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7.1 Introduction

With global population expansion, the demand for high quality protein, especially from aquatic sources, is rising dramatically. Increased aquaculture production is clearly needed to meet this demand. In the third millennium, because capture fishes are at capacity or showing precipitous declines due to over-fishing, habitat destruction, and increasing population, increase in capture fishes is not anticipated under the global conditions [1].

Development of better fish breeds that can contribute to increased fish production, while ensuring protection of biodiversity and the environment, is seen as one of the key solutions to meet future food demands of the growing world population [2, 3]. The advent of induced spawning techniques, such as hypophysation (the use of pituitary gland extract to induce ovulation), synthetic hormones, *in vitro* fertilization technologies, and increased knowledge of reproductive biology, has enabled aquaculturists to induce breeding and domesticate many fish species for aquaculture. As domestication of fish species increases, the possibility of increasing fish production through appropriate genetic improvement methods also increases. Hybridization is considered as one of the simple, inexpensive, and potential tools of such enhancement programs in fishes; it is a useful method for combining the desirable traits of selected species.

The mating of two different species is a process called hybridization, with the offspring known as hybrids. Hybrids can have some characteristics of both parental species. A hybrid with selected or favored characteristics of each parent is one of the goals of animal husbandry. When a hybrid has characteristics superior to both parents, it is said to have hybrid vigor or positive heterosis, which, of course, is the ultimate breeding goal.

Hybridization occurs widely in fishes under natural conditions [4–6], and is observed in fish more commonly than in other vertebrate animal groups [7, 8]. Several factors have been suggested as contributing to the high incidence of natural hybridization among closely related fish species, including external fertilization, weak behavioral isolating mechanisms, unequal abundance of the two parental species, competition for limited spawning habitat, and decreasing habitat complexity [4, 7]. Hybrid zones are defined

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as areas of narrow regions where genetically distinct populations or species meet, mate, and produce hybrids [9].

Intraspecific hybridization (cross-breeding) is a classical approach for the genetic improvement of livestock animals [10–21]. This method has also shown its potential in aquaculture. Increases by 55% and 22% in the growth rate of channel catfish and rainbow trout hybrids, respectively, were achieved using this technique [22, 23]. However, there was no increase in growth rates in Chum Salmon crossbreeds when compared with parental strains [24]. Cross-breeds of different strains of European catfish, *Silurus glanis*, exhibited higher adaptability under warm water conditions and mixed diet feeding regimes [25].

Gjerde and Refstie [26] investigated the heterosis effect between crosses of five Norwegian strains of Atlantic salmon. They did not find a significant heterosis effect for either growth rate or survival rate. Similarly Friars *et al.* [27] found no heterosis effect for growth rate of Atlantic salmon fry.

Interspecific hybrids have, thus, attracted attention because they can improve productivity through hybrid vigor, transfer desirable traits, or produce sterile animals [28–33]. Hybridization may also be used to combine other valuable traits, such as better growth and flesh quality, disease resistance, and increased environmental tolerances. In recent years, hybrids of major carps have been successfully produced in public and private hatcheries, and are available for farming, due to high resistance against unfavorable ecological conditions [34, 35].

Many molecular biologists and fish geneticists have realized that the use of inter-specific hybrids in global fisheries production is not well-reported nor examined properly. On the other hand, there have still been some controversies in global acceptance for using interspecific hybrid organisms that have been genetically modified (GMOs) [36–38]. Intraspecific hybrids are GMOs. They are sometimes created through natural means, but represent a combination of the genes of two different "species." This study focuses on the crossing among different genetically distinct species and rearing of hybrids, to understand the potentiality of hybrids in the world's aquaculture production.

7.2 Inter-specific Hybrids and Their Applications in Aquaculture

Inter-specific hybridization has long been practiced in various species of fishes to increase growth rate, improve flesh quality, produce sterile animals, increase disease resistance and environmental tolerance, and to improve other quality traits to make fish more profitable (Table 7.1) [25].

