Pros and cons of alien fish introductions: a case scenario from Pakistan

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Abstract- The intentional introductions of alien fishes as food and sport fishes or unintentional escapes from aquaria, bait buckets and water gardens etc. in freshwater ecosystems are continuously influencing the biodiversity of native fauna worldwide. This study aims to raise concern for the introduction of alien fishes in Pakistan as the authorities responsible for these introductions are only focusing on their economic benefits rather than their impacts on the biodiversity of freshwater ecosystems of the country. For this purpose around 220 articles having information regarding global alien fish introductions and their respective ecological and socioeconomic losses were considered. This review provides a bird's eye view of the impacts of the introduction of alien fishes in freshwater ecosystems of different continents and their strategies to cope with this problem. In addition it has provided the range expansion of introduced fishes in the freshwater ecosystems of Pakistan. Lack of a proper strategy along with poor management and control of such introductions can lead to long-lasting ecological damages by alien fishes in Pakistan.

Index Terms- alien fishes, Pakistan, freshwater, ecological, socioeconomics

I. INTRODUCTION

Alien fishes are those non-native species that exist outside their usual ranges and have the potential to establish in these regions. The trend of using alien species in the fisheries industry along with the trading of ornamental fishes is increasing due to economic and social benefits [1]. Alien species can flourish and produce self-sustaining individuals. They can grow to a number that can affect the normal fish fauna and the whole ecosystem. They are then known as invasive species as they have invaded the area they were first introduced. These non-native species can have a great impact on biodiversity by competing for space and resources, predating and hybridizing with the native fish fauna and transmitting diseases [2].

They possess a threat, reduce genetic variation and disrupt the gene pools if left unconcerned leading to the extirpation of the endemic species by altering their natural habitats [3]. The introduction of alien fishes into native waters has been occurring for centuries [4]. They were introduced into African lakes to increase fish production and create a hatchery of fishes where those fishes did not exist previously. These alien species had negative as well as positive impacts after their introduction [5]. In Asia, these introductions are reported from the times of immigration of the Chinese which led to the dispersal of cyprinids, especially common carp and crucian carp [4].

Translocation of fishes started in Europe in the early 1st century A.D. when Romans used to retain several fish species in their fish farms. *C. carpio* was the first fish that was transferred from its native area to Rome and then to further countries in Europe. Later on, for religious purposes, fish were kept in ponds and were introduced to nearby streams. Then this tradition was carried on by the general people and fish farming became famous during the Renaissance period. Although the idea of transferring fishes developed in the Renaissance period but the introduction of non-native fishes at a large scale started in the 19th Century. Although these introductions were made with good purposes, their side effects were observed once the fishes invaded those areas where they were introduced [6].

The Pacific coast of North and South America are the two incursion sites of freshwater fishes. More than one-fourth of the total fish per basin is constituted by the exotic fishes in these waters [7]. Although the threat posed by the exotic fishes in the Neotropics is being increased, the facilitating factors of species intrusive capacity are not properly known. This region constitutes almost 30 per cent of global fish diversity. Exotic fishes are continuously being introduced in this region despite the drastic effects of these fishes are observed at local levels [8]. The fisheries industry plays a major role in the export income of Pakistan and is mandatory for the national economy. 10% of the total fish catches are exported on annual basis. When Pakistan was founded in 1947, its fisheries industry centred on scale fisheries without any port or fish processing plants [9].

The first fish port was built in Karachi in 1958 [10]. Even in the 1970s, there were a few private fish farms that had low production per unit area. To increase productivity, alien fish fauna was introduced into the country [11], rather than enhancing the production quality of native fishes. Fish farming mainly revolves around carp species including native and exotic Chinese carps. Local carps include *Catla catla*, *Labeo rohita*, and *Cirrhinus mrigala*. On the other hand, Chinese carps: *Hypophthalmichthys molitrix*, *Ctenopharyngodon idella*, *H. nobilis* and *Cyprinus carpio* are introduced species in the aquaculture system in Pakistan [12].

Grass carp (*C. idella*) was imported to Pakistan from China in 1964 to biologically control aquatic weeds in natural waterways, rivers and lakes [13]. Common carp (*C. carpio*) was introduced from Thailand and United Kingdom in 1964 in captive and inland waters [11]. Bighead carps (*H. molitrix* and *H. nobilis*) were introduced to increase the number of species [14]. Other exotic species introduced to Pakistan for aquaculture purposes were Tilapia spp. *Oreochromis mossambicus* (Mozambique tilapia) was imported from Malaya in 1951, while *O. aureus*, and *O. niloticus* were brought from Egypt in 1985 [15].

This review aims to provide possible environmental impacts of alien fish species in freshwater ecosystems of Pakistan by summarizing the global impacts of alien fishes in various freshwater bodies. Additionally, we have provided the conceivable management tactics for the conservation of the native ichthyodiversity.

II. MATERIALS AND METHODS

Concerning the investigation of the impacts of alien fishes, an ample review of literature on the introductions and impacts of freshwater alien fishes in all the continents except Antarctica was carried out. To achieve our aim, we cast an eye over published articles with open and limited access available on Elsevier, Springer, Wiley, etc. This effort led to the in-depth analysis of almost 600 published articles related to fish introductions in different regions. Out of these 600 articles, only 220 were selected that provided the data regarding years, areas, reasons and the impacts of alien species in the introduced regions. We have included the diadromous species (migratory between fresh water and salt water) in our study, as they are also contributing to the alteration of ecosystem functioning although they keep on migrating from freshwater ecosystem to marine water ecosystem.

