapped in aluminum foil, labeled, and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. After cooking, fillets were refrigerated at 2 ± 2 °C refrigerator overnight, then raised to room temperature ~72°F (22°C) prior to texture profile analyses. Each fillet was then sampled using TA-XT2i Texture Analyzer shear machine (Texture Technologies Corp., Scarsdale, NY) loaded with a 5 kg load cell with a ½' diameter ball probe attachment (TA-18) (Bland et al., 2018). Seven attributes were evaluated for each fillet: gumminess, chewiness, springiness, hardness, cohesiveness resilience, and adhesiveness (Table 30). Each fillet was sampled in triplicate, with the mean average of each being used for statistical analyses.

Table 30.

Texture profile attributes analyzed, formula used for each output, and the definition of each attribute analyzed.

Attribute	Formula	Description
Hardness	Force at anchor 1	Maximum force applied during the first compression
Gumminess	Hardness x Cohesiveness	Energy needed to disintegrate a semi solid food until it is ready to swallow
Chewiness	Hardness x Cohesiveness x Springiness	Energy needed to chew a solid food until ready to swallow
Springiness	Distance2/Distance 1	Rate at which a sample returns to its original size and shape
Adhesiveness	Area 3	Work required to overcome stickiness between the probe and the sample
Resilience	Area 2/ Area 1	How well a product returns to its original shape and size during the first probe
Cohesiveness	Area 4/ Area 1	How well a product returns to its original shape and size in the second probe relative to the first probe

2.6 Statistical Analyses

All data was analyzed using SAS statistical analysis software (v.9.4; SAS Institute Inc., Cary, NC, USA). Data was tested for normality using a Shapiro-Wilk test (Shapiro and Wilk 1965) and was considered non normally distributed at an alpha =0.05. A non-parametric one-way ANOVA using a Kruskal Wallis test was used to evaluate differences in ordinal dependent categories (gonad development, visceral fat development, and all sensory attributes) and texture attributes that were not normally distributed. Statistical differences were assumed at an alpha of = .05. To adjust for size differences between hybrid catfish used for texture and sensory analyses, a regression was used to adjust for size using the formula $Y_A = Y - b_{xy} X_i - X_p$ where Y_A is the adjusted attribute, Y is the actual attribute value, bxy is the regression coefficient, X_i is the mean replicate weight, and X_p is the mean weight of all replicates. General combining ability (GCA) for the sire and dam is equal to the sire and dam variance respectively, and specific combining ability (SCA) is equal to the sire x dam variance (Cotterill et al., 1987). To evaluate combining ability of sensory data graded on a discrete ordinal scale, sensory evaluation values were divided by the largest score possible and then multiplied by 100 resulting in a 0-100 scale for each sensory trait with 0 correlating with the lowest and 100 correlating with the highest for each trait (Lien et al., 2015). Proc Mixed function with a restricted estimation of maximum likelihood was used due to unbalanced data and Proc Varcomp (variance components estimated procedure) was used as a verification of variance. Proc GLM was used to evaluate significance of sire, dam, and sire x dam variance using the tests of hypotheses for random model analysis of variance. When a significant effect was observed for sire GCA, dam GCA, or SCA, a one-way ANOVA with a Tukey's Post Hoc test was conducted to evaluate differences within significant groups and rank individuals or crosses.

3. RESULTS

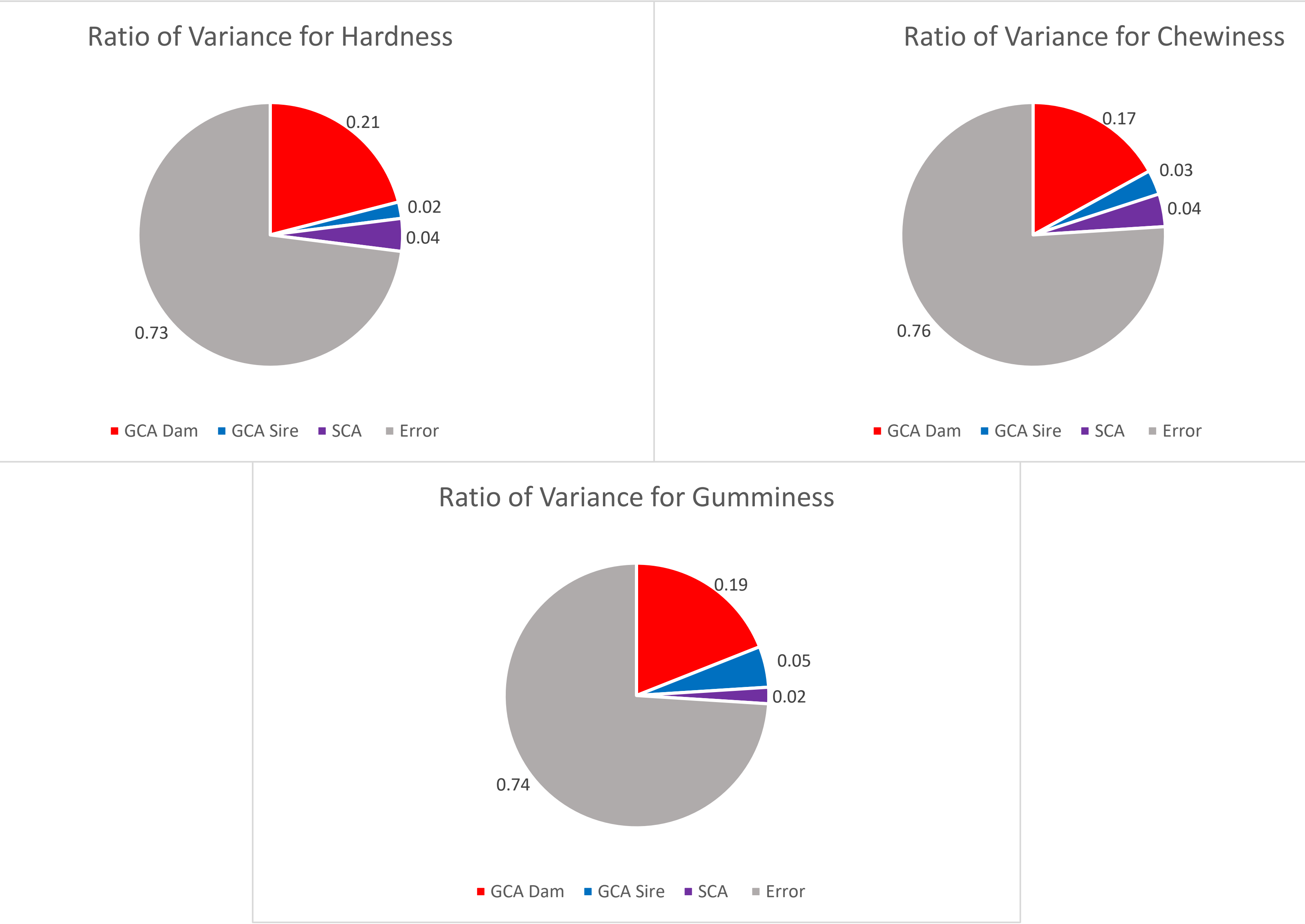
Means, standard deviations, and coefficient of correlations between KR and Kmix hybrid types are found in Table 31. There are two types of hybrid catfish produced and evaluated in this study, hybrid catfish from control and selected Kansas channel catfish females. Differences were found for fillet % ($P < 0.05$), yellowness ($P < 0.05$) and adhesiveness ($P <0.05$) for these two hybrid types. General combining ability for sires and dams, specific combining abilities for crosses, and the error variance are reported in Table 32 and the ratio of variance on a scale of 0-1 is reported by sire, dam, and sire x dam crosses are reported in the ratio column. Figures 1, 2, and 3 each show ratios of texture traits, fillet color, and fillet %. Significant specific combining ability values which indicate significant effect on crosses for these phenotypic traits were found for fillet %, cook loss %, yellowness (Y), resilience and springiness. Significant dam effects from female channel catfish were found for texture traits, hardness, gumminess, and chewiness. Genetic selection captures the additive genetic variance to enhance the desired trait by selecting for individuals or families that demonstrate the highest trait. No significant sire effects were found for any phenotypic traits measured.

Table 31.

