Reproduction and Breeding 6 (2026) 77–90

Contents lists available at ScienceDirect

Reproduction and Breeding

journal homepage: www.keaipublishing.com/en/journals/reproduction-and-breeding

Innovation of Siluriformes fish germplasm and its research progress

Sijin Fan [a], Yu Hu [c,d], Xinyue Deng [c,d], Yalan Zhang [c,d], Wei Chen [c,d], Gaode Zhong [c,d], Xin Wang [c,d], Zebin Huang [c,d], Hanyu Liu [c,d], Fangzhou Hu [b,c,d], Chang Wu [b,c,d], Wuhui Li [b,c,d], Shi Wang [b,c,d,*], Shaojun Liu [b,c,d,**]

[a] Fisheries College, Jimei University, Xiamen, 361021, Fujian, PR China
[b] Yuelushan Laboratory, Changsha, 410128, Hunan, PR China
[c] Engineering Research Center of Polyploid Fish Reproduction and Breeding of the State Education Ministry, College of Life Sciences, Hunan Normal University, Changsha, 410081, Hunan, PR China
[d] State Key Laboratory of Developmental Biology of Freshwater Fish, Hunan Normal University, Changsha, 410081, Hunan, PR China

ARTICLE INFO

Keywords:
Siluriformes
Germplasm resources
Genetic breeding
Germplasm innovation

ABSTRACT

Siluriformes fish are widely distributed across China and are highly favored by consumers for their strong adaptability, rapid growth, palatable flesh, and low number of intermuscular bones. These attributes render them particularly well-suited for artificial aquaculture, highlighting their considerable economic value. Globally, the order comprises approximately 34 families and over 2300 species, representing 6.61% of all known fish species worldwide. In terms of genetic improvement, breeding programs have primarily focused on enhancing growth performance, leading to the successful development of several high-quality new varieties. For example, selective breeding has successfully produced the longsnout catfish (*Leiocassis longirostris*) "Chuanjiang No. 1", which effectively mitigates issues related to germplasm degradation. In the field of hybrid breeding, superior varieties including channel catfish (*Ictalurus punctatus*) "Jiangfeng No. 1", hybrid yellow catfish (*Pelteobagrus fulvidraco*) "Huangyou No. 1" and "Baixiong No. 1" have been developed, demonstrating significant advantages in growth rate, yield, and stress resistance. Regarding sex-controlled breeding, YY super-male yellow catfish and other lineages have been established through hormonal sex reversal, gynogenesis, and test cross validation. Significant advances have also been achieved in modern molecular breeding technologies. Molecular marker-assisted breeding has enabled the identification of X/Y chromosome-linked markers—such as AFLP, SCAR, SSR, and SNP—for precise trait locus selection. Furthermore, cutting-edge techniques including genome-wide selection, gene editing, stem cell-mediated nuclear transfer, and transgenesis have been successfully implemented. Collectively, these approaches have contributed to the establishment of a diversified and integrated breeding technology system. This paper provides a comprehensive review of the research history, industrial development, germplasm resources, and recent progress in the application of aquatic genetic breeding technologies for germplasm innovation in Siluriformes fish in China.

1. History and current status of Siluriformes cultivation

Siluriformes, an order within the class Osteichthyes, comprises approximately 34 families and over 2300 species globally. While exhibiting diverse body morphologies, most species possess scaleless, smooth skin, though some are armored with bony plates. Their skin typically secretes a protective mucus, which also minimizes hydrodynamic drag. Characterized by a unique skull structure, Siluriformes lack parietal and subopercular bones. Their maxillae are vestigial, primarily serving as support for the barbels rather than for mastication. The pectoral and dorsal fins of Siluriformes frequently feature rigid spines, employed as a defensive mechanism. These spines are articulated with the internal skeleton and can be rapidly erected when the fish perceives a threat, significantly enhancing their defensive capabilities. Furthermore, many species possess well-developed pharyngeal teeth, ideally adapted for capturing slippery prey. Despite their relatively small eyes,

Peer review under the responsibility of Editorial Board of Reproduction and Breeding
* Corresponding author. College of Life Sciences, Hunan Normal University, Changsha, 410081, Hunan, PR China.
** Corresponding author. College of Life Sciences, Hunan Normal University, Changsha, 410081, Hunan, PR China.
E-mail addresses: wangshixyz@126.com (S. Wang), lsj@hunnu.edu.cn (S. Liu).

https://doi.org/10.1016/j.repbre.2026.02.001
Received 20 November 2025; Received in revised form 8 January 2026; Accepted 8 February 2026
Available online 13 February 2026
2667-0712/© 2026 The Authors. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

their highly acute senses of smell and touch enable effective foraging in dimly lit aquatic environments. Siluriformes hold a crucial ecological position in global freshwater ecosystems, functioning both as important food sources and popular targets for recreational angling.

The taxonomic study of Siluriformes in China has a rich and ancient history, with references appearing in venerable texts such as the Classic of Poetry and the Erya. Nutritionally rich and easily digestible, they are particularly beneficial for the elderly, children, and individuals with compromised digestive systems. They also offer restorative properties for those experiencing physical weakness, deficiency, or malnutrition. Consequently, Siluriformes have been esteemed as significant food and medicinal economic fish since antiquity.

Before the mid-19th century, comprehensive taxonomic works on Chinese Siluriformes were scarce, often relying on illustrative depictions rather than preserved specimens. In 1803, the French naturalist Lacepède published descriptions of five novel species of Chinese Siluriformes in his work, Histoire Naturelle des Poissons. Subsequently, in 1846, the British ichthyologist Richardson provided the first systematic overview of Chinese Siluriformes, documenting 22 species, seven of which were newly described [1].

The 20th century marked the beginning of systematic taxonomic studies of Siluriformes by scholars both domestically and internationally. Zhenhuang Shou is recognized as the first Chinese scholar to describe Siluriformes adhering to international taxonomic standards. His contributions included the documentation of species such as *Leiocassis longirostris*, *Silurus asotus*, *Pelteobagrus fulvidraco*, and *Clarias fuscus* [1]. In 1928, the Swedish ichthyologist Rendahl published his seminal work, Studies on Chinese Freshwater Fishes, which systematically summarized approximately 170 years of taxonomic research on Chinese freshwater fishes, dating back to 1758. This publication remains a work of significant reference value. Subsequently, in 1931, Chinese scholar Yuanding Zhu published Index of Fishes in China, which stands as the first comprehensive compilation of fish taxonomy in the country [1]. Later, in 1960, Chinese scholar Zhang Chunlin authored Monograph of Chinese Catfishes, representing the first systematic study of the classification, distribution, and origin of Siluriformes within China [2]. By the end of the 1970s, research on Siluriformes was significantly advanced by the compilation of various faunal works [1].

Siluriformes are widely distributed, nearly globally. With the notable exception of the families Ariidae (sea catfishes) and Plotosidae (eel-tailed catfishes), which predominantly inhabit marine environments (though certain species can tolerate brackish or even freshwater conditions), the overwhelming majority of Siluriformes species are freshwater dwellers. Asia and South America are their primary distribution regions, followed by Africa [1].

According to the “2025 China Fishery Statistical Yearbook”, China's total aquatic product output in 2024 reached 73.5758 million tons, a year-on-year increase of 3.39%. Freshwater product output accounted for 36.4872 million tons (up 3.34%). Within this category, catfish production totaled 314,200 tons, experiencing a marginal year-on-year decrease of 0.68%. Meanwhile, channel catfish output surged to 526,200 tons, representing a substantial 19.32% year-on-year increase; yellow catfish production reached 627,700 tons, showing a modest increase of 0.81%; and longsnout catfish output stood at 51,600 tons, growing by 6.06%. Collectively, Siluriformes species accounted for 4.17% of the total freshwater product output.

Amidst the growing global emphasis on sustainable development and environmental protection, the aquaculture industry is undergoing a significant transformation towards larger-scale, more intensive, and highly efficient production methods. Concurrently, as aquaculture densities escalate, a series of inherent challenges confronting the industry has become increasingly pronounced. For example, the erosion of genetic diversity within Siluriformes species has heightened their vulnerability to various pathogens. Consequently, Siluriformes farming is now gravely jeopardized by a multitude of infectious diseases, including Edwardsiellosis, Gill Rot, Saprolegniasis, Ichthyophthiriasis, and Viral Hemorrhagic Disease. Furthermore, the continuous emergence of novel microbial pathogens leads to the manifestation of new disease threats. These persistent issues collectively represent critical bottlenecks that impede the sustainable advancement of both the aquatic seed and aquaculture sectors.

The availability of high-quality varieties is paramount for the sustained growth and resilience of the aquaculture industry. Therefore, promoting superior varieties and standardizing farming techniques are of utmost importance. According to information meticulously reviewed and officially released by the National Certification Committee for Aquatic Stocks and Varieties (NCCASV), eight improved Siluriformes varieties are currently deemed suitable for widespread promotion. These certified varieties possess the potential to substantially enhance the overall efficiency of the aquaculture industry, mitigate losses attributable to disease outbreaks, and ensure a consistent supply of aquatic products. Looking ahead, future endeavors should prioritize the breeding of novel Siluriformes varieties characterized by rapid growth rates, high yields, superior flesh quality, robust stress tolerance, and enhanced disease resistance.

2. Germplasm resources of Siluriformes

Siluriformes are prevalent throughout China, with numerous species flourishing in natural aquatic environments. Their succulent and palatable flesh is highly favored by consumers, making them a group of significant economic value in fisheries. According to pertinent research findings, China harbors 11 families, 28 genera, and 111 native Siluriformes species [3], including, but not limited to, *Pelteobagrus fulvidraco*, *Pelteobagrus vachelli*, *Leiocassis longirostris*, *Leiocassis crassilabris*, *Pseudobagrus ussuriensis*, *Clarias fuscus*, and *Silurus meridionalis* Chen. Furthermore, China has introduced numerous high-quality aquaculture varieties from international sources. These include American species such as *Ictalurus punctatus*, *Ictalurus nebulosus*, and *Ictalurus furcatus*; the European *Silurus glanis* from Germany; *Clarias gariepinus*, *Clarias macrocephalus*, and *Clarias batrachus* from Egypt and Thailand; *Pangasius sutchi* and *Pangasianodon gigas* from Thailand; and *Hypostomus plecostomus* from South America. These introduced Siluriformes species frequently exhibit advantageous traits such as rapid growth rates, large body size, robust adaptability, superior flesh quality, and high yields. Consequently, the total number of Siluriformes species documented in China has expanded to encompass 13 families, 32 genera, and 132 species [4]. A subset of these varieties is characterized by relatively low production costs, high fecundity, and significant economic returns, which contributes to increased fishery output value and higher farmer incomes. Importantly, they have substantially augmented China's Siluriformes germplasm resources, providing invaluable parental stock for breeding novel varieties [5]. Following rigorous review and official approval by the National Certification Committee for Aquatic Stocks and Varieties, eight excellent farmed Siluriformes varieties designated for promotion are enumerated in Table 1. Specifically, these comprise one selectively bred variety (GS-01 series), three hybrid varieties (GS-02 series), two introduced varieties (GS-03 series), and two additional varieties (GS-04 series).

The rapid expansion of the global aquaculture industry is largely driven by significant advances in genetic breeding technologies. Currently, fish breeding has progressed from traditional approaches (e.g., selective breeding, hybridization, and gynogenesis) to incorporate modern biological techniques (e.g., sex control, molecular marker-assisted selection, and genome-wide selection). However, the integration between traditional and modern techniques remains insufficient, hindering the development of a leading, integrated breeding technology system. At present, selective breeding and hybridization remain dominant. Among newly developed fish varieties, 43.66% originate from selective breeding and 34.51% from hybridization [6]. The effective integration of traditional and modern techniques to establish such a system would significantly accelerate the development of novel,

Table 1
Excellent farming of Siluriformes fish varieties in China.

Variety Name	Year	Registration Number	Category	Parental Source
Channel catfish	1996	GS-03-005-1996	Introduced variety	Introduced from the United States in 1984
Clarias gariepinus	1996	GS-03-008-1996	Introduced variety	Introduced from Egypt in 1981
Yellow catfish "Quanxiong No. 1"	2010	GS-04-001-2010	Other variety	Yellow catfish (♀) × YY super-male yellow catfish (♂)
Channel catfish "Jiangfeng No. 1"	2013	GS-02-003-2013	Hybrid variety	Channel catfish Mississippi 2001 selective breeding lineage (♀) × channel catfish Arkansas 2003 selective breeding lineage (♂)
Hybrid yellow catfish "Huangyou No. 1"	2018	GS-02-001-2018	Hybrid variety	Yellow catfish (♀) × *Pelteobagrus vachelli* (♂)
Yellow catfish "Quanxiong No. 2"	2023	GS-04-001-2023	Other variety	Wild populations in the Yueyang Sector of Dongting Lake, Hunan, and the Huainan Section of the Huai River, Anhui
Longsnout catfish "Chuanjiang No. 1"	2023	GS-01-003-2023	Selective variety	Wild population of longsnout catfish from the Yibin to Luzhou section of the Yangtze River
Hybrid yellow catfish "Baixiong No. 1"	2024	GS-02-003-2024	Hybrid variety	XX all-female yellow catfish (♀) × YY super-male *Pelteobagrus vachelli* (♂)

breakthrough varieties and foster the sustainable development of aquaculture globally.