III. RESULTS

Global socioeconomic impacts explained the estimated economic losses that each continent has faced due to invasion of alien fishes. These economic losses were greater than the benefits that were obtained from the introduced fishes in aquaculture. Global ecological impacts (continent wise) of alien fishes belonging to various families along with their year, region and reason of introduction are summarized in tables 1, 2a, 2b, 3a, 3b, 4a, 4b, 4c, 5a, 5b, 5c, 5d, 6 and 7. The literature regarding range expansions of alien fishes in freshwater ecosystems of Pakistan gave an insight into the areas that the introduced fish species have occupied since their introduction.

It can help the authorities to monitor and control the propagation of alien species in freshwater bodies of Pakistan. The management strategies adopted by different countries to deal with the alien fish invasions explained how tactfully those countries have coped up with the ecological disasters brought by the alien species. Recommendations for the management and control of alien fish introductions, on the basis of measures adopted by other countries urged to apply similar or related strategies to manage and control alien fish invasions in Pakistan.

Table 1: Introductions of alien fish in different regions of Africa; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Centrarchidae	*Micropterus salmoides*	1928 (S. Africa)	N/A	Predation on native fauna in Zimbabwe + alter invertebrate community in Wit River	[16]
Cichlidae	*Oreochromis andersonii*	Early 1970s (Shashe Dam)	Aquaculture purposes	Affect the genetic integrity of indigenous congeneric	[17]
	Oreochromis aureus	1910 (S. Africa)	Aquaculture purposes	Competes and hybridizes with native *O. mossambicus* in Limpopo River Basin	[18], [19]
	Oreochromis niloticus	1950s (Lake Victoria & Kyoga) B/w 1998-2010 (Tanzania)	Aquaculture purposes	Displaced green head tilapia and *O. mortimeri* + excluded *O. esculentus* + extinction of *Oreochromis urolepis* from Lake Hombolo in Tanzania	[20], [21], [17]
	Tilapia zillii	1950s (Lake Victoria & Kyoga)	N/A	Competition with *O. variabilis*	[21]
Cyprinidae	*Carassius auratus*	1726 (S. Africa)	Ornamental fish	Introduced parasites	[18]
	Ctenopharyngodon idella	1967 and 1975 (Vaal River)	Biological weed control	Changed plant abundance, altered water transparency + disturbed sediments	[22]
	Cyprinus carpio	1859 1999 (Lake Naivasha)	Ornamental fish/ escaped juveniles during flood	Declined submerged vegetation &caused re-suspension of sediments	[18], [23]
	Hypophthalmichthys molitrix	1975 (S. Africa)	Aquaculture practices	Changed zooplankton, phytoplankton and fish community structure and decreased the abundance of indigenous fish	[18], [24]
Latidae	*Lates niloticus*	Unofficially 1954 (Lake victoria+ Kyoga) Officially 1962 and 1963	Consume haplochromine cichlids + improve fisheries	Destructed native cichlid fauna of Lake Victoria and increased turbidity + declined native fauna	[25], [21], [5], [26]
Poeciliidae	*Poecilia reticulata*	1912 (S. Africa)	Mosquito control	Host to nematode *Camallanus cotti*	[27]
Salmonidae	*Oncorhynchus mykiss*	1897 (S. Africa)	Angling species	Fragmentation, competition and predation	[28], [29]
	Salmo salar	1896 (S. Africa)	Angling species	Host to *Kudoa thyrsites* and/or *K. paniformis*	[30], [31]
	Salmo trutta	1890 (S. Africa)	Angling species	Fragmentation, competition and predation + endangered the native Border barb	[28], [29]

Table 2a: Introductions of alien fish in different regions of Asia; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	Reference
Anguillidae	*Anguilla rostrata*	Taiwan	Eel trade	Introduction of anguillicolosis epizootic parasite	[32]
Centrarchidae	*Lepomis macrochirus*	1970s (South Korea)	Promote species diversity	Reduced biodiversity, simplified food web structure	[33]
	Micropterus salmoides	1925(Japan) 1929 (Kenya) 1970s (South Korea)	Sport fishing/ Promote species diversity in fish communities	Suppressed *Pseudorasbora parva*, *Rhinogobius spp*, *Palaemon paucidens* and *Procambarus clarkia*	[33], [34]
Channidae	*Channa argus*	1923 (Japan)	Establish a recreational fishery	Predation on native species	[35]
Cichlidae	*Oreochromis mossambicus*	1930s (Asia) 1950s (Philippines)	Control aquatic weeds and insects/ Aquaculture purposes	Competes for food and space with native milkfish in Philippines	[36], [37], [38]
		1952 (India) 1991 (Jaisamand Lake)	Experimental culture	Dominated and virtually eliminated all other indigenous fishes and endemic 'car and catfishes	[39], [40]
		(Sri Lanka)	Source of protein	Reduced the population of *Labeo porcellus* and *Labeo dussumieri*	[41]
		1957 (S. China)	Increase fish supply	Harmed native fish populations and reduced biodiversity	[42], [43]
	Oreochromis niloticus	1975 (Sri Lanka)	Aquaculture purposes	Hybridization with the native fish	[44]
		(Philippines)	Food culture	Threaten the indigenous species such as *Gobiopterus lacustris* in Laguna de Bay, *Sardinella tawilis* in Taal lake, *Mistichthys luzonensis* in Lakes Buhi and Bato	[44]
	Tilapia zilli	1978 (China)	Aquaculture purposes	Harmed native fish populations	[43]
Clariidae	*Clarias batrachus*	(Philippines)	Aquaculture purposes	Displaced the endemic catfish (*C. macrocephalus*) in Laguna de Bay and other water bodies in Luzon	[45], [37]
Cyprinidae	*Ctenopharyngodon idella*	1878 (Japan)	Enhance fisheries	Reported to be a host of nematode *Camallanus cotti*	[46]
	Cyprinus carpio	1930s (Iran)	Enhance fish production	Turbidity in water	[47]
	Hypophthalmichthys molitrix	1966 (Israel)	To consume the phytoplankton not consumed by native fish	Competition for food with the native fish + reduced populations of microcrustaceans	[48]
	Hypophthalmichthys nobilis	(India)	Illegally introduced	Hybridization + competes with *Catla catla*	[49]
	Leuciscus idus	(Caspian Sea)	Not available	Host of a trematode parasite *Opisthorchis felineus*	[50]

