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Review Article

Environmental Impact and Sustainable Practices in Aquaculture: A Comprehensive Review

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Abstract

Aquaculture is the fastest-growing food production sector, now contributing more to global fish biomass than capture fisheries. While much of this expansion has occurred over the past 50 years, it has been accompanied by numerous environmental challenges, including aquatic pollution driven by urbanization, industrialisation, harbour dredging, sand filling, pesticide runoff from agricultural activities, and land-use conflicts between aquaculture, industry, and tourism. These environmental concerns have heightened the focus on sustainability, particularly in relation to ecological preservation. This review explores the various types of waste generated by industries, households, and other establishments that are discharged into aquatic ecosystems, examining their potential impacts on aquaculture. In addition, it evaluates mitigation strategies aimed at reducing or eliminating these environmental threats. Increasing attention has been placed on raising awareness of environmental issues and adopting sustainable practices to minimise aquaculture's ecological footprint. While environmental degradation was not viewed as a critical issue in the early stages of the industry's development, it has now become a central concern across academic, governmental, industrial, and market sectors.

Keywords: Aquaculture, Aquaculture Ecology, Environmental Threat, Ecological approaches.

INTRODUCTION

Aquaculture systems share many parallels with agriculture, as both practices involve converting land for the purpose of cultivating organisms. In aquaculture, land is often transformed into ponds for raising aquatic species, much like how land is cleared for row crops in agriculture. Additionally, aquaculture utilizes cages and other containment systems in natural water bodies to grow fish, a practice comparable to concentrated animal feeding operations (CAFOs) in terrestrial farming. While large-scale land conversion for aquaculture is a potential concern, significantly less land has been repurposed for aquaculture compared to traditional agriculture.

However, certain aquaculture practices can pose threats to biodiversity (Goldberg and Triplett, 1997), prompting environmental groups to advocate for the reduction or even elimination of specific forms of aquaculture. These concerns partly stem from the inherent difficulty in comparing the environmental impacts of aquaculture with those of other land and water uses. Moreover, assessing the sustainability of seafood, whether farmed or wild-caught, against traditional agricultural products remains challenging. No food production system is entirely sustainable when evaluated in terms of energy consumption and biodiversity preservation. All systems generate waste, consume energy and water, and alter land cover. Nevertheless, food production systems, including aquaculture, play a crucial role in stimulating economic activity. This economic impact is especially vital in developing countries, where aquaculture often provides an alternative to more ecologically harmful income-generating activities for small-scale farmers (Rönnbäck *et al.*, 2002). As such, while aquaculture does present environmental risks, it also has the potential to contribute to economic development and sustainable food systems, provided that appropriate ecological practices are implemented.

The significance of aquaculture in fostering socio-economic growth is undeniable. It enhances the production of animal protein to meet the nutritional needs of a rapidly expanding global population, generates high-value commodities for export, thereby earning foreign exchange, and provides numerous employment opportunities. Additionally, aquaculture makes productive use of vast tracts of otherwise idle land and water resources. In response to the stagnation of capture fisheries, aquaculture has experienced substantial global development in recent years to meet the increasing demand for food (Goldberg and Triplett, 1997).

Although aquaculture dates back to at least 2000 BCE (Rabanal, 1988), its most rapid and systematic global expansion occurred during the latter half of the 20th century. This growth can be attributed not only to technological advancements and the evolution of farming practices but also to the widespread dissemination of knowledge at both national and international levels, along with the need for a reliable source of protein for human consumption (Jones, 1987). A pivotal breakthrough in aquaculture occurred in the 1970s with the advent of seed production and induced spawning techniques for key species such as Asian carp, tilapias, and penaeid shrimp.

The 1970s and 1980s marked a critical turning point for global aquaculture, characterised by significant increases in both production area and output. This growth has involved the cultivation of a wide variety of species and has been largely driven by a combination of factors, including rising global demand for fish and shellfish, increasing urbanisation, wealth growth, stagnation of capture fisheries, and continued population growth (Worm *et al*., 2006; Halpern *et al*., 2008; Godfray *et al*., 2010). These developments have positioned aquaculture as a vital component of the global food system, capable of addressing food security challenges while contributing to economic growth.