3. Advances in Siluriformes germplasm innovation

Aquatic germplasm resources constitute the fundamental material basis for China's fishery production, serving as a crucial source of protein for human consumption. However, advances in aquaculture technology and growing market demand have collectively driven continuous increases in stocking density, which in turn has led to environmental deterioration and frequent disease outbreaks. Concurrently, high levels of inbreeding have resulted in germplasm degradation within existing varieties, manifested by diminished growth rates and reduced resistance to diseases and environmental stresses. Consequently, germplasm innovation has emerged as a pivotal element for the sustainable development of China's aquaculture industry. The principle that "developing aquaculture must begin with the seed industry" underscores this necessity. In this context, germplasm innovation is paramount, and substantial progress in breeding superior varieties has significantly propelled the development and efficiency enhancement of the aquaculture industry [7].

China has achieved remarkable success in aquatic genetics and breeding, evidenced by the successful development of numerous new varieties possessing excellent traits. Specifically, in the genetic breeding of Siluriformes, researchers have not only employed traditional techniques such as family-based selective breeding, hybridization, and gynogenesis, but have also actively integrated modern biotechnologies. These include molecular marker-assisted breeding, genome-wide selective breeding, sex-controlled breeding, and gene editing techniques (Table 2).

Table 2
Siluriformes fish breeding technology and its progress.

Breeding techniques	Process	Representative of varieties
Selective breeding techniques	Based on family-lineage selective breeding, this technique systematically evaluates key phenotypic traits such as growth rate, body conformation, and disease resistance. Combined with genetic background analysis, it identifies broodstock with superior characteristics, laying the genetic foundation for new variety development	Longsnout catfish "Chuanjiang No. 1" (Variety Registration Number: GS-01-003-2023)
Hybrid breeding techniques	Hybrid varieties such as hybrid yellow catfish, hybrid catfish, and hybrid channel catfish exhibit significant heterosis, including faster growth rates, improved tolerance to low oxygen, and enhanced disease resistance [8–12]	Channel catfish "Jiangfeng No. 1" (Variety Registration Number: GS-02-003-2013); Hybrid yellow catfish "Huangyou No. 1" (Variety Registration Number: GS-02-001-2018); Hybrid yellow catfish "Baixiong No. 1" (Variety Registration Number: GS-02-003-2024)
Gynogenesis breeding techniques	Gynogenetic individuals have been successfully induced: yellow catfish using genetically inactivated heterospecific sperm from longsnout catfish; *Pelteobagrus vachelli* using genetically inactivated heterospecific sperm from yellow catfish; and channel catfish using genetically inactivated homologous sperm via hydrostatic pressure shock [13–16]	Yellow catfish "Quanxiong No. 1" (Variety Registration Number: GS-04-001-2010); Yellow catfish "Quanxiong No. 2" (Variety Registration Number: GS-04-001-2023)
Androgenesis breeding techniques	YY super-males have been produced by fertilizing UV-irradiated yellow catfish eggs, and then all-male populations were produced [17]	None
Molecular marker-assisted breeding techniques	Molecular markers—including mitochondrial gene *COI*, nuclear gene *ITS*, microsatellite SSR, and SNP—are key molecular tools for studying Siluriformes' phylogenetics, genetic diversity, and evolution. They facilitate screening loci associated with growth and sex traits for molecular marker-assisted breeding [18–20]	None
Genome-wide selective breeding techniques	A chromosome-level genome has been assembled for yellow catfish. Genome-wide SNP analysis has elucidated domestication signatures in channel catfish. Integration of second and third-generation sequencing enabled a high-quality chromosome-level genome assembly for *Silurus meridionalis*, and combined with resequencing of the male and female mixed pool, the sex chromosomes and sex determination regions of	None

(*continued on next page*)

Table 2 (*continued*)

Breeding techniques	Process	Representative of varieties
	Silurus meridionalis were successfully located [21–23]	
Sex-controlled breeding techniques	YY super-males in yellow catfish and *Pelteobagrus vachelli*, and physiological female YY super-male yellow catfish have been developed using hormonal sex reversal, gynogenesis, and test-crossing. Sex reversal has also been achieved in channel catfish [13–15,24]	Yellow catfish "Quanxiong No. 1" (Variety Registration Number: GS-04-001-2010); Yellow catfish "Quanxiong No. 2" (Variety Registration Number: GS-04-001-2023)
Polyploid breeding techniques	Triploid induction trials in yellow catfish have been conducted using cold shock, heat shock, and hydrostatic pressure methods [25]	None
Transgenic techniques	Research has been conducted on transgenic channel catfish, yellow catfish, and *Clarias gariepinus* [26–29]	None
Gene editing techniques	The myostatin (*mstn*) gene has been knocked out in yellow catfish, and the luteinizing hormone (*LH*) gene has been knocked out in channel catfish using ZFN technology [30,31]	None
Stem cell transplantation techniques	The optimal window for transplanting blue catfish donor stem cells into triploid channel catfish recipients was determined to be 4 to 6 days post-hatch [32]	None

3.1. Advances in traditional selective breeding of Siluriformes

Selective breeding is a fundamental method in fish breeding, which screens high-quality individuals based on their phenotypic characteristics for reproduction. Through multi-generational selection, desirable traits are progressively accumulated as the frequency of beneficial genes increases and that of unfavorable genes diminishes. This process ultimately culminates in the development of novel varieties or the enhancement of existing ones.

As of 2025, data reviewed and released by the National Certification Committee for Aquatic Stocks and Varieties indicates that longsnout catfish "Chuanjiang No. 1" is among the improved, selective breeding Siluriformes varieties suitable for widespread promotion. This particular variety exhibits comprehensive advantages, including rapid growth, high yield, excellent quality, and favorable farming economics. It has effectively addressed the issues of germplasm degradation and individual miniaturization prevalent in farmed *L. longirostris* [33].

Liu et al. [34] established 63 family lineages using yellow catfish from Chaohu Lake, Gehu Lake, Hongze Lake, and Taihu Lake. By meticulously comparing the growth performance across these diverse families, they successfully identified the optimal cross combination, utilizing the Chaohu Lake population as the maternal parent and the Gehu Lake population as the paternal parent. Rezk et al. [35] undertook large-scale selective breeding over three consecutive generations, employing two distinct lineages of channel catfish with body weight as the primary selection criterion. This rigorous effort yielded significant weight gains of 29% and 21% in the respective lineages. Qin et al. [36] introduced parental channel catfish from five geographical populations and subsequently established 54 family lineages, comprising 49 hybrid families and five within-population crosses. Their observations revealed that the fastest-growing family lineage attained an average body weight 3.53 times greater than that of the slowest-growing lineage, thereby unequivocally demonstrating the efficacy of family selective breeding in identifying genotypes with superior growth traits.

In summary, traditional selective breeding remains a pivotal component of genetic improvement programs for Siluriformes. This methodology entails multi-generational, directional selection and breeding focused on key economic traits—such as growth rate, body conformation, disease resistance, and adaptability—to identify and propagate individuals possessing superior genetic characteristics. Through continuous selection and breeding, breeders can progressively enhance the overall performance of the population, ultimately culminating in the development of novel Siluriformes varieties exhibiting specifically targeted economic attributes.

3.2. Advances in hybrid breeding of Siluriformes

As a fundamental and widely used breeding method, hybrid breeding facilitates gene exchange between parental lines to integrate superior traits and achieve heterosis. This technology holds significant importance in the genetic improvement of fish germplasm. By crossing distinct species (varieties or lineages), beneficial traits from the parents can be effectively combined, with the majority of hybrid offspring frequently exhibiting substantial heterotic effects. Consequently, heterosis has emerged as a pivotal strategy for augmenting fish production and enhancing desirable phenotypic attributes [37,38].

Certification data released by the National Certification Committee for Aquatic Stocks and Varieties highlight three superior hybrid Siluriformes varieties designated for widespread dissemination: channel catfish "Jiangfeng No. 1", hybrid yellow catfish "Huangyou No. 1", and hybrid yellow catfish "Baixiong No. 1".

The channel catfish "Jiangfeng No. 1" is an F_1 hybrid resulting from the cross between a female line originating from the 2001 Mississippi breeding population and a male line from the 2003 Arkansas breeding population. Both parental lineages were established through population and family selective breeding techniques. This new variety exhibits a 25.3% increase in body weight at 18 months relative to conventional channel catfish [39]. The integration of selective and hybrid breeding techniques augments growth rate and survival, enhances genetic diversity, improves environmental adaptability and disease resistance, and mitigates the risk of inbreeding. Similarly, the hybrid yellow catfish "Huangyou No. 1" is an F_1 generation derived from crossing a female yellow catfish line, which underwent three consecutive generations of selective breeding, with a male *Pelteobagrus vachelli* line selectively bred over two generations. Studies on this new hybrid [40] have demonstrated that it surpasses its parental lineages in both body length and weight, exhibiting significant growth advantages and enhanced genetic diversity. Furthermore, the hybrid yellow catfish "Baixiong No. 1" is generated through the cross between an all-female yellow catfish (♀) serving as the maternal parent and a super-male *Pelteobagrus vachelli* (♂) as the paternal parent. Under standardized aquaculture conditions, its body weight at 12 months of age averages 22.99% higher than that of unselected hybrid yellow catfish (*Pelteobagrus fulvidraco* ♀ × *Pelteobagrus vachelli* ♂), with the male proportion exceeding 95.40%. This variety is recommended for aquaculture in freshwater environments with water temperatures ranging from 10 to 32 °C. Moreover, extensive research has documented hybrid breeding within the family Bagridae (Siluriformes), primarily involving interspecific and intergeneric crosses (Table 3).

Analysis of these hybrid combination experiments reveals several consistent patterns: specifically, in intergeneric crosses, combinations such as *Pelteobagrus vachelli* (♀) × *Leiocassis crassilabris* (♂), *Pseudobagrus ussuriensis* (♀) × *Pelteobagrus vachelli* (♂), *Pelteobagrus vachelli* (♀) × *Leiocassis longirostris* (♂), and *Pelteobagrus fulvidraco* (♀) × *Leiocassis longirostris* (♂), and the interspecific cross *Pelteobagrus fulvidraco* (♀) × *Pelteobagrus vachelli* (♂), consistently yielded F_1 hybrids that significantly outperformed their parental lineages across multiple performance indicators, including fertilization rate, survival rate, growth rate, disease resistance, and stress tolerance. This robust performance is

Table 3
Hybrid breeding situation of Bagridae fish.

	Hybridized combination	Characteristic of hybrids	References
Intergeneric Hybridization	*Pelteobagrus vachelli* (♀) × Longsnout catfish (♂)	Hybrid fry resemble the maternal parent in morphology, activity distribution, and body color; market-size fish resemble the paternal parent	He [41]
	Pelteobagrus vachelli (♀) × *Leiocassis crassilabris* (♂)	High fertilization and hatching rates; fertilized eggs and larvae exhibit strong tolerance to high temperatures	Wang [42, 43]
	Yellow catfish (♀) × *Leiocassis crassilabris* (♂)	Low hatching rate	
	Pseudobagrus ussuriensis (♀) × Yellow catfish (♂)	*Pseudobagrus ussuriensis* (♀) × Yellow catfish (♂): This combination showed the highest survival rate advantage (avg. 17.03%).	Shi [44]
	Yellow catfish (♀) × *Pseudobagrus ussuriensis* (♂)	Yellow catfish (♀) × *Pseudobagrus ussuriensis* (♂): This combination showed the most significant body weight advantage (avg. 24.11%). However, the heterosis gradually weakens over the aquaculture period	
	Yellow catfish (♀) × *Pseudobagrus ussuriensis* (♂)	Faster growth rate, higher survival rate, and better feed utilization efficiency than the parents	Qiu [45]
	Pelteobagrus vachelli (♀) × *Pseudobagrus ussuriensis* (♂)	Hybrid fish showed a higher weight gain rate, specific growth rate, growth index, and body weight coefficient of variation than the parents	Wang [46]
	Pseudobagrus ussuriensis (♀) × *Pelteobagrus vachelli* (♂)		
	Pseudobagrus ussuriensis (♀) × *Pelteobagrus vachelli* (♂)	Embryonic development duration was intermediate between the two parental species	Qin [47]
	Yellow catfish (♀) × Longsnout catfish (♂)	Hybrids exhibited richer genetic diversity, higher gene heterozygosity, and improved edible and nutritional value compared to parents	Wang [48]
Interspecific Hybridization	Yellow catfish (♀) × *Pelteobagrus vachelli* (♂)	High hatching and fertilization rates	Wang [8]
		Growth rate exceeds the paternal parent	Wang [49]
		Obvious maternal effects	Wang [42, 43]
		Hybrid varieties exhibit heterosis in terms of growth, disease resistance, and nutritional components	Zhang [50]
		Heterosis was observed in the hybrid offspring in terms of immunity, metabolism, digestion, cell proliferation, and development	Zhang [51]
	Pelteobagrus vachelli (♀) × Yellow catfish (♂)	Low fertilization rate and hatching rate	Wang [42, 43]

indicative of significant heterosis. Phenotypic traits of these hybrids typically displayed paternal, maternal, or intermediate characteristics.

