Furthermore, research organizations must work in close collaboration with policymakers and government agencies to better understand and apply environment-friendly technologies and attain sustainable and responsible aquaculture.

7.1.7 Genetics in Aquaculture

In 2018, global aquaculture production (82.1 million mt) was almost at par with capture fisheries production (96.4 million mt) with the increased farmed fish production dominated by contributions from Southeast Asian countries (FAO, 2020). Aquaculture production statistics in 2018 showed that Indonesia, Philippines, Thailand, and Viet Nam are among the top aquaculture-producing countries in the region. This notwithstanding, the annual growth rate of aquaculture production, in general, has been decreasing for the past 10 years, which could be attributed to global challenges in fish farming and inbreeding such as the lack of quality seedstock, adverse impacts of climate change, environmental degradation, fish diseases, high cost of inputs (*e.g.*, feeds), and others. Some of these problems could be due partly to aquaculture intensification, which could be avoided or minimized. Aquaculture in the Southeast Asian region has not been spared from such issues; hence, research and innovations, be these environmental and genetic interventions that could help resolve these challenges, are important.

Genetic tools for improved fish production

Environmental or non-genetic methods, *e.g.*, culture systems improvement, husbandry techniques, and others, that can improve subtropical and tropical aquaculture yield, have been well studied in Southeast Asia. In contrast, research and programs on genetic and genomic interventions in aquaculture have been relatively slow, especially since these approaches, particularly genomics, require scientific and highly technical laboratory and bioinformatics skills. This situation occurs because information on linkage maps, reference genomes, and single nucleotide polymorphism (SNP) arrays in tropical aquaculture species is still lacking. In addition, such programs (*e.g.*, genome-wide association studies or GWAS) have high investment costs since genomic selection requires genotyping large numbers of samples (Khatkar, 2017).

Research advancements in aquaculture genetics, which applies theories of heredity and variation of inherited characters or traits in farmed fish, and aquaculture genomics, which is a branch of molecular biology that deals with the structure, function, and mapping of complete sets of genes (also known as genomes) in aquatic organisms, have become of interest in recent years. Genetics and genomics are both biological disciplines that allow an understanding of how production and performance traits are passed on through generations in a particular aquatic species and how their genes influence the expression of phenotypic traits and physiological functions. As a means or tool in stock improvement, genetics has been used more often in plant breeding (*e.g.* variety development) since plants can be easily bred and manipulated genetically. On the other hand, aquatic animals have more complex genetic, reproductive, and physiological mechanisms. Nevertheless, several genetic improvement programs on commonly farmed fish and crustaceans have been implemented in Southeast Asia in three decades, starting with applying traditional selective breeding schemes mostly on low-value species that have short generation intervals such as tilapias. In the last five years, advanced schemes supported by genetic markers or genomic information have been conducted. Starting with genetic profiling of aquaculture stocks using DNA markers (*e.g.*, mitochondrial DNA markers, simple sequence repeat markers or microsatellite markers, single nucleotide polymorphism markers, and others), the results can later be used as a reference to fast-track genetic improvement via marker-aided broodstock management and selective breeding. **Table 75** summarizes the various species and the conventional genetic programs (some complimented with DNA marker tools for tagging and genetic traceability) used by public research and development agencies and some privately-operated fish production industries in quality strain development.

Genomics studies, on the other hand, have likewise been pursued and later on applied to determine the genes linked to important production traits, such as growth, reproductive efficiency, disease resistance, stress tolerance (especially heat stress due to climate change and sex determination), among others. Genomic data such as RNA sequencing (RNA-seq) to profile transcriptomes provide a valuable resource to evaluate gene function and genetic variants within genes. It is particularly useful in identifying genes involved in immune response and an organism's reaction to environmental factors like water temperature (as reviewed in Yañez *et al*., 2020). Most of these genetics and genomics research, aside from earlier studies on tilapia genetic improvement, which mainly utilized international funds, is supported by grants from both international and local sources. Some research is also done as collaborative initiatives among Southeast Asian countries with the primary intent of sustainably managing aquatic genetic resources in conservation and aquaculture. Examples are the genetic management and conservation of the tropical Anguillid eels, Carangid species, commercially farmed seaweeds, mangrove crabs, and others. **Table 76** lists the different genetic stock diversity studies and aquaculture genomics work on stocks bred and developed in Southeast Asia. Although costly, the ultimate goal of having a genetic marker or genome-wide molecular marker research is to generate reference data for marker-assisted selection, genome-wide association studies, genomic selection, and, if permitted, gene editing and other more advanced genetic improvement technologies.