Means, standard deviations, and coefficient of variations for body weight, fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight), lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, chewiness, and sensory evaluated traits toughness, mushiness, flakiness, fibrousness, and flavor of the interspecific hybrid of channel catfish *(Ictalurus punctatus)* female and blue catfish *(Ictalurus furcatus)* male in two genetic types are presented. Differences between hybrid genetic types were evaluated using a one-way ANOVA with a Tukey's post hoc test. An alpha =0.05 was considered significant.

	KR $\bar{X}$ ± SD (CV)	KMIX $\bar{X}$ ± SD (CV)
Trait	n=211	n=287
Body Weight	0.79±.31(.38)	.84±.35(.42)
Trait	n=81	n=68
Fillet %	26.22±3.08(.12)	27.38±2.34(.08)**
Cook Loss %	23.71±4.75(.20)	23.23±4.76(.21)
L	55.21±3.15(.06)	55.24±3.30(.06)
R	2.28±1.73(.76)	2.15±1.61(.75)
Y	8.36±3.67(.44)	6.27±3.63(.58)***
Hardness	598.48±194.76(.33)	600.95±172.63(.29)
Adhesiveness	-4.88±3.40(.70)	-7.04±6.45(.92)**
Resilience	19.67±3.13(.16)	19.08±4.85(.25)
Cohesion	0.55±.05(.08)	0.50±.07(.14)
Springiness	70.56±5.52(.08)	69.75±5.69(.08)
Gumminess	301.58±107.75(.36)	299.12±98.03(.33)
Chewiness	213.24±80.51(.38)	210.80±77.08(.37)
Toughness	1.93±.46(.24)	2.00±.46(.23)
Mushiness	2.23±.56(.25)	2.18±.66(.30)
Flakiness	2.41±.33(.14)	2.43±.35(.14)
Fibrousness	1.59±.32(.20)	1.63±.26(.16)
Flavor	7.43±.70(.09)	7.57±.76(.10)

1. * Indicates significant difference at $P<0.05$, ** indicates significance at $P<0.01$, *** indicates significance at $P<0.001$, and **** indicates significant difference at $P<0.0001$ after analyses using a one-way ANOVA



Ratio of Variance for Hardness

Ratio of Variance for Chewiness

Ratio of Variance for Gumminess

Figure 1.

Fillet texture traits hardness, gumminess, and chewiness that showed a high GCA from the dam channel catfish (*Icatlurus punctatus*) are presented. The ratio of dam GCA, sire GCA from the blue catfish (*Ictalurus furcatus)*, SCA of the cross, and error variances are shown.

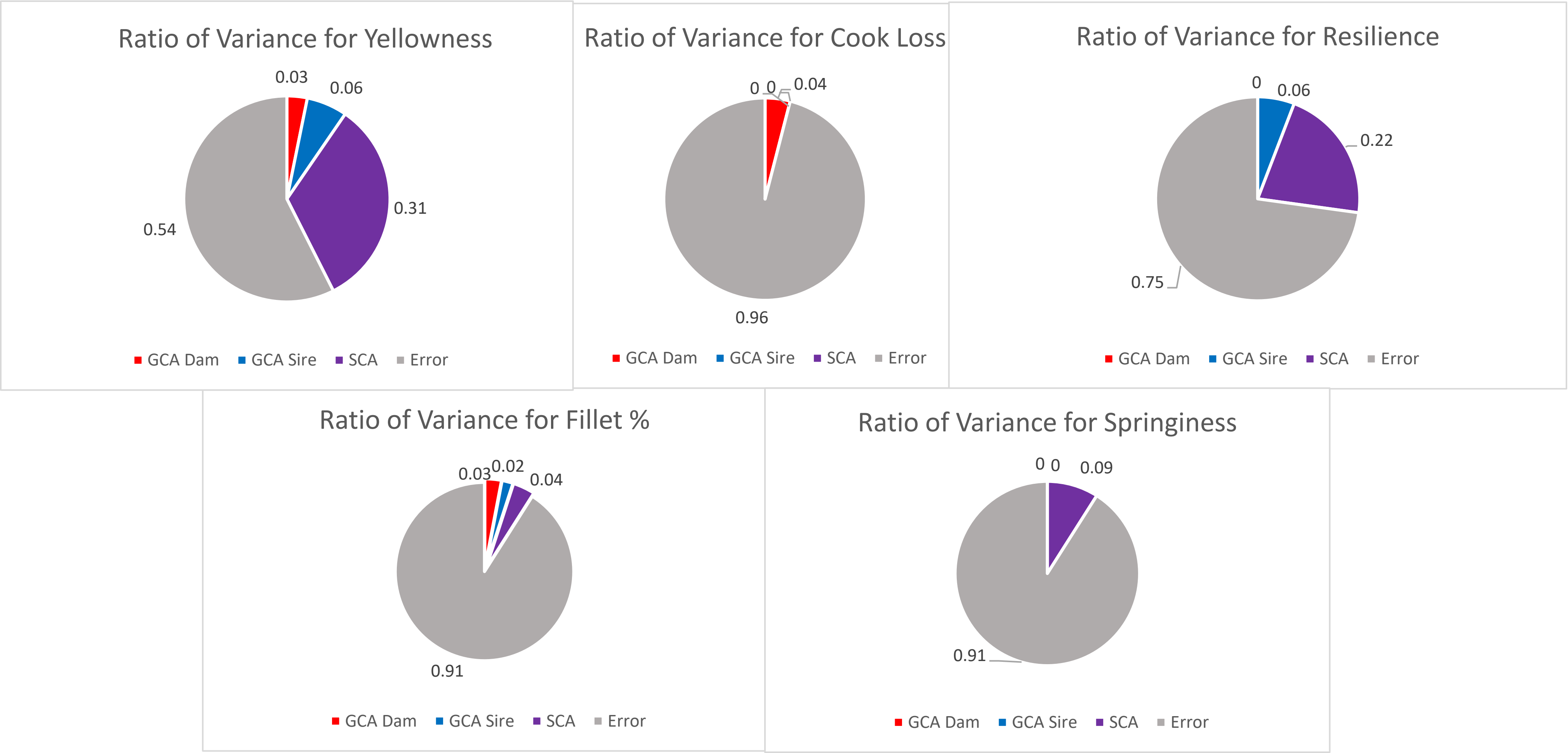


Figure 2.

Fillet color trait yellow, cook, fillet %, and texture traits resilience and springiness that showed a high SCA between the dam channel catfish (*Ictalurus punctatus*) and the sire blue catfish (*Ictalurus furcatus)* are presented. Ratio of the variance for GCA of the dam, GCA of the sire, SCA of the cross, and error are presented.

Table 32.

Estimates of general combining ability (GCA) in channel catfish (*Ictalurus punctatus)* females, general combining ability in blue catfish (*Ictalurus furcatus*) males, and specific combining ability (SCA) of hybrid catfish (channel catfish female x blue catfish male) ± standard error (SE) for fillet % (fillet total weight divided by live weight), cook loss % (cooked fillet weight divided by raw fillet weight), lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, chewiness, and sensory evaluated traits toughness, mushiness, flakiness, fibrousness, and flavor. The variance trait is the total variance for each trait evaluated, while ratio is the variance on a scale of 0-1 that explains the percentage total of variance. A one-way ANOVA was used to determine significance withing combining ability estimates.