Furthermore, other instances of successful hybrid breeding within various Siluriformes species have also been documented (Table 4).

Integrating hybrid breeding with complementary technologies to fully exploit heterosis is an effective strategy for developing novel hybrid varieties that meet market demands while exhibiting stable genetic traits.

Table 4
Hybrid breeding situation of other Siluriformes fish.

Hybridized combination	Characteristic of hybrids	References
Silurus meridionalis (♀) × *Silurus asotus* (♂)	Hybrid offspring exhibited a relatively low fertilization rate, with no significant differences in hatching or fry survival rates compared to parents. Growth rate was like that of the maternal parent	Wang [52]
Clarias fuscus (♀) × *Clarias gariepinus* (♂)	The hybrid's growth rate was faster than that of the maternal parent but slower than that of the paternal parent	Xian [53]
Clarias fuscus (♀) × *Clarias gariepinus* (♂)	The hybrid's growth rate was comparable to that of the paternal parent and faster than that of the maternal parent. The survival rate increased by 30-50% compared to the paternal parent	Zhang [54, 55]
Clarias gariepinus (♀) × *Clarias fuscus* (♂)	Hybrid offspring demonstrated superior cold tolerance, adaptability, and fry survival rate compared to the paternal parent, showing significant heterosis	
Silurus meridionalis (♀) × *Silurus asotus* (♂)	Hybrids achieved a survival rate of 84%. Key performance metrics (growth rate, weight gain rate, daily weight gain per tail, specific growth rate, and meat content rate) surpassed those of the paternal parent. Nutritional analysis showed higher total amino acid, essential amino acid, and flavor-associated amino acid content than the maternal parent	Kang [56]

The application of distant hybridization in fish has, to date, facilitated the development of a series of genetically stable tetraploid and diploid fish lineages. These lineages have subsequently been utilized for breeding superior triploid and diploid hybrids. A prominent example involves the distant hybridization between female red crucian carp (*Carassius auratus* red var.) and male Xiangjiang wild common carp (*Cyprinus carpio*), which yielded a fertile allotetraploid hybrid lineage. Subsequent crossing of these tetraploids with conventional diploid fish resulted in sterile triploid varieties, specifically Xiangyun crucian carp and Xiangyun carp. Through rigorous investigation, the team led by Academician Shaojun Liu has elucidated the genetic and reproductive mechanisms underpinning distant hybridization in freshwater fish. They successfully established both one-step and multi-step breeding technologies, leading to the development of improved triploid hybrid varieties, such as Xiangyun crucian carp II, and enhanced diploid hybrid varieties, including Hefang crucian carp, Hefang crucian carp II, the triple hybrid ((blunt snout bream ♀ × topmouth culter ♂) × blunt snout bream ♂), and the cross between blunt snout bream (♀) and Bleeker's yellow tail (♂). These distant hybrids frequently exhibit significant heterosis across various traits, including enhanced growth rate, disease resistance, stress tolerance, improved meat quality, and increased yield [57]. These findings have not only enriched the theoretical framework of fish genetic breeding but also ensured a sustainable provision of superior germplasm resources for aquaculture [58,59].

In hybrid breeding, parental selection is of paramount importance. Researchers [58] have comprehensively summarized the genetic and reproductive principles governing distant hybridization in fish and advocated for a systematic approach to parental selection. This requires careful consideration of multiple factors, including chromosomal compatibility, phylogenetic relationships, reproductive strategies, feeding habits, morphological characteristics, growth rates, and stress resistance. By meticulously selecting parents with complementary superior traits for cross-pairing, it becomes possible to efficiently generate hybrid offspring possessing desired qualities. This rigorous selection process thus establishes a robust foundation for the development of novel superior hybrid varieties [60].

3.3. Advances in gynogenesis breeding of Siluriformes

Gynogenesis is a reproductive strategy characterized by the development of an offspring solely from maternal genetic material following activation by sperm. In fish, gynogenesis is broadly categorized into artificially induced and naturally occurring forms. Artificial gynogenesis entails the use of genetically inactivated spermatozoa to activate oocytes, leading to the formation of haploid embryos. Diploidization is subsequently achieved by inhibiting the extrusion of the second polar body or by arresting the first mitotic division of the zygote, thereby producing homozygous diploid offspring. Typical induction methods encompass physical treatments (thermal shock or hydrostatic pressure), chemical agents, and biological approaches (distant hybridization). In nature, over ten fish species exhibit natural gynogenesis [61].

Artificial gynogenesis technology offers substantial application value, enabling rapid strain purification, sex manipulation, and the screening for recessive pathogenic traits [62]. This technique has been applied in Siluriformes breeding and, particularly when integrated with other biotechnologies, has led to the development of all-male yellow catfish varieties such as “Quanxiong No. 1” and “Quanxiong No. 2”.

Liu et al. [13,14] successfully developed YY super-male yellow catfish and physiological female YY super-male yellow catfish utilizing a combination of hormonal sex reversal, gynogenesis, and test cross verification techniques. Specifically, physiological female XY yellow catfish underwent artificial gynogenesis, and a subset of the resulting gynogenetic offspring were sex-reversed via 17β-estradiol treatment. Subsequent test crosses identified both YY super-males and physiological female YY super-males. The cross-breeding of these physiological female YY super-males with YY super-males facilitated the mass production of YY super-males. Subsequently, a portion of these YY super-males underwent sex reversal to generate physiological female YY super-males in batches. This established a cyclical process: crossing YY super-males with these feminized YY super-males enabled the large-scale production of YY super-males. These YY super-males were then crossed with normal XX females to achieve the large-scale production of all-male yellow catfish (“Quanxiong No. 1”). Beyond the practical applications, these studies also investigated the sex determination mechanism in yellow catfish, postulating the existence of XY male heterozygosity and indicating that environmental factors, such as temperature, may modulate sex determination. Furthermore, the all-male yellow catfish, owing to its advantageous traits of rapid growth rate, uniform size, and high yield, holds promising market application potential and is expected to substantially enhance the economic benefits of the aquaculture industry.

Further reports detailing gynogenesis breeding in Siluriformes fish are comprehensively summarized in Table 5.

Li et al. [66] successfully established the optimal conditions for inducing gynogenesis in *Silurus lanzhouensis*. They achieved this by using UV-inactivated heterospecific yellow catfish sperm to activate the eggs, followed by a precise cold-shock treatment. Their investigation provided compelling evidence for an XX/XY sex determination system in this species and thoroughly elucidated the genetic purity and sex characteristics of the resulting gynogenetic offspring. Concurrently, Pan et al. [67] utilized UV-inactivated homologous sperm of *Pseudobagrus ussuriensis* to determine the optimal cold-shock protocol, leading to the successful production of gynogenetic diploids. Through subsequent sex ratio analysis and male-specific AFLP marker screening, they corroborated the presence of an XX/XY sex determination system in *Pseudobagrus ussuriensis*. Furthermore, Xiong et al. [15] applied UV-inactivated yellow catfish sperm to induce gynogenesis in sex-reversed *Pelteobagrus vachelli*. This process yielded super-males of *P. vachelli*, which are critical as core broodstock for the subsequent breeding of all-male *P. vachelli* and the development of novel all-male hybrid yellow catfish varieties.

In a separate investigation, UV-irradiated sperm from grass carp (*Ctenopharyngodon idella*) were employed for the artificial fertilization of European wels catfish (*Silurus glanis*) eggs. The control group, without ploidy manipulation, yielded normal diploid offspring, a phenomenon indicative of spontaneous genome doubling of the maternal chromosome set [68]. Naturally occurring gynogenetic fish, such as the gibel carp (*Carassius auratus gibelio*) [69] and certain loach species, are also observed in natural populations.

Table 5
Gynogenesis breeding situation of Siluriformes fish.

Species	Maternal parent egg	Paternal parent sperm	Inducing method	References
Gynogenetic *Silurus meridionalis*	*Silurus meridionalis*	*Silurus meridionalis*	5 min after fertilization, 41 °C heat shock for 1 min	Wu [63]
Gynogenetic *Silurus asotus*	*Silurus asotus*	*Silurus asotus*	5 min after fertilization, 2 °C cold shock for 40 min	Cheng [64]
Gynogenetic yellow catfish	Yellow catfish	Longsnout catfish	4 min after fertilization, 4 °C cold shock for 20 min	Liu [14]
Gynogenetic *Pelteobagrus vachelli*	*Pelteobagrus vachelli*	Yellow catfish	4 min after fertilization, 4 °C cold shock for 20 min	Xiong [15]
Gynogenetic *Silurus lanzhouensis*	*Silurus lanzhouensis*	Yellow catfish	6 min after fertilization, 4 °C cold shock for 25 min	Li [65]

Despite its significant importance in both theoretical research and aquaculture, the practical application of artificially induced gynogenesis continues to face obstacles, including low progeny survival rates and complex identification protocols. However, recent advancements in artificially induced gynogenesis breeding technology have substantially improved the survival rates of gynogenetic fish, thereby significantly promoting the broader application of this technology in aquaculture. The strategic implementation of effective stimulants, such as sperm derived from distantly related fish species, offers a dual benefit: it not only enhances the survival rate of gynogenetic fish but also streamlines the identification process, collectively providing a robust and viable methodology for genetic breeding research in gynogenetic fish [62].

3.4. Advances in androgenesis breeding of Siluriformes

Androgenesis, a mode of sexual reproduction, stands in contrast to gynogenesis. It is characterized by the inactivation of maternal genetic material within the egg, with subsequent embryonic development relying exclusively on the genetic contributions from the sperm.

There are two main methods for producing androgenetic offspring in fish. The first method entails the fertilization of genetically inactivated eggs with haploid sperm (n) derived from a normal diploid individual. This yields haploid embryos, which subsequently undergo suppression of the first mitotic division to induce chromosomal doubling, thereby producing homozygous diploid individuals [70]. The second approach utilizes diploid sperm (2n) obtained from a tetraploid individual to fertilize genetically inactivated eggs, directly generating viable diploid androgenetic offspring. Androgenesis technology holds substantial importance across several domains, including the rapid establishment of purebred lineages, the elucidation of sex determination mechanisms, the utilization of unisexual populations, and the conservation of endangered fish species [61].

A specific study [17] successfully induced diploid androgenetic yellow catfish by inactivating maternal genetic material via UV-irradiation. This involved optimizing parameters such as UV dosage (which influenced fertilization, hatching, and malformation rates), the protective efficacy of egg storage solutions, and heat shock conditions

for inducing chromosomal doubling. Subsequent investigations have further refined UV-irradiation protocols for the induction of androgenetic haploidy in species such as *Heteropneustes fossilis* [71] and *Clarias gariepinus* [72], thereby establishing a foundation for future androgenesis breeding research in these species.

The generation of artificially androgenetic fish populations utilizing haploid sperm remains relatively infrequent, primarily due to challenges in inactivating the egg's genetic material and artificially doubling the sperm's chromosomal set. These aforementioned factors significantly impede embryonic development and subsequent viability, consequently resulting in diminished survival rates among androgenetic individuals. Conversely, the employment of diploid sperm derived from tetraploid fish circumvents the necessity for artificial chromosome doubling, thereby mitigating developmental abnormalities and enhancing the success rate of androgenesis [38]. Reports indicate the successful induction of diploid androgenetic fish utilizing diploid sperm from both artificially induced tetraploid rainbow trout (*Oncorhynchus mykiss*) and naturally occurring tetraploid loach (*Misgurnus anguillicaudatus*), without the requirement for additional ploidy manipulation [73,74].

Artificial androgenesis technology can rapidly establish genetically homozygous improved populations, providing a new way to boost production efficiency and economic benefits in the aquaculture industry. Additionally, this technology shows significant promise in various areas, including research on sex determination mechanisms, the utilization of single-sex populations, the protection of endangered fish species, and genetic analysis.

3.5. Advances in molecular marker-assisted breeding of Siluriformes

Molecular marker-assisted breeding (MAS) represents a powerful technique that enhances breeding efficiency through the identification of molecular markers closely linked to target traits, thereby facilitating the direct selection of individuals possessing desirable alleles. This methodology translates advancements in genomics research into practical applications for aquatic germplasm improvement. Its core processes encompass the development of genetic markers, the analysis of trait-marker associations, and the selection of superior genotypes. To date, various marker technologies, including restriction fragment length polymorphism (RFLP), simple sequence repeats (SSR), mitochondrial DNA (mtDNA), random amplified polymorphic DNA (RAPD), single nucleotide polymorphism (SNP), and amplified fragment length polymorphism (AFLP), have been systematically employed in germplasm resource identification, population genetic structure analysis, and genetic linkage map creation [75–77]. The widespread adoption of next-generation sequencing (NGS) technologies has revolutionized the field. Consequently, high-throughput and cost-effective markers, such as SSRs and SNPs, are progressively superseding less efficient methods like RAPD, thereby substantially enhancing the precision and efficacy of breeding selection.