While aquaculture has the potential to address global food security challenges, its reliance on finite natural resources presents significant sustainability concerns. The environmental impacts of aquaculture are well-documented, and numerous scientists and environmental advocates have raised alarms about its potential harm to ecosystems (Dierberg and Kiattisimukul, 1996; Boyd, 2003). These impacts manifest in various ways, including land-use conflicts, ecosystem alterations, and, most notably, water pollution. Among these concerns, water pollution has garnered the most widespread attention across nations (Tookwinas, 1996; Boyd and Tucker, 2000; Cripps and Bergheim, 2000).

Discharges from flow-through aquaculture systems—such as raceways and tanks—contain organic matter, nutrients, and suspended solids, which can lead to oxygen depletion, eutrophication, and increased turbidity in receiving water bodies. When released untreated, these effluents can severely degrade water quality (Forenshell, 2001; Miller and Semmens, 2002; Schulz *et al*., 2003). The cumulative effect of such discharges poses a serious threat to aquatic ecosystems, making water pollution one of the primary environmental challenges associated with aquaculture.

In recent years, there has been growing interest in implementing environmentally friendly and sustainable aquaculture practices, particularly through improved waste management strategies. Mathematical modelling of water quality has become an essential tool in the decision-making process for water resource management, with its use in environmental sciences dating back to the 1960s. These models and simulations enable rapid assessment of pollution by elucidating cause-and-effect relationships. One of the primary advantages of modelling is its capacity to analyse various future scenarios in real time (Erturk, 2005). As a result, model outputs can significantly inform decision-making processes, providing the ability to predict the environmental impacts of future developments and optimise strategies to mitigate negative effects on aquatic ecosystems.

2. Environmental Threats to the Development of Coastal Aquaculture

2.1. Effects of Domestic Wastes

The direct discharge of untreated domestic waste, including kitchen waste, faeces, and urine, poses significant threats to aquatic ecosystems. Industrial waste further exacerbates this issue, with the specific pollutants and waste materials varying according to the nature of the industry involved in the discharge. These pollutants contribute to increased microbial loads, nutrient enrichment, and contamination of both soil and aquatic environments (Oyelola and Babatunde, 2008). Additionally, such waste promotes the growth of bacteria by providing a suitable substratum. The ecological impacts are wide-ranging, including a decrease in dissolved oxygen levels, reduced biodiversity and species distribution, diminished water transparency due to suspended solids, and the onset of eutrophication (Harold, 1997). These consequences collectively degrade the health and functionality of aquatic ecosystems.

One significant consequence of the elevated microbial load in aquaculture systems is the increased susceptibility of cultured fish to various diseases, particularly in conditions of high stocking density. Nutrient enrichment within the ecosystem often leads to the excessive growth of phytoplankton and higher aquatic plants, resulting in algal blooms. Furthermore, the accumulation of undissolved solids can reduce light penetration in the water column, thereby inhibiting phytoplankton growth and disrupting the aquatic food web.

2.2 Effects of Pesticides

Pesticides are chemical agents designed to exert specific toxic effects on target pest species to which they are particularly sensitive (Zdenka *et al*., 1993). The term "pesticides" encompasses a wide range of chemicals, including insecticides, acaricides, herbicides, fungicides, algicides, and other agents used to manage unwanted organisms, excluding bacteria. From an environmental perspective, pesticides must be non-persistent to prevent the accumulation of harmful concentrations in various environmental compartments, which could lead to unforeseen ecological side effects.

2.3 Effects of oil and oil dispersants

Oil pollution has become one of the most pervasive contaminants in the Lagos lagoons. Oil, particularly crude oil, is a complex mixture containing thousands of compounds, many of which are toxic to aquatic organisms. These compounds behave differently in the environment—some dissolve in water, others evaporate at the surface, some form extensive slicks, while others settle on the seafloor, binding with sand to form globules (Laws, 1980). The effects of oil on aquatic organisms vary depending on the type of oil. According to Laws (1980), these effects can be categorised into two types: the first involves the physical coating or smothering of organisms, while the second relates to the disruption of metabolic functions due to the ingestion of oil. Hydrocarbons incorporated into the lipids or tissues of organisms at sufficient concentrations can disrupt physiological processes (Chukwu & Odunzeh, 2006).