	σ 2 GCA dam (±SE)		σ 2 GCA sire (±SE)		σ 2 SCA cross (±SE)		σ 2 error (±SE)	
	Ratio	Variance	Ratio	Variance	Ratio	Variance	Ratio	Variance
Fillet %	0.01	0.12±0.35	0.00	0.00	0.10	0.79±0.89*	0.89	7.02±2.65
Cook Loss %	0.00	0.00	0.00	0.00	0.16	3.45±1.86*	0.84	18.98±4.36
L	0.03	0.22±.47	0.02	0.28±0.53	0.04	0.37±0.61	0.91	9.17±3.03
R	0.04	0.11±0.33	0.00	0.00	0.00	0.00	0.96	0.004
Y	0.09	1.47±1.21	0.06	0.99±0.99	0.31	5.33±2.31**	0.54	9.17±3.03
Hardness	0.21	5522.61±74.31****	0.02	534.57±23.12	0.04	1123.98±33.53	0.73	19753±140.55
Adhesiveness	0.03	0.90±0.95	0.04	1.00±1.00	0.11	2.81±1.68	0.82	21.75±4.66
Cohesion	0.00	.00001±.003	0.08	0.0003±.02	0.11	.0004±.02	0.81	0.002±0.05
Resilience	0.00	0.00	0.06	0.58±0.76	0.22	3.42±1.85**	0.75	11.70±3.42
Springiness	0.00	0.00	0.00	0.00	0.09	2.73±1.65**	0.91	28.62±5.35
Gumminess	0.19	1672.83±40.90*	0.05	428.36±20.70	0.02	184.47±13.58	0.74	6324.02±79.52
Chewiness	0.17	840.22±28.99***	0.03	171.41±13.09	0.04	205.12±14.32	0.76	3863.44±62.16
Toughness	0.00	0.00	0.00	0.00	0.00	0.00	1.00	123.76±11.12
Mushiness	0.00	0.00	0.00	0.00	0.01	1.03±1.02	99.0	206.39±14.37
Flakiness	0.00	0.00	0.00	0.00	0.00	0.00	1.00	63.83±7.99
Fibrousness	0.00	0.00	.01	.65±.81	0.00	0.00	0.99	51.09±7.15
Flavor	0.00	0.00	.002	.086±.29	0.02	1.05±1.02	0.98	51.70±7.15

1. * indicates P <0.05, ** indicates P <0.01, *** indicates P<0.001 **** indicates P<0.0001

4. DISCUSSION

Little additive genetic variance was evident for carcass, texture and fillet color traits when channel catfish females and blue catfish males were crossed to produce hybrid progeny. Hardness, gumminess, and chewiness all showed significant dam combining ability, and these traits are interrelated and derived from hardness. The overall ratio of additive genetic variance in the dam was 20% of total variance, indicating additive genetic effects and or maternal effects that are either genetic or environmental (Wilham 1981). Genetic maternal effects are heritable, and in theory, can affect selection response positively or negatively (Kirkpatrick and Lande 1989, Räsänen and Kruuk 2007, Charmantier et al. 2013, White and Wilson 2019).

Maternal effects in fish and other organisms are more essential in the early life stages and decline as the progeny age (Cundiff 1972), and this has been observed in many examples including (*Morone chrysops* ♀ × *Morone saxatilis* ♂) (Wang et al., 2006) and rainbow trout (*Oncorhynchus mykiss*) (Henryon et al., 2002). The hybrid catfish in the current study were harvested at an age of 40 months it is unlikely environmental maternal effects are the reason for this variance being detected from the dam, but more likely additive genetic or maternal genetic effects.

Specific combining ability was found to be significant for fillet %, cook loss %, yellowness of the fillet, resilience, and springiness. A specific combining ability estimate is indicative genetic crosses performing below or above expectations based on average performance of all the crosses and is indicative of epistasis, dominance, and can be used for evaluation of heterosis when progeny perform better than their parents (Hayman 1957). Resilience had a significant SCA indicating different crosses showed differences in their performance which can be attributed to dominance or epistasis (Hayman 1957). A slight (0.06) GCA was found for the sire in resilience indicative of the potential for some additive genetic variance from blue catfish males contributing to the hybrid progeny, although the higher SCA (0.22) shows that dominance or epistasis interactions are the main genetic mechanism.

Specific combining ability for fillet %, 10%, for hybrid catfish matings in the current study, were similar, 7%±5% to that of a channel catfish female X blue catfish male hybrid catfish examined by (Bosworth and Waldbieser 2014). The SCA from the current study indicates the potential to select for different crosses of female channel catfish and male blue catfish that produce hybrid progeny genetically improved for fillet %. This potential genetic improvement for hybrid catfish fillet % would increase profits as hybrid catfish have been shown to have a higher fillet % than channel catfish in multiple studies, and capturing an increased flesh & from the same sized fish is sure to increase profits to catfish farmers and catfish processors (Argue et al., 2003; Bosworth et al., 2004; Dunham and Masser 2012). In contrast to the current study, (Bosworth and Waldbieser 2014), observed a strong dam GCA (0.81±0.39) from hybrid progeny, indicating a large quantity of additive genetic variance for increased fillet %. This difference between the two studies could be related to overall genetic variation as Delta strain channel catfish in the Bosworth and Waldbieser (2014) study were derived and selected from a pool originating from 12 farms and a multitude or rivers, whereas the channel catfish females in the current study were of a single lineage, Kansas, originating from the Ninnescha River 110 years ago (Dunham and Smitherman 1984).

Yellowness observed in hybrid catfish fillets had the highest specific combining ability of all traits and the highest variance not related to error. Yellowness in catfish fillets are an industry wide problem in catfish aquaculture, and yellow fillets are often reduced in price in the market due to the consumers preference for white fillets (Hu et al., 2013). Xanthophylls are the primary pigments responsible for yellowness in catfish fillets and since catfish are unable to produce xanthophylls naturally they are absorbed into their body via feed or natural microorganisms in the pond (Li et al., 2007; Hu et al., 2013). While catfish are unable to produce xanthophylls and the yellow pigmentation is a result of the xanthophylls accumulation in the flesh (Tsushima et al., 2002), the genetic variance found in hybrid progeny evaluated could potentially be explained by varying absorption and deposition rates of carotenoids in the progeny (Iwamoto et al., 1990). It has been shown that three major carotenoids (lutein, zeaxanthin, and alloxanthin) have a strong relationship with yellowness of fillets (Li et al., 2013), and marketing this yellow fillet color could be a potential strategy for catfish processors as these carotenoids make the fillets more nutritious to consumers.

Though the general combining ability for yellowness was low, the high specific general combining ability indicates epistasis and dominance (Hayman 1957). To alter this yellowness of the fillet, reciprocal recurrent selection would be the best strategy to genetically change yellowness in hybrid catfish fillets. Additive genetic correlations for yellowness in channel catfish females was observed to be very high with lightness of the fillet (.99), with lightness of the fillet also having a low but potentially significant dam heritability indicative of maternal genetic effects for these traits (0.15±0.01) (Chapter 3). Though the carotenoid itself is responsible for coloration in catfish fillets, genetic research into farmed salmon for their red flesh color is widely researched (Norris and Cunningham 2004; Araneda et al., 2005; Vieira et al., 2007; Dufflocq et al., 2017). This pigmentation for redness in Atlantic Salmon (*Salmo salar*) found low genetic correlation (.41±.08) between the observed color using a chromameter and pigment content suggesting that perceived color and retention of pigment are likely not controlled by the same genes (Norris and Cunningham 2004). Potentially, there is a chance that genes inherited in the hybrid progeny from the channel catfish female are influencing yellowness retention in the flesh and are related observed yellowness.

The only research conducted on blue catfish texture and its relationship to texture of hybrid catfish is found in Chapter 1. Blue catfish texture and carcass traits tend to be more similar to hybrid catfish than channel catfish, indicating various forms of dominance and paternal predominance (Dunham et al., 1982), sometimes being complete dominance and others incomplete dominance. Resilience in blue catfish broodstock sized fish was lower than channel catfish (Chapter 1) and hybrids have a lower resilience than channel catfish at market size. Paternal predominance may be the explanation for the SCA associated with resilience.

Specific combining ability is indicative of different crosses performing better or worse to the expected average of all crosses and is indicative of epistasis or dominance effects. While fillet %, cook loss, yellowness, resilience, and springiness did not have a high additive effect that can be captured for a breeder to enhance their stock, the knowledge of dominance and epistasis effects and evaluating individual crosses is beneficial and can be used to produce the best progeny by evaluating specific crosses. Since SCA is the main genetic effect, reciprocal recurrent selection should be the bet genetic enhancement strategy for this suite of traits.

Significant and high dam GCA for hardness, gumminess, and chewiness are indicative of additive genetic variance in the channel catfish dams used in the current study. Selecting channel catfish females with the best hardness, gumminess, or chewiness and breeding them with blue catfish should enhance these traits in hybrid progeny compared to hybrid progeny non-selected families. While hardness, gumminess, and chewiness are all significant, gumminess and chewiness are derived in their calculations from hardness potentially explaining the significance of all three, and alleles influencing hardness are likely also influencing chewiness and gumminess. Thus, a selection index and a response to multiple traits, reciprocal selection may be possible.