Table 2b: Introductions of alien fish in different regions of Asia; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	Reference
Loricariidae	*Pterygoplichthys disjunctivus*	1991 (India)	Aquarium fish trade	Made burrows that cause water leakage, damaged fishing nets + decline of local fish species	[51], [52]
	Pterygoplichthys multiradiatus	1970s (Taiwan) (Bangladesh)	Aquarium trade/ escapes from aquaculture farms	May reduce native fish (minnow) in Bangladesh by accidentally feeding on their eggs	[53], [54]
	Pterygoplichthys pardalis	(Thailand)	N/A	Consume eggs of the native fish, reduce their population and also compete for resources	[55]
Osmeridae	*Hypomesus nipponensis*	1940s (China) 1991 (Lake Ulungur)	Consume phytoplankton not consumed by native fauna	Extinction of *Perca fluviatilis* in Lake Ulungur	[56]
Poeciliidae	*Gambusia affinis*	1913(Taiwan), 1924 (Shanghai), 1940s (Hong Kong)	Mosquito control	Threatened Some southern endemic fishes like *Tanichthys albonubes* and *Oryzias latipes* + amphibians *Philautus romeri*	[57]
	Gambusia holbrooki	1920s (Iran)	Anti-malarial agent	Prey on eggs of others fishes, attack fish larger than themselves and compete directly with cyprinids	[47]
Salmonidae	*Oncorhynchus mykiss*	1960s (Turkey)	Aquaculture purposes	Monopolized resources, hybridization with native salmonids and predate on native fauna	[58]
Synbranchidae	*Monopterus albus*	Around 2000 (Philippines)	Aquaculture purposes	Burrowing habits destruct dikes and terraces	[59]

Table 3a: Introductions of alien fish in different regions of Australia; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Cichlidae	*Oreochromis mossambicus*	1970s (North-East Queensland)	Aquarium species + Ornamental fish	Competition + predation + habitat alteration + transmission of diseases	[60], [38]
	Tilapia mariae	N/A	Ornamental fish	Changes in composition of species abundance assemblages in a catchment in Queensland	[61], [62]
Cobitidae	*Misgurnus anguillicaudatus*	Early 1960s	Ornamental fish	Introduction of monogean parasite *Gyrodactylus macracanthus* + Increases turbidity in water	[63], [64], [65], [62]
Cyprinidae	*Carassius auratus*	19th century	Ornamental species	Competes with native fish + transmit diseases + increases water turbidity, depletes aquatic vegetation + stimulates cyanobacteria blooms	[66], [62]
	Cyprinus carpio	1860	Ornamental species + aquaculture purposes	Destruction of aquatic vegetation, increased turbidity and altered composition of invertebrate communities	[67], [68]
	Rutilus rutilus	1861	Acclimatization societies of the time/ Recreational angling	Supposed to compete with native fish for food and habitat	[62], [69]
Gobiidae	*Acanthogobius flavimanus*	Not available	Ballast water	Considered as pest	[70], [62]
Percidae	*Perca fluviatilis*	Mid 1800s	Recreational angling	Carries epizootic haematopoietic necrosis virus	[71], [62]

Table 3b: Introductions of alien fish in different regions of Australia; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Poeciliidae	*Gambusia affinis*	Not available	Control mosquitoes	Declined or disappearance of *Litoria aurea*	[57], [72]
	Gambusia holbrooki	1925	Control mosquitoes	Threaten the native fauna + effects the growth of native *Pseudomugil signifer* + declined *Litoria aurea*	[73], [74], [75]
	Phalloceros caudimaculatus	1963	Aquarium trade	Can exclude *G. holbrooki* by aggressive interactions, competition for resources, or predation with native fish	[76], [77]
	Poecilia reticulata	1910	Ornamental fish	Changed the composition of species abundance assemblages in a Far North Queensland catchment	[61], [62], [78]
Salmonidae	*Oncorhynchus mykiss*	1902	Recreational fisheries	Significant predatory influence on *C. coxii*	[79], [80]
	Salmo trutta	1870s (Western Australia)	Recreational purposes	Competition with and predation on native fish + intimidated the already threatened fish *Galaxias pedderensis* through predation and competition	[28], [62], [81], [82]

