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Adopt and adapt nature's design principles to create sustainable aquaculture systems

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Sustainable development of aquaculture faces many constraints. An approach that offers solutions to these challenges is emulating nature's patterns and strategies. There are many elements of sustainability employed by nature that can be adopted for aquaculture systems through necessary adjustments (or adaptations). Analysis of empirical data generated by a series of experiments on different aquaculture systems generated new knowledge of practical importance. An outcome of the analysis pertaining to two important aspects of aquaculture, the sex control in captive stocks of commercially important protogynous hermaphrodite grouper and the operation of integrated multi-trophic aquaculture systems is presented here. Both cases serve as outstanding examples of the relevance of examining and applying nature's principles for finding sustainable solutions to aquaculture problems.

Keywords: Aquaculture, nature's design, systems approach, sustainability.

WITH the capture fisheries stagnating and declining, aquaculture has increased its contribution to global seafood supplies to more than 50%. It is the only farming system that can bridge the gap between supply and demand of seafood. However, sustainability of aquaculture systems remains an elusive goal. Applying nature's principles in producing organisms that constitute our seafood raises hope because of their core elements of sustainability. Adapting them to aquaculture systems can address the

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multiple challenges threatening the sustainability of fish farming systems irrespective of their diversity.

Ironically, beginning of aquaculture and its early history of development were inspired by nature. Later, when seafood demand increased and aquaculture showed potential as a lucrative business, interest shifted to engineering and technology solutions for commercial-scale production. However, in this process of industrialization of aquaculture, sustainability was compromised and it still remains unattainable. The initial developments dubbed as primitive or traditional farming practices followed the innovatively adapted processes as they occur in nature, and were, therefore, very much in harmony with environment. Recent years have witnessed a revival of interest in incorporating those very elements in aquatic farming systems, which as a matter of fact are compatible with environment. Evidences emerging from experimental studies are beginning to show that the designs which mimic natural processes hold promise for aquaculture sustainability.

Modern aquaculture can learn from nature's problem-solving ways. Nature solves problems impeding sustainability, but this happens over a long period of time. However, adopting the basic elements of nature's blueprint and adapting them for short-term effects with long-term outcomes look promising to the extent that we feel convinced that learning from those options for the modern aquaculture industry provides the way forward.

Synthesis of knowledge from our experiments in ecological aquaculture suggests the relevance of looking to nature for design guidance in fish farming for solutions to the problems. The focus of our study has been on two key issues namely, sex control in fish stocks held captive in the hatchery and nutrient cascading in multiple species culture for production efficiency.

Sex control is one of the most important and highly targeted areas of aquaculture research due to its application in broodstock management, productivity and economics[1]. The role of hatchery in seed production is seriously undermined if this biological phenomenon is not effectively managed. It is more challenging in protogynous hermaphrodites (which begin life as female and sometime later change to male). Some of the most popular aquaculture species such as groupers belong to this category.

Thanks to the dedicated efforts of researchers committed to ecological aquaculture, nature-inspired solutions are now receiving attention. A lot more efforts are needed for motivating the aquaculture industry to attempt transition to farming models that possess the attributes of nature. Obviously, documented benefits of biomimicry application in aquaculture will contribute a great deal to support this approach. Some of the contributions made in this area by us are the basis of this communication. Sex differentiation of grouper in the hatchery is among the problems receiving attention. Mustafa *et al.*[2] first examined how sex differentiation occurs in nature[3] with the aim of allowing it to happen in culture systems. The experiment required rearing all-female protogynous hermaphrodite tiger grouper (*Epinephelus fuscoguttatus*) in tanks as large as 150 m^3 volume. Five out of 68 specimens were seen to transition to male sex to ensure reproduction. This demonstrated the role of socio-demographic cues in sex differentiation and questioned the need for human intervention in either manipulating the sex ratio by introducing male fish from outside or injecting hormones into potential broodstock for the purpose of captive breeding. In nature, no one injects hormones or introduces male fish to the wild grouper population where sex change is cued by social structure or attainment of a critical age or size[4–6]. When fish of the same sex (female) notices absence of male and a distinct size gradient, this triggers an urge for larger specimens in the cohort to change sex which is then followed by internal processes that radically transform the ovary into testis and establish a behaviour typical of male. The genesis of this natural sex change in a culture system should involve multiple transformation pathways that are behavioural, anatomical, neuroendocrine and molecular. The presence of crypts of resting spermatogenic tissues within the ovarian germinal epithelia prior to sex change in groupers[7,8] could facilitate this process. Other processes expected are degeneration of oocytes and ovarian follicle cells, and formation of spermatogonia and Leydig cells followed by further anatomical differentiations. Generally, these structural differentiations are supported by two gonadal hormones, estrogen (17β-estradiol) and androgen (11-ketotestosterone). During the process of sex change, there is a noticeable shift in sex steroid levels in the blood in the form of a significant increase in male sex hormone and suppression of female hormone. The estrogen–androgen balance is controlled by well-established hypothalamic-pituitary-gonadal (HPG) axis. Gonadotropin releasing hormone (GnRH), released from the hypothalamus, stimulates the pituitary to produce and release the gonadotropic hormones (GtHs) of two types – follicle stimulating hormone (FSH) and luteinising hormone (LH) into circulation. GtHs directly regulate gonadal steroidogenesis via receptor-mediated stimulation of ovarian follicle cells or somatic Leydig cells in the testis.