No significant GCA for the sire was observed in the present study, and this lack of GCA variance in the sire demonstrates the lack of additive genetic effects from the blue catfish male that is being expressed in the hybrid progeny. This lack of additive variance also indicates that genes from the blue catfish males influencing evaluated attributes are either epistatic, dominant, or do not affect these traits. This lack of additive variance also indicates that it is likely heritability in blue catfish for these traits would likely be very low and it would not be feasible to enhance blue texture and sensory traits, unless there is significant additive variation for carcass and texture traits in female blue catfish.

5. Conclusion

Observed SCA was the highest genetic variance for fillet %, yellowness of the fillet, and mechanical texture traits resilience, springiness, adhesiveness, and cohesion in hybrid progeny of channel catfish females and blue catfish females in the current study. This observation of high SCA for these traits is indicative of paternal predominance in hybrid catfish progeny. Sensory components of this study including flavor are generated by the palate of the sensory panel and have no genetic basis. Hardness, gumminess, and chewiness in this study had high GCA for the channel catfish dam, indicating additive genetic variance in channel catfish dams used in the current study. Using recurrent reciprocal selection for traits with high SCA is the most feasible genetic enhancement tool to improve these traits in hybrid progeny. Identifying channel catfish females from families with high hardness, gumminess, and chewiness traits and selecting for these traits within channel catfish lines is the best potential genetic enhancement tool to improve these traits in hybrid catfish progeny. Future evaluations for traits that influence texture such as muscle fiber quantity, diameter, and gaping may need to be evaluated in blue catfish and channel catfish to identify underlying causes of texture differences, and use these results to further enhance and potentially develop a genetic enhancement strategy to improve hybrid progeny of channel catfish females and blue catfish males.

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CHAPTER 5

TEXTURE, SENSORY, AND FILLET COLOR DIFFERENCES AMONG COMMERCIALLY AVAILABLE UNITED STATES FARMED CHANNEL CATFISH (*Ictalurus punctatus)* AND HYBRID CATFISH *(*CHANNEL CATFISH ♀ × BLUE CATFISH (*Ictalurus furcatus)* ♂) AND IMPORTED VIETNAMESE SWAI (*Pangasianodon hypophthalmus*)

ABSTRACT

Imported swai (*Pangasianodon hypophthalmus*) have played a key role in the United States domestic catfish fillet market. Total market share of imported frozen swai fillets rose 20 to 80 percent in a nine-year span. There are several likely explanations for the success of Vietnamese imports, however, catfish processors have pointed to the potential of the “mushiness” of hybrid fillets *(*channel catfish (*Ictalurus punctatus*) ♀ × blue catfish (*Ictalururs furcatus*) ♂) compared to swai. Commercially available frozen control catfish fillets, frozen control swai fillets, and sodium phosphate treated swai and hybrid catfish fillets were evaluated for texture, sensory, and fillet color traits. Color attributes adhesiveness and springiness showed no consistent pattern among treatments. Control untreated swai fillets were harder, chewier, chewier, tougher, and most fibrous compared to channel catfish control fillets, and treated hybrid and swai fillets with sodium phosphate treatments had the lowest values for these traits. Mushiness was found to have the highest value in treated swai and hybrid catfish fillets, with channel catfish being the intermediate, and swai fillets having the lowest mushiness. Channel catfish and hybrid catfish were more resilient and cohesive than the swai imports. Sodium phosphate treated hybrid catfish and and swai fillets had very similar attributes. No differences existed for two key attributes, flavor and flakiness. With treated hybrid catfish and treated swai having near identical attributes, it is likely that mushiness of hybrid catfish is likely not the reason for swai dominance in the imported catfish market and other factors are more important.

1. INTRODUCTION

Catfish aquaculture in the United States is the largest contributor to US aquaculture production, accounting for approximately 50% of US food-fish production (Vilsack and Reilly, 2013). In 2017 US catfish aquaculture accounted for 74% of fin-fish production and 29% of total aquaculture by volume (FAO, 2019). With such heavy production, the catfish aquaculture industry created its own space and market within the US whitefish market, one of the largest seafood markets in the US (Asche et al., 2009). Being the largest food-fish production species in the US catfish aquaculture plays a key role in the economy of rural areas of the southern United States and provides opportunity in areas impacted by unemployment, poverty, and food shortages (Kaliba and Engle, 2007).

In the earlier stages of its commercial life stage catfish aquaculture was once thought to be a sideline farming activity (Jolly et al., 2001). Catfish aquaculture was originally based on the farming of channel catfish (*Icatlurus punctatus*) and despite investments and improvements on US catfish production, overall commercial production began declining after peaking in 2003 and catfish processing volume has yet to recover to the original peak (USDA, 2006, 2009, 2012, 2015, 2018; Hanson, 2018). This sharp decline can be contributed to many factors including a sluggish economy, rising input costs, the terrorist attacks on September 11, 2001, and dumping of foreign import products from Vietnam and China (Engle and Stone, 2013; Engle et al., 2018).

Within the US catfish industry, many point to the dumping of imports from Vietnam that contributed to the decline of total domestic volume of catfish production in the US after 2003 (Martin, 2016). Between the years 2005 and 2014, foreign imports of frozen catfish fillets saw a 400% increase in market share increasing from 20% of total market share to 80% in the nine-year span (Hanson and Sites, 2015). The Catfish Farmers of America filed a dumping lawsuit against Vietnam in 2002 in which some, but not all, Vietnamese producers were found guilty of selling their products below fair-market price (Martin, 2016). Pangasius import share of total fillet supply in the United States has decreased since 2012 (Surathkal and Dey, 2020), but total catfish aquaculture production in the United States hasn't increased to meet this gap, and volume of sales has decreased between 2012 and 2018 (Engle et al., 2021).

Imported catfish from Vietnam are generally products of the genus *Pangasianodon,* a different genus than the domestic farmed catfish (*Ictalurus),* though both fall under the order *Surliformes* (Scuderi and Chen, 2018). Asian countries account for 90% of total world aquaculture, and pangasius products are main products shipped internationally (FAO, 2018; Ellis-Iverson, et al,. 2020). Pangasius exports from Vietnam now account for 91% of all pangasius products traded globally (Centre for the Promotion of Imports from Developing Countries CPI, 2015). In 2018 alone, Vietnam produced 1.33 million metric tons of pangasius product, namely from striped pangasius (*Pangasianodon hypophthalmus*) resulting in a total dollar value of $2.36 billion dollars (Vu et al., 2020). When compared to the $335 million dollar value of pond bank sales of catfish production in the US in 2018 (Hanson, 2018), the striking difference in revenue is easily observed and leads to the question of product differences in pangasius imports and domestic catfish products.

Market dynamics has forced the US catfish aquaculture industry to evolve continuously through time and adopt new and better management and production methods (Engle, 2003). These commercial improving management and production methods range from early use of tractor-powered paddlewheels in the 1970's (Boyd, 1998), increased usage of efficient electrical aeration paddlewheels (Engle, 1989), use of genetics to selectively breed and enhance genetic performance of channel catfish (Dunham and Elaswad, 2017), and a more recent interest in catfish farmers to use alternative production methods such as intensively aerated ponds, split-pond systems, and in-pond raceways (Kumar 2015; Kumar et al. 2016; Kumar and Engle 2017). These intensive systems only work when hybrid catfish, a cross between a channel catfish female and blue catfish (*Ictalurus furcatus)* male are stocked. Commercialization of the hybrid catfish, has had a major role in the recent survival of the catfish indurstyty during and after the decline due to its increase in resistance to disease, increased feed conversion, improved fillet yield, increased dress out percentage, increased tolerance of low dissolved oxygen, and faster growth compared to the channel catfish (Yant et al., 1976; Dunham et al., 1983; Dunham et al., 1987; Dunham and Argue, 1998; Bosworth et al., 2004; Dunham and Masser, 2012; Arias et al., 2012; Dunham et al., 2014).

