

Growth Performance of Genetically Improved Farmed Tilapia in Polyculture With Indian Major Carps

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ABSTRACT

Genetically improved farmed tilapia, usually called GIFT, are often recommended as an addition to pond polyculture of the Indian major carps, catla, rohu and mrigal, on the argument that a fast-growing omnivore will use food niches the carps leave open. This narrative review asks how far published work supports that argument and what can fairly be said about the growth of GIFT in such ponds. It draws on literature on the breeding history of the strain, the feeding habits of the species involved, pond nutrient dynamics, stocking and species interactions, and the environmental debate over introduced tilapias, and it reports no new data. The pattern that emerges is conditional. Niche separation is real but incomplete, so competition for natural food is most likely where fertilisation or feeding is light and tilapia are stocked heavily. Growth reported for one stocking ratio, pond and season travels poorly to another, and pond-to-pond variation is often as large as the treatment difference. Claims of genetic gain across generations depend on contemporary comparisons and on the test environment, and a gain measured in one system need not be reproduced in another. Escape and establishment risks differ by region and deserve separate assessment. The review ends with a list of what a decisive polyculture trial should report.

Keywords: GIFT tilapia; Nile tilapia; Indian major carps; Polyculture; Stocking ratio; Genetic gain; Narrative review

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1. Introduction

Fish farming in South Asia has long rested on the Indian major carps, catla, rohu and mrigal, grown together in earthen ponds so that each species takes food from a different part of the water. The arrangement is old, cheap and well understood by farmers, and it remains an important source of fish for people across the region [1, 2]. One frequent suggestion for raising production from the same pond is to add a fast-growing tilapia.

The tilapia usually proposed is the genetically improved farmed tilapia, or GIFT, a strain of Nile tilapia developed through several rounds of selective breeding for growth [3, 4]. Its appeal is easy to state. Tilapia are hardy omnivores that eat plankton, periphyton and detritus, and a strain bred for faster growth should in principle convert the same pond resources into more fish [5, 6]. If the carps leave part of the natural food unused, a tilapia might fill the gap without displacing them.

Whether that happens in practice is a harder question than the sales pitch suggests. A claim that GIFT grows well in polyculture with Indian major carps has a biological part and an ecological part, and each can fail independently. The strain may be genetically superior in a monoculture test and still grow no faster than any other tilapia in a crowded carp pond. This review sets out what is known about the strain, the pond and the species that share it, and how much weight the published evidence can bear.

The article is a narrative review. It draws on published work on tilapia breeding, pond ecology, polyculture and the environmental debate over introduced fish, and it deliberately reports no new data. Where studies of GIFT in carp ponds are thin, we say so, and we describe the evidence a convincing trial would need instead of quoting figures that we have not been able to check against their sources.

2. Literature Review

2.1 Origins and Breeding of the GIFT Strain

The GIFT programme built a synthetic base population from several farmed Asian strains and wild African populations of Nile tilapia, and then selected from it for growth over successive generations [3, 4]. The strain was subsequently disseminated to many countries, which raises questions about how the material was exchanged and how well its diversity was kept [7, 8]. Reviews of selective breeding describe tilapia as one of the clearer success stories, in part because fish have large families and traits that respond to selection [6, 9].

Estimates of genetic parameters in the strain showed that live weight is heritable enough to respond to selection [10], and later analyses followed body weight across generations and in several test environments [11]. The broader literature on genetic improvement of carp, tilapia and prawns in Asia treats these programmes as achievements, but it also lists the lessons: breeding goals that were too narrow, dissemination that outran quality control, and difficulty in keeping the benefit once fish leave the nucleus [12, 13]. A strain name is therefore not a guarantee, since the fish in a farmer's pond may be several generations removed from the breeding population and bred under very different management; fish also differ widely in how far domestication has progressed [14]. This is why the same strain can look excellent in one report and ordinary in the next.

2.2 Indian Major Carps and Their Feeding Niches

The rationale for carp polyculture is niche separation. Catla feeds mainly in the upper water on zooplankton, rohu takes food from the middle of the water column, and mrigal feeds near the bottom on detritus and benthic organisms; common carp are often added as a further bottom feeder [15, 16]. The separation is never complete, however, and diets overlap more as food becomes scarce. Table 1 lists the zones and main foods usually described for the species discussed here, and Figure 1 shows them in a pond cross-section.