The majority of the earlier works on hybridization was conducted for salmonid fishes, but these species did not usually produce hybrids of commercial importance [25]. For this reason, hybrids in these fishes do not draw the attention of fish culturists [39]. Due to the increased expansion of fish farming throughout the world, hybrids produced from inter-specific crosses play a substantial role for global aquaculture production. The increased use of artificial breeding and *in vitro* fertilization techniques, and increased knowledge of reproductive biology, encourage aquaculturists to produce hybrids in order to improve the quality traits over their pure parental siblings. Some of the important traits and performances that have been improved through hybridization among different species of fishes are evaluated below.

7.2.1 Improved Growth Performances

Increased growth rate is the most desirable trait for stock improvement in aquaculture. Growth increase may result from dominant variance [40], or from increasing the number of polymorphic loci in an individual. Increased heterozygosity has been implicated in improved growth in a variety of species, as

Table 7.1 Summarization of hybrid fishes in global aquaculture production and stock enhancements [25].

Hybrids	Characteristics, effects, and advantages	References
Cyprinid fishes		
Rohu × catla (*Labeo rohita* × *Catla catla*)	Hybrid is hardy and combines first growth of catla with desirable small head shape of rohu.	[34]
Catla × fringe-lipped peninsular carp (*C. catla* × *L. fimbriatus*)	Hybrid has desirable head and body shape, improved dressing percentage, and growth performances similar to those exhibited by catla	[34]
Silver carp × bighead carp (*Hypophthalmichthys molitrix* × *Aristichthys nobilis*)	Hybrids are fertile and exhibits positive heterosis in growth. Pure lines may have disappeared because of the fertility of hybrids. Food and feeding strategy is intermediate to parental species.	[46]
Grass carp × bighead carp (*Ctenopharyngodon idella* × *A. nobilis*)	Hybrids are generally sterile and functional triploids with higher growth rates.	[57]
Common carp × catla (*Cyprinus carpio* × *C. catla*) and common carp × mrigal (C. carpio × *Cirrhinus mrigala*)	Hybrids are usually functional triploids and sterile, having higher growth and survival in monoculture practices and with good seinability	[49]
Tilapia fishes		
Nile tilapia × blue tilapia (*Oreochromis niloticus* × *O. aureus*)	Hybrids of some strains yield all-male offspring with superior growth. Some hybrids are fertile with increased cold and salinity tolerance. Reciprocal cross gives 50% males and females.	[61], [65], [66]
Nile tilapia × long-finned tilapia (*O. niloticus* × *O. macrochir*)	Hybrid yields predominately male offspring, but strain of Nile tilapia is important for good fry production.	[61]
Nile tilapia × Wami tilapia (*O. niloticus* × *O. hornorum*)	Hybrid yields predominately male offspring with some strains producing red-skinned fish with salt tolerance.	[61]
Mozambique tilapia × Nile tilapia (*O. mossambicus* × *O. niloticus*)	Recognized as Taiwan red with higher salinity tolerance; progeny of these hybrids display a variety of different skin colors.	[76]
Mozambique tilapia × Wami tilapia (*O. mossambicus* × *O. hornorum*)	Hybrid yields predominately male offspring and are fertile. Certain strains produce Florida red tilapia with salinity tolerance and good growth.	[46], [59], [60], [61]
Salmon and Trout		
Atlantic salmon × brown trout (*Salmo salar* × *S. trutta*)	Triploid hybrid exhibits the higher growth and survival to a comparable level to Atlantic salmon, but offspring becomes sterile.	[81]
Brown trout × brook trout (*Salmo trutta* × *Salvelinus fontinalis*)	Hybrid known as tiger trout is sterile, with low early survival, but grows well in later stages.	[63]
Rainbow trout × char trout (Oncorhynchus *mykiss* × *Salvelinus* sp.)	Hybrid shows increased disease resistance to salmonid viruses.	[73]
Lake trout × brook trout (*Salvelinus namaycush* × *S. fontinalis*)	Hybrid commonly recognized as splake, and is fertile, fast growing, and tolerant of acid water.	[77]
Chum salmon × Chinook salmon (*O. keta* × *O. tshawytscha*)	Triploid hybrids have early seawater tolerances.	[82]
Hybridization among the Pacific salmons (*Oncorhynchus* spp.)	Majority of the diploid hybrids are not useful for aquaculture, but have potential for disease resistance, sterility, and early seawater tolerance when the diploid hybrids are made triploid. These are also useful for production of all-female using denatured sperm and rediploidized eggs.	[63], [73], [80], [82]

well as other desirable characteristics such as developmental compatibility [41], food conversion efficiency, and oxygen metabolism [42, 43].