Maintaining and ensuring quality and nutritional integrity are key components of processors aiming to sell packaged frozen fish fillets and are largely influenced on handling and processing of the product (Dang, et al., 2018). Frozen fish fillets are susceptible to temperature fluctuations in freezing, leading to formation of ice crystals and recrystallization (Pham and Mawson, 1997). As a result of this phenomena, rupture of cell walls, lipid oxidation, hydrolysis, any protein denaturation can occur and will lead to a loss in nutritional value, lead to off flavor, discoloration, and effect texture and taste of the frozen product (Zaritzky, 2008). To combat this issue, many processors treat their products with phosphate salts additives and use vacuum packaging to mitigate ice crystallization (Erickson, 1997).

Texture of fish products is of great importance to consumers and drives consumer demand and acceptance of market fish products (Coppes et al., 2002). Texture and taste go hand in hand in driving sensory stimulation in consumers and plays a key role in acceptability of various fish products by the consumer (Sawyer et al., 1984, 1988). With sensory and texture playing a key role in consumer demand and acceptance of a product, it is key to determine these sensory and texture differences of commercially available consumer products of domestic catfish and imported catfish products.

Our objective was to evaluate the sensory and texture differences of commercially available domestic catfish products and imported pangasius products. Three commercial markets were visited and frozen catfish products were purchased, of both control, non-treated channel catfish and imported pangasius catfish, as well sodium phosphate hybrid catfish and treated imported pangasius catfish. Sensory and texture attributes were evaluated to determine differences among commercially available non treated channel catfish product, sodium phosphate treated channel catfish product, non-treated pangasius catfish product, and sodium phosphate treated pangasius catfish product. Treated channel catfish product was not available.

2. METHODS and MATERIALS

2.1 Acquisition of commercially available products

Three common United States grocery store chains were visited to obtain control and sodium phosphate treated catfish and pangasius fillets. Pangasius products are not labeled as "catfish" in the United States due to the United States Food and Drug Administration (US FDA) ruling in 2002 only members of the *Ictaluridae* family can be labeled as "catfish" by fish distributors (U.S. FDA, 2002). As a result, commercial fish distributors often label pangasius fillets and products as "Swai". Frozen individually vacuum sealed channel catfish controls and frozen individually vacuum sealed swai control fillets were purchased from commercial grocery store A. Grocery store A channel controls were imported and products of China. Treated hybrid catfish of up to 15% water, sodium phosphate, salt, and ice glazed frozen fillets were purchased from commercial grocery store B along with individually vacuum sealed treated swai fillets of up to 30% solution of water, Sodium Tripolyphosphate, and salt. Another control of individually vacuum sealed non-treated swai fillets were purchased from commercial grocery store C.

2.2 Preparing of catfish and swai fillets for sensory and texture profile analyses

Prior to sensory and texture profile analyses, catfish and swai fillet products were thawed in a 2 ± 2 °C refrigerator overnight until thoroughly thawed. Raw fillets were sampled for color with a CR 300 Minolta Chromameter (Osaka, Japan) to evaluate lightness (L), redness (R), and yellowness (Y). Raw fillets were also weighed prior to cooking and cooked fillets weighed after cooking to evaluate cook loss. Individual fillets were wrapped in aluminum foil, labeled, and baked in a preheated 350°F (177°C) oven and cooked until an internal temperature of 165°F (74°C) was reached based on thermocouple monitoring. Fillets from each treatment were divided into two groups, one cooked fillet for sensory analyses and one cooked fillet to be used for texture profile analyses.

2.3 Sensory analyses of channel catfish, hybrid catfish and swai fillets

Following American Meat Science Association (AMSA) Research Guidelines for Cookery, Sensory Evaluation, and Instrumental Tenderness Measurements of Meat (2nd ed.) (AMSA, 2015) guidelines, a group of 12 individual panelists were trained to evaluate 5 different key attributes of catfish fillets; toughness, flakiness, mushiness, fibrousness, and flavor (Bland, et al., 2018). Each fillet sample was graded on a scale of 1-4, with 1 being the least and 4 being the most of each attribute, and each corresponding value was correlated with a food item to calibrate the panel to the attributes of the fillet (Table 33). Flakiness was graded on a 1-3 and flavor was graded on a scale of 1-10, with 1 being severe off flavor, a flavor of 5 had distinct off flavor, 7 mild to little off flavor, and 10 corresponding with no off flavor. Panelists were trained on five different occasions before the sensory evaluation of catfish fillets, with calibration sessions occurring each week of sensory evaluation. Panelists were served equal portions of a fillet (1.27 cm x 1.27 cm) in plastic 2 oz serving cups with a lid. Samples were portioned after being allowed to rest for 10 minutes after reaching an internal temperature of 74 °C. Three groups of 4 panelists were divided to ensure replication of each fillet and were given 12 blind samples with random numbers during each sensory session to reduce bias. Panelists scored their 5 attributes using a blind survey using Google Forms (Google, Mountain View CA, US, 2021) to prevent bias by observing other panelists scores. In between each sample, panelists drank a sip of room temperature water, took a bite of a saltine cracker, then drank another sip of water to cleanse the palate.

Table 33.

Corresponding food items correlated to their score for each sensory attribute. This scale was used to calibrate the semi-trained panel in their sensory understanding of each attribute and to be able to properly evaluate catfish fillet sensory attributes.

Attribute	1	2	3	4
Toughness Force required to bite through a fillet sample	Canned Dole Pineapple Chunk 1’ cube	Heritage Farm Chicken Hotdogs 2cm diameter piece	Hebrew National Beef Hotdog 2cm diameter piece	Starkist Solid White Albacore Canned Tuna in water 2 cm diameter serving
Mushiness How much a fillet sample dissipated after initial bite	Hebrew National Beef Hotdog 2 cm diameter piece	Raw White Mushroom Whole	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Simple Truth Organic Extra Firm Tofu 1’ cube
Flakiness Ease of which fillet samples were broken into individual muscle components	Cooked Wild Caught Pan Seared Sea Scallops ¼ scallop	Canned Dole Pineapple Chunk 1’ cube	Chicken of the Sea Canned Traditional Style Pink Salmon 2 cm diameter serving	N/A
Fibrousness Perception of amount of muscle tissue strands or filaments were left after chewing	Bumblebee Canned Lump Crab Meat 2 cm diameter serving	Canned Dole Pineapple Chunk 1’ cube	Raw Asparagus stem	Raw Asparagus base

2.4 Texture profile analyses of channel catfish, hybrid catfish and swai fillets

Fillets were individually wrapped in aluminum foil, labeled, and baked in a preheated oven at 350°F (177°C) until reaching an internal temperature of 165°F (74°C) based on thermocouple monitoring. After cooking, fillets were refrigerated at 2 ± 2 °C refrigerator overnight, then raised to room temperature ~72°F (22°C) prior to texture profile analyses. Each fillet was then sampled using TA-XT2i Texture Analyzer shear machine (Texture Technologies Corp., Scarsdale, NY) loaded with a 5 kg load cell with a ½' diameter ball probe attachment (TA-18) (Bland et al., 2018). Seven attributes were evaluated for each fillet: gumminess, chewiness, springiness, hardness, cohesiveness resilience, and adhesiveness (Table 34). Each fillet was sampled in triplicate, with the mean average of each being used for statistical analysis.

Table 34.

Texture profile attributes analyzed, formula used for each output, and the definition of each attribute analyzed.

Attribute	Formula	Description
Hardness	Force at anchor 1	Maximum force applied during the first compression
Gumminess	Hardness x Cohesiveness	Energy needed to disintegrate a semi solid food until it is ready to swallow
Chewiness	Hardness x Cohesiveness x Springiness	Energy needed to chew a solid food until ready to swallow
Springiness	Distance2/Distance 1	Rate at which a sample returns to its original size and shape
Adhesiveness	Area 3	Work required to overcome stickiness between the probe and the sample
Resilience	Area 2/ Area 1	How well a product returns to its original shape and size during the first probe
Cohesiveness	Area 4/ Area 1	How well a product returns to its original shape and size in the second probe relative to the first probe

2.5 DNA extraction for catfish genetic type identification

DNA was extracted from store A untreated frozen catfish fillets and grocery store B treated frozen catfish fillets to confirm genetic identity. Store A untreated frozen channel catfish fillets were products of China and store B treated frozen catfish fillets were products of the USA. DNA was extracted following the protocol of (Waldbieser and Bosworth 2008). First a cell lysis solution that contained 600 µl of DNA extraction cocktail buffer [100 mM NaCl, 10 mM Tris-HCl (pH 8.0), 25 mM EDTA (pH 8.0), 0.5% sodium dodecyl sulfate] and 3 µl of 20 mg/ml freshly made proteinase K (Sigma-Aldrich, St. Louis, MO) was used for control sample digestion. Samples were incubated in the cell lysis solution at 55°C for 4-5 hours. DNA was precipitated by isopropanol and protein was precipitated by a protein precipitation solution (Qiagen). DNA was washed twice with 75% cold ethanol and allowed to air dry, then resuspended in RNAse/DNAse free water. DNA samples were quantified using NanoDropTM 2000 spectrophotometer (NanoDrop Technologies, Wilmington, Delaware).