Table 4a: Introductions of alien fish in different regions of Europe; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Acipenseridae	*Acipenser baeri*	1956 (France, Hungry, USSR) 1962–1966 (Baltic Sea) 1965-1967 (Lake Ladoga) 1995 (Spain)	To consume benthos not consumed by other fish/ Aquaculture purposes	Hybridization with the native sturgeons and posing a threat to their survival in Danube River	[83], [84], [6], [85]
Anguillidae	*Anguilla japonica*	(France, Italy) 1980s (Germany)	N/A	Introduction of parasite i.e. *Anguillicola crassus*	[6], [32]
Centrarchidae	*Ambloplites rupestris*	1930 (France)	N/A	Two well established populations	[86], [6]
	Lepomis auritus	1895 (Germany, Italy)	N/A	Host of parasite *Onchocleidus ozer*	[87], [6]
	Lepomis gibbosus	1885 (Austria, Belgium, Czech Republic, Bulgaria, France, Germany, Greece, Hungary, Italy, Netherlands, Poland, Portugal, Romania, Spain, Switzerland, USSR)	Ornamental fish + sport fish	Competes for resources with *Perca fluviatilis* in England + Host of parasite *Onchocleidus ozer*, *Cleidodiscus robustus* and *Gyrodactylus macrochiri*	[88], [87], [6], [89]
Cobitidae	*Misgurnus anguillicaudatus*	Unknown	Ornamental fish/ food fish	Can have negative influences on the populations of Cobitis, Barbatula loaches & the freshwater blenny	[90], [63]

Table 4b: Introductions of alien fish in different regions of Europe; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Cyprinidae	*Carassius auratus*	1611 (Portugal) 1975- 1976 (Czech Republic) 17th century (Spain)	Immigration/ ornamental fish	Competitive, as well as destructive, effects on the native ichthyofauna in Czech Republic, feeding and uprooting of aquatic plants, predation on amphibians, molluscs, annelids, crustaceans and insects, hybridization+ transfer of diseases	[84], [91], [2]
	Ctenopharyngodon idella	1949 (Albania, Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, France, Germany, Greece, Hungary, Italy, Netherlands, Poland, Romania, Sweden, UK, USSR, Yugoslavia)	Enhance fish production + Bioamelioration	Decreased density and biomass of fishes (pike, common carp) whose reproduction invariably needs aquatic plants + introduction of the tapeworm (*Bothriocephalus gowkongensis*) in Czech Republic	[6], [92], [93]
	Leuciscus leuciscus	1889 (Ireland)	Fish escape	Introduction of parasites	[94]
	Phoxinus phoxinus	1960s and 1970s (Translocation in Norway)	Live bait or angling purpose	Reduced populations of brown trout and two crustaceans (*G. lacustris* and *L. arcticus*) in Ovre Heimdalsvatn	[95], [93]
	Pseudorasbora parva	1960 (Albania, Austria, Bulgaria, Hungary, Czech Republic, Germany, Romania, USSR, Yugoslavia) 1976 (Czech Republic)	Unintended introduction via fish translocations + imported with stocks of various fish in Czech Republic	Introduction of protozoan parasite (*Sphaerothecum destruens*)	[6], [96], [92], [97]
	Rutilus rutilus	1889 (Ireland) 1910-1913 (Spain)	Improvement of wild stocks	Local extinction of Arctic charr, reduced *A. brama* in Irish waters	[84], [98]
	Scardinius erythrophthalmus	(Lake Banyoles) (Netherlands)	N/A	Decline of macrophytes + extinction of *Gasterosteus aculeatus* (Lake Banyoles) + shift in species composition (Netherlands)	[99], [100]
	Tinca tinca	1500s	Translocation for aquaculture purposes	Introgression with native tench	[101], [102]

Table 4c: Introductions of alien fish in different regions of Europe; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Esocidae	*Esox lucius*	(England, Ireland) 1949 (Spain)	Angling species	Eradication of salmonids + decrease of cyprinids in England and Ireland + extinction of fish species in Spain	[84]
Gobiidae	*Neogobius melanostomus*	(Netherlands)	Ballast water releases	Competition	[103]
Percidae	*Gymnocephalus cernuus*	1980s (Germany)	Probably accidental release by anglers	Potential to reduce white fish and coregonus by consuming their eggs	[104], [105]
Poeciliidae	*Gambusia affinis*	1921 (France, Greece, Hungary, Italy, Portugal, Romania, Spain, USSR)	Mosquito control	Declined some amphibians (e.g., *Triturus alpestris* and *T. helveticus*)	[6], [72]
	Gambusia holbrooki	1921 (Spain)	Mosquito prophylaxis	Changed ecosystem functioning	[106], [84], [107]
Salmonidae	*Oncorhynchus mykiss*	Late 19th century (Spain)	Angling species	Introduction of *Gyrodactylus salaris* & furunculosis + compete with *Thymallus thymallus*	[84], [108]
	Salmo salar	Not available	Salmon farming industry	Hybridization with the native fauna	[109]
	Salmo trutta	(England)	Stocking in salmonid fisheries	Changed species composition of stream invertebrates, declined dragonfly nymphs, dytiscid larvae & a beetle	[28], [110]
	Salvelinus fontinalis	1883 (Norway) 1936 (streams in the Pyrenees Mountains) Late 19th century (Spain)	Stocking/ Angling species	Genetic impairment by hybridization + number declining in Norway	[111], [84], [112], [113]