Table 1. Feeding zones and main food resources of the species in carp-tilapia polyculture.

Species	Usual zone in the pond	Main natural food
Catla	Surface and upper water	Zooplankton and some phytoplankton
Rohu	Middle water column	Plankton, detritus and plant fragments
Mrigal	Bottom	Detritus and benthic organisms [15]
GIFT tilapia	Whole column, margins and bottom	Phytoplankton, periphyton, detritus and supplementary feed [5, 16]

Note: Qualitative summary of widely described habits. Diets shift with age, season and pond fertility, and the categories overlap.

Studies of bottom-feeding species in major carp polyculture show that the addition of a species with a different feeding habit can change the growth of the others, for better or worse depending on what it does to the pond [15]. Bottom feeders stir sediment, release nutrients and raise turbidity, and the net effect on plankton and on the other fish depends on stocking density and on how much fertiliser or feed the pond receives. This is the context in which a tilapia is added: not an empty niche, but an already busy pond. It is a habit worth keeping even when the expected answer seems obvious.

2.3 Tilapia in the Pond: Feeding and Biology

Nile tilapia are omnivores that graze phytoplankton, scrape periphyton, take detritus and readily accept formulated feed [5]. This breadth is both their advantage and the source of the ecological worry. A fish that can use almost any food in the pond does not sit neatly into an empty niche; it overlaps with each of the carps to some degree, with catla and rohu through plankton and with mrigal through detritus. Tilapia also breed in ponds, and uncontrolled reproduction can fill a pond with small

competitors, which is why all-male or male-biased stocking is common [5, 13]. A pond that has had time to settle behaves differently from one that has just been filled.

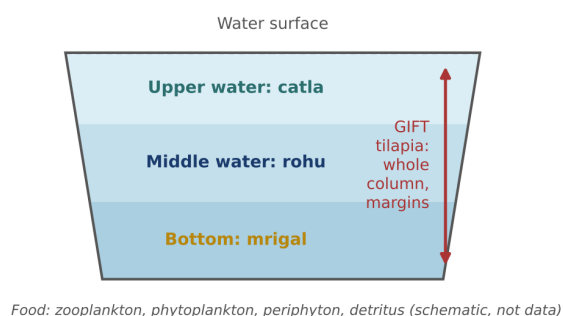


Figure 1. Pond cross-section showing the feeding zones of the species in carp-tilapia polyculture (schematic, not data).

2.4 Pond Nutrients, Natural Food and Management

Production in a semi-intensive pond depends on the supply of natural food, which in turn depends on fertilisation, feed and the cycling of nutrients [16]. Feed that is not eaten and fish waste add nitrogen and carbon to the water, and the ratio of carbon to nitrogen influences whether bacteria assimilate inorganic nitrogen into biomass that fish can graze [17, 18]. The tilapia's ability to harvest microbial and detrital material can be useful, but it also means direct competition with the carps for that material.

2.5 Stocking Ratio, Competition and Pond Variation

The response of each species to the presence of another depends on how many of each are stocked. A few tilapia in a pond that is rich in natural food may grow well and affect the carps little; many tilapia in a lightly fertilised pond are likely to reduce the food available to the filter-feeding and plankton-eating carps [15, 16]. No single ratio is best in general: it depends on fertility, feeding, season and price, and most published ratios come from one set of ponds in one place.

Pond-to-pond variation adds to the difficulty. Ponds that look alike may differ in soil, depth, shade and history [16], and a trial with few ponds can find a difference that is nothing more than pond-to-pond variation. Small differences at stocking can grow into large ones by harvest.

2.6 Genetic Gain Across Generations and Environments

Genetic gain is usually described as the difference in performance between a selected line and a

reference. How that difference is measured matters. Comparing fish from one generation with fish from another reared at different times is vulnerable to year effects, so a fair comparison rears the lots together [9, 10]. Selection response is also not unlimited: as a closed population is selected over generations, relatedness rises and care is needed to keep diversity [8, 12].

Environments matter just as much. Genotype-by-environment interaction means that the ranking of strains, or of families within a strain, can change from one system to another [19], and the breeding work on GIFT itself has tested performance across several environments for that reason [11]. A strain selected in one system may not keep its advantage in a carp pond with a different food base and different competitors. Table 2 gathers the questions a reader can put to a claim of genetic gain.