A hybrid between white bass (*Morone chrysops*) and the striped bass (*M. saxatilis*), called sunshine bass, exhibits faster growth and has many more good culture characteristics than either of the parents under captive culture systems [44]. Crosses of the black crappie × white crappie (*Pomoxis nigromaculatus* × *P. annularis*), stocked in small ponds and impoundments [45]; silver carp × bighead carp (*Hypophthalmichthys molitrix* × *Aristichthys nobilis*) [46] in polyculture systems; and catfish hybrids between the African catfish (*Clarias gariepinus*) and the Vundu (*Heterosneustes longifilis* or *H. bisorsalis*) in intensive concrete tanks [47, 48], were reported to grow faster (positive heterosis) than conspecific parents.

Improved growth performances were also obtained from crosses of mrigal (*Cirrhinus mrigala*) and catla (*Catla catla*), and common carp (*Cyprinus carpio*) with rohu (*Labeo rohita*) in pond culture systems in India [49]. Intergeneric hybrids between catla (*Catla catla*) and fimbriatus (*Labeo fimbriatus*) were observed to combine desirable qualities, such as the small head of the fimbriatus and the deep body of the catla, and exhibited heterosis in terms of meat yield with higher flesh content than either of the parents [50].

Hybrids between tambaqui (*Clossoma macropomum*) and pacu (*Piaractus brachypoma*) in Brazil and Venezuela raceways and ponds grew faster than either parent [51]. Crosses of the green sunfish (*Lepomis cyanellus*) with bluegill (*L. macrochirus*) [52, 53], and crosses of the gilthead sea bream (*Sparus auratus*) with red sea bream (*Pagrus major*), also had positive heterosis in growth and other culture characteristics [54]. Several hybrids have been produced in the Mediterranean, with the cross between red sea bream and common dentex (*Dentex dentex*) being especially fast growing in cage culture management [55].

7.2.2 Production of Sterile Animals

Hybridization often results in offspring that are either sterile or have reduced reproductive capacity. Production of sterile animals may be advantageous to diminish unwanted reproduction, or to improve growth rate and avoid energy loss due to prolific breeding. Examination of species karyotype is a good general indication of whether or not hybridization will result in offspring that are sterile [25, 39]. Karyotypes describe the chromosome count from the nucleus in a eukaryotic cell of an organism, and what these chromosomes look like under a light microscope, where attention is usually paid to their length, the position of the centromeres, banding pattern, differences between the sex chromosomes, and any other physical characteristics [56].

Natural hybrids produced from the cross between grass carp (*Ctenopharyngodon idella*) and bighead carp (*Aristicthys nobilis*) are functionally triploids, generally sterile, but with a small proportion being diploid and fertile [57]. Hybrids between Indian major carps are generally fertile because of similar chromosome numbers ($2n = 50$). Indian major carps crossed with Common Carp ($4n = 102$) results in hybrids that are sterile because they are functionally triploid [34, 49]. However, crosses of some sturgeon species with different chromosome numbers, as well as most tilapia crosses, produce fertile offspring [58–61].

The cross between the black crappie (*Pomoxis nigromaculatus*) and white crappie (*P. annularis*) exhibits positive heterosis, and is often recommended for stocking in small impoundments, because of reduced fertility of the F_2 generation that would prevent overpopulation [45]. The sunshine bass is generally sterile but, apparently, an undetermined percentage of these hybrids are capable of reproduction, as evidenced by hybrid mating and backcrossing [62]. The red sea bream × gilthead sea bream cross also produces sterile hybrids, and this may be an important quality in marine aquaculture due to improved growth rate and good overall performance in cage culture [54]. The tiger trout, a hybrid between brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*) is sterile, with poor early survival, but good growth rate, and therefore is useful for stocking areas where reproduction is very limited [63].