Table 75. List of species and the traditional selective breeding programs used to produce improved strains in Southeast Asia (SEASOFIA 2017 list, updated)

Genetic Improvement Program/ Method	Technology and Product (Strain) Produced	Country Where It Was Developed* and/or Available
TILAPIAS		
Nile tilapia		
Genetically improved (GIFT) farmed tilapia program/ combined family and within-family selection for improved growth	GIFT Technology/ GIFT Malaysia (20+ generations)	Malaysia, Philippines*
Genome Supreme Tilapia (GST)/ rotational mating scheme, combined selection for improved growth yield and robustness, marker-assisted selection (using SSR markers)	GST Technology/ Genomar Supreme Tilapia (GIFT derived stock; 29+ generations)	Philippines*
GET-Excel Program/ Outcrossing two fast-growing strains (FAST and GIFT) for improved growth	GET Excel Technology/ GETExcel and i-EXCEL or improved GET Excel stocks	Philippines*
Genetically Male Tilapia Project/ Sex reversal and chromosome manipulation methods (androgenesis/gynogenesis)	YY Supermale	Philippines *
Streptococcus agalactiae*-resistant Nile tilapia*/ family selection (Suebsong *et al*., 2019)	Disease resistant Nile tilapia (F_1 using a commercial stock)	Thailand*
Manit Farm and Akvaforsk Genetics project (2009)/family selection Source: http://www.manitfarm.com	Super black Nile tilapia Disease resistant, fast-growing Nile tilapia (with microchip ID for backtracing)	Thailand*
Brackishwater Enhanced Selected Tilapia (BEST) Program/ Hybridization and outcrossing, size-specific selection	BEST Technology/ Salt tolerant BEST Tilapia strain, improved BEST or iBEST	Philippines*
Cold Tolerant Tilapia/ hybridization	Cold tolerant tilapia	Philippines*
Freshwater Aquaculture Center Selected Tilapia (FAST) Program/ Rotational mating, hybridization	FAST Tilapia	Philippines*
Molobicus or SaltUno project/ hybridization to produce salt-tolerant tilapia	SaltUno strain	Philippines*
Red tilapia		
Streptococcus agalactiae*-resistant Red tilapia*/family selection (Sukhavana *et al*., 2019)	Disease resistant red tilapia (F_1 using a commercial stock)	Thailand*
Manit Farm and Akvaforsk Genetics project (2009)/family selection Source: http://www.manitfarm.com	Super red tilapia Disease resistant fast-growing red tilapia (with microchip ID for backtracing)	Thailand*
Interspecific hybridization conventional breeding of red tilapia for propagation	Red tilapia strains (Philippines, Taiwan, and Thailand strains)	Philippines*, Taiwan*, Thailand*, Malaysia, Indonesia
CARP		
Common carp (*Cyprinus carpio*)/ genomic selection, combined selection (four generations family selection) (Su *et al*., 2018)	Freshwater Fisheries Research Center's Xinlong strain and the synthetic carp strain (from Jian carp x Huanghe carp and later with Heilongjiang carp)	Freshwater Fisheries Research Center, China*
Julien's golden price carp (*Probarbus jullieni*) Molecular biology and genetic engineering techniques	Cryopreserved sperm for planned breeding	Malaysia*
CATFISH		
Clariid catfishes		
African catfish crossbreds/ interpopulation crossbreeding (Sunarma *et al*., 2016)	EN (Egypt female x Netherlands male) African catfish crossbreed	Indonesia*
Interspecific hybridization (*C. macrocephalus* x *C. gariepinus*; *C. batrachus* x *C. gariepinus*)	Clariid catfish hybrids	Philippines, Thailand
Mass selection (*Clarias macrocephalus*) for fast growth, disease resistance (against *A. hydrophila*)	Except for improved strain developed in Pitsanulok FTRC, Dept of Fisheries, Thailand, no improved strain was identified; however, 4th and 2nd generation *C. macrocephalus* used in growth improvement (Jarimopas *et al*., 1990; Komainprairin *et al*., 2004) and strain used in *A. hydrophila* disease resistance (Na-nakorn *et al*., 1994) were produced.	Thailand (not disseminated but used only for research purposes; Na-nakorn and Brummett, 2009)
Pangasiid catfishes		
Siamese catfish (*Pangasianodon hypophthalmus*) breeding/ family selection	growth improvement in the second generation selected Siamese catfish (Tahapari *et al*., 2018)	Indonesia*