2.7 Introduced Tilapia and the Environment

Tilapia are among the most widely introduced freshwater fish. A review of introduced tilapias found effects on native biodiversity in many regions, through competition, habitat change, predation on eggs and young, and hybridisation [20]. Studies of the Mozambique tilapia describe its invasive populations and the difficulty of control once it is established [21], and modelling work on the potential distribution of common carp and Nile tilapia indicates large areas where establishment is possible [22]. Global records show that fish introductions have accumulated over decades, often for aquaculture [23].

Table 2. Questions to ask of a claim of genetic gain in tilapia.

Question	Concern	Check
Compared with what?	Old and new lots reared apart [10]	Same-time comparison, same pond
In which environment?	Rankings can change between systems [11, 19]	Test in the target system
How many generations?	Gain may slow with inbreeding [8, 12]	Breeding records, effective numbers
Which trait?	Weight is not the only goal [6]	Survival, yield and feed use
Which source?	Strains circulate under one name [7]	Pedigree and origin of the lot

Note: Compiled from the breeding literature cited in the text; the checks apply to any strain, not only to GIFT.

The picture is not uniformly negative. Introduced fish have brought food and income to many communities, and some authors argue that blanket condemnation overlooks differences between cases [24]. Aquaculture and conservation need not

conflict if species are chosen and managed with escape risk in mind [25, 26], and the argument is best made locally.

3. Materials and Methods

3.1 Scope and Question

The review asks a single question in two parts: does adding GIFT tilapia to a pond of Indian major carps plausibly raise the growth and yield of the system, and how reliable is the evidence for the growth of the tilapia themselves? We divided the question into the sub-questions that a trial would have to answer: what was stocked and in what proportions, what the pond received as fertiliser or feed, how growth was measured, how pond-to-pond variation was handled, and what was claimed about the strain. None of these steps is difficult, but each one is easy to skip.

3.2 Literature Assembly

The review draws on peer-reviewed work in four areas: the genetic improvement of tilapia and carp; the biology and feeding of the species concerned; pond ecology, nutrient dynamics and polyculture; and the wider literature on aquaculture, food supply and the environment. Sources were chosen for relevance, citation in the field and the clarity of their methods. Studies of monoculture and cage culture are used for what they teach about genetics and ecology, not as evidence of growth in carp ponds.

We did not run a formal systematic search and we do not claim one. This is a narrative synthesis, and the choice of sources reflects the authors' judgement. The review is therefore a better guide to what a good polyculture trial should contain than to the size of any reported growth advantage, and it avoids quoting growth figures from individual trials that could not be checked against the primary papers.

3.3 Appraisal Framework

To judge how far a growth report can be trusted, we used a short framework with four questions. Is the pond, rather than the fish, treated as the unit of replication? Are the stocking ratios, fertiliser and feed described well enough to repeat the trial [15, 16]? Is the source and generation of the tilapia stated, so that a genetic claim can be assessed [3, 7]? And are costs and environmental inputs recorded so that the result can be judged on resource use [26, 27]? Table 3 lists the sources of variation we looked for.

Table 3. Sources of variation in reported tilapia growth in polyculture ponds.

Source	Why it matters	What to report
Stocking ratio	Sets competition for natural food [15]	Number and size of every species
Fertilisation or feeding	Changes natural food supply [16, 17]	Inputs by type, rate and timing
Pond and season	Water quality and temperature differ [16]	Pond size, depth, dates, climate
Strain and generation	Genetic level differs between lots [3, 11]	Source, generation, breeding records
Sex and size at stocking	Early differences persist	Sex ratio, stocking weight
Unit of analysis	Fish in one pond are not independent	Pond as the replicate

Note: Items are those most often discussed in the cited pond and breeding literature; none is attributed to a single study.

4. Results

4.1 What GIFT Tilapia Add to a Carp Pond

The literature describes a strain that has been improved for growth and that retains the omnivory and hardiness of the species [3, 5]. In a carp pond it is best understood as an additional consumer of the same pool of plankton, periphyton and detritus, with a growth rate that depends on how much of that pool remains after the carps have taken their share. Where natural food is abundant there is room for another species. Where it is not, the tilapia compete more directly, and faster growth does not remove the constraint. A gain that disappears when feed and labour are priced is not one a pond owner would see.

This is the central reading of the review. Genetic improvement raises the rate at which a fish can convert food into body weight; it does not create food. A strain that grows faster than a reference in a pond with adequate resources may grow no faster in a pond where resources limit everyone. A report that does not describe the food supply cannot say which situation it examined.