It is difficult to elaborate scientific details of the perception and processing of external cues into the physiological responses, and elaboration of physiological cues in achieving sex change. What is, however, known is that rapid neurochemical changes in brain drive behavioural sex change and gonadal restructuring, which is coordinated by the HPG axis in several days[9–11]. In the case of wrasse, the removal of male has been reported to lead to dramatic changes in neurochemicals and neuroendocrine processes in the brain of large females and this is reflected in their behavioural change[5,11]. While not established in the case of groupers, similar mechanisms are most likely to occur in this group of fish as well. These observations establish that mimicking nature in culture systems can achieve the expected outcomes in terms of anatomical, physiological, behavioural and possibly other manifestations.

Replication of some elements of nature's model to an integrated multi-trophic aquaculture (IMTA) system is yet another problem that is receiving a great deal of interest. In addition to nutrient cascading in culture system that can mimic the functional dynamics of a natural ecosystem for recycling and minimizing waste, another attribute of nature in this system is maximizing exposure of animals to environmental diversity. This helps in building the cue system far beyond the innate one and is an adaptive part of fish life. The experiment involved an integrated culture of spiny lobster (*Panulirus ornatus*), sea cucumber (*Holothuriua scabra*) and seaweed (*Kappaphycus alvarezi*) where nutrient uptake and recycling were investigated[12]. The waste produced by the lobster was subjected to the action of organic extractive (sea cucumber) and inorganic extractive (seaweed) for biomass growth at the expense of what would otherwise become a pollutant, while it contributed to water quality remediation for all the species. It deserves mention that for successful outcome of IMTA the selection of species is important, since all the species are not amenable to recirculating aquaculture system or some might fail to adjust to life in captivity. This was also noticed by Estim and Mustafa[13] on giant grouper (*Epinephelus lanceolatus*) and Asian seabass (*Lates calcarifer*) and separately on two species of seaweeds, *Eucheuma cottonii* and *E. spinosum*[14]. This sort of IMTA system is akin to natural environment and a showcase of biomimicry model, where populations grow in a community. Attributes of nature simulated in such culture systems are modelled for species diversity (polyculture), interdependence (synergies in diversity), resource efficiency (optimizing and minimizing) and adaptability[15].

While the most conspicuous process of IMTA is nutrient cascading, presumably there are cues that need to be explored and understood, beyond nutrient recycling, that are generally highlighted in IMTA. In their wild environment, species do not live in isolation. A hyper-controlled artificial mono-species farming system creates an environment of 'loneliness' to the animal that in nature lives and grows in a web of life. Even if there are many individuals of the same species, the fish does not get the experience of 'something different', essentially biodiversity. This puts stress on the fish.

To experience biodiversity is innate and essential for perceiving many cues that link it to the ecosystem. It can be considered as part of the ecological values of nature. These observations serve to show how little we know about the science of signals and cues in fish, and how important these are for developing nature-based designs for aquaculture systems.

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