PCR product was used to confirm the species of Store A untreated frozen channel catfish fillets and store B treated frozen catfish fillets following an established protocol (Waldbieser and Bosworth 2008). Marker genes used for species identification were follistatin (*Fst*) and hepcidin (*Hamp*); antimicrobial proteins of channel catfish and blue catfish. The primers used are listed in Table 26. PCR reactions were carried out in a 10.0-µl reaction containing 1.0 µl (20–250 ng) genomic DNA, 1.0 µl 10× buffer, 0.4 µl 50 mM MgCl2, 0.8 µl 2.5 mM dNTP, 0.6 µl 10 µM each Fst primer, 0.3 µl 10 µM each Hamp primer, 0.1 µl 5 U/µl platinum Taq polymerase, and the remaining volume was RNAse-free water. Thermocycling conditions that were used included an initial denaturation at 95°C for three minutes with the first amplification cycles at 95°C for 1 minute, 63°C for 1 minute, and 75°C for another minute. 35 PCR amplifications 95°C for 30 seconds, 63°C for 30 seconds, and 72°C for one minute. A final extension at 72°C was run for 4 minutes. *Fst and Hamp* amplifications were resolved in an ethidium-bromine-stained 2.5% agarose gel. To check band size, a 100-bp DNA ladder (New England Biolabs, Ipswich, Massachusetts) was used. All reactions for each sample were repeated 3 times.

Table 35.

Primers for channel catfish *(Ictalurus punctatus)*, blue catfish (*Ictalurus furcatus*), and their interspecific hybrid (channel catfish ♀ × blue catfish ♂) using *Fst* and *Hamp* genes.

Gene	Forward Primer (5’-3’)	Reverse Primer (3’-5’)	Size of Amplicon (bp)
Fst	ATAGATGTAGAGGAGCATTTGAG	GTAACACTGCTGTACGGTTGAG	channel catfish 348
			blue catfish 399
			hybrid catfish 348 and 399
Hamp	ATACACCGAGGTGGAAAAGG	AAACAGAAATGGAGGCTGGAC	channel catfish 222
			blue catfish 262
			hybrid catfish 222 and 262

2.7 Statistical Analyses

All data was analyzed using SAS statistical analysis software (v.9.4; SAS Institute Inc., Cary, NC, USA). One-way ANOVA using the proc mixed function was used to calculate differences color, cook loss, and texture attributes among the five different treatments: grocery store A untreated frozen channel catfish and swai fillets, grocery store B treated frozen hybrid catfish and swai fillets, and grocery store C untreated swai fillets. Tukey's post hoc was conducted to determine differences among groups. Values were tested for normal distribution using a Shapiro-Wilke test for normalcy (Shapiro and Wilk 1965). A Kruskall Wallis test was used to observe differences among the commercial products evaluated using sensory ordinal data between the five treatment groups and an alpha =0.05 was considered statistically significant.

3. RESULTS

3.1 DNA analyses of catfish fillets

Figure 1 highlights the results of DNA analysis to determine genetic type of store A channel catfish fillets and store B treated catfish fillets. DNA evaluation of Store B treated “catfish” product revealed that 100% of fillets were hybrid catfish fillets. These samples came from two different bags from the same store. In the United States hybrid catfish fillets are not labeled differently than channel catfish, and only need to be labeled as “catfish products” (USDA 2002).

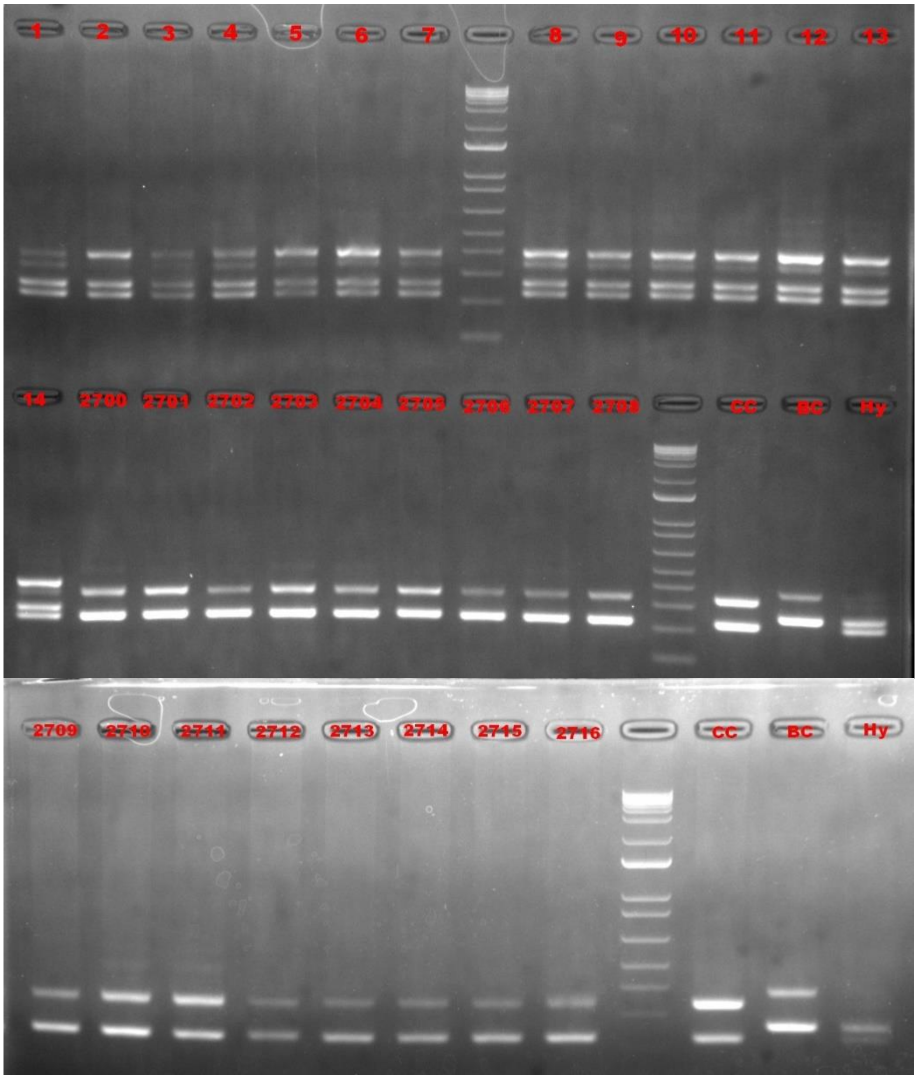

Figure 3.

Agarose gel results of electrophoresis to identify the species of store A untreated channel catfish (*Ictalurus punctatus*) control (2700-2716) and store B 15% sodium phosphate treated catfish fillets (1-14). Control banding patterns for channel catfish (CC) , blue catfish *(Ictalurus furcatus)* (BC) and hybrid catfish (channel catfish female x blue catfish male) (Hy). Results show that Store A untreated channel catfish are all channel catfish, and store B treated catfish fillets are all hybrid catfish.