Table 5a: Introductions of alien fish in different regions of North America; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Centrarchidae	*Micropterus salmoides*	(Texas)	N/A	Decreased population of threadfin shad, confined minnows to shallow water + declined planktivorous golden shiners	[34]
	Micropterus dolomieu	1874 (California) 1869 (Nova Scotia, New Brunswick)	Live bait	Cause many bacterial, viral, and parasitic diseases + change the abundance of chironomid, odonata and crayfish + competition with and predation on native fish + reduced Atlantic salmon in eastern Canada	[114], [115]
Cichlidae	*Amatitlania nigrofasciata*	1950s-1970s	Ornamental fish	Carrier of parasites	[47], [116]
	Cichlasoma urophthalmus	1980s (Mexico)	Cultured as food fish	Vector of parasites (71 different helminth species) and a tapeworm (genus Bothriocephalus)	[117]
	Oreochromis aureus	Not available	Aquaculture + Stocking + Aquarium	Predation + competition	[7]
	Oreochromis mossambicus	(Mexico)	Aquaculture purposes	Competition for food, space and spawning locations, effected species flock of native pupfish	[7], [38]
		(California)	Control insects and aquatic weeds	Declined endemic cichlid	[38]
	Oreochromis niloticus	N/A	Aquaculture purposes	Competition with other fish and prey on juveniles of other fish and amphibians	[7], [118]
	Tilapia mariae	Between 1972-1974 (Florida)	Escaped from tropical fish farms	Compete with smaller native fish and invertebrates for green algae in the desert springs	[61]
	Tilapia zilli	(California)	Aquaculture	Habitat alteration by elimination of aquatic macrophytes + competition + threaten desert pupfish and killifish	[7], [47]
Clupeidae	*Alosa pseudoharengus*	Unknown	May be stocking with American shad	Predation on larvae of yellow perch + decimated the population of deepwater sculpins in Lake Michigan	[119], [120]

Table 5b: Introductions of alien fish in different regions of North America; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Cyprinidae	*Carassius auratus*	1600s/ mid 1800s	Food and ornamental fish	Reduced populations of Empetrichthys latos	[121], [122]
	Ctenopharyngodon idella	1963	Control aquatic macrophytes	Compete with native crayfishes and snails; in Texas it has affected the biomass of bluegill and crappie	[47], [123]
	Cyprinella lutrensis	1950s (Colorado River basin)	Bait bucket + aquarium releases	Decline in the population of native spikedace in Arizona and New Mexico	[124], [125],
	Cyprinus carpio	1886 (Illinois River)	Food fish	Affected endemic aquatic macrophyte species via direct consumption + increased turbidity levels + upheaval of nutrients	[126], [127], [93]
	Hypophthalmichthys molitrix	1970s	Biological control in aquaculture facilities + wastewater treatment plants	Compete with native species including bigmouth buffalo and gizzard shad for resources + disruption of recreational boating with jumping habits	[128], [93], [129], [130]
	Hypophthalmichthys nobilis	1970s	Improve water quality in aquaculture facilities	Reduced phytoplankton and zooplankton biomass and competing with larval fishes and other planktivores	[128], [93]
	Pseudorasbora parva	(Ebro Delta)	Ornamental fish	Preys on eggs and young of other fish + competes with them for resources + Introduction of parasite Sphaerothecum destruens	[47], [131], [63]
	Scardinius erythrophthalmus	19th century	Ornamental fish & bait fish	Can affect littoral habitat and fish assemblies+ translocation of nutrients	[132], [133]
	Tinca tinca	1922 (California)	Pond culture	Transmission of parasites, competition + reduced growth of macrophytes + reduced water clarity	[101]
Esocidae	*Esox lucius*	1970s (Coeur d'Alene system in California)	Illegally transported	Posed a threat to the established recreational fisheries of Lake Davis	[134], [135]

Table 5c: Introductions of alien fish in different regions of North America; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Gobiidae	*Acanthogobius flavimanus*	1963	Ballast water release or as eggs laid in the Pacific oyster	Considered as a reason for the decline in tidewater goby population in San Francisco Bay	[136], [137], [138]
	Neogobius melanostomus	1990 (Great Lakes)	Ballast water release	Decline of the native mottled sculpin in southern Lake Michigan + competition + predation on larval and adult fishes + reduced Diporeia spp.	[139], [119], [140]
Ictaluridae	*Pylodictis olivaris*	(Susquehanna River drain)	N/A	Reduced native fish populations in Cape Fear River	[114]
Loricariidae	*Pterygoplichthys anisitsi*	(Texas)	Aquarium release	Changes food web structure + competition (Florida) + displacement of algae-feeding fishes (Texas)	[141]
	Pterygoplichthys multiradiatus	(Mexico)	Unknown	Reduced fisheries of carps and tilapias in Infiernillo Reservoir, Michoacan, and damaged fishing gear	[93], [142]
	Pterygoplichthys pardalis	(Tabasco)	Aquarium releases	Economic losses due to damage to gillnets + reduction in the production of freshwater prawn	[54], [142]
Moronidae	*Morone americana*	1950s (Lake Erie)	N/A	Caused substantial changes in native fish populations and affected community stability	[143], [144]
Osmeridae	*Osmerus mordax*	(Laurentian Great Lakes)	May be sport fishing	Prey on coregonine eggs and larvae + reduced Lake Whitefish and cisco + competition between O. mordax and yellow perch in Crystal Lake	[119], [145]
Petromyzontidae	*Petromyzon marinus*	1920s (Great lakes)	Invaded from Atlantic Ocean	Declined populations of large native fishes + alterations to food webs, high mortality on nearly all teleost species, especially the lake trout	[146], [147]