7.2.3 Manipulation of Sex Ratio

Production of monosex populations in fish is often preferable for aquaculture development. This preference may be due to growth differences between sexes (e.g., male tilapia grow faster than females, whereas female salmonids and sparids grow better than males). A specific sex chromosome (XX chromosomes for female and XY for male individuals) may produce a valuable product and monosex populations, and help reduce unwanted reproduction [39].

Hybridization between some species of tilapias, such as the Nile tilapia (*Oreochromis niloticus*) and the blue tilapia (*O. aureus*), results in the production of predominantly male offspring, and reduces unwanted reproduction in grow-out pond culture management [64]. This cross produces predominantly males, because of different sex-determining mechanisms in the two species, and the hybrid males have superior growth over pure parental species. Nile tilapia has the XX, XY system, with the male being heterogametic, whereas blue tilapia has the ZZ, ZW, with the heterogametic genotype being female [61, 65, 66].

Similarly, crosses between Nile tilapia (*O. niloticus*) and Wami tilapia (*O. honorum*), Nile tilapia and long-finned tilapia (*O. macrochir*), and Mozambique tilapia (*O. mossambicus*) and Wami tilapia produce hybrid offspring that are predominantly male, with excellent growth and production [61]. Hybridization between striped bass (*Morone saxatilis*) and yellow bass (*M. mississipiensis*) produces 100% females, with excellent survival and growth in culture systems [67].

7.2.4 Overall Improvement

The principal aim of hybridization is to combine desirable traits from different species to increase the overall production or marketability of a cultured species. The major hybrid catfish cultured in Thailand is a cross between African (*Clarias gariepinus*) and Thai (*C. macrocephalus*) catfish, which combines the fast growth rate of the African catfish with the desirable flesh characters of the Thai catfish [48]. The overall product is improved, and the flesh is still acceptable to Thai consumers, although it does not grow as fast as the pure African catfish.

The rohu × catla hybrid grows almost as fast as pure catla, but has the small head of the rohu and is, therefore, useful in Indian aquaculture [34]. Catla × fringed-lipped peninsula carp (*Labeo fimbriatus*) were reported to have small heads of the fringed-lipped peninsula carp, and deep body and nearly equal growth rate to the catla; the dressing percentage also improved in this hybrid [50]. The sunshine bass hybrid (white bass × striped bass) has a suite of advantageous traits, including good osmoregulation, high thermal tolerance, resistance to stress and disease, high survival in culture and modified water-bodies, and ability to utilize soy beans as a protein source [44, 55]. The overall growth performances of hybrids (*C. catla* × *L. rohita*) fed on wheat bran was consistently higher, followed by rice broken, and blood meal [35].

Among the cultivatable hybrids, red tilapia is more desirable than darker skinned tilapia in Cuba, Venezuela, Thailand, Europe, and the United States. Most red tilapia are descended from the Nile × blue tilapia cross [66], but red tilapia also result from the cross of Wami tilapia (*O. urolepis hormorum*) × Mozambique tilapia [60]. It has been reported that red tilapia from Nile tilapia × Mozambique tilapia, and Nile tilapia x Wami tilapia, are being farmed in central Thailand to Lao PDR for aquaculture purposes (Welcomme, personal communication). The latter cross is also salt-tolerant and used for coastal aquaculture in parts of Southeast Asia [68]. Stability of the skin coloration is often a problem in successive generations, and studies have been undertaken to understand the genetic mechanisms of color inheritance [69, 70].

Hybrids between different species of North American catfish have been researched for more than 30 years. Among the interspecific catfish hybrids, crosses between channel catfish (*Ictalurus punctatus*) and blue catfish (*I. furcatus*) exhibit good culture characters of the channel catfish, with the ease of harvesting characteristics of the blue catfish, such as better angling and increased seinability [71]. Once breeding problems are worked out, these hybrids may be useful in culture, as they show heterosis for growth rate and are superior to channel catfish in low oxygen tolerance, disease resistance uniformity in body shape, angling vulnerability, seinability, and dress-out percentage [71].