Since the 1980s, numerous fish genes have been successfully cloned, among which the growth hormone (*GH*) gene was one of the first to be used in aquatic germplasm identification and variety selective breeding [78]. The growth hormone receptor (*GHR*) gene is functionally closely related to *GH*, as growth hormone mediates bone and muscle development through binding to its cognate receptor, thereby promoting overall organismal growth. Furthermore, other genes pivotal in selective breeding programs encompass insulin-like growth factors (*IGFs*) and their respective receptors. Chu et al. [79] examined the expression profiles of *IGF1*, *IGF2*, and *IGF3* genes in hybrid yellow catfish, identified an SNP locus in *IGF2*, and demonstrated its critical role in growth. Peterson et al. [80] investigated the endocrine responses in fast- and slow-growing families of channel catfish. Comparative analysis of mRNA levels for genes within the *GH-IGF* network revealed elevated *IGF-II* mRNA levels in the muscle tissue of fast-growing fish. Wu et al. [81] performed transcriptome sequencing analysis on normal and malformed *Silurus asotus* larvae, identifying several genes associated with growth hormone synthesis and secretion, as well as pathways implicated in protein digestion, absorption, and pancreatic secretion.

The myostatin (*MSTN*) gene has the function of negatively regulating muscle growth and development. Researchers [82] used PCR-SSCP technology to detect and genotype SNPs in the *MSTN* gene of yellow catfish. In another study [83], RT-PCR was applied to analyze differences in *MSTN* gene expression across various tissues and developmental stages in channel catfish. Disease-related losses pose significant challenges in aquaculture, making identifying disease resistance genes a research priority. Researchers [84] successfully bred the first generation (F_1) of African catfish (*Clarias gariepinus*) resistant to *Aeromonas hydrophila* by using major histocompatibility complex (MHC) class I as a molecular marker. They evaluated marker inheritance, resistance to *A. hydrophila*, and growth performance in the cultured second generation (F_2).

SNP markers and high-density genetic maps are critical for molecular marker-assisted selection, precise quantitative trait locus (QTL) mapping, and genomic structural analysis. Poompuang et al. [85] constructed the first genetic linkage map for *Clarias macrocephalus* using AFLP technology. Guo et al. [86] identified 24 SNP markers in *Pelteobagrus vachelli* based on RAD-seq technology. Xie et al. [87] developed a high-density genetic linkage map for *Silurus meridionalis*. Zhang et al. [88] constructed a high-density genetic linkage map for channel catfish using SNP markers from an F_1 family comprising 156 offspring and two parents. Additionally, Zhang et al. [89] developed a high-density genetic linkage map for *Pelteobagrus vachelli*. The construction of these high-density genetic linkage maps has established the groundwork for fine-mapping quantitative trait loci (QTLs) associated with economically important traits in Siluriformes species.

Molecular marker-assisted breeding stands as a pivotal technology within the realm of fish genetics and breeding. By facilitating the identification of specific DNA markers linked to economically important traits, MAS effectively shortens breeding cycles, enhances selection efficiency and accuracy, and ultimately aims to develop novel fish varieties possessing a comprehensive suite of desirable traits, including accelerated growth, superior quality, and robust resistance to diseases and environmental stressors.

3.6. Advances in genome-wide selection breeding of Siluriformes

Genomic selection (GS) is a breeding method that relies on genome-wide molecular markers. It examines the relationships between molecular markers throughout the entire genome and phenotypic traits to develop genetic models for estimating individuals' genomic estimated breeding value (GEBV). The rapid adoption and increased efficacy of this technology are largely driven by advances in high-throughput SNP genotyping and the widespread application of genome-wide association studies (GWAS) [90].

GWAS utilize an extensive array of genetic markers to facilitate the fine-mapping of loci associated with target traits across the entire genome [91]. This powerful technology significantly enhances the capability to precisely delineate genomic regions harboring genes that govern specific traits, thereby substantially increasing the probability of discovering critical genetic determinants [75].

A high-throughput SNP chip for channel catfish was developed by a research team led by Zhanjiang Liu, serving as a foundational platform for GWAS. Using this resource, the team subsequently undertook QTL mapping studies in both channel catfish and its hybrids. Specifically, Shi et al. [92] identified QTLs associated with resistance to enteric septicemia across three distinct families of channel catfish. Concurrently, Zhong et al. [93] detected QTLs related to tolerance to low dissolved oxygen in hybrid catfish. Furthermore, within backcross progenies derived from channel catfish (♀) × hybrid catfish (♂) (channel catfish (♀) × blue catfish (♂)), Geng et al. [90] successfully mapped QTLs conferring resistance to columnaris disease. Li et al. [94] pinpointed a genomic region significantly associated with body weight, alongside

four additional QTLs linked to muscle growth and skeletal development in backcross individuals. Most recently, Wang et al. [95] elucidated the critical role of the NF-κB signaling pathway in resistance to motile *Aeromonas hydrophila* septicemia in catfish, concurrently identifying associated QTLs. The precise identification of these economically important QTLs is instrumental in advancing the development of genome-wide selection breeding strategies for Siluriformes species.

Gong et al. [21] integrated Illumina, PacBio, and Hi-C technologies to successfully assemble a chromosome-level genome for the yellow catfish, providing a high-quality genomic resource critical for investigating economically important traits and sex determination mechanisms. Huang et al. [96] employed GWAS to identify SNPs and candidate genes associated with body length and body weight in yellow catfish. Mou et al. [97] successfully identified growth-related SNP markers and candidate genes in longsnout catfish using high-throughput SNP genotyping and genome-wide association analysis.

In a separate endeavor, Liu et al. [98] utilized single-tube long fragment read (stLFR) technology for sequencing library construction and performed sequencing on the BGISEQ-500 platform. Subsequently, they integrated Hi-C data with bioinformatic analysis to successfully assemble a chromosome-level genome for the electric catfish (*Malapterurus electricus*).

The increasing accessibility of high-throughput sequencing and the expanding application of genome-wide selection technology in Siluriformes breeding have progressively facilitated the identification of molecular markers and QTLs governing diverse traits within this taxonomic group. These advancements not only provide an in-depth molecular understanding of genetic improvement in Siluriformes but also provide directly applicable genetic markers for selection, thereby making Siluriformes breeding more scientifically rigorous and efficient.

3.7. Advances in sex-controlled breeding of Siluriformes

Sex control technology, which finds extensive application in fish genetic breeding, involves the artificial intervention in and regulation of offspring sex ratios during the natural reproductive cycle. Its core methodologies encompass interspecific hybridization, artificially induced gynogenesis (androgenesis), triploid induction, exogenous hormone stimulation, and temperature manipulation [99].

Sex determination and sex differentiation, while inherently linked, represent two distinct biological processes. Sex determination refers to the mechanism by which an organism establishes its sex, which can be genetically predetermined, environmentally influenced, or governed by a complex interplay of both genetic and environmental factors. In contrast, sex differentiation describes the subsequent developmental process where an organism's gonads mature into either testes or ovaries, consistent with the determined sex. The emergence of secondary sexual characteristics typically accompanies this process and generally exhibits a degree of plasticity [100].

In nature, numerous fish species exhibit pronounced sexual dimorphism, characterized by significant differences between males and females in morphology, coloration, or behavior. Research has consistently demonstrated that in species such as yellow catfish [101] and channel catfish [102], males typically exhibit a significantly faster growth rate than females. Conversely, species including common carp (*Cyprinus carpio*), rainbow trout (*Oncorhynchus mykiss*) [103], olive flounder (*Paralichthys olivaceus*) [104], Japanese seabass (*Lateolabrax japonicus*) [105], and Atlantic salmon (*Salmo salar*) [106] present the opposite trend, with females demonstrating substantially superior growth. Consequently, precise control over the sex ratio in aquaculture can significantly accelerate breeding cycles, facilitate the production of mono-sex populations, and ultimately enhance economic returns.

The mechanisms and efficacy of sex reversal in fish depend on the specific sex hormone employed. Among various androgens, 17α-methyltestosterone is widely used due to its ease of synthesis, stability in feed, and high efficacy. Regarding estrogens, the principal types employed for sex reversal are 17β-estradiol and estrone. In 1996, Liu et al. [107] successfully induced sex reversal in *Clarias gariepinus* fry through dietary administration of methyltestosterone (MT) and estradiol (E2), concurrently confirming a female homogametic (XX) genetic sex determination system in this species.

As mentioned previously, Liu et al. [13] successfully screened out YY super-male yellow catfish and physiological female YY super-male yellow catfish by adopting hormonal sex reversal technology, gynogenesis technology and test cross verification technology, which is of great significance for the creation of new yellow catfish varieties and the development of the aquaculture industry. Some researchers [101] conducted sex control studies on yellow catfish: they screened out X or Y chromosome-specific AFLP fragments, converted them into SCAR markers, and established a PCR-based chromosomal genotype identification method, which plays a key role in sex identification of yellow catfish and large-scale continuous production of all-male fry. Furthermore, to accurately identify YY super-male individuals, some scholars [108] cloned the Pf62-Y and Pf62-X sequences via chromosome walking technology, revealed significant genetic differentiation between the corresponding X and Y chromosomal allelic sequences, and designed specific primers based on this to efficiently distinguish YY super-male, XY male, and XX female fish, thereby enabling more precise breeding selection.

In addition to hormonal and genetic regulation, environmental factors can also significantly affect fish sex differentiation. For example, in yellow catfish, studies [109] have found that high-temperature treatment (34 °C for 60 consecutive days) applied during artificially induced sex reversal can shift its sex determination mechanism from the typical genotypic mode (XX/XY) to a temperature-dependent mode, leading to 100% of XX individuals developing into functional males. This indicates that under specific conditions, environmental factors can override genetic background in sex differentiation, offering a new avenue for sex control technology.

With the continuous deepening of research on sexually dimorphic fish, the biotechnology for sex control using X and Y chromosome-linked genetic markers has gradually matured. This technology has been applied in species such as yellow catfish [101,108,110], *Pelteobagrus vachelli* [89], *Pseudobagrus ussuriensis* [111], longsnout catfish [112], channel catfish [113,114], *Silurus lanzhouensis* [115], and *Silurus meridionalis* [116]. Challenges still lie ahead in this field: expanding the existing technical system to more economic fish species; further deciphering the complex mechanism of environment-genetic interaction to develop more environmentally friendly regulatory strategies; and systematically evaluating the production performance and genetic stability of unisexual populations in long-term cultivation. Continuously deepening these studies will effectively promote the germplasm innovation and industrial upgrading of Siluriformes fish.

3.8. Advances in polyploid breeding of Siluriformes

Polyploid organisms possess three or more complete sets of chromosomes and are prevalent in natural ecosystems, playing a pivotal role in speciation [117]. Compared to their diploid ancestors or closely related species, polyploids frequently exhibit enhanced traits, including accelerated growth, heightened adaptability, and augmented disease resistance [118].

A notable characteristic of fish chromosomes is their high plasticity, which makes them susceptible to artificial chromosome set doubling. This characteristic offers a theoretical basis for the development of artificially induced polyploid technology. Common methods for inducing polyploidy in fish encompass temperature shock, chemical treatment, application of hydrostatic pressure, electric shock, colchicine treatment, and distant hybridization. Among these, combining distant hybridization with chromosome doubling can create fertile tetraploid lineages. The main way these tetraploid lineages produce polyploid offspring is as follows: tetraploid spermatogonia or oogonia undergo

normal meiosis to form diploid gametes (2n) with halved chromosome numbers. These gametes, when combined with normal haploid gametes (n), usually produce triploid (3n) offspring [119,120].

The accelerated growth of triploid fish is primarily attributed to induced sterility. Energy typically allocated to reproduction is redirected to somatic growth. Because triploid fish possess three chromosome sets, homologous chromosomes cannot pair correctly during meiosis, impairing functional gamete production and resulting in abnormal gonadal development and infertility [119,121,122].

To date, numerous polyploid aquatic animals have been successfully produced, including induced or distant hybridization-derived polyploids in salmon and trout, common carp (*Cyprinus carpio*), crucian carp (*Carassius auratus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), *Paramisgurnus dabryanus*, olive flounder (*Paralichthys olivaceus*), *Pagrus major*, and *Monopterus albus*, among others [123]. There have also been reports of artificially induced polyploidy in species within the order Siluriformes (Table 6).