Table 5d: Introductions of alien fish in different regions of North America; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Poeciliidae	*Gambusia affinis*	(California)	N/A	Reduced endemic Sonoran topminnow + reduce or made extinct amphibians such as *Taricha torosa*	[144], [72]
Salmonidae	*Oncorhynchus mykiss*	2004	Intentionally by State and Federal agencies	Shifts in behavior and microhabitat that reduces minnow's fitness	[148]
	Salmo trutta	1883 (New York and Michigan)	Stocking programs	Compete with native species and eliminated or made extinct species like golden trout, mountain yellow-legged frog and some aquatic invertebrates	[149], [150], [151]
	Salvelinus fontinalis	1885 (Au Sable River)	N/A	Competition with *S. trutta*	[150]
	Salvelinus namaycush	1800s (Yellow stone Lake)	Stocking programs	Limited dispersal of bull trout + noteworthy population declines of cutthroat trout	[152], [146], [153]
Synbranchidae	*Monopterus albus*	20th century (Hawaii)	Food fish/ Illegally introduced	Eliminated native sunfishes in some Georgia ponds	[154], [155]

Table 6: Introductions of alien fish in different regions of South America; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year of introduction	Reason of introduction	Impacts of introduction	References
Centrarchidae	*Micropterus salmoides*	1922 (Brazil) 1990 (São Leopoldo)	Introduced by Jair Lins	Consume zooplankton, insects, and other invertebrates as juveniles + predation	[156]
Cichlidae	*Cichla kelberi*	(Paraná river basin)	Sport fishing	Hybridization + predation + parasitism + competition	[157]
	Cichla ocellaris	(Panama) (North Eastern Brazil)	Food & sport fishing	Decreased abundance and species diversity of zooplankton and phytoplankton + water turbidity	[158], [159]
	Cichla piquiti	(Paraná river basin)	Sport fishing	Competition + predation + parasitism + hybridization	[157]
	Oreochromis aureus	20th century (Brazil)	Illegally introduced	Threats to fish fauna	[7]
	Oreochromis mossambicus	20th century (Venezuela)	Aquaculture purposes	Disappearance of native species	[7] ,[38]
Cyprinidae	*Ctenopharyngodon idella*	(Brazil) 1970s (Peru)	Weed control + research purposes	Introduction of parasites in Panama Canal	[160], [161], [162]
	Cyprinus carpio	19th century (Argentina)	Ornamental + aquaculture purposes	Increased turbidity levels + upheaval of nutrients	[127], [163]
	Cyprinella lutrensis	1970s	Bait bucket or aquarium releases	Hybridization + displacing native congeners and other Cyprinids	[164]
	Hypophthalmichthys molitrix; *Hypophthalmichthys nobilis*	1973	Accidental introduction	Outcompete native species and threaten the trophic structure	[165]
Poeciliidae	*Poecilia reticulata*	1957 (Tunure River)	Intentional introduction by Haskins	Replacing the native guppy stock	[166], [26]
Salmonidae	*Oncorhynchus mykiss*	1890 (Chile) 1904 (Argentina)	Sport fishing	Competitive exclusion + predation + devastating the fish diversity in Chile + threatened some native species such that several species are the only existing members of their family such as N. inermis	[167], [168]
	Salmo trutta	1947-1962 (Falkland Islands)	Enhance recreational fishing	Threatened once-common native galaxid, zebra trout	[169], [170]

Table 7: Introductions of alien fish in different regions of Zealandia; their year and mode of introduction and their impacts on environment in the introduced areas

Family	Introduced species	Year	Reason	Impacts	References
Cyprinidae	*Carassius auratus*	1860s	N/A	Recognized as pests	[171], [122]
	Scardinius erythrophthalmus	1967 (New Zealand)	Illegal transport	Alters aquatic macrophyte assemblages + increases water turbidity	[172], [173]
Poeciliidae	*Gambusia affinis*	(New Zealand)	Biological control of mosquitoes	Predate and harass native fish	[57], [174]
Salmonidae	*Oncorhynchus mykiss*	1888 &1889 (Lake Rotoiti)	Recreational purposes	Reduced populations of galaxiid species (*Galaxias gracilis*)	[28], [175], [176], [177], [170]
	Salmo trutta	1867 (New Zealand) 1888 (Lake Rotoiti)	Angling species	Extinction of the native grayling *Prototroctes oxyrhynchus*	[175], [170], [178]
	Salvelinus fontinalis	1800s (New Zealand)	Recreational purposes	Reduced populations of galaxiid species	[176], [177], [170]

IV. DISCUSSION

I. Global Socioeconomic Impacts

There are international codes of practices for the implementation of aquatic translocations that are signed by many nations but unfortunately, there are fewer adherences to these provided codes. Even in those nations where laws are formed to minimize or prevent the dispersion of alien species, their implementation is ineffective and there are various factors that contribute to this negligence. Mostly the inter-continental introductions are given more attention than the intra-continental ones [4].

The world-wide economic loss of 27 reported fish species invasions is estimated to be about US$37.08 billion with the highest cost of US$31.79 billion calculated for North America, US$5.01 for Europe, US$31.61 million for Asia, US$22.91 million for Central America, US$376.15 thousand for Antarctica or Sub-Antarctica and US$215.11 million for Oceania. There are no reported costs for African and South American regions for such losses; therefore, this cost estimate is expected to be less than the actual costs [179]. Alien fishes that have become invasive in the USA make up a yearly cost of $5.4 billion [180]. Even after causing such massive economic costs worldwide, alien fishes are still being imported for various purposes [181].

II. *Range expansions of alien fishes in freshwater ecosystems of Pakistan*

It was the need of the hour to import alien fishes into Pakistan after its independence to bridge the gap between fish production and its demand and to enhance aquaculture activities. Unfortunately, those introductions were made without making any assessments of the ecological risks that the introduced species would pose. Although the concern regarding the negative impacts of alien species on aquatic systems has been raised globally, there are only a few studies available in Pakistan on this issue [182], [15], [183], [184], [185], [186].