The hybrid produced from the crosses between the muskellunge (*Esox masquinongy*) and the pike (*E. luscious*) is sterile and well-adapted to intensive culture systems. However, the hybrid has similar sport fish characteristics to the pure parental muskellunge, but higher protein requirements than both parental species [72].

7.2.5 Disease Resistance and Environmental Tolerances

Hybridization may be used to improve disease resistance by breeding a higher resistant species with a less resistant one. Dorson *et al.* [73] reported that crosses of coho salmon (*Oncorhynchus kisutch*) with other species, such as rainbow trout, had increased disease resistance to a variety of salmonid viruses, but other culture characteristics were poor. Viability was increased when hybridization was followed with triploidization, and Dorson *et al.* [73] stated that the rainbow trout (*O. mykiss*) × char (*Salvelinus* spp.) triploid hybrids had increased resistance to several pathogenic salmonid viruses and early sea water tolerance.

Hybrids may have increased environmental tolerances when one parental species has a wide range of tolerance (e.g., euryhaline species), a specific tolerance (cold tolerance species), or because of increased heterozygosity sometimes being associated with a broad niche [74, 75]. Mozambique tilapia and Wami tilapia can reproduce in saline waters, but the Nile tilapia has improved culture performance in many aquaculture systems. Hybridization between Mozambique and Nile tilapias yields a red tilapia with salinity tolerance [76]. Hybrids between Mozambique and Wami tilapia, called the Florida Red strains, have high growth rates and can reproduce in salinities of 19 ppt [59]. Crosses between Nile tilapia and blue tilapia also resulted in progeny with good salinity tolerances [61, 65]. Hybrids also may be used to exploit degraded aquatic environments.

Lakes affected by acid rain may not be suitable for native salmonids, but splake, a hybrid between lake trout (*Salvelinus namaycush*) and brook trout (*S. fontinalis*) can tolerate the reduced pH levels of 4.9–5.4 of the acid lakes of Ontario. Lake trout reproduce successfully only in waters with pH values above 5.5 [77]. The splake has also been shown to have higher survival and growth than both brook and lake trout in lakes with pH in the range of 5.5–7.2 [78].

7.2.6 Hybrid Polyploidization

Hybridization combined with chromosome manipulation may increase the viability and developmental stability of hybrid fishes during early life history stages [79]. Polyploid hybrid salmon appear to be better suited for a variety of culture situations than either polyploid or hybrid salmon are on their own. Although many diploid salmonid hybrids are not used for culture, triploidization of the hybrids may confer increased viability, growth, and survival [80].

Triploidization of Atlantic salmon (*Salmo salar*) × brown trout (*S. trutta*) hybrids increased survival and growth rate to a level comparable to Atlantic salmon [81].

General disease resistance was improved by triploidizing the cross between rainbow trout and char; rainbow trout and coho salmon triploid hybrids had increased resistance to infectious disease, but the latter hybrids grew more slowly [73]. Triploid Pacific salmon hybrids between chum salmon (*Oncorynchus keta*) and Chinook salmon (*O. tshawytscha*) have earlier seawater acclimatization times [82].

7.2.7 Experimental Hybridization

Laboratory hybridization experiments have been utilized extensively to confirm the probable hybrid nature of certain individuals, by demonstrating that two taxa will interbreed when provided with the opportunity to do so, or that gametes from two taxa can be artificially cross-fertilized. Hybrids produced from appropriate cross-fertilization techniques among commercially important fish species have been tested for their growth performance, viability, and fertility. A hybrid recently produced experimentally between sheim (*Acanthopagus latus*) and sobiaty (*Sparidentex hasta*) in Kuwait appears to have good growth, flesh quality, and is fertile (Khaled Al-Abdul-Elah Kuwait Institute of Scientific Research, personal communication).