Laws (1980) also noted that adult fish exhibit some resistance to oil contamination, as their bodies, including their mouths and gill chambers, are coated with a slimy mucus that prevents oil from adhering. However, crude and fuel oil have been found to be highly toxic to fish eggs at concentrations as low as 0.5 to 10 ppm. These challenges represent a significant threat to the sustainable development of coastal aquaculture.

2.4 Effects of Urban Development

Another significant environmental threat to the development of aquaculture is the rapid urbanisation of coastal communities. This urban expansion has rendered coastal lands that are suitable for aquaculture financially inaccessible to small-scale fish farmers. This phenomenon illustrates the adverse effects of urbanisation on coastal areas worldwide. Landowners are increasingly inclined to sell their properties to industrialists or property developers rather than to fish farmers. A notable example is the Lekki Peninsula in Lagos, which was once an ideal site for aquaculture. However, after extensive sandfilling, it is now dominated by commercial and residential developments.

2.5 Agriculture pollution

As aquaculture production expands, there is a corresponding increase in pollution and environmental degradation. The primary pollutants include dissolved nutrients, which can lead to localised eutrophication in water bodies. Additionally, particulate nutrients and uneaten feed settle on the seabed or pond floor, resulting in significant alterations to sediment chemistry and biological communities. Chemical pollutants, such as antifoulants used on boats, treatments applied to fish cage nets, medications, and the escape of farmed species, further exacerbate environmental challenges by altering the genetic composition of wild fish populations and negatively impacting biodiversity.

2.6 Impacts of eutrophication-related pollution

The release of nitrogen and phosphorus from fish cages and aquaculture ponds presents a constant risk of promoting eutrophic conditions. These nutrients can either directly stimulate phytoplankton growth by providing a readily available nutrient source or indirectly contribute to eutrophication through the removal of oxygen and the subsequent decomposition of waste solids. Whether a nutrient acts as a pollutant in an aquatic system depends on several factors, including whether it is a limiting nutrient in that particular environment, its concentration, and the ecosystem's carrying capacity. In freshwater systems, phosphorus is typically the limiting nutrient, meaning its availability controls the extent of primary production, such as algal growth. In marine environments, nitrogen serves as the limiting nutrient and plays a similar role. Elevated nutrient levels can lead to harmful algal blooms, which reduce water clarity and diminish sunlight penetration to other organisms. Additionally, when these algae die and decompose, they can deplete oxygen levels in the water column, further threatening aquatic life.

2.7 Genetic pollution

Escapes of juvenile or adult fish are a constant possibility if operational or technical failures occur at fish farms. In some cases, due to the large numerical imbalances of caged compared to wild populations, escapees raise important concerns about ecological and genetic impacts. Such impacts are very similar to those described in the case of stock enhancement and culture-based fisheries.

An Ecological Approach to Aquaculture

In 2006, the Fisheries and Aquaculture Department of the Food and Agriculture Organization (FAO) acknowledged the need for an ecosystem-based management approach to aquaculture, similar to the Code of Conduct for Responsible Fisheries. FAO proposed that an ecological approach to aquaculture should focus on three key objectives: human well-being, ecological well-being, and the achievement of both through effective governance, all within a scalable hierarchical framework applicable at farm, regional, and global levels (Soto *et al*., 2008). In 2008, FAO further defined an Ecosystem Approach to Aquaculture (EAA) as "a strategy for the integration of aquaculture within the wider ecosystem in such a way that it promotes sustainable development, equity, and the resilience of interconnected social-ecological systems." The EAA, like other ecosystem-based resource management frameworks, incorporates a wide range of stakeholders, spheres of influence, and interlinked processes. Implementing an ecosystem-based approach necessitates planning for physical, ecological, social, and economic systems as integral components of community development while considering the broader social, economic, and environmental stakeholders that influence aquaculture (Soto *et al.*, 2008). FAO outlined three principles and key considerations for the successful implementation of EAA at various societal levels.