In addition data regarding the range expansion of these alien species is also scarce. It is also not well documented how long it took for these species to establish in Pakistan's inland waters. The Common carp has thrived in both hot and cold water along with the hostile water quality due to its hardy nature [187], prolific breeding potential, and high tolerance to turbidity and temperature. This species was released in inland and captive waters of Pakistan to fill the gap in aquacultural activities. It was promptly established in the majority of the inland waters such as lakes, rivers, streams, wetlands, canals as well as village ponds, particularly in Sindh and Punjab. A study conducted in 2010 showed that this species contributed 52% of the average catch at Mangla Reservoir Pakistan [188]. Later in 2013, with an increase of 2.4%, it contributed to almost 54.4% of the average catch [189].

In River Jhelum, among the cyprinids that were abundantly found with a 67% average rate, common carp contributed 10% of the total fish catch [190]. *C. carpio* was reported as the dominant species in the River Swat [191]. From a study conducted from September 2014 to April 2015 in River Ravi, 229 specimens of *C. carpio* were recorded making it the most dominant species [192]. Introduced *C. carpio* is documented to cause environmental alterations mainly eutrophication by increasing turbidity and mobilizing nutrients from benthos to the water column due to its bottom rooting or digging habit [23].

As stated in Table 3a, increased turbidity, dismantled aquatic vegetation, and altered composition of invertebrate communities were observed after the introduction of exotic *C. carpio* in Australia. It is reported to have a dietary overlap with native fishes of Pakistan including *C. mrigala* [185], *T. putitora* and *Barilius pakistanicus* [186]. *C. auratus* was imported to Pakistan as an ornamental fish and were sold to various pet shops [193]. It has been found in Chashma reservoir [182], River Panjkora [194], [195], River Kabul [196], Head Balloki and Head Qadirabad [185].

It was reported to occur in Taunsa Barrage for the first time by Khan, et al. [182]. This somehow predicts that this species is expanding beyond the sites of their intentional or unintentional introduction. *C. auratus* has been reported to introduce parasites into the freshwaters of Africa as shown in Table 1. It is responsible for the depletion of aquatic vegetation and stimulation of cyanobacteria blooms in Australia as mentioned in Table 3a. Its introduction led to reduced populations of *Empetrichthys latos* in North America as stated in Table no. 5. *A. foliaceus*, a crustacean parasite is native to the UK [197]. This parasite has spread extensively due to the importation of live fish due to the development of aquaculture along with the growing popularity of carp fisheries such as the breeding of koi and ornamental carp [198].

It has been reported several times that this exotic species has led to the introduction of parasites such as *Argulus foliaceus*, *Dactylogyrus extensus*, *Gyrodactylus* sp., *Trichodina* sp., and *I. multifiliis* in Pakistan [193], [199], [200], [201]. As the cited literature explains that after years of the first report of the introduction of parasites, no precautionary measures were taken to control the importation of these infected fish species. Chinese carps *H. molitrix* and *H. nobilis* were imported from China for aquaculture purposes while *C. idella* was introduced to biologically control aquatic weeds [15].

H. molitrix has been reported from Tanda Dam [202], River Kabul [196] and River Harrow [203]. *C. idella* has been found in Head Trimmu and Head Balloki [183]. The three of them are documented to be present in Ghandiali Dam, KPK [204]. Grass carp and silver carp are reported to occur in Chashma and Taunsa reservoirs in a study during 2005-2006 [182]. Both these species were also present in Head Qadirabad in 2007 and 2008 but were not captured in 2009. They were also caught from Head Khanki in 2007 but were not obtained in 2008 and 2009 [205]. This shows that the Chinese carp have not established in these waterbodies. Their presence in River Satluj during 2012-2013 also has been reported [206]. They have been documented to occur in Keenjhar and Manchar Lake during 2016-2017 [207].

A study reported the presence of grass carp in River Ravi and Jhelum while it does not report any catch of the other two Chinese carps [15]. It is stated that bighead carp does not breed in small streams or still water. Hormone stimulation is required to make it artificially breed [208]. The introduction of silver carp led to its competition for food with the native fish and a reduction in populations of microcrustaceans in Israel as stated in Table 2a. It competes with native species including bigmouth buffalo and gizzard shad for resources in North America as stated in Table 5b.

Silver carp is reported to have dietary overlap with native *C. catla* of Pakistan. Competition between native *C. mrigala* and two Chinese carps (*H. nobilis* and *H. molitrix*) has also been observed in Head Balloki. *H. nobilis* has been found to have dietary competition *with L. calbasu* in Head Qadirabad [185]. *O. aureus*, *O. mossambicus* and *O. niloticus* were introduced to enhance aquaculture in Pakistan [15]. During a study in 2005-2006, *O. aureus* was reported as the dominant fish in the Chashma reservoir while absent in the Taunsa reservoir. Contrary to that, *O. mossambicus* was reported to be present in the Taunsa reservoir but absent in Chashma reservoir [182]. However, a study conducted in later during 2016-2017 reported the presence of both *O. aureus* and *O. mossambicus* in the Chashma reservoir [209].