Hybrids resulting from crossing several sunfish species have been used for the past three decades to improve farm pond fishing. The most desirable hybrids result from crossing the female green sunfish *(Lepomis cyanellus)* with males from one of three other species. These include the bluegill *(L. macrochirus)*, the redear, or shellcracker *(L. microlophus)*, and the warmouth, or goggleye *(L. gulosus)*. The most commonly used hybrid in the southeast United States is the male bluegill (BG) × female green sunfish (GS) cross. This BG × GS hybrid has the most desirable set of characteristics, which means that the hybrids can outperform their parental species in one or more ways.

Rapid and superior growth is one way hybrid sunfish exhibit hybrid vigor. Experimental hybrids between dusky grouper (*E. marginatus*) and the white grouper (*E. aeneus*) were evaluated, but all the hybrids died within 10 days post-hatching [83]. The camouflage grouper (*Epinephelus polyphekadion*) is more resistant to environmental stress and disease than the marbled grouper (*E. fuscoguttatus*). Experimental hybrids (marbled grouper × camouflage grouper) exhibited faster growth performances and increased conversion efficiency [84]. A hybrid between the beluga (*Huso huso*) and Russian sturgeons (*Acipenser guldenstati*) was evaluated, and appeared to have a wide salinity tolerance to both fresh and seawater, as well as good growth rate [85]. These hybrids are now being considered for culture in Russia and Iran (Shilat, Iranian Fisheries Company, personal communication).

Two loach (*Misgumus* spp.) are cultured both for food and for ceremonial purposes by Buddhists in Korea [86] – the mud loach (*M. mizolepis*) and the cyprinid loach (*M. anguillicaudutus*). The mud loach grows to a larger size, has a faster growth rate, and is more resistant to diseases, while the cyprinid loach has a more desirable body color. These two species of loach were hybridized to combine the fast growth and large size of the mud loach with the desirable body color of the cyprinid loach. Fertilization, hatching, survival, and karyology of the hybrids were very similar to the parents [87]. These hybrids are now being cultured commercially, and continued studies are planned to combine other desirable characteristics of the hybrids and their fertility.

Hybrids produced using the eggs of Asian catfish (*Clarias batrachus*) and African catfish (*C. gariepinus*) perform as well as either parental control during the alevin stage, and better in the fry and advanced fry stages, while the reciprocal hybrids are inferior in all performance traits. During the different experiments, this hybrid group showed the highest survival from post-larval stage to market size fish [88, 89]. Growth performance was always better than maternal control and, in some cases, better than or close to paternal control. Preliminary observations of organoleptic testing revealed that the hybrid showed superior taste performance, compared with parental groups [88]. Further research is needed to examine other desirable traits of the hybrids and their sterility.

Hybridization between giant catfish (*Pangasiodon gigas*) and giant pangus (*Pangasius sanitwonsei*) are now being practiced in Thailand (Pongthana, National Aquaculture Genetics Research Institute, Thailand, personal communication). Both of these catfishes are extraordinarily large, reaching 3 m and 300 kg, with the giant catfish considered as an endangered species whose trade is restricted under the Convention on International Trade in Endangered Species of Wild Flora and Fauna. Hybrids between these two catfish species show good growth performance, and should be used to reduce pressure on the giant catfish, so as not to endanger it through excessive catch of brood fish from the wild, or through genetic introgression of the two parental species [25, 90].

Due to the wide geographical distribution of yellow bass (*Morone mississippiensis*), hybridization tests with striped bass, and comparisons with the sunshine bass have been conducted. The yellow bass hybrid exhibited 65% survival to harvest, compared with 45% for the sunshine bass, but poorer growth rate and condition factor when raised in tanks continuously supplied with pond water [67]. Further research has been undertaken to explore the possibility of combining other desirable traits in the above hybrid progeny.

7.2.8 Unplanned/Accidental Hybridization

Unplanned and accidental hybridization in hatchery stocks may cause a genetic deterioration in aquaculture production and open water fisheries. During the production of Indian major carp seeds, different species often are induced to spawn in a common spawning tank, thus providing the opportunity for unintentional hybridization [91]. Silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*) are sometimes hybridized inadvertently, because of their similar appearance, and because of the shortage of "the correct" species at spawning time, due to differences in maturation times between males and females. This hybridization often results in a fish that does not feed efficiently, as its gill rakers are intermediate in shape between those of the silver carp (which eats phytoplankton) and those of the bighead carp (which consumes zooplankton).