Table 75. List of species and the traditional selective breeding programs used to produce improved strains in Southeast Asia (SEASOFIA 2017 list, updated) *(Cont'd)*

Genetic Improvement Program/ Method	Technology and Product (Strain) Produced	Country Where It Was Developed* and/or Available
GIANT FRESHWATER PRAWN (GFP)		
Mass selection on five GFP strains (Barito, Musi, Asahan, Ciasem, and GI Macro) (Khasani *et al*., 2018)	Heritability and selection response after four generations	Indonesia*
Multi-trait selective breeding program/ optimal genetic contribution selection, incomplete diallel crossing using founder stocks from Bengal, Myanmar, Thailand, and selected population (Nantaihu strain) (Sui *et al*.,2019)	Heritability (harvest body weight)	China*
Giant freshwater prawn breeding program for improved growth (10 years or 10 generations) at the National Breeding Centre for Southern FW Aquaculture (NABRECSOFA)/ 3 x 3 diallel cross, selection done per generation (Vu and Nguyen, 2018)	Selected line (using base populations from Mekong and Dong Nai rivers)	Vietnam* (Research Institute for Aquaculture or RIA 2)
MARINE SHRIMPS		
***Fast-growing* Penaeus monodon**/ via triploidy induction using cold shock (Pongtippatee *et al* 2018)	Triploid black tiger shrimp	Thailand*
Selective breeding in Penaeid shrimps/(*e.g.*, family and mass selection) for fast growth and/or disease resistance (some programs are marker-assisted); hybridization	High health shrimp stock (SPF/SPR) (*P. monodon*, *L. stylirostris*, *L. vannamei*); markers related to disease resistance Thai strain SPF *P. monodon* is both fast-growing and WSSV disease resistant Thai strain *L. vannamei* resistant to both WSSV and Vibrio	Brunei Darussalam*, Thailand* (Withyachumnarnkul *et al*. and Songsangjinda in FAO, 2016), Indonesia
MARINE FISHES		
Grouper		
Domestication, broodstock management, individual selection, Interspecific hybridization	Purebreds (2nd generation *C. altivelis*, 3rd generation *P. leopardus*), fast-growing and/or disease-resistant hybrids (*E. fuscogutattus* x *E. lanceolatus*, *E. fuscoguttatus* x *E. polyphekadion*)	Gondol Research and Development Institute for Mariculture (GRDIM), government and private hatcheries in Indonesia* (Sugama *et al*.,2016)
Milkfish (*Chanos chanos*)		
Broodstock Management (possibly marker-assisted)	Domesticated Philippine stocks	Indonesia, Philippines
Asian sea Bass (*Lates calcarifer*)		
Selective breeding for disease resistance	High health *L. calcarifer* stock	Malaysia*
Mass selection to measure growth and fillet trait heritability (Pattarapanyawong *et al*., 2021)	Genetic parameters for growth and fillet trait	Thailand*
Pompano (*Trachinotus blochii*)		
Mass selection ***Broodstock development*** and management	Ongoing mass selection and broodstock development	Philippines
SHELLFISHES		
Abalone (*Haliotis* spp.)		
Interspecific hybridization	Better (hybrid) stocks that are fast-growing and have good carcass quality	Philippines*, Thailand*
Oyster		
Triploidy induction	Triploid oysters produced	Malaysia*, Philippines*
Green Mussel (*Perna viridis*)		
Asian green mussel domestication and broodstock management	Local broodstock	Philippines
SEAWEEDS (Eucheuma, Gracilaria, and others)		
Genetic manipulation Conventional selection for disease resistance Tissue culture Marker-assisted selection Polyploidy	Disease resistant seaweeds Seaweeds with improved carrageenan quality	Malaysia*, Philippines*