Table 6 illustrates that polyploid induction in Siluriformes species is predominantly achieved through physical methodologies, such as cold shock, heat shock, and hydrostatic pressure. Nevertheless, these methods nonetheless present challenges for the large-scale production of fry. Consequently, researchers are actively investigating biological strategies, such as the development of allotetraploids, to facilitate the future mass production of triploid fry. Triploid fish typically offer advantages, including accelerated growth, enhanced stress resistance, superior flesh quality, and increased yields, thereby giving them significant economic value and promising applications in aquaculture [133]. Furthermore, researchers [134] observed lower mtDNA copy numbers in the muscle of triploid fish during winter, suggesting that this adaptation may reduce individual energy expenditure when food is scarce. Moreover, owing to their inherent sterility, allotriploid fish play a crucial role in conserving natural germplasm resources and preventing undesirable gene introgression [58].

3.9. Advances in the application of transgenic technology in Siluriformes germplasm innovation

Transgenic technology is a highly integrated form of molecular biotechnology that involves inserting specific foreign genes into animal chromosomes using genetic engineering techniques, allowing genetic modifications through cultured cells or germ cells. A variety of gene delivery techniques are employed, including microinjection, electroporation, gene gun bombardment, sperm-mediated gene transfer, chemical induction, and viral transfection [99,135].

In a landmark achievement, the team led by Zuoyan Zhu pioneered the world's first transgenic fish in 1985, establishing a crucial model system [136,137]. Subsequently, research into transgenic fish has expanded globally. Lu et al. [29] were the first to produce transgenic yellow catfish via microinjection, observing a 50% faster growth rate compared to their non-transgenic counterparts. Building on this, Ge et al. [138] cloned the yellow catfish growth hormone gene and introduced a GH construct into fertilized eggs via microinjection. Of 301 injected embryos, 40 were transgenic, successfully establishing a genetic engineering platform for this species. Su et al. [139] investigated the effects of transgenic sterilization constructs and inhibitory compounds on channel catfish embryos, finding that transgene expression could reduce hatching and early survival, while compounds like sodium chloride and doxycycline further reduced hatchability. In a related study, domestic researchers [140] reported that growth hormone transgenic channel catfish demonstrated significant growth advantages over their non-transgenic counterparts at both 6 and 12 months of age. Dwi et al. [141] successfully generated transgenic catfish by transferring a catfish growth hormone gene into sperm using electroporation. Similarly, Dewi et al. [142] introduced a growth hormone gene from striped catfish (*Pangasianodon hypophthalmus*) into African catfish sperm via electroporation. This intervention yielded fast-growing F0 transgenic African catfish that exhibited significantly higher body weight compared to non-transgenic controls. Collectively, these studies underscore that transgenic fish offer substantial advantages, including enhanced production efficiency, improved stress resistance, and robust adaptability, primarily achieved through the precise regulation of growth-related gene expression. This technology thus represents a pivotal approach for advancing fish genetic improvement programs.

While transgenic technology has undeniably made substantial contributions to the genetic improvement of farmed aquatic species, its application has also raised significant concerns about food safety and

Table 6
Polyploid breeding situation of Siluriformes fish.

Species	Inducing method	Temperature/ pressure	Treatment time (post-fertilization)	Duration time	Result	References
Yellow catfish	Cold shock	5 °C	2 min	20 min	Embryonic triploidy rate ~70%; Hatching rate ~50%; Detection rate of triploids (including chimeras) at larval stage: 25%	Song [124, 125]
	Heat shock	40 °C	2 min	2 min	Embryonic triploidy induction rate 58%; Hatching rate 39%; Detection rate of triploids (including chimeras) at larval stage: 40%	
	Cold shock	4 °C	3 min	10 min	Embryonic triploidy rate 58%; Relative hatching rate 53%	Wu [25]
	Heat shock	40.5 °C	2 min	2 min	Embryonic triploidy rate 59%; Relative hatching rate 36%	
	Heat shock	(40.5 ± 0.2) °C	~45 min and ~54 min	1.5~1.8 min	Gastrula stage tetraploidy rate: 10.61-62.16%; Hatching stage tetraploidy rate: 11.11~75.00%; Relative hatching rate: 9.77~36.05%	
	Hydrostatic pressure shock	550 kg/cm^2	3 min	3 min	Embryonic triploidy rate 55%; Relative hatching rate 54%	
	Cold shock	4 °C	3 min	15 min	Triploid induction rate 63.3%; Hatching rate 82.3%	Li [126]
	Heat shock	40 °C	8 min	2 min	Triploid induction rate 93.3%; Hatching rate 78.6%	
Channel catfish	Heat shock	41 °C	90 min	3 min	Tetraploid induction rate 62%	Bigwell [127]
	Cold shock	5 °C	5 min	60 min	Triploid induction rate 100%; Hatching rate 79%	Chrisman [128]
Clarias gariepinus	Heat shock	41 °C	3 min	20 min	Triploid induction rate 80.09%; Hatching rate 56.31%	Hassan [129]
Pimelodus maculatus	Heat shock	38 °C	2 min	2 min	Triploid induction rate 96.7%; Hatching rate 42.91%	Bertolini [130]
Silurus asotus	Cold shock	4 °C	5 min	60 min	Triploid induction rate 98.7%	Kim [131]
Heteropneustes fossilis	Cold shock	4 °C	2 min	30 min	Triploid induction rate 94.13%; Hatching rate 71.79%	Tiwary [132]

ecological security. The integration of exogenous genes can alter the phenotype (e.g., morphology), physiology, and overall health of transgenic fish. A more serious concern is the potential ecological risk if transgenic fish escape into natural ecosystems. Such escapes could lead to hybridization with wild relatives, causing potentially irreversible genetic pollution. Therefore, the establishment and enforcement of rigorous risk assessment and management systems for transgenic organisms are essential.

3.10. Advances in the application of gene editing technology in Siluriformes germplasm innovation

Gene editing technology enables the precise modification of genomic DNA through targeted insertion, deletion, replacement, or alteration of specific sequences. The primary methodologies employed in this domain comprise zinc finger nucleases (ZFNs) [143], transcription activator-like effector nucleases (TALENs) [144], and the clustered regularly interspaced short palindromic repeats-associated protein nine nuclease system (CRISPR/Cas9) [145,146]. As one of the most pivotal technologies in the contemporary life sciences, gene editing is currently experiencing accelerated progress across both fundamental research and practical applications, particularly within the domain of aquaculture.

One of the earliest successful applications in aquaculture was the use of ZFNs to knock out the *mstn* (myostatin) gene in yellow catfish [30]. Zhang et al. [147] used ZFNs to successfully knock out the *mstna* gene in yellow catfish, resulting in increased body weight and skeletal muscle hyperplasia. Additionally, the *Myostatin B* gene was successfully inactivated in yellow catfish via TALENs [148]. A later study on the offspring of *Myostatin B* knockout yellow catfish [149] found that they had fewer vertebrae, reduced body length, and shorter intervertebral spacing, resulting in an overall shorter body. In a separate endeavor, ZFNs technology was employed to ablate the luteinizing hormone (*LH*) gene in channel catfish, successfully generating sterile individuals. This achievement represented not only the first successful gene editing in channel catfish but also the inaugural application of ZFNs technology for inducing reproductive sterility in an aquaculture species [30]. More recently, Coogan et al. [150] utilized CRISPR/Cas9 technology to inactivate the myostatin gene in channel catfish, resulting in phenotypes characterized by accelerated growth and enhanced disease resistance. Furthermore, the same research group also implemented a CRISPR/Cas9-based 2H2OP strategy for the targeted insertion of a transgenic vector (ccβA-msElovl2), carrying an elongase gene (*Elovl2*) from *Oncorhynchus masou*, into the mc4r gene locus of channel catfish.

Gene editing technology offers substantial potential for aquaculture, enabling the precise improvement of key economic traits such as growth rate, feed conversion efficiency, disease resistance, and stress tolerance. Beyond directly improving traits, it also plays a pivotal role in functional genomics and the development of precise breeding strategies. Consequently, gene editing is ushering in a new era for the sustainable development of aquaculture. Future efforts should focus on leveraging gene editing to further optimize traits, improve its efficiency and safety, and promote industrial applications to support the robust and sustainable growth of the sector.

3.11. Advances in the application of stem cell transplantation technology in Siluriformes germplasm innovation

Cell engineering breeding encompasses genetic improvement strategies executed at the cellular or chromosomal level, primarily comprising nuclear transplantation (nuclear-cytoplasmic hybridization), gynogenesis/androgenesis, polyploid breeding, and germ cell transplantation (GCT) [90].

In contrast to other established cellular engineering breeding techniques, germ cell transplantation (GCT) represents a more recently developed methodology [90]. The first successful demonstration of primordial germ cell (PGC) transplantation was achieved in chickens (*Gallus gallus domesticus*) in 1993 [151]. Within piscine research, Takeuchi et al. [152] successfully transplanted primordial germ cells (PGCs) from rainbow trout into *Oncorhynchus masou* embryos in 2003, subsequently observing the colonization and differentiation of donor PGCs within the recipient gonads. Fish germ cell transplantation experiments are broadly categorized into three types: intraspecific transplantation, interspecific transplantation, and transplantation into sterile triploid recipients. Perera et al. [153] demonstrated this by transplanting spermatogonial stem cells from blue catfish into the gonads of treated, sterile triploid channel catfish, whereupon the triploid recipients successfully produced blue catfish sperm. This seminal work not only validated the successful production of heterologous catfish but also constituted the inaugural report of generating 100% donor-derived offspring using this surrogate technique. Hettiarachchi et al. [32] later optimized this process by identifying the optimal timeframe for donor stem cell transplantation into recipient fish as 4 to 6 days post-hatch (DPH). This refinement significantly enhances the efficiency of commercial heterologous catfish production.

Over the past two decades, significant progress in fish germline stem cell and transplantation technologies has opened new avenues for conserving, restoring, and genetically enhancing fish germplasm resources. Nonetheless, the effective translation of these laboratory achievements into practical aquaculture applications necessitates continued in-depth research and technical optimization by the aquaculture sector.

4. Prospects for germplasm innovation in Siluriformes

China's aquaculture industry has entered a phase of high-quality development. Cultivating new drivers of growth and advancing the modernization of the sector are crucial to achieving this transformation. Propelling the high-quality development of fisheries requires: a transition to green and low-carbon practices; enhancements in quality and efficiency; strengthened conservation and sustainable use of aquatic germplasm resources; accelerated technological innovation; and a stable, secure supply of aquatic products.

Aquaculture has emerged as a pivotal pillar supporting the global supply of aquatic products, with germplasm innovation playing an instrumental role in enhancing both the quality and yield of these products [154]. Since the turn of the 21st century, China's aquatic genetic breeding technology has undergone rapid advancement, transitioning from traditional techniques—such as traditional selective breeding, hybrid breeding, and gynogenesis—to sophisticated modern biotechnologies, including molecular marker-assisted selection (MAS) and genome-wide selection (GWS). The synergistic application of these diverse technologies enables the development of novel varieties possessing superior economic traits, such as enhanced growth rates, superior flesh quality, robust disease resistance, and improved stress tolerance, thereby substantially elevating both the productivity and quality of aquaculture output.

China's aquaculture breeding sector is actively driving the transformation and upgrading of its seed industry through the systematic integration of traditional and modern biotechniques. Traditional or classical breeding methodologies—such as selective breeding, hybridization, and polyploid breeding—have been instrumental in the genetic improvement of key aquaculture species, including the “Four Major Domestic Fishes” (black carp, grass carp, silver carp, and bighead carp), common carp, crucian carp, and blunt snout bream. This progress has largely relied on extensive, long-term empirical selection. However, these approaches often face limitations, including an insufficient understanding of underlying genetic mechanisms, suboptimal efficiency in trait enhancement, and constrained progress in developing robust stress resistance. In contrast, modern biotechnologies, such as genome-wide selection (GWS), molecular marker-assisted selection (MAS), and gene editing, offer high precision and specificity. Despite this potential, their widespread application remains limited; many of these advanced

techniques are still predominantly at the laboratory research stage, and their broad implementation in aquaculture species, particularly fish, is nascent. Nevertheless, compelling examples exist where the judicious integration of traditional breeding methods with modern biotechnologies has successfully yielded novel fish varieties exhibiting superior traits. The technical paradigms demonstrated by these successes offer valuable blueprints for the genetic improvement of new Siluriformes varieties. For instance, multi-omics integration can elucidate the genetic architecture of complex traits such as growth, disease resistance, and hypoxia tolerance. Subsequent application of genome-wide selection (GWS) can significantly augment the precision of selective breeding, while molecular marker-assisted selection (MAS) facilitates targeted screening, thereby accelerating the development of disease-resistant or stress-tolerant lineages. Similarly, integrating distant hybridization, gynogenesis, and polyploid breeding can rapidly produce superior sterile triploids, as seen in Xiangyun crucian carp No. 2. Combining sex control with gene editing enables efficient production of unisexual populations and precise regulation of growth. Although research on novel Siluriformes varieties is still in its early stages, these integrated approaches hold great promise. Identifying and precisely editing genes associated with desirable traits can yield novel germplasm, opening new avenues for developing robust varieties suitable for high-density aquaculture.