There is much anecdotal evidence of genetic deterioration of carp hatchery stocks in Bangladesh, through inbreeding, negative selection, and hybridization [92]. Stocks of exotic (i.e., non-indigenous) carps are particularly vulnerable to such degradation, given that the opportunities to go back to wild populations for brood stock replenishment are very limited. Furthermore, anecdotal evidence suggests that hybridization between silver carp and bighead carp is common, at least partly due to a shortage of mature bighead carp males toward the end of the breeding season. Reported aquaculture production of the silver carp in Bangladesh in 2001 was 130,000 tons, or 21.7% of freshwater aquaculture production [93], while there was no reported production figure for bighead carp. Bighead carp brood stock are present in many hatcheries so, presumably, aquaculture production of bighead carp is present, but not high enough to be reported separately.

Hybridization between silver carp has also been reported to occur fairly frequently in commercial aquaculture hatcheries in Bangladesh. The consequences of hybridization for brood stock purity have recently been investigated. Allelic variation at three microsatellite DNA loci isolated from silver carp routinely distinguished between silver carp and bighead carp. These markers were used in the analysis of samples collected from hatcheries in different regions of Bangladesh. Of 422 hatchery broodstock that were morphologically identified as silver carp, 8.3% had bighead allele(s) at one or more of the three microsatellite loci, while 23.3% of the 236 fish morphologically identified as bighead carp had silver carp allele(s) at one or more loci. The results suggested that, while some of these fish might be F_1 hybrids, others had more complex genotypes, suggesting further generations of hybridization, or introgression between the species in hatcheries, with potentially damaging consequences for the integrity of these stocks and their performance in aquaculture [94].

Interspecific hybridization in some carp species has recently been reported in Bangladesh [93]. Either out of scientific interest, or shortage of adequate hatchery populations (i.e., brood stock), introgressed hybrids are being produced intentionally or unintentionally by private hatchery operators, and sold to hatchery and nursery owners. These hybrids are being ultimately stocked, knowingly or unknowingly, either in grow-out ponds, or in open water bodies like floodplains under the government's massive carp seed stocking program. There is widespread concern that mass stocking of such hybrids in the floodplains and other related open water might cause a serious genetic introgression problem, which could adversely affect aquaculture and inland open water fish production. There is every possibility of segregation of genes, with the result that some of the fish carrying the introgressed genes could not be easily distinguished from the pure species [92].

Hybrid introgression in major carp species is very likely to have negative consequences, as a result of loss of distinct feeding strategies of the pure species, which are the basis of successful polyculture systems [95]. If the introgressed hybrids reproduce in natural water bodies, or are used as broodstock in hatcheries, they will not be true breeders; therefore, collection of carp seed from the pure species/strains will be difficult.

Hybridization with wild fish is especially prevalent in tilapia ponds connected to natural water bodies that contain indigenous or feral tilapia populations. Such uncontrolled and unintentional hybridization could undermine the performance of cultured stocks, and make future use of the contaminated stocks as broodstock questionable. For example, wild three-spotted tilapia (*Oreochromis andersoni*) invaded Nile tilapia ponds in Mozambique, and produced hybrid tilapia that was less marketable than pure Nile tilapia. Inadvertent hybridization at a Chinook salmon hatchery was suggested as the probable explanation for the appearance of Chinook × Coho salmon hybrids in a California stream [96]. The level of unintentional or accidental hybridization has important considerations of aquatic biodiversity, and will influence risk assessment on the use of hybrid fishes in aquaculture.

7.3 Discussion

A number of hybridization studies in fishes have been reported [25, 55] but certainly not all of the hybrids are contributing to commercial aquaculture production. However, the contributions that hybrid fishes make to global aquaculture production are underestimated. Approximately 80% of Thai catfish production is from hybrids, and there is a growing concern that these hybrids may be impacting native catfish [90]. The tilapia hybrids in Israel are the main tilapia produced, but the 6,691 mt reported were not identified as hybrid [54]. Production of 4,257 mt of hybrid striped bass was reported from the United States, but production of no other fishes was reported, in spite of the fact that red tilapia and other tilapia hybrids are being produced and sold in Florida [25].