Table 75. List of species and the traditional selective breeding programs used to produce improved strains in Southeast Asia (SEASOFIA 2017 list, updated) *(Cont'd)*

Genetic Improvement Program/ Method	Technology and Product (Strain) Produced	Country Where It Was Developed* and/or Available
MANGROVE CRABS		
Selective breeding (mass selection)	Fast-growing mangrove crabs with improved reproductive ability	Philippines*
SANDFISH/SEA CUCUMBER (*Holothuria scabra*)		
Broodstock development, mass selection	Ongoing	Philippines

**Note that the list is not exhaustive*

Table 76. Examples of genetic stock diversity and genomics studies* in selected aquaculture species found/ developed in Southeast Asia

SPECIES/strain	Genetic diversity	Genomics
NILE TILAPIA		
Genomar Supreme Tilapia		58K SNP array, High-density linkage map (Joshi *et al.*,2018)
Different farmed tilapia strains	Maternal mismatches in farmed tilapias in the Philippines based on COI gene (Ordoñez *et al.*, 2017)	
Molobicus hybrid tilapia strain		Species composition in the Molobicus hybrid tilapia using ten diagnostic SNP markers (Bartie *et al.*, 2020)
Different tilapia species *O. mossambicus*, *O. niloticus* and *O. urolepis*	DNA barcoding of tilapia from Papua and Indonesia (cytochrome oxidase I marker) (Dailami *et al.*, 2021)	
Nile and **RED TILAPIA** strains	Microsatellite and mitochondrial DNA marker-based assessment of farmed Nile and red tilapia strains in the Philippines (Romana-Eguia *et al.*,2004)	Genome-wide association study and genomic prediction of *Streptococcus* resistance in red tilapia using low-density marker panels (Sukhavachana *et al.*, 2021; Sukhavachana *et al.*,2020)
CARP		
Mud carp (*Cirrhinus molitorella*)	Genetic diversity and population structure (microsatellite markers) of mud carp from Mekong, Red, and Pearl rivers (Nguyen and Sunnucks, 2012)	
CATFISH		
Pangasiid catfishes	Genetic diversity (mtDNA-RFLP) and population history of *Pangasionodon hypothalamus* and Pangasius bocourti in the Cambodian Mekong River (So *et al.*, 2006)	
Clariid catfishes	Microsatellite genetic variation in farmed African catfish populations in Indonesia (Imron *et al.*, 2011)	
TROPICAL ANGUILLID EELS		
	Genetic diversity and population structure of *Anguilla bicolor Pacifica* in Southeast Asia using DNA control region (Marini *et al.*, 2021)	
SNAKEHEAD		
Snakehead (*Channa striata*)	Genetic diversity (cyt b and D-loop) and structure of snakehead in the Lower Mekong Basin (cross country comparison) (Duong *et al.*, 2019)	
GIANT FRESHWATER PRAWN (GFP)		
Macrobrachium rosenbergii	Microsatellite loci characterization in the Malaysian giant river prawn (Bhassu *et al.*, 2008)	
	Genetic diversity of hatchery stocks of GFP in Thailand (Charoentawee *et al.*, 2007)	

Table 76. Examples of genetic stock diversity and genomics studies* in selected aquaculture species found/ developed in Southeast Asia (Cont'd)