In breeding new Siluriformes varieties, current research has predominantly focused on improving growth performance. This has led to the successful development of several new varieties, including channel catfish “Jiangfeng No.1”, hybrid yellow catfish “Huangyou No.1”, hybrid yellow catfish “Baixiong No.1”, all-male yellow catfish “Quanxiong No.1”, and all-male yellow catfish “Quanxiong No.2”. However, under large-scale industrialized cultivation, significant challenges have progressively emerged, notably the degradation of meat quality traits and insufficient stress resistance. Existing Siluriformes varieties often exhibit persistent shortcomings in key quality indicators, such as protein content and flavor substance composition, making it difficult to meet the evolving demands of a premium consumption market. Concurrently, disease management presents a major obstacle: frequent outbreaks of bacterial, parasitic, and fungal pathogens lead to widespread mortality within farmed populations. This inflicts substantial economic losses and severely erodes producer confidence. Collectively, these factors significantly constrain the market competitiveness of the Siluriformes aquaculture industry. Despite the current absence of disease-resistant Siluriformes varieties developed in China, the breeding of such varieties is of paramount importance. It holds the potential to significantly mitigate production costs and enhance yields, thereby promising substantial dual economic and ecological benefits.

Meanwhile, incorporating feed conversion efficiency, a core economic trait directly affecting aquaculture costs and the environment, into breeding objectives has become a crucial direction for promoting the green transformation and high-quality development of the industry. The breeding of new varieties with superior feed utilization efficiency is therefore of paramount importance for mitigating production costs, enhancing operational efficiency, and fostering sustainable industrial growth. Current research on improving feed efficiency adopts a dual approach. Firstly, nutritional strategies focus on optimizing dietary components, such as the protein-to-lipid ratio, and exploring alternative protein sources. Secondly, and more fundamentally, there is a strong commitment to genetic improvement. This involves deciphering the genetic basis underlying feeding, digestion, and metabolism through multi-omics technologies, rigorously evaluating the heritability of FCE traits, and developing precise molecular markers. These efforts represent the cutting-edge directions for breeding new varieties inherently endowed with high feed conversion efficiency. Ultimately, achieving genetic improvement and enhancing feed utilization efficiency at the genetic source of varieties is a foundational measure to realize significant cost reductions, efficiency gains, and environmentally sustainable, low-carbon aquaculture practices.

At present, research on key economic traits of Siluriformes, such as disease resistance, flavor and taste, and feed conversion rate, remains relatively inadequate. Yet, improving these traits is essential for the market competitiveness of new varieties. The systematic integration of traditional and modern biotechnologies to establish a comprehensive, precision breeding system will be the core driver for developing new varieties with superior comprehensive traits, including high yield, quality, stress tolerance, disease resistance, and feed efficiency. This will not only significantly enhance the market competitiveness and industrial benefits of new Siluriformes varieties, provide strong germplasm support for the sustainable development of aquaculture industry, but also substantially promote breakthroughs in basic theoretical innovation and frontier technological application in the discipline of fish genetics and breeding, ultimately leading the Siluriformes seed industry and aquaculture industry into a new stage of innovation-driven, green and efficient high-quality development.

CRediT authorship contribution statement

Sijin Fan: Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Yu Hu:** Conceptualization, Investigation. **Xinyue Deng:** Data curation, Investigation. **Yalan Zhang:** Visualization, Supervision, Formal analysis. **Wei Chen:** Conceptualization, Investigation. **Gaode Zhong:** Visualization, Investigation. **Xin Wang:** Conceptualization. **Zebin Huang:** Conceptualization. **Hanyu Liu:** Writing – review & editing, Resources. **Fangzhou Hu:** Writing – review & editing, Resources. **Chang Wu:** Writing – review & editing, Resources. **Wuhui Li:** Writing – review & editing, Resources. **Shi Wang:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Shaojun Liu:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Funding

This work was supported by Yuelushan Laboratory Breeding Program (Grant No. YLS-2025-ZY01011), the National Natural Science Foundation of China (Grant No. 32373119, 32293252), the Youth Science and Technology Talents Lifting Project of Hunan Province (Grant No. 2023 TJ-N02), the earmarked fund for China Agricultural Research System (Grant No. CARS-45), 111 Project (D20007).

Declaration of competing interest

Shaojun Liu is the editor-in-chief for Reproduction and Breeding and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

References

[1] X.L. Chu, Fauna of China. Osteichthyes. Siluriformes, Science Press, Beijing, 1999 (in Chinese).
[2] C.L. Zhang, Fauna of Chinese Siluroid Fishes, People's Education Press, Beijing, 1960 (in Chinese).
[3] X.L. Chu, The geographical distribution of siluriform fishes in China, zool, Res. 10 (3) (1989) 251–261 (in Chinese).
[4] M.D. Li, Checklist of fishes of China V: characiformes, Siluriformes, Esociformes, Osmeriformes, Salmoniformes, Stomiiformes, Tianjin Fish (1) (2003) 8 (in Chinese).
[5] J.J. Wei, Application of ecological aquaculture models in the cultivation of channel catfish (*Ictalurus punctatus*), Henan Fish (3) (2024) 40–41 (in Chinese).
[6] S. Wang, Q.L. Xu, Q.B. Qin, et al., Establishment of a system for improved varieties, cultivation, and marketing of fish, J. Fish. China 47 (11) (2023) 9–33 (in Chinese).
[7] Y.Q. Chang, Y. Tian, W.J. Zhang, Progress in genetic breeding technologies for marine aquaculture species in China, J. Agric. Sci. Technol. 15 (6) (2013) 8–15 (in Chinese).
[8] W.M. Wang, A.S. Yan, Z.G. Zhang, et al., A Study on the hybridization between female *Pelteobagrus fulvidraco* and Male *pelteobagrus vachelli*, Freshw. Fish. (3) (2002) 3–5 (in Chinese).