4.2 Niche Overlap and Competition

Figure 2 sketches the overlap between the tilapia and each carp in the use of natural food. Overlap is highest where the food resource is shared, such as plankton for catla and rohu or detritus for mrigal, and lowest where the species use distinct zones. The figure is qualitative and shows no measured values. It is meant to make one point: because the tilapia can reach several resources, they touch the niches of all three carps, and they cannot be assumed to be a neutral addition. Competition can show up as slower growth of the carps, as slower

growth of the tilapia themselves, or as both, depending on stocking and fertility [15, 16].

4.3 Stocking Ratio and Pond-to-Pond Variation

Stocking ratio emerges as the main lever the farmer controls. The literature does not support a universal ratio; it supports a process. Begin with the pond's fertility and feeding regime, estimate what natural food the system can support, stock the carps at a density suited to that supply, and add the tilapia in a proportion that leaves the carps their zones [16, 28]. The proportion, sex ratio and stocking size should be recorded, because early size differences persist and can be mistaken for strain effects.

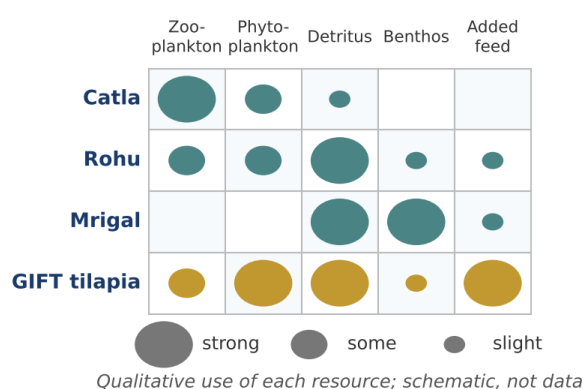


Figure 2. Qualitative overlap in use of natural food resources among the species (schematic matrix, not data).

Reported growth also varies from pond to pond and from season to season. Even replicate ponds receiving the same treatment may differ markedly, so a comparison based on a few ponds can mislead, and analysis that treats each fish as an independent replicate will overstate precision. The pond is the correct unit. Table 3 collects these issues. The point is not that a trial is poor, only that its result travels less far than its abstract suggests.

4.4 Genetic Gain: What the Evidence Says and Does Not Say

For GIFT, the breeding literature shows that growth responds to selection and that progress has been documented under controlled testing [3, 10]. What it does not show, in the sources we reviewed, is the size of the advantage in carp polyculture ponds, because that is a different environment from the test systems. Genotype-by-environment interaction makes this transfer uncertain [11, 19], and the history of dissemination makes the genetic identity of any particular lot uncertain too [7, 8].

Generation matters in a second way. Relatedness rises in a closed line, and without careful mating plans the benefit can erode [8, 12]. A farm that keeps its own broodstock will, over time, be farming a strain that differs from the one it bought, and reports that call a fish GIFT without stating source and generation give the reader no way to know what was stocked.

Put plainly, the literature supports a cautious statement. Selection for growth in Nile tilapia works, and the GIFT strain is the best documented example [3, 9]. The size of the benefit in a carp polyculture pond is not established by evidence we can cite with confidence, and the best summary is that it is likely to be positive where food is not limiting, uncertain elsewhere, and dependent on the identity and management of the broodstock (Figure 3 sets out the sequence of questions we suggest asking of any reported advantage). That is a modest claim, and it is the one the literature can currently carry.

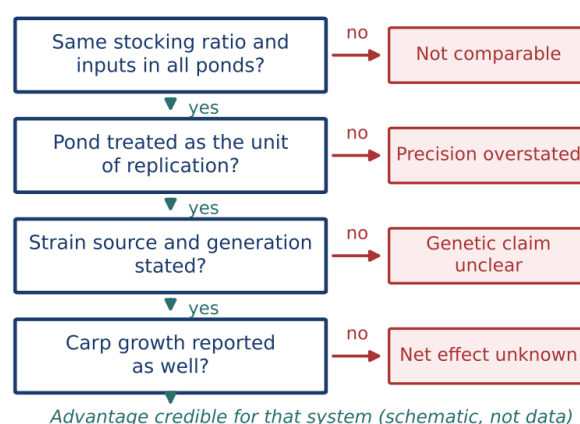


Figure 3. Decision sequence for judging a reported growth advantage (schematic, not data).