SPECIES/strain	Genetic diversity	Genomics
MARINE FISH		
Milkfish (*Chanos chanos*)	Genetic diversity of Indonesia milkfish using AFLP (Adiputra *et al*., 2012),	
	Microsatellite marker diversity assessment of Philippine milkfish stocks (Romana-Eguia *et al*., 2018 and Santos *et al*., 2015)	Developing ómics-enabled resources, tools, and technologies to enhance milkfish aquaculture production (Ravago-Gotanco *et al*., ongoing)
Grouper		
Grouper *Epinephelus suillus*	Genetic variability and population structure of stocks from Makassar Strait and Bone Bay, South Sulawesi, Indonesia (RAPD DNA) (Parenrengi and Tenriulo, 2008)	
Orange spotted grouper (*Epinephelus coiodes*)	Genetic population structure using allozyme electrophoresis in Brunei and Sabah (Sulaiman *et al*., 2008)	
Red snapper (*Lutjanus malabaricus*)	Genetic population structure using allozyme electrophoresis in Brunei Darussalam and Sabah (Sulaiman *et al*., 2008)	
Sea bass (*Lates calcarifer*)	Genetic variation in *Lates calcarifer* from Wallacea Region estimated using RAPD markers (Irmawati *et al*., 2021)	Multi-trait genomic prediction of harvest and fillet traits in Asian sea bass (Sukhavachana *et al*., 2021)
	Genetic relatedness and differentiation of hatchery populations of Asian sea bass broodstock in Thailand inferred from microsatellite genetic markers (Senanan *et al*., 2015)	
MARINE SHRIMP		
Tiger shrimp (*Penaeus monodon*)	Cryptic diversity of giant tiger shrimp *Penaeus monodon* in Indonesia (COI mtDNA) (Yudhistra and Arisuryanti, 2019)	Chromosome level whole-genome assembly of *P. monodon* to facilitate the identification of growth-associated genes (Uengwetwanit *et al*., 2021)
CRABS		
Blue swimming crab (*Portunus pelagicus*)	Genetic diversity (COI marker) of blue swimming crab (*Portunus pelagicus*) from several waters in Indonesia (Fujaya *et al*.,2019)	
Mangrove crab (*Scylla* spp.)	RAPD-based genetic diversity in mud crabs in Eastern Thailand (Klinbunga *et al*., 2000)	Genetic differentiation and local adaptation signatures for a highly dispersive *Scylla olivacea* in the Sulu Sea using RADSeq (Mendiola and Ravago-Gotanco, 2021)
	COI gene sequence genetic diversity of *Scylla tranquebarica* in Sabah, Malaysia (Sharif *et al*., 2016)	
	Genetic diversity in orange mud crab *Scylla olivacea* in the Philippines (Paran *et al*., 2021)	
	Genetic identification of four mangrove mud crab species using multiple molecular markers (Mandal *et al*., 2021)	
SEAWEEDS		
Kappaphycus spp.	Genetic diversity analysis of cultivated *Kappaphycus* in Indonesia using COI gene (Ratnawati *et al*., 2020)	