[9] W.H. Hu, C. Dan, W.J. Guo, et al., Comparison of morphology and gonadal development between *Pelteobagrus fulvidraco* and hybrid yellow catfish "Huangyou No. 1", Acta Hydrobiol. Sin. 43 (6) (2019) 1231–1238 (in Chinese).
[10] W.Z. Pan, H.B. Yin, W. Liu, et al., Study on distant hybrid breeding technology between female *Silurus soldatovi* and Male *Silurus asotus*, Chin. J. Fish. 15 (2) (2002) 74–79 (in Chinese).
[11] D.R. Yanp, R.O. Smitherman, Production of hybrid (blue × channel) catfish and channel catfish in ponds, Proc. Annu. Conf. Southeast. Assoc. Game Fish Comm. 29 (1975) 86–89.
[12] A. Gutiérrez-Barragán, A. Varela-Romero, F.J. García-De León, et al., A review of catfish (Siluriformes) hybridization, Rev. Fish Biol. Fish. 35 (1) (2025) 145–174.
[13] H. Liu, B. Guan, J. Xu, et al., Genetic manipulation of sex ratio for the large-scale breeding of YY super-male and XY All-male yellow catfish (*Pelteobagrus fulvidraco* (Richardson)), Mar. Biotechnol. 15 (3) (2013) 321–328.
[14] H.Q. Liu, S.Q. Cui, C.C. Hou, et al., Production of YY super-male yellow catfish through gynogenesis from XY females, Acta Hydrobiol. Sin. 31 (5) (2007) 718–725 (in Chinese).
[15] Y. Xiong, J.Q. Hu, Y.B. Jiang, et al., Artificial induction of sex reversal and gynogenesis in *Pelteobagrus vachelli*, J. Fish. China 49 (3) (2025) 48–60 (in Chinese).
[16] G.C. Waldbieser, B.G. Bosworth, S.M.A. Quiniou, Production of viable homozygous, doubled haploid channel catfish (*Ictalurus punctatus*), Mar. Biotechnol. 12 (4) (2010) 380–385.
[17] H. Xu, Study on Artificial Induction of Androgenesis in Yellow Catfish (*Pelteobagrus fulvidraco*), Northeast Agricultural University, Harbin, 2008 (in Chinese).
[18] S. Zheng, W. Tao, H. Yang, et al., Identification of sex chromosome and sex-determining gene of southern catfish (*Silurus meridionalis*) based on XX, XY, and YY genome sequencing, Proc. R. Soc. A B. 289 (1971) (2022) 20212645.
[19] W. Chen, M. Zou, Y. Li, et al., Sequencing an F_1 hybrid of Silurus asotus and S. meridionalis enabled the assembly of high-quality parental genomes, Sci. Rep. 11 (1) (2021) 13797.
[20] H.G. Chen, X.P. Zhu, W. Li, et al., Phylogeny of some siluriform fishes based on the mitochondrial COI gene, J. Fish. Sci. China 25 (4) (2018) 762–771 (in Chinese).
[21] H.G. Chen, X.P. Zhu, W. Li, et al., Phylogeny of partial Siluriformes species based on mitochondrial COI gene, J. Fish. Sci. China 25 (4) (2018) 762–771 (in Chinese).
[22] L. Sun, S. Liu, R. Wang, et al., Identification and analysis of genome-wide SNPs provide insight into signatures of selection and domestication in channel catfish (*Ictalurus punctatus*), PLoS One 9 (10) (2014) e109666.
[23] S.Q. Zheng, Development of Sex-Linked Molecular Markers and Identification of Sex Determination Candidate Genes in Southern Catfish (*Silurus meridionalis*) Based on Whole-Genome Sequencing, Southwest University, Chongqing, 2021 (in Chinese).
[24] S.Q. Xu, S.Y. Zhang, Y.Q. Duan, et al., Feminization of channel catfish (*Ictalurus punctatus*) induced by 17β-Estradiol, Acta Hydrobiol, Sin. 46 (11) (2022) 1668–1674 (in Chinese).
[25] Q.C. Wu, Study on Artificial Induction of Polyploidy in Yellow Catfish (*Pelteobagrus fulvidraco*), Huazhong Agricultural University, Wuhan, 2011 (in Chinese).
[26] D. Buwono, J. Junianto, I. Iskandar, et al., Growth and expression level of growth hormone in transgenic mutiara catfish second generation, J. Biotech. Res. 10 (2019) 102–109.
[27] N.Y. Abass, B. Su, A. Alsaqufi, et al., Growth differences of growth hormone transgenic female and Male channel catfish, *Ictalurus punctatus*, grown in earthen ponds to sexual maturation, Mar. Biotechnol. 23 (6) (2021) 870–880.
[28] Ge, Z. Dong, J. Li, et al., Isolation of yellow catfish β-actin promoter and generation of transgenic yellow catfish expressing enhanced yellow fluorescent protein, Transgenic Res. 21 (5) (2012) 995–1004.
[29] P. Lu, W.L. Du, W.F. Pu, Study on breeding technology of transgenic yellow catfish, Sci. Fish Farm. (11) (2011) 10 (in Chinese).
[30] Z. Dong, J. Ge, K. Li, et al., Heritable targeted inactivation of Myostatin gene in yellow catfish (*Pelteobagrus fulvidraco*) using engineered zinc finger nucleases, PLoS One 6 (12) (2011) e28897.
[31] Z. Qin, Y. Li, B. Su, et al., Editing of the luteinizing hormone gene to sterilize channel catfish, *Ictalurus punctatus*, using a modified zinc finger nuclease technology with electroporation, Mar. Biotechnol. 18 (2) (2016) 255–263.
[32] D.U. Hettiarachchi, V.N. Alston, L. Bern, et al., Maximizing colonization and proliferation of blue catfish (*Ictalurus furcatus*) donor stem cells for the creation of xenogenic catfish: identifying the best host age of triploid channel catfish (*I. punctatus*), Aquaculture 571 (2023) 739400.
[33] D. Liu, Y.H. Wei, Analysis of breeding and cultivation of three new aquatic varieties, Sci. Fish Farm. (11) (2023) 7–10 (in Chinese).
[34] P.P. Liu, X.H. Chen, L.Q. Zhong, et al., Comparison of growth performance among different families of yellow catfish (*Pelteobagrus fulvidraco*), J. Nanjing Norm. Univ. Nat. Sci. (1) (2013) 90–93. Ed. 36 (in Chinese).
[35] A. Rezk, R.O. Smitherman, J.C. Williams, et al., Response to three generations of selection for increased body weight in channel catfish, *Ictalurus punctatus*, grown in earthen ponds, Aquaculture 228 (1-4) (2003) 69–79.
[36] Q. Qin, W.J. Bian, Y.X. Cai, et al., Study on growth performance of channel catfish (*Ictalurus punctatus*) family breeding nucleus group and selection of superior parents, J. Shanghai Ocean Univ. 20 (1) (2011) 63–70 (in Chinese).
[37] S.W. Yin, H. Huang, C.G. Lei, et al., Research progress on genetic breeding of marine economic fishes, Fish. Sci. 26 (7) (2007) 416–419 (in Chinese).
[38] Y.D. Lou, Fish Breeding, China Agriculture Press, Beijing, 1999 (in Chinese).
[39] H. Yu, Channel Catfish "Jiangfeng No.1", Rural Hundred Things (14), 2016, p. 38 (in Chinese).
[40] J.J. Zhang, Preliminary Study on Heterosis of Hybrid Yellow Catfish "Huangyou No.1, Nanjing Normal University, Nanjing, 2021 (in Chinese).
[41] Y.P. He, J. Zeng, J. Feng, et al., Experimental hybridization culture of *Pelteobagrus vachelli* and *Leiocassis longirostris*, Aquaculture (5) (2008) 33–34 (in Chinese).
[42] F. Wang, W. Wang, Preliminary report on hybrid breeding of *Pseudobagrus vachelli, Pelteobagrus fulvidraco* and *Leiocassis crassilabris*, Fish. Sci. Technol. Inf. 31 (1) (2004) 10–11 (in Chinese).
[43] F. Wang, Analysis of morphological differences among *Pseudobagrus vachelli, Pelteobagrus fulvidraco, Leiocassis crassilabris*, and their hybrid F_1 generation, Chin. Agric. Sci. Bull. 29 (2) (2013) 36–43 (in Chinese).
[44] W.J. Shi, Study on the heterosis between *Pseudobagrus ussuriensis* and *Pelteobagrus fulvidraco*, Open J. Fish. Res. 3 (4) (2016) 63–70.
[45] C.F. Qiu, B. Wang, X.S. Yu, Breeding and cultivation experiment of a hybrid between female *Pelteobagrus fulvidraco* and male *Pseudobagrus ussuriensis*, Sci. Tech. Inf. (4) (2009) 314 (in Chinese).
[46] H. Wang, Y.X. Cai, X.H. Chen, et al., Comparison of growth performance between hybrid (*Pseudobagrus ussuriensis* × *Pelteobagrus vachelli*) and self-mating offspring, Fish. Sci. 32 (1) (2013) 50–54 (in Chinese).
[47] Q. Qin, D.N. Liang, M.H. Wang, et al., Study on embryonic development of hybrid catfish (*Pseudobagrus ussuriensis* ♀ × *Pelteobagrus vachelli* ♂), J. Nanjing Norm. Univ. Nat. Sci. (3) (2012) 81–86. Ed. 35 (in Chinese).
[48] H.Y. Wang, Preliminary Study on Crossbreeding of *Pelteobagrus fulvidraco* and *Leiocassis longirostris*, Nanjing Normal University, Nanjing, 2022 (in Chinese).
[49] M.B. Wang, Q. Chen, Y.B. Chen, et al., Study on hybridization technology between *Pelteobagrus fulvidraco* and Pelteobagrus vachelli, Mod. Agric. Sci. Technol. (24) (2012) 273, 278 (in Chinese).
[50] H.Y. Zhang, Study on Molecular Mechanism of Heterosis in Hybrid Yellow Catfish "Huangyou No.1, Nanjing Normal University, Nanjing, 2020 (in Chinese).
[51] G. Zhang, J. Li, J. Zhang, et al., Integrated analysis of transcriptomic, miRNA and proteomic changes of a novel hybrid yellow catfish uncovers key roles for miRNAs in heterosis, Mol. Cell. Proteomics 18 (7) (2019) 1437–1453.
[52] C.M. Wang, Study on Genetic Markers of Southern Catfish (*Silurus Meridionalis*), Catfish (*Silurus Asotus*), and their Hybrid F_1, Huazhong Agricultural University, Wuhan, 2005 (in Chinese).
[53] C.B. Xian, G.M. Wu, Preliminary study on comparison of economic traits between hybrid first generation (*Clarias fuscus* ♀ × *Clarias leather* ♂) and their parents, Freshw. Fish. (4) (1987) 26–29 (in Chinese).
[54] J.Q. Zhang, Hybridization experiment between local Clarias fuscus and Egyptian Clarias leather, Guangxi Agric. Sci. (6) (1986) 42–44 (in Chinese).
[55] J.Q. Zhang, Hybridization experiment between Clarias leather and local Clarias fuscus, Guangxi Agric. Sci. (3) (1989) 41–42 (in Chinese).
[56] Q.J. Kang, Comparative Study on Main Traits of Hybrid Catfish (*Silurus meridionalis* ♀ × *Silurus asotus* ♂) F_1 Generation and Silurus asotus, Henan Normal University, Xinxiang, 2012 (in Chinese).
[57] Q. Liu, K. Luo, X. Zhang, et al., A new type of triploid fish derived from the diploid hybrid crucian carp (♀)×autotetraploid fish (♂), Reprod. Breed. 1 (2) (2021) 122–127.
[58] K. Xu, W. Duan, J. Xiao, et al., Development and application of biological technologies in fish genetic breeding, Sci. China Life Sci. 58 (2) (2015) 187–201.
[59] S. Liu, Distant hybridization leads to different ploidy fishes, Sci. China Life Sci. 53 (4) (2010) 416–425.
[60] S. Wang, C. Tang, M. Tao, et al., Establishment and application of distant hybridization technology in fish, Sci. China Life Sci. 62 (1) (2019) 22–45.
[61] H. Komen, G.H. Thorgaard, Androgenesis, gynogenesis and the production of clones in fishes: a review, Aquaculture 269 (1-4) (2007) 150–173.
[62] J. Xiao, T.M. Zou, L. Chen, et al., Microsatellite analysis of different ploidy offspring of artificial gynogenesis in Cyprinus carpio, J. Fish. Biol. 78 (1) (2011) 150–165.
[63] F.R. Wu, X.Y. Zhang, D.S. Wang, Optimal parameters for artificial induction of gynogenesis in Southern catfish (*Silurus meridionalis*), Chin. J. Zool. 41 (1) (2006) 27–31 (in Chinese).
[64] G. Cheng, X.J. Li, Z.G. Qiao, et al., Cold shock induction of diploid gynogenesis in Yellow River catfish (*Silurus asotus*), J. Anhui Agric. Sci. 36 (23) (2008) 10006–10007, 10045 (in Chinese).
[65] L.L. Li, W. Xiao, L.M. Xing, et al., Study on embryonic development and morphological characteristics of Gynogenetic Lanzhou Catfish (*Silurus asotus*), Chin, J. Cell Biol. 42 (5) (2020) 820–828 (in Chinese).
[66] L. Li, Z. Lian, W. Xiao, et al., Induction of meiotic gynogenesis in Lanzhou catfish (*Silurus lanzhouensis*) with heterologous sperm and evidence for female homogamety, Aquac. Res. 53 (9) (2022) 3318–3330.
[67] Z.J. Pan, C.K. Zhu, H. Wang, et al., Induction of meiotic gynogenesis in bagrid catfish (*Pseudobagrus ussuriensis*) with homologous sperm and its confirmation for female homogamety, Aquac. Res. 48 (11) (2017) 5659–5665.
[68] D. Fopp-Bayat, P. Woznicki, Spontaneous gynogenesis in Wels catfish Silurus glanis L, Caryologia 62 (1) (2009) 75–79.
[69] J. Gui, L. Zhou, Genetic basis and breeding application of clonal diversity and dual reproduction modes in polyploid Carassius auratus gibelio, Sci. China Life Sci. 53 (4) (2010) 409–415.
[70] Z.S. Zhao, Q.J. Wu, G.Q. Gao, Research progress on androgenesis in fish, Hereditas Beijing 22 (2) (2000) 109–113.
[71] J. Christopher, A. Murugesan, N. Sukumaran, Optimization of UV treatment to induce haploid androgenesis in the stinging catfish, Heteropneustes fossilis, Int. Aquat. Res. 4 (1) (2012) 4.