4.5 Environmental and Invasive-Species Considerations

Moving tilapia into a region of carp ponds raises the escape question. Ponds flood, and tilapia that reach open water can establish and compete with native fish [20, 22]. The risk depends on climate, on whether tilapia are already present and on local fisheries, and it is handled by site choice, screening and regulation instead of general statements [23, 24].

There are also genetic concerns that are separate from invasion. Strains developed for aquaculture can interbreed with local tilapia, and exchange of genetic resources needs records and quarantine [7, 8]. Environmental assessment of aquaculture now looks at whole systems and supply chains [26, 29], and tilapia polyculture should be assessed in that frame, including water and feed use [28, 30,

31].

5. Discussion

5.1 Interpretation and Practical Reading

The main finding of this review is a conditional one. GIFT tilapia are most likely to grow well and add to total yield in carp ponds where natural food is plentiful, stocking is moderate and management keeps oxygen and water quality in range. They are least likely to in lightly fertilised, heavily stocked ponds, where they compete directly with the carps. That fits the general picture of pond productivity as being set by nutrients and food supply [16, 17], and it implies that the useful question for a farmer is not whether GIFT works but what the pond can feed. Nothing here argues against stocking tilapia; it argues for recording what happens when they are stocked.

The second conditional concerns evidence for genetic gain. The breeding record of the strain is strong [3, 6], but it was made in test systems, and the step to a polyculture pond depends on the match between environments [19].

A third point concerns resource use and the wider food system. Aquaculture has expanded to supply a growing share of fish for human diets, and it matters for nutrition in countries where fish is an important and affordable source of animal protein [2, 32]. Fish are widely seen as a way to meet future food needs [33, 34], but the same literature stresses that the benefit depends on how production is organised, on feed sources and on environmental costs [35, 36]. Polyculture of carps with tilapia is one of the low-input options, and it merits evaluation on those terms [37, 38]. These points apply to any new strain or species added to a pond, not only to GIFT.

Three findings would change this reading. A well-designed trial showing a clear and persistent advantage of GIFT over another tilapia in carp ponds with limiting natural food would suggest that the strain converts scarce resources better than expected. A trial showing that adding tilapia raised total pond yield at several fertility levels, with carp growth recorded alongside, would settle the case for those settings. And evidence of escape and establishment under local conditions would require the environmental question to move to the front of any advice [20, 21].

5.2 Limitations

This is a narrative review and shares the limitations of that form. The selection of sources reflects judgement, no formal search or quality scoring was done, and the review does not quote

numerical results from individual polyculture trials, because these could not be checked against the primary reports for this article. A reader who needs a growth figure should consult the original studies, applying the appraisal questions above, or wait for a formal systematic review.

The review also draws on evidence from monoculture, cage culture and breeding programmes, which are imperfect proxies for a carp polyculture pond. We have used them to frame hypotheses, and the conclusions should be read in that light. Reviews are more useful when they say where the evidence stops than when they smooth it over.

5.3 Implications for Trial Design

A trial that could settle the question would use enough ponds to detect a modest difference, with the pond as the unit of analysis. It would stock the carps at a fixed density and vary the proportion of tilapia across several levels. Read this way, a null result from a few ponds is not proof that no difference exists. It would state the source and generation of the tilapia, include a non-improved lot reared in the same system for a fair contemporary comparison, report growth and survival of the carps too, and record inputs, temperature and oxygen throughout [10, 19].

5.4 Directions for Future Work

Three needs stand out. First, direct comparisons of GIFT and other tilapia lots in carp ponds under contemporary conditions, with enough ponds and a clear description of the broodstock. Second, studies of how tilapia change the supply of natural food and the growth of each carp over a production cycle, which would clarify competition and indirect effects [15, 28]. Third, regional assessments of escape and establishment risk so that advice on stocking tilapia can be matched to local conditions [22, 25]. A farmer reading a trial report wants one answer: would this have worked in my pond?

6. Conclusion

GIFT tilapia are a plausible addition to ponds of Indian major carps. The strain has a well-documented history of selection for growth, and the species uses food resources that complement those of the carps in part. The evidence, as we can responsibly summarise it, does not yet establish how large the growth advantage is in such ponds, or how much the tilapia affect the carps. What the literature does show is when benefit should be largest, which interactions and sources of variation make

reported results hard to transfer, and which environmental checks should accompany the decision to stock.