3.2 Texture and color attributes of 5 commercially available swai and catfish products

Means, standard deviations, and coefficients of variations of texture and color attributes of five commercially available “catfish” products are found in Table 36. Store B treated hybrid catfish had the most light-colored fillet (P <0.05). Store C control swai was lighter (P <0.05) than store B control swai, but no other differences between groups were observed. Store A swai fillets had the reddest fillet (P <0.05) and store A channel catfish and store C swai had a redder fillet than store B treated swai (P <0.05). No other differences among products were observed for redness. Store B treated hybrid catfish and Store C control swai had the most yellow fillets (P <0.05) and and store B treated swai was less yellow than all other fillets (P <0.05). Store A products were not different between each other for yellowness of the fillet (P >0.05)

Control swai from Store A and Store C were harder than all other fillet products analyzed (P <0.05). Store A channel catfish was more adhesive than store A swai control and Store B treated hybrid catfish (P <0.05). Store A swai control was less resilient than Store A channel catfish, and Store B treated hybrid and swai fillets (P <0.05). Store A swai control was less cohesive than Store A channel catfish and Store B treated hybrid catfish (P<0.05). Store B treated swai was springier than Store A swai control and Store C swai control (P <0.05). Store C control swai was gummier than Store A control channel catfish, Store B treated hybrid catfish, and Store B treated swai (P <0.05), and Store A channel catfish was gummier than Store B treated hybrid catfish (P <0.05). Store C control swai was chewier than all other commercially fillet products except for store A swai control (P <0.05). Store B treated hybrid catfish was less chewy than Store A swai control (P <0.05). No other differences were observed among commercial products for color and texture attributes.

Table 36.

Mean values for lightness (L), redness (R), yellowness (Y), hardness (N), adhesiveness, resilience, cohesion, springiness, gumminess, and chewiness, ± standard deviation (SD) and coefficient of variation (CV) of measured commercial products Store A channel catfish (*Ictalurus punctatus)* untreated control , Store A untreated control swai (*Pangasianodon hypophthalmus*), Store B 15% sodium phosphate treated hybrid catfish (channel catfish female x blue catfish (*Ictalurus furcatus*) male), Store B 30% sodium tripolyphosphate treated swai, and store C untreated control swai fillets. One way ANOVA results with a Tukey's post hoc test was used to determine differences among groups. Highest significant P values are listed in the last column, an alpha =0.05 was considered significant.

Attribute	Store A	Store A	Store B	Store B	Store C	P value
	Channel Catfish Control	Swai Control	Treated Hybrid Catfish	Treated Swai	Control Swai	
	Mean±SD(CV)	Mean±SD(CV)	Mean±SD(CV)	Mean±SD(CV)	Mean±SD(CV)	
L	54.52±1.45(.02)^{bc}	54.02±2.89(.05)^{bc}	59.48±2.60(.04)^{a}	52.49±2.32(.04)^{c}	55.31± 1.86(.03)^{b}	0.009
R	-.25±.51(2.10)^{b}	.49±.56(1.14)^{a}	-1.00±.54(.53)^{bc}	-1.11±.93(.83)^{c}	-.379±.39(1.03)^{b}	0.023
Y	4.96±.83(.17)^{b}	6.05±1.50(.25)^{b}	8.96±1.49(.17)^{a}	2.23±2.33(1.04)^{c}	10.21±.71(.06)^{a}	0.0002
Hardness	477.44±87.30(.18)^{b}	681.26±147.90(.22)^{a}	335.86±42.84(.13)^{b}	434.44±60.68(.14)^{b}	853.33±177.90(.20)^{a}	0.002
Adhesiveness	-2.52±1.22(.48)^{a}	-8.44±3.13(.37)^{b}	-8.50±4.38(.52)^{b}	-5.15±2.11(.41)^{ab}	-6.48±1.55(.24)^{ab}	0.004
Resilience	19.44±1.94(.10)^{a}	14.49±.95(.07)^{b}	20.31±1.58(.08)^{a}	18.61±2.16(.12)^{a}	17.20±3.29(.19)^{ab}	0.011
Cohesion	.53±.02(.04)^{a}	.48±.01(.04)^{b}	.53±.02(.04)^{a}	.52±.03(.06)^{ab}	.51±.05(.10)^{ab}	0.05
Springiness	71.19±3.87(.05)^{ab}	63.86±4.49(.07)^{c}	70.68±3.04(.04)^{ab}	74.71±4.13(.06)^{a}	64.86±5.05(.08)^{bc}	0.03
Gumminess	254.93±43.14(.17)^{b}	330.01±70.90(.21)^{ab}	179.75±20.87(.12)^{c}	226.94±27.97(.12)^{bc}	436.26±122.44(.28)^{a}	.004
Chewiness	181.49±27.92(.15)^{bc}	211.01±43.15(.20)^{ab}	127.62±17.09(.13)^{c}	169.87±20.07(.12)^{bc}	284.08±84.69(.30)^{a}	0.02

In each row, significantly different means are not followed by the same letter, significant differences are assumed at an alpha =0.05

3.3 Sensory analyses among five swai, channel catfish, and hybrid catfish products

Means, standard deviations, and coefficient of variations for sensory attributes of five commercially available “catfish” products evaluated by a semi-trained panel are reported in Table 37. Control swai from Store A and B were the most tough of all commercial catfish products evaluated ($P < 0.05$), and treated swai and hybrid catfish fillets were less tough than control channel catfish fillets ($P < 0.05$). Treated swai and hybrid catfish fillets were the mushiest ($P < 0.05$) and Store C treated swai controls were less mushy than Store A channel control fillets ($P < 0.05$). Store A swai control was the most fibrous fillet ($P < 0.05$) and was more fibrous than all fillets evaluated except Store C swai control fillets. Treated swai and hybrid catfish fillets were the least fibrous fillets evaluated ($P < 0.05$). No differences across commercial products were observed for flakiness and off flavor.

Table 37.

Mean sensory values evaluated by a panel of semi-trained panelists for toughness (1-4), mushiness (1-4), flakiness (1-3), fibrousness (1-4), and flavor (1-10), ± standard deviation (SD) and coefficient of variation (CV) of obtained commercial frozen fillet products from store A channel catfish (*Ictalurus punctatus*) untreated control, Store A untreated control swai (*Pangasianodon hypophthalmus*), Store B 15% sodium phosphate treated hybrid catfish (channel catfish female x blue catfish (*Ictalurus furcatus*) male), Store B 30% sodium tripolyphosphate treated swai, and store C untreated control swai fillets. Significant differences between groups are denoted by different letters in a row. An alpha =0.05 considered significantly different after evaluation using a Kruskal-Wallis test.

	Store A Channel Catfish Control	Store A Swai Control	Store B Treated Hybrid Catfish	Store B Treated Swai	Store C Control Swai	P value
Attribute	Mean±SD(CV)	Mean±SD(CV)	Mean±SD(CV)	Mean±SD(CV)	Mean±SD(CV)	
Toughness	1.96±.29(.15)^{b}	2.55±.30(.12)^{a}	1.18±.17(.14)^{c}	1.24±.29(.24)^{c}	2.53±.45(.18)^{a}	.025
Mushiness	2.37±.42(.22)^{b}	2.05±.32(.15)^{bc}	3.27±.26(.08)^{a}	3.17±.58(.18)^{a}	1.61±.46(.29)^{c}	.016
Flakiness	2.36±.28(.12)	2.22±.21(.09)	2.21±.33(.15)	2.27±.36(.16)	2.34±.22(.09)	N/S
Fibrousness	1.77±.29(.16)^{b}	2.19±.28(.13)^{a}	1.27±.37(.30)^{c}	1.35±.54(.40)^{c}	2.04±.32(.16)^{ab}	.045
Flavor	7.24±1.15(.16)	7.65±.78(.10)	7.0±1.05(.15)	6.65±.96(.14)	7.04±.67(.10)	N/S

4. DISCUSSION

The impact of imported “swai” products from Vietnam has had a large impact on the domestic catfish aquaculture industry in the United States due to the considerably lower price, large numbers of import products, and the overall influence of dumping of Vietnamese import products that were sold below fair market prices in some situations (CPI 2015; Hanson and Sites, 2015; Martin, 2016; Vu et al., 2020). As a result of the impacts on the domestic market the United States Congress enacted and passed a law that forced imported Pangasius products to not be labeled as “catfish” in the United States resulting in imported Pangasius products to commonly be labeled as “Swai” (U.S. FDA, 2002). Despite decrease in swai fillet quantity and total fillet supply in the United States since 2012, domestic catfish aquaculture has not increased to fill this gap fillet supply and domestic volume of sales has decreased between 2012 and 2018 (Surathkal and Dey 2020; Engle et al., 2021). To elucidate factors related to this import problem and potential genetic influences, commercially available frozen control channel catfish fillets from China, frozen control swai fillets, and sodium phosphate treated swai and hybrid catfish fillets from the United States were evaluated for texture, sensory, and fillet color traits.