Principle 1:

"Aquaculture should be developed within the framework of ecosystem functions and services, including biodiversity, without causing degradation beyond the resilience capacity of these systems." The critical challenge lies in determining resilience capacity, or the thresholds of "acceptable environmental change." Various terms have been employed to define these limits, such as "environmental carrying capacity," "environmental capacity," "limits to ecosystem functions," "ecosystem health," "ecosystem integrity," and "fully functioning ecosystems." Each of these concepts is shaped by specific social, cultural, and political contexts (Hambrey and Senior, 2007). Traditional environmental impact assessments address only a subset of these concerns. While the application of the precautionary approach remains important, it is often insufficient or misapplied by decision-makers in aquaculture. Instead, the adoption of aquaculture risk assessments is gaining traction as a more effective tool (GESAMP, 2008).

Principle 2:

"Aquaculture should improve human well-being and equity for all relevant stakeholders." To achieve this, aquaculture must provide equitable opportunities for development, ensuring that its benefits are widely distributed, particularly at the local level, without disadvantaging any segment of society, especially marginalised populations. Aquaculture plays a critical role in promoting both food security and food safety, essential components of human well-being, particularly for impoverished communities in developing countries. The contribution of aquaculture to human well-being extends beyond addressing hunger; it also supports local livelihoods by creating employment opportunities and fostering small businesses and local markets. However, in certain regions, particularly in parts of Latin America and Africa, the low cultural preference for fish consumption can act as a barrier to the successful development of small-scale or family-run aquaculture operations in rural areas.

Any new aquaculture project should prioritise the well-being of all stakeholders, particularly rural communities and the most vulnerable groups, ensuring that their conditions improve—or at the very least do not worsen, especially when environmental costs are involved. These costs should be accepted and addressed only if the sector provides significant social benefits. However, a comprehensive assessment of aquaculture's social, economic, and environmental impacts across different scales is seldom undertaken to evaluate the overall net effect and make informed decisions on project approval. In this context, defining ecosystem boundaries from both social and economic perspectives is essential, though it is far more complex than doing so for environmental purposes due to the expansive nature of aquaculture trade and the indirect effects linked to the provision of inputs such as seeds, feeds, and services.

Principle 3

Aquaculture should be developed within the broader context of other sectors, policies, and overarching goals. The interactions between aquaculture and its surrounding natural and social environments must be acknowledged. While aquaculture may have a smaller environmental footprint than other human activities, such as agriculture and industry, it does not occur in isolation. There are numerous opportunities to integrate aquaculture with other primary production sectors to promote resource efficiency, materials recycling, and energy conservation. This principle has been particularly evident in Asia, where integrated production systems—such as livestock-fish farming (Little and Edwards, 2003) and fish-rice production (Halwart and Gupta, 2004)—have been successful. Connections between aquaculture and fisheries, such as the production of fishmeal from capture fisheries (a service to aquaculture) or aquaculture-based fisheries benefiting from aquaculture innovations, are well documented but often not fully formalised or operationalised. However, negative interactions can arise, such as competition for markets or environmental damage from escaped farmed species, as seen with Atlantic salmon in Norway. Furthermore, terrestrial food production systems and industrial activities can adversely impact aquaculture through the degradation of water quality and availability, as well as potential risks to feed quality and safety (Hites *et al*., 2004).

Applying an Ecological Aquaculture Approach to Different Scales of Society

There are three physical scales important in planning for and assessing progress toward an ecosystem approach to aquaculture: farm scale, watershed/aquaculture zone, and global. Each has important planning and assessment needs.

Farm Scale

Regarding principle 1, Planning for aquaculture farms is often straightforward in terms of physical boundaries, typically extending only a few meters beyond the farming structures. However, the increasing scale and intensity of certain operations, such as large-scale shrimp or salmon farming, have the potential to impact entire water bodies or watersheds.

Concerns are mounting regarding the trajectory and rapid growth of industrial-scale operations for fed aquaculture. Traditional concerns about the environmental and social impacts of current aquaculture development models are evolving due to technological advancements. These innovations are facilitating the transition toward ecological aquaculture approaches. Projections suggest that by 2050, large-scale aquaculture may fully embrace ecological principles, integrating sustainability as a core component of its development.

Regarding Principle 2, Several issues are particularly relevant at the farm scale in aquaculture development. In regions where aquaculture is relatively new, the low local interest in and consumption of fish can present a significant bottleneck, hindering the growth of family-owned farms and limiting opportunities to enhance protein intake. At this scale, aquaculture has the potential to improve family livelihoods and create employment opportunities. However