For the practitioner the message is practical rather than discouraging. Tilapia can be tried, provided the pond is fertile enough, the stocking ratio and fish source are recorded and the risk of escape has been considered. For the researcher, the opportunity is a set of replicated, fully described trials in carp ponds that turn a plausible idea into a measured result.

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9. Conflict of Interest

The authors declare no conflict of interest.

10. Author Contributions

S.E. conceived the review and wrote the sections on tilapia breeding and genetic gain. D.K. wrote the sections on pond ecology, feeding and stocking. T.B. wrote the sections on fisheries management and environmental considerations. All authors revised the manuscript and approved the final version.

11. Ethics Statement

This is a review of published literature. No animals were used and no ethical approval was required.

12. Data Availability

No new data were generated. All sources are cited in the reference list.

13. References

- [1] Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., ... Corner, R. (2010). Aquaculture: Global status and trends. *Philosophical Transactions of the Royal Society B*, 365(1554), 2897-2912. DOI: [10.1098/rstb.2010.0170](https://doi.org/10.1098/rstb.2010.0170)
- [2] Belton, B., & Thilsted, S. H. (2014). Fisheries in transition: Food and nutrition security implications for the global South. *Global Food Security*, 3(1), 59-66. DOI: [10.1016/j.gfs.2013.10.001](https://doi.org/10.1016/j.gfs.2013.10.001)
- [3] Ponzoni, R. W., Nguyen, N. H., Khaw, H. L., Hamzah, A., Bakar, K. R. A., & Yee, H. Y. (2011). Genetic improvement of Nile tilapia (*Oreochromis niloticus*) with special reference to the work conducted by the WorldFish Center with the GIFT strain. *Reviews in Aquaculture*, 3(1), 27-41. DOI: [10.1111/j.1753-5131.2010.01041.x](https://doi.org/10.1111/j.1753-5131.2010.01041.x)
- [4] Eknath, A. E., Bentsen, H. B., Ponzoni, R. W., Rye, M., Nguyen, N. H., Thodesen, J., & Gjerde, B. (2007). Genetic improvement of farmed tilapias: Composition and genetic parameters of a synthetic base population of *Oreochromis niloticus* for selective breeding. *Aquaculture*, 273(1), 1-14. DOI: [10.1016/j.aquaculture.2007.09.015](https://doi.org/10.1016/j.aquaculture.2007.09.015)
- [5] Beveridge, M. C. M., & McAndrew, B. J. (Eds.). (2000). *Tilapias: Biology and exploitation*. Springer. DOI: [10.1007/978-94-011-4008-9](https://doi.org/10.1007/978-94-011-4008-9)
- [6] Gjedrem, T., Robinson, N., & Rye, M. (2012). The importance of selective breeding in aquaculture to meet future demands for animal protein: A review. *Aquaculture*, 350-353, 117-129. DOI: [10.1016/j.aquaculture.2012.04.008](https://doi.org/10.1016/j.aquaculture.2012.04.008)
- [7] Eknath, A. E., & Hulata, G. (2009). Use and exchange of genetic resources of Nile tilapia (*Oreochromis niloticus*). *Reviews in Aquaculture*, 1(3-4), 197-213. DOI: [10.1111/j.1753-5131.2009.01017.x](https://doi.org/10.1111/j.1753-5131.2009.01017.x)
- [8] Lind, C. E., Ponzoni, R. W., Nguyen, N. H., & Khaw, H. L. (2012). Selective breeding in fish and conservation of genetic resources for aquaculture. *Reproduction in Domestic Animals*, 47(s4), 255-263. DOI: [10.1111/j.1439-0531.2012.02084.x](https://doi.org/10.1111/j.1439-0531.2012.02084.x)
- [9] Gjedrem, T., & Rye, M. (2018). Selection response in fish and shellfish: A review. *Reviews in Aquaculture*, 10(1), 168-179. DOI: [10.1111/raq.12154](https://doi.org/10.1111/raq.12154)
- [10] Ponzoni, R. W., Hamzah, A., Tan, S., & Kamaruzzaman, N. (2005). Genetic parameters and response to selection for live weight in the GIFT strain of Nile tilapia (*Oreochromis niloticus*). *Aquaculture*, 247(1-4), 203-210. DOI: [10.1016/j.aquaculture.2005.02.020](https://doi.org/10.1016/j.aquaculture.2005.02.020)
- [11] Bentsen, H. B., Gjerde, B., Nguyen, N. H., Rye, M., Ponzoni, R. W., Palada de Vera, M. S., ... Eknath, A. E. (2012). Genetic improvement of farmed tilapias: Genetic parameters for body weight at harvest in Nile tilapia (*Oreochromis niloticus*) during five generations of testing in multiple environments. *Aquaculture*, 338-341, 56-65. DOI: [10.1016/j.aquaculture.2012.01.027](https://doi.org/10.1016/j.aquaculture.2012.01.027)
- [12] Nguyen, N. H. (2016). Genetic improvement for important farmed aquaculture species with a reference to carp, tilapia and prawns in Asia: Achievements, lessons and challenges. *Fish and Fisheries*, 17(2), 483-506. DOI: [10.1111/faf.12122](https://doi.org/10.1111/faf.12122)
- [13] Gjedrem, T. (Ed.). (2005). *Selection and breeding programs in aquaculture*. Springer. DOI: [10.1007/1-4020-3342-7](https://doi.org/10.1007/1-4020-3342-7)
- [14] Teletchea, F., & Fontaine, P. (2014). Levels of domestication in fish: Implications for the sustainable future of aquaculture. *Fish and Fisheries*, 15(2), 181-195. DOI: [10.1111/faf.12006](https://doi.org/10.1111/faf.12006)
- [15] Wahab, M. A., Rahman, M. M., & Milstein, A. (2002). The effect of common carp, *Cyprinus*