Accurate identification of hybrids is important, not only for sustainable aquaculture development, but also to allow for a better understanding of biodiversity and conservation issues. It would be unfortunate to experience widespread loss of pure species in aquaculture, as happened with tilapia, as a result of widespread loss of pure species and subsequent hybridization [97]. It would be a significant cause for concern if hybrid Thai catfish or hybrid Venezuelan characids poses more of a threat to local species than the pure species. The following points need to be addressed to overcome the above situations, as well as to understand the role of hybrids in global aquaculture production [25, 39].

1) Good broodstock management needs to be promoted to avoid inbreeding and interbreeding problems.
2) Species and traits relevant to low-input systems need to be prioritized for genetic enhancement, through proper hybridization programs that better address food security issues.
3) Genetic stock improvement through inter-generic or inter-specific hybridization of cultured fish species should be initiated under well-designed breeding plans at research institutes and lead central hatcheries, under the guidance of fish breeding specialists/biologists.
4) Data on parental origins and stock identity should be recorded for each hybrid. When crosses are made, the female species should be listed first; random crosses in regards to sex of each parent should also be identified.
5) As much information as possible should be made available concerning the hybrid. Necessary information includes the stock and sex of each parental species, a comparative evaluation of the reciprocal crosses including a basic description of culture facility of environment, and an assessment of the fertility of the hybrids [25].
6) Consideration should be given to establishing a recognizable name for established hybrids and those that appear to have good potential for aquaculture and fisheries [25]. The bester and sunshine bass are examples of two accepted names of interspecific hybrids that signify specific hybrids. A number of researchers working on the hybridization of sparids in the Mediterranean have adopted an informal nomenclature, where the cross between the genera *Dentex* and *Pagrus* was regarded as "dentagrus," while the reciprocal cross was named as "pantex" [55].
7) In order to maintain genetic integrity, proper care needs to be undertaken so that the hybrids should not be intermingled and do backcross with their parental siblings [33, 98–100].
8) Many private hatchery operators hybridize fish without knowledge of breeding biology and genetics that may cause deterioration of hatchery populations. Therefore, governments should immediately ban the unplanned/intentional hybridization practices being carried out by the hatchery operators and fish seed multiplication farms.
9) Linkages should be established among the general public, organizations, scientists, industry, and governments, to address hybridization issues and to support the development of practical regulation and sound policy.
10) Dissemination of genetically improved aquatic organisms for aquaculture should only be carried out within the framework of adequate regulations and policy.

The management and conservation issues associated with hybridization and introgression in aquatic species are experiencing a renewed interest, based in part on scholarly treatments of the subject [101], and in part because of controversies and difficulties associated with legal mandates such as the Endangered Species Act. In the half century since Hubbs's [4] seminal synthesis on his work with interspecific hybrids, our view of hybridization has drifted away from doctrines that considered it a rare "mistake," toward a more evolutionary perspective that considers it a more common and, occasionally, constructive process. We hope this information serves as a springboard toward more scientific endeavors to understand hybridization as an evolutionarily important phenomenon, and an important living resource management issue, rather than an idle curiosity in nature.

7.4 Conclusion

It should be concluded that hybridization is not only a preferred method of genetic improvement, but also a potential tool for stock improvement through transmitting desirable traits to the inferior parents. Appropriate evaluation of hybridization depends solely on the genetic structure, crossing patterns, gamete compatibility, and gene flow patterns of the parental species. Practical knowledge on the genetic constitution of brood fishes, including the maintenance of true parental species and avoidance of inbreeding, inadvertent hybridization, or backcrossing, is very crucial before initiating hybridization experiments. It cannot be ignored that some non-generic factors, such as weather conditions, culture systems, seasons, and stresses associated with selecting, collecting, handling, breeding, and rearing of broodstock and progeny, may influence hybridization success to a greater extent. Further studies are also required for large-scale production of fish hybrids that can be utilized for species conservation and commercial aquaculture.

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