**Note that the list is not exhaustive*

Way Forward

Through the years, most of the research outputs from SEAFDEC/AQD regarding genetics and genomics in aquaculture have been geared towards assessing the genetic diversity of key species mostly found in the Philippines (and adjacent countries), to include the Nile tilapia, red tilapia, giant freshwater prawn, mangrove crab, abalone, shrimps and more recently, the Philippine milkfish and the tropical Anguillid eels (Cuvin-Aralar *et al*., 2019, Romana-Eguia *et al*., 2019, Romana-Eguia *et al*., 2018, Romana-Eguia *et al*., 2004). The main objective of such studies is to know the species and/or genetic stock structure and diversity either for conservation, stock management, or selective breeding. At SEAFDEC/AQD, research initiatives on genetics and selective breeding, in particular, began in the mid-1980s, with funds from the International Development Development Centre of Canada (IDRC) under a regional network, then referred to as the International Network on Genetics in Aquaculture (INGA). SEAFDEC/AQD embarked on a farmer-friendly tilapia mass selection scheme while the other Southeast Asian countries under INGA, conducted family selection and/or combined family and within family selection methods to improve farmed Nile tilapias and Asian carps. No region-wide genetic improvement project has been conducted since thence. Genetics, especially genomics, has been applied extensively in several aquaculture research areas, *e.g.* from nutrition to fish health management and ecological (*e.g.* climate change) studies. Current applications cover nutrigenomics, immunogenetics, molecular marker-based disease diagnosis, and researches that require an understanding of aquatic organisms' resiliency towards environmental stressors through 'omics (transcriptomics, etc.) principles. Recently, interest in gene editing as applied in tropical aquaculture species such as tilapia has been noted. Since such studies require advanced technical/laboratory skills and equipment, major research funds are needed to support infrastructure and capacity building. In the Philippines, several aquaculture genetics/genomics projects have been undertaken with support from the Philippine Department of Science and Technology (DOST) apart from the Department of Agriculture's Biotechnology Program. Several of the DOST projects which started a decade ago were initiated with SEAFDEC/AQD as one of the cooperating agencies, together with major academic institutions such as the University of the Philippines and several private universities. The milkfish genetic diversity studies were part of this program (Romana-Eguia *et al*., 2019). However, currently, the DOST has prioritized the provision of funding support to the academic institutions which have continued these genetics/genomics-based researches, *e.g.* on mud crab, milkfish, oysters, and seaweeds.

Therefore, SEAFDEC need to reinforce linkages and collaborate or form research networks among its Member Countries as well as come up with comprehensive genetics/genomics programs towards the improvement of priority species in aquaculture, targeting important traits such as fast growth, disease resistance, and climate resilience.

7.1.8 Traceability of Aquaculture Products

The Codex Alimentarius Commission (2004) defines traceability or product tracing as 'the ability to follow the movement of a food through specified stage(s) of production, processing, and distribution." Traceability has become an important tool to deal with issues that are associated with food safety and quality assurance to prevent risk and gain consumers' support. Traceability has now become a common feature for the international trade of fish and fishery products. The strengthened ties between countries across the globe have encouraged and facilitated bilateral trade. In trade, records of traceability are used as proof of compliance to food safety, biosecurity, and regulatory requirements. These records also ensure that quality and other contractual requirements are fulfilled. In situations such as a food recall, a robust traceability system will allow efficient tracking of affected products through the supply chain.

The AMSs also export a significant volume of aquaculture fish and fishery products annually to regional and global markets. As traceability becomes a trade requirement for eligibility to export aquaculture products to major markets such as Japan, the European Union (EU), and the United States of America (USA), establishing reliable traceability systems is important for the sustainable development of the aquaculture industry in the Southeast Asian region. To tap into demand for aquaculture fish, several large-scale aquaculture companies in the region can comply with the stringent export requirements. Governments and organizations have also been developing different systems on seafood traceability such as TraceFish of the EU and TraceShrimp of Thailand.

Other than the strict regulatory requirements, stress from the general public has led to businesses implementing traceability systems for aquaculture products. A new generation of educated consumers with a higher level of awareness has driven increasing market demand for food safety, security, and sustainability for aquaculture products. Consumers are also becoming more cautious of the food they eat—whether the food is from a safe and sustainable source, and whether production, transportation, and storage conditions can ensure food safety and quality.

Traceability is a component of a food safety management system and it helps to ensure the safety and quality of aquatic organisms in the aquaculture supply chain and verify that they are farmed in accordance with national or international management requirements or to meet national security and public safety objectives. Traceability should provide the linking of vital information across each stakeholder to ensure that the products can be traced effectively. By implementing a traceability system that includes keeping proper records throughout the supply chain of aquaculture products, transparency of product information is guaranteed for all stakeholders. This allows a greater sense of security to consumers who are at the receiving end of the supply chain. Reliable information and comprehensive documentation also allow timely information sharing as well as prompt and effective intervention by relevant competent authorities should problems arise. In times of massive aquaculture, product recalls, traceability system implemented allows timely identification of batch affected or stakeholder involved along the supply chain. Thus, traceability enables prompt verification of records, and through the effective