- carpio* (L.) and *mrigala*, *Cirrhinus mrigala* (Hamilton) as bottom feeders in major Indian carp polycultures. *Aquaculture Research*, 33(8), 547–556. DOI: [10.1046/j.1365-2109.2002.00692.x](https://doi.org/10.1046/j.1365-2109.2002.00692.x)
- [16] Boyd, C. E., & Tucker, C. S. (1998). *Pond aquaculture water quality management*. Springer. DOI: [10.1007/978-1-4615-5407-3](https://doi.org/10.1007/978-1-4615-5407-3)
- [17] Avnimelech, Y. (1999). Carbon/nitrogen ratio as a control element in aquaculture systems. *Aquaculture*, 176(3–4), 227–235. DOI: [10.1016/S0044-8486\(99\)00085-X](https://doi.org/10.1016/S0044-8486(99)00085-X)
- [18] Crab, R., Defoirdt, T., Bossier, P., & Verstraete, W. (2012). Biofloc technology in aquaculture: Beneficial effects and future challenges. *Aquaculture*, 356–357, 351–356. DOI: [10.1016/j.aquaculture.2012.04.046](https://doi.org/10.1016/j.aquaculture.2012.04.046)
- [19] Sae-Lim, P., Gjerde, B., Nielsen, H. M., Mulder, H., & Kause, A. (2016). A review of genotype-by-environment interaction and micro-environmental sensitivity in aquaculture species. *Reviews in Aquaculture*, 8(4), 369–393. DOI: [10.1111/raq.12098](https://doi.org/10.1111/raq.12098)
- [20] Canonico, G. C., Arthington, A., McCrary, J. K., & Thieme, M. L. (2005). The effects of introduced tilapias on native biodiversity. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 15(5), 463–483. DOI: [10.1002/aqc.699](https://doi.org/10.1002/aqc.699)
- [21] Russell, D. J., Thuesen, P. A., & Thomson, F. E. (2012). A review of the biology, ecology, distribution and control of Mozambique tilapia, *Oreochromis mossambicus* (Peters 1852) (Pisces: Cichlidae) with particular emphasis on invasive populations. *Reviews in Fish Biology and Fisheries*, 22(3), 533–554. DOI: [10.1007/s11160-011-9249-z](https://doi.org/10.1007/s11160-011-9249-z)
- [22] Zambrano, L., Martínez-Meyer, E., Menezes, N., & Peterson, A. T. (2006). Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. *Canadian Journal of Fisheries and Aquatic Sciences*, 63(9), 1903–1910. DOI: [10.1139/f06-088](https://doi.org/10.1139/f06-088)
- [23] Casal, C. M. V. (2006). Global documentation of fish introductions: The growing crisis and recommendations for action. *Biological Invasions*, 8(1), 3–11. DOI: [10.1007/s10530-005-0231-3](https://doi.org/10.1007/s10530-005-0231-3)
- [24] Gozlan, R. E. (2008). Introduction of non-native freshwater fish: Is it all bad? *Fish and Fisheries*, 9(1), 106–115. DOI: [10.1111/j.1467-2979.2007.00267.x](https://doi.org/10.1111/j.1467-2979.2007.00267.x)
- [25] Diana, J. S. (2009). Aquaculture production and biodiversity conservation. *BioScience*, 59(1), 27–38. DOI: [10.1525/bio.2009.59.1.7](https://doi.org/10.1525/bio.2009.59.1.7)
- [26] Edwards, P. (2015). Aquaculture environment interactions: Past, present and likely future trends. *Aquaculture*, 447, 2–14. DOI: [10.1016/j.aquaculture.2015.02.001](https://doi.org/10.1016/j.aquaculture.2015.02.001)