[72] B.J. Bongers, D. Nguenga, E.H. Eding, et al., Androgenesis in the African catfish, Clarias gariepinus, Aquat. Living Resour. 8 (4) (1995) 329–332.
[73] S. Dobosz Babiak, K. Goryczko, et al., Androgenesis in rainbow trout using cryopreserved spermatozoa: the effect of processing and biological factors, Theriogenology 57 (4) (2002) 1229–1249.
[74] Arai, M. Ikeno, R. Suzuki, Production of androgenetic diploid loach Misgurnus anguillicaudatus using spermatozoa of natural tetraploids, Aquaculture 137 (1) (1995) 131–138.
[75] Y. Lu, Y.Y. Kuang, X.H. Zheng, et al., Research progress on marker-assisted breeding in aquatic animals, J. Fish. China 43 (1) (2019) 36–53 (in Chinese).
[76] Gong, X. Wang, J. Yang, et al., Protection and utilization status of Parabramis and Megalobrama germplasm resources, Reprod. Breed. 3 (1) (2023) 26–34.
[77] X. Sun, D. Liu, X. Zhang, et al., SLAF-seq: an Efficient Method of Large-Scale De Novo SNP Discovery and Genotyping Using High-Throughput Sequencing, PLoS One 8 (3) (2013) e58700.
[78] B. Agellon, T.T. Chen, Rainbow trout growth hormone: molecular cloning of cDNA and expression in Escherichia coli, DNA (N. Y.) 5 (6) (1986) 463–471.
[79] Chu, Y. Jia, Z. Wu, et al., Genome-wide characterization of three *IGFs* in hybrid yellow catfish (*Pseudobagrus fulvidraco*♀×*Pseudobagrus vachelliii*♂) and the association of *IGF2* allelic variants with growth traits, Aquac. Rep. 26 (2022) 101315.
[80] B.C. Peterson, B.C. Small, G.C. Waldbieser, et al., Endocrine responses of Fast- and slow-growing families of channel catfish, N. Am. J. Aquac. 70 (3) (2008) 240–250.
[81] Y. Wu, J. Fu, J. Chu, et al., Identification of key genes affecting development and nutrient metabolism in the early seedling stage of Dongting catfish (*Silurus asotus*), Reprod. Breed. 4 (4) (2024) 212–220.
[82] Y.Y. Zhu, H.W. Liang, Z. Li, et al., Polymorphism of *MSTN* gene and its association with growth traits in yellow catfish (*Pelteobagrus fulvidraco*), Hereditas Beijing 34 (1) (2012) 72–78.
[83] M. Kocabas, H. Kucuktas, R.A. Dunham, et al., Molecular characterization and differential expression of the myostatin gene in channel catfish (*Ictalurus punctatus*), Biochim. Biophys. Acta 1575 (1-3) (2002) 99–107.
[84] F. M. Putri Alimuddin, D. Wahjuningrum, et al., Resistance Against Aeromonas Hydrophila infection and growth of Second Generation (F2) African Catfish [*Clarias Gariepinus*] using selected molecular markers, BIOTROPIA 25 (2) (2018) 95–102.
[85] S. Poompuang, U. Na-Nakorn, A preliminary genetic map of walking catfish (*Clarias macrocephalus*), Aquaculture 232 (1-4) (2004) 195–203.
[86] Guo, Development of SNP markers and validation 24 SNPs in darkbarbel catfish (*Pelteobagrus vachelli*), Conserv. Genet. Resour. 12 (2020) 413–416.
[87] Xie, Y. Ming, F. Shao, et al., Restriction site-associated DNA sequencing for SNP discovery and high-density genetic map construction in southern catfish (*Silurus meridionalis*), R. Soc. Open Sci. 5 (5) (2018) 172054.
[88] S. Zhang, X. Zhang, X. Chen, et al., Construction of a high-density linkage map and QTL fine mapping for Growth- and sex-related traits in channel catfish (*Ictalurus punctatus*), Front. Genet. 10 (2019) 251.
[89] G. Zhang, J. Li, J. Zhang, et al., A high-density SNP-based genetic map and several economic traits-related loci in Pelteobagrus vachelli, BMC Genom. 21 (1) (2020) 700.
[90] X.J. Zhang, L. Zhou, J.F. Gui, Biotechnological innovations in genetic breeding and green development of aquaculture, Sci. Sin. Vitae 49 (11) (2019) 1409–1429 (in Chinese).
[91] X. Geng, A genome-wide association study in catfish reveals the presence of functional hubs of related genes within QTLs for columnaris disease resistance, BMC Genom. 16 (2015) 196.
[92] H. Shi, T. Zhou, X. Wang, et al., Genome-wide association analysis of intra-specific QTL associated with the resistance for enteric septicemia of catfish, Mol. Genet. Genom. 293 (6) (2018) 1365–1378.
[93] X. Zhong, X. Wang, T. Zhou, et al., Genome-wide association study reveals multiple novel QTL associated with low oxygen tolerance in hybrid catfish, Mar. Biotechnol. 19 (4) (2017) 379–390.
[94] Li, T. Zhou, X. Geng, et al., Identification of novel genes significantly affecting growth in catfish through GWAS analysis, Mol. Genet. Genom. 293 (3) (2018) 587–599.
[95] W. Wang, S. Tan, J. Luo, et al., GWAS analysis indicated importance of NF-κB signaling pathway in host resistance against motile aeromonas septicemia disease in catfish, Mar. Biotechnol. 21 (3) (2019) 335–347.
[96] Huang, W. Guo, Y. Wang, et al., Genome-wide association study reveals the genetic basis of growth trait in yellow catfish with sexual size dimorphism, Genomics 114 (3) (2022) 110380.
[97] Y. Mou, Y. Li, J. Zhou, et al., Genome-wide association study reveals growth-related markers and candidate genes for selection in Chinese longsnout catfish (*Leiocassis longirostris*), Aquaculture 560 (2022) 738513.
[98] M. Liu, Y. Song, S. Zhang, et al., A chromosome-level genome of electric catfish (*Malapterurus electricus*) provided new insights into order Siluriformes evolution, Mar, Life Sci. Today 6 (1) (2023) 1–14.
[99] J. Ding, L.S. Han, Y.Q. Chang, New technologies for germplasm creation in aquatic animals and their applications in genetic breeding of sea cucumber and sea urchin, Prog. Fish. Sci. 42 (3) (2021) 1–16 (in Chinese).
[100] J. E. Mank Bachtrog, C.L. Peichel, et al., Sex determination: why So many ways of doing it? PLoS Biol. 12 (7) (2014) e1001899.
[101] Wang, Isolation of Y- and X-linked SCAR markers in yellow catfish and application in the production of all-male populations, Anim. Genet. 40 (6) (2009) 978–981.
[102] B.A. Simco, C.A. Goudie, G.T. Klar, et al., Influence of sex on growth of channel catfish, Trans. Am. Fish. Soc. 118 (4) (1989) 427–434.
[103] R. Johnstone, A.F. Youngson, The progeny of sex-inverted female Atlantic salmon (*Salmo salar L.*), Aquaculture 37 (2) (1984) 179–182.
[104] M. Yoneda, Y. Kurita, D. Kitagawa, et al., Age validation and growth variability of Japanese flounder Paralichthys olivaceus off the Pacific Coast of northern Japan, Fish. Sci. 73 (3) (2007) 585–592.
[105] A. Fostier, Saillant, B. Menu, et al., Sexual growth dimorphism in sea bass, Aquaculture 202 (3-4) (2001) 371–387.
[106] V.J. Bye, R.F. Lincoln, Commercial methods for the control of sexual maturation in Rainbow Trout (*Salmo gairdneri R.*), Aquaculture 57 (1-4) (1986) 299–309.
[107] S. Liu, Z. Yao, Y. Wang, Sex hormone induction of sex reversal in the teleost Clarias lazera and evidence for female homogamety and Male heterogamety, J. Exp. Zool. 276 (6) (1996) 432–438.
[108] C. Dan, J. Mei, D. Wang, et al., Genetic differentiation and efficient sex-specific marker development of a pair of Y- and X-linked markers in yellow catfish, Int. J. Biol. Sci. 9 (10) (2013) 1043–1049.
[109] Y. Xiong, S. Wang, J.F. Gui, et al., Artificially induced sex-reversal leads to transition from genetic to temperature-dependent sex determination in fish species, Sci. China Life Sci. 63 (1) (2020) 157–159.
[110] X. Chen, J. Mei, J. Wu, et al., A comprehensive transcriptome provides candidate genes for sex Determination/differentiation and SSR/SNP markers in yellow catfish, Mar. Biotechnol. 17 (2) (2015) 190–198.
[111] C. Zhu, H. Liu, L. Cheng, et al., Identification of sex-specific sequences through 2b-RAD sequencing in *Pseudobagrus ussuriensis*, Aquaculture 539 (2021) 736639.
[112] S. Dai, Y. Zhou, X. Guo, et al., Sex-specific markers developed by genome-wide 2b-RAD sequencing confirm an XX/XY sex determination system in Chinese longsnout catfish (*Leiocassis longirostris*), Aquaculture 549 (2022) 737730.
[113] Pan, M. Wang, L. Zhong, et al., Identification of male-specific SNP markers and development of rapid PCR-based genetic sex identification method in channel catfish (*Ictalurus punctatus*), Aquaculture 547 (2022) 737535.
[114] G. Gong Liao, J. Wang, et al., Identification of sex-linked codominant markers and development of a rapid LAMP-based genetic sex identification method in channel catfish (*Ictalurus punctatus*), Aquaculture 572 (2023) 739556.
[115] S. Zheng, Screening and characterization of sex-linked DNA markers and marker-assisted selection in the Southern catfish (*Silurus meridionalis*), Aquaculture 517 (2020) 734783.
[116] T. Wang, Production of YY males through self-fertilization of an occasional hermaphrodite in Lanzhou catfish (*Silurus lanzhouensis*), Aquaculture 539 (2021) 736622.
[117] C. Song, S.J. Liu, J. Xiao, et al., Research advances in polyploid organisms, Sci. China Life Sci. 42 (3) (2012) 173–184 (in Chinese).
[118] L. Zhou, J. Gui, Natural and artificial polyploids in aquaculture, Aquac. Fish. 2 (3) (2017) 103–111.
[119] C. Zhang, S.J. Liu, Y.D. Sun, et al., Studies on chromosomes of germ cells in diploid and polyploid fishes derived from distant hybridization, J. Mol. Cell Biol. 41 (1) (2008) 53–60 (in Chinese).
[120] J.Z. Li, S.J. Liu, X.J. Zhang, et al., Studies on sperm polymorphism in F2 hybrids of *Carassius auratus* (♀) × *Cyprinus carpio* (♂), Acta Biol. Exp. Sin. 37 (4) (2004) 276–282 (in Chinese).
[121] S.J. Liu, F. Hu, G.J. Zhou, et al., Observation on the gonad structure of triploid Xiangyun crucian carp during breeding season, Acta Hydrobiol. Sin. 24 (4) (2000) 301–306 (in Chinese).
[122] S.J. Liu, Y.D. Sun, S.F. Li, et al., Analysis of gonadosomatic index of triploid Xiangyun crucian carp, J. Fish. China 26 (2) (2002) 111–114 (in Chinese).
[123] J.F. Gui, Applications of genetic breeding biotechnologies in Chinese aquaculture, in: Aquaculture in China: Success Stories and Modern Trends, Wiley, 2018, pp. 1–23.
[124] L.M. Song, W.M. Wang, X.Y. Zhou, et al., A comparative study on the induction of triploidy in yellow catfish (*Pelteobagrus fulvidraco*) by cold and heat shock, J. Fish. China 34 (5) (2010) 768–776 (in Chinese).
[125] L.M. Song, Studies on Triploid Induction by Temperature Shock and Ploidy Identification in Yellow Catfish (*Pelteobagrus fulvidraco*), Huazhong Agricultural University, Wuhan, 2010 (in Chinese).
[126] Y.R. Li, S.J. Dong, L.M. Chen, et al., Comparative study on artificial induction methods for triploid yellow catfish (*Pelteobagrus fulvidraco*), J. Tianjin Norm. Univ. Nat. Sci. (2) (2012) 84–87. Ed. 32 (in Chinese).
[127] C.A. Bidwell, C.L. Chrisman, G.S. Libey, Polyploidy induced by heat shock in channel catfish, Aquaculture 51 (1) (1985) 25–32.
[128] C.L. Chrisman, W.R. Wolters, G.S. Libey, Triploidy in channel catfish, J. World Maric. Soc. 14 (1-4) (1983) 279–293.
[129] Hassan, Embryonic development of diploid and triploid eggs of Clarias gariepinus (Burchell, 1822), Caryologia 71 (4) (2018) 372–379.
[130] M. Bertolini, L.S. Lopez, N.F. Do Nascimento, et al., Strategies for aquaculture and conservation of Neotropical catfishes based on the production of triploid Pimelodus maculatus, Aquac. Int. 28 (1) (2020) 127–137.
[131] D.S. Kim, H.J. Cho, I.S. Park, et al., Cytogenetic traits and gonad development of induced triploidy in far eastern catfish, *Silurus asotus*, Kor. J. Genet. 23 (1) (2001) 55–62.
[132] B.K. Tiwary, Induction of Triploidy by Cold Shock in Indian catfish, *Heteropneustes fossilis* (Bloch), Asian Fish Sci. 10 (2) (1997) 137–142.
[133] T.J. Benfey, The physiology and behavior of triploid fishes, Rev. Fish. Sci. 7 (1) (1999) 39–67.
[134] M. Luo, Zhang, Y. Tai, et al., mtDNA copy number contributes to growth diversity in allopolyploid fish, Reprod. Breed. 4 (2) (2024) 55–60.

[135] J. Zou, A.J. Ma, X.A. Wang, et al., Research progress on fish breeding technologies, Fish, Inf. Strat. 28 (3) (2013) 199–207 (in Chinese).
[136] Z. Zhu, L. He, S. Chen, Novel gene transfer into the fertilized eggs of gold fish (*Carassius auratus L.* 1758), J. Appl. Ichthyol. 1 (1) (1985) 31–34.
[137] Z.Y. Zhu, K.S. Xu, Y.F. Xie, et al., The establishment of a transgenic fish model, Sci. China Ser. B Chem. Life Sci. Earth Sci. 32 (2) (1989) 147–155 (in Chinese).
[138] J.C. Ge, W. Song, Z.J. Dong, et al., Establishment of the "all-fish" growth hormone gene transgenic yellow catfish (*Pelteobagrus fulvidraco*) founders, J. Nanjing Univ. Nat. Sci. 49 (1) (2013) 123–131 (in Chinese).
[139] B. Su, M. Shang, C. Li, et al., Effects of transgenic sterilization constructs and their repressor compounds on hatch, developmental rate and early survival of electroporated channel catfish embryos and fry, Transgenic Res. 24 (2) (2015) 333–352.
[140] Y.L. Zhang, Study on Some biology-related Characteristics of Growth Hormone Gene (GH) Transgenic Channel Catfish (*Ictalurus punctatus*), Shanghai Ocean University, Shanghai, 2022 (in Chinese).
[141] Dwi Buwono, M.U. Kurnia Agung, U. Subhan, PERAKITAN IKAN LELE (Clarias sp.) TRANSGENIK DENGAN TEKNIK ELEKTROPORASI SPERMA, J. Biol. Udayana 20 (1) (2016) 1–10.
[142] R.S.P.S. Dewi, H. Marnis, R. Suprapto, et al., PRODUKSI ikan lele cepat tumbuh GENERASI F-0 MENGGUNAKAN metode transgenesis, J. Ris. Akuakultur 8 (2) (2016) 173–182.
[143] F.D. Urnov, E.J. Rebar, M.C. Holmes, et al., Genome editing with engineered zinc finger nucleases, Nat. Rev. Genet. 11 (9) (2010) 636–646.
[144] K. Joung, J.D. Sander, TALENs: a widely applicable technology for targeted genome editing, Nat. Rev. Mol. Cell Biol. 14 (1) (2013) 49–55.
[145] M. Jinek, K. Chylinski, I. Fonfara, et al., A programmable Dual-RNA–Guided DNA endonuclease in adaptive bacterial immunity, Science 337 (6096) (2012) 816–821.
[146] H. Wang, H. Yang, C.S. Shivalila, et al., One-step generation of mice carrying mutations in multiple genes by CRISPR/Cas-Mediated genome engineering, Cell 153 (4) (2013) 910–918.
[147] X. Zhang, F. Wang, Z. Dong, et al., A new strain of yellow catfish carrying genome edited myostatin alleles exhibits double muscling phenotype with hyperplasia, Aquaculture 523 (2020) 735187.
[148] Z. Dong, J. Ge, Z. Xu, et al., Generation of Myostatin b Knockout yellow catfish (*Tachysurus Fulvidraco*) using transcription activator-like effector nucleases, Zebrafish 11 (3) (2014) 265–274.
[149] X. Zhang, F. Wang, M. Ou, et al., Effects of Myostatin b knockout on offspring body length and Skeleton in yellow catfish (*Pelteobagrus fulvidraco*), Biology 12 (10) (2023) 1331.
[150] M. Coogan, V. Alston, B. Su, et al., CRISPR/Cas-9 induced knockout of myostatin gene improves growth and disease resistance in channel catfish (*Ictalurus punctatus*), Aquaculture 557 (2022) 738290.
[151] M. Naito Tajima, Y. Yasuda, et al., Production of germ line chimera by transfer of primordial germ cells in the domestic chicken (Gallus domesticus), Theriogenology 40 (3) (1993) 509–519.
[152] M. Venkatesan, C.B. Fitzgerald, J.M.D. Coey, Unexpected magnetism in a dielectric oxide, Nature 430 (7000) (2004) 630.
[153] D.A. Perera, A. Alsaqufi, M. Shang, et al., Xenogenesis-Production of channel catfish × blue catfish hybrid progeny by fertilization of channel catfish eggs with sperm from triploid channel catfish males with transplanted blue catfish germ cells, N. Am, J. Aquac. 79 (1) (2017) 61–74.
[154] F. Hu, H. Zhong, C. Wu, et al., Development of fisheries in China, Reprod. Breed. 1 (1) (2021) 64–79.