It can be inferred that this species has developed established populations in the Chashma reservoir. *O. aureus* was also observed at three sampling sites i.e. Dhand, Jhelum Bridge and Sheikhupura of River Jhelum [190]. It was also reported in River Ravi near Balloki Headworks during 2014-15 [192]. Surprisingly a study conducted in the same time span (2014-2015) reported the occurrence of *O. aureus*, *O. mossambicus* and *O. niloticus* in River Ravi [210]. *O. niloticus* has also been found in Manchar and Keenjhar Lake during a study conducted during 2016-2017 [207]. *O. aureus* is reported to compete and hybridize with native *O. mossambicus* in Limpopo River Basin, Africa. *O. niloticus* is documented to have displaced green head tilapia and *O. mortimeri*. It has excluded *O. esculentus* and caused the extinction of *O. urolepis* from Lake Hombolo in Tanzania as mentioned in Table 1.

The introduction of *O. mossambicus* led to its competition for food, space and spawning locations with the native fish. It also affected species flock of native pupfish and declined endemic cichlid in North American regions as mentioned in Table 5a. A study conducted at Head Balloki, Pakistan has shown dietary competition between native *Labeo calbasu* and these three tilapian species (*O. aureus*, *O. mossambicus* and *O. niloticus*) [185]. It can be inferred from the above discussion that more research is required to monitor the range expansion of the alien species along with their impacts on the freshwater ecosystems of Pakistan. Such species that are disturbing the native ichthyofauna should be bred in private fish farms rather than stocking them in the natural waterways. Sooner or later there can be a possibility that the native fish populations be declined to a level where they cannot be recovered.

III. *Management strategies adopted by different countries*

Although alien fish introduction started as early as Pakistan came into being, to our misfortune, the organizations that supported these introductions never thought of evaluating the impacts of these exotic species in the introduced regions. Scientists all around the world have made such studies but till now there is no such data documented in Pakistan. Recently, a pioneer study was conducted to assess the impacts brought by these introduced species in Punjab [184].

As records of the previous declines in the population of native aquatic fauna due to these exotic fishes lack, it cannot be inferred that the main reason for the reduction in native fish fauna is the introduction of native fishes. We aim to raise concern for this issue as it is a worldwide problem; indeed many countries have succeeded in managing the exotic species populations so that they can only serve the purpose of their introduction rather than affecting the aquatic ecosystems. For instance in Africa, the government has made legislation for the importation of non-native species into or within the country. The invasive species are divided into various categories and there are different strategies for the management of each category [211].

In Philippines, three species i.e. *Elops hawaiiensis*, *Megalops cyprinoides* and *Lates calcarifer* were introduced for the biological control of *O. mossambicus* in aquaculture ponds and were found effective for this purpose [38]. Invasive tilapias in Jaisamand, India were controlled by selective fishing with the permission of the state Fisheries Department. This technique along with the stocking of fingerlings of the native Indian major carps proved successful in the recovery of the production of these carps [40]. In Australia, carps were controlled by an integrated pest management (IPM) program developed in the early 2000s, which involved the study of koi herpesvirus (KHV) causing koi herpesvirus disease in cyprinids. As this virus is specific to carp, *Cyprinus carpio* infects them through their skin and then enters the tissues, specifically damaging their gills, gut and kidneys. This leads to loss of osmoregulatory functions in fishes thus causing their death. As there are no native cyprinids in Australia, therefore, this technique was successful in reducing carp population in Australia [67].

T. mariae and *O. mossambicus* were successfully eradicated by using rotenone from a creek in Queensland in 2008 [38]. In the United Kingdom, the application of a preventive approach to the introduction of fishes is followed under the Import of Live Fish (England and Wales) Act 1980 (ILFA) and the Import of Live Fish (Scotland) Act 1978. This prevents the importation of fish fauna that has risk assessment of establishing self-sustaining populations in British waters [18]. Introduced brook and rainbow trout were eradicated from a lake in the US by intensive gill netting [212].

Fish farming is still underdeveloped in Pakistan. There are management problems in many parts of the country regarding aquaculture [13]. Various provisions are made to avoid unlawful and unreported fishing. As management actions adopted by one country can extremely risk the exploitation undertakings of other countries, Pakistan aims to sign a treaty for management and conservation due to the migratory habits of the fish stocks between the countries like India, Iran, Maldives, Oman, Pakistan and Yemen [10].

V. CONCLUSION

It can easily be inferred that alien fish introductions can cause great ecological and socioeconomic losses. Various techniques are being adopted by different countries for the management of these introductions or rehabilitating the fisheries. There is a need for such research to be made in Pakistan too. How can one find a solution to a problem which is not been identified yet? This research is not intended to discourage the importation of fish from different countries but to make certain legislations for such introductions. There are many acts and legislations for the management and conservation of fish species but none for the introduction of alien species is made yet. We do understand that there are benefits in the rearing of these exotic fish for the country but we cannot underestimate the devastating effects on the ecosystem. No doubt that these introduced species have economic benefits, but reviewing the literature depicts that undoing the negative impacts of these exotic species, it may cost more than the benefits we gain from them.

To overcome these problems, risk assessments should be made for each fish species that is to be introduced into the country. Those species that can be invasive should be reared in restricted pond cultures from the sites where they cannot escape to the wild. Even after the introduction of a species of exotic fish, their growth should be monitored and controlled. Those that have become invasive and are influencing the native fauna should be eradicated using different measures such as overfishing, biological control, poisoning etc. The best approach will be to promote the rearing and stocking of native fish. Awareness should be spread among the fishermen, people related to fisheries and the general public about the advances in this field and their management. Fishing licenses should be made compulsory. Strict punishments or fines should be made for those who illegally introduce fish in prohibited areas.

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