- [27] Boyd, C. E., Tucker, C., McNevin, A., Bostick, K., & Clay, J. (2007). Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. *Reviews in Fisheries Science*, 15(4), 327–360. DOI: [10.1080/10641260701624177](https://doi.org/10.1080/10641260701624177)
- [28] Verdegem, M. C. J., Bosma, R. H., & Verreth, J. A. J. (2006). Reducing water use for animal production through aquaculture. *International Journal of Water Resources Development*, 22(1), 101–113. DOI: [10.1080/07900620500405858](https://doi.org/10.1080/07900620500405858)
- [29] Ahmed, N., Thompson, S., & Glaser, M. (2019). Global aquaculture productivity, environmental sustainability, and climate change adaptability. *Environmental Management*, 63(2), 159–172. DOI: [10.1007/s00267-018-1117-3](https://doi.org/10.1007/s00267-018-1117-3)
- [30] Tacon, A. G. J., & Metian, M. (2008). Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture*, 285(1–4), 146–158. DOI: [10.1016/j.aquaculture.2008.08.015](https://doi.org/10.1016/j.aquaculture.2008.08.015)
- [31] Hua, K., Cobcroft, J. M., Cole, A., Condon, K., Jerry, D. R., Mangott, A., ... Strugnell, J. M. (2019). The future of aquatic protein: Implications for protein sources in aquaculture diets. *One Earth*, 1(3), 316–329. DOI: [10.1016/j.oneear.2019.10.018](https://doi.org/10.1016/j.oneear.2019.10.018)
- [32] Thilsted, S. H., Thorne-Lyman, A., Webb, P., Bogard, J. R., Subasinghe, R., Phillips, M. J., & Allison, E. H. (2016). Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy*, 61, 126–131. DOI: [10.1016/j.foodpol.2016.02.005](https://doi.org/10.1016/j.foodpol.2016.02.005)
- [33] Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.-I., & Williams, M. (2015). Feeding 9 billion by 2050 – Putting fish back on the menu. *Food Security*, 7(2), 261–274. DOI: [10.1007/s12571-015-0427-z](https://doi.org/10.1007/s12571-015-0427-z)
- [34] Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., ... Troell, M. (2021). A 20-year retrospective review of global aquaculture. *Nature*, 591(7851), 551–563. DOI: [10.1038/s41586-021-03308-6](https://doi.org/10.1038/s41586-021-03308-6)
- [35] Naylor, R. L., Goldburg, R. J., Primavera, J. H., Kautsky, N., Beveridge, M. C. M., Clay, J., ... Williams, M. (2000). Effect of aquaculture on world fish supplies. *Nature*, 405(6790), 1017–1024. DOI: [10.1038/35016500](https://doi.org/10.1038/35016500)
- [36] Troell, M., Naylor, R. L., Metian, M., Beveridge, M., Tyedmers, P. H., Folke, C., ... de Zeeuw, A. (2014). Does aquaculture add resilience to the global food system? *Proceedings of the National Academy of Sciences*, 111(37), 13257–13263. DOI: [10.1073/pnas.1404067111](https://doi.org/10.1073/pnas.1404067111)
- [37] Subasinghe, R., Soto, D., & Jia, J. (2009). Global aquaculture and its role in sustainable development. *Reviews in Aquaculture*, 1(1), 2–9. DOI: [10.1111/j.1753-5131.2008.01002.x](https://doi.org/10.1111/j.1753-5131.2008.01002.x)
- [38] Cressey, D. (2009). Aquaculture: Future fish. *Nature*, 458(7237), 398–400. DOI: [10.1038/458398a](https://doi.org/10.1038/458398a)