Swai untreated control products were different for sensory and texture attributes compared to control non-treated channel catfish fillets. Species, as well as other factors such as size, age, and seasonal influences have been shown to impact texture of fish fillets (Cheng et al., 2014). Myofibrillar structure and connective tissues can be different across species and are impacted by farming and rearing methods and each play a role in evaluation of texture (Fuentes et al., 2012). Handling, packaging, freezing and frozen storage, and muscle gaping (Anderson et al., 1997 Sigholt et al., 1997; Fuentes et al., 2012; Aubourg et al., 2013) all potentially contribute to texture traits. Despite coming from two different companies and stores, and possibly varying in genetics, culture, processing and handling methods, the two untreated swai controls were only different for redness and yellowness.

The sodium phosphate treatment had a large impact on texture as the differences between the untreated channel catfish control and the treated swai product was greatly increased compared to the difference between untreated channel catfish and untreated swai. Traits impacted were redness, yellowness, hardness, springiness, gumminess, chewiness, toughness, mushiness, and fibrousness.

Sodium phosphate treatment appeared to mitigate any textural differences between species as no textural differences were observed between treated swai and hybrid catfish fillets, although a treatment with channel catfish would have strengthened this observation. Sodium phosphate is commonly used in frozen foods to enhance water retention, decrease pathogen populations, and extend shelf life of frozen fish products (Masniyom et al., 2005). The effect of sodium phosphate treatment is different across various species and has been shown to have significant impact on sea bass (*Dicentrarchus labrax*) and made treated fillets softer, less chewable, and highly cohesive while these trends were not seen in treated saith (*Pollachius virens*) (Kilinc et al., 2009). For channel catfish, sodium phosphate treatments have been shown to decrease shear force and increase the tenderness of the fillet that have been vacuum tumbled (Kin et al., 2009). Overall, the sodium phosphate treatment seemed to mitigate and erase any significant texture differences between *Pangasianodon* and *Ictalurus* fillets and no textural differences were found between the two genera after sodium phosphate treatment.

Color differences among could be indicative of an indirect estimate of chemical composition differences that were not measured as well as influence of different feed components that can affect fillet color rather than species specific differences (Francis 1995;

Gatlin et al., 2007). Sodium phosphate treatment appears to have significantly impacted lightness of treated catfish fillets compared to all other groups. Reduction of yellowness of fillets as a result of sodium phosphate treatment has been observed previously in channel catfish (Lu 2008; Kin et al., 2009), however redness was not as impacted in these studies. Variation in redness and lightness could result from environmental factors as well as store B treated catfish fillets being hybrid catfish rather than a result of the sodium phosphate treatment.

Sensory results between treatments were more definitive in grouping the different treatments. Differences were observed between store A channel fillets and at least one of the swai control groups for every attribute except lightness, flakiness, and flavor. Treated fillets from either species could be classified as low toughness, high mushiness, low fibrousness and moderate flakiness. Swai controls were medium-high toughness, low mushiness, moderate fibrousness and flakiness and channel control fillets as a moderate to low toughness, moderate to high mushiness, moderate flakiness and low to moderate fibrousness. While species differences were observed in the sensory panel evaluations, sodium phosphate treatment overwhelms potential species differences in some cases, and has the most impact on sensory evaluation of the fillet regardless of species. “Texture” “acceptance” and “taste” of treated Nile tilapia (*Oreochromis niloticus*) fillets with a 5% sodium tri polyphosphate solution were all significantly better than a control dipped in water (Wangtueai et al., 2014) indicating a preference of treated fillets over non treated fillets. While our panel did not evaluate acceptance of the fillet, the overall mushiness of the treated fillets and noted saltiness from the treatment was reported by some to be “too mushy” or “too salty” while other panelists preferred the salted treatment and the mushier fillets. The evaluation of a less tough fillet in treated swai and hybrid catfish fillets could be explained by the injection of the phosphate treatment that would serve to tenderize the fillet (Bland et al., 2018). A reduction in fibrousness compared to nontreated fillets could also be explained by the sodium phosphate solution, which has been shown to reduce muscle fiber toughness as a result of cooking and drip loss (Hale and Waters 1998). Bland et al., (2018) showed that fresh frozen non-treated channel catfish fillets were less fibrous then treated channel catfish fillets when evaluated by a sensory panel, and the contradiction between the current and those results could be explained by a panelist differences in evaluation, scoring, and training (Bland et al., 2018). Differences observed between control groups of swai and channel catfish could be attributed to physical differences between species (Cheng et al., 2014) as well as handling, farming techniques, feed inputs, and other environmental factors or any combination thereof (Sigholt et al., 1997; Fuentes et al., 2012; Aubourg et al., 2013; Anderson et al., 1997).

At least one US catfish processor has expressed concern about marketability of domestic hybrid catfish product due to their soft and “mushy” texture when compared to the Vietnamese imports. In the current study, it is clear that treated channel-blue hybrid catfish fillets are equivalent to treated swai fillets for mushiness, toughness, and similar traits. If texture and sensory attributes are similar when comparing commercial products, price that consumers are willing to pay for products becomes important for decision making. In 2012 import catfish fillets made up 80% of the domestic catfish supply and has fallen to 60% in 2014 and these pangasius imports lead in quantity supply and compete based on price (Ashe et al., 2009; Surathkal and Dey 2020). The United States relies heavily on imported seafood to meet demands and imported seafood makes up 21.5 billion dollars of total seafood product and surpassed Japan as the largest seafood importer in the world (National Marine Services, 2018; Surathkal and Dey 2020). This high import shock has forced farmers and processors to decrease price and decrease profit margins (Surathkal and Dey 2020) however pangasius imports are still much cheaper than domestic products due to lower water regulations in Vietnam which allows farmers to flush large amounts of water through cages and race-way ponds (Engle and Stone 2013). This lack of regulation coupled with cheap labor, an air breathing product (*Pangasianodon)* that reduces aeration cost, year-round culture due to an ideal climate, allows for astronomical production per ha and cost of the product extremely lower. In theory if the US were to remove regulatory costs and had a similar structure to Vietnam, it would be possible for US catfish farmers to obtain the same yields. If Vietnam had the same stringent regulations as the US, pangasius yields in Vietnam would be similar in cost to the US (Engle and Stone 2013). To put perspective on cost of frozen swai and catfish fillets in the market, all catfish products used in this study were more expensive than swai fillet products. Store A channel control cost $15.42/kg, Store A swai control cost $8.81/kg, Store B treated hybrid catfish cost $14.11/kg, Store B treated swai cost $6.77/kg, and Store C control swai cost $10.27/kg.

5. CONCLUSION

Hybrid catfish and swai products treated with a sodium phosphate solution were significantly different than controls of each species in sensory evaluation by a semi-trained panel for attributes including toughness, mushiness, and fibrousness. To a lesser extent, differences in sensory attributes between controls of each species were also observed. Hardness, adhesiveness, resilience, cohesion, and springiness were significantly different between a channel catfish control and one swai control group, but not the other swai control. No texture or sensory differences were observed between the two swai control groups. This study highlights the texture and sensory differences between *Ictalurid* catfish and Vietnamese *Pangasianodon,* and observable differences were noticeable in every category analyzed except important traits, flakiness and flavor. In summary, control untreated swai fillets were harder, chewier, tougher, gummier, and more fibrous than channel catfish and treated hybrid and swai fillets, with the two treated products having the lowest value for these traits. Regarding the key trait of concern, mushiness, treated hybrid and swai products had the highest mushiness, channel catfish intermediate, and control swai the lowest values. No differences existed for two key attributes, flakiness and flavor. Considering that attributes of treated hybrid catfish and treated swai fillets are nearly identical, the mushiness of the hybrid catfish and imported swai is likely not a main factor and other factors are likely more important to the dominance of imported catfish in the market. Additional research regarding these effects and acceptability should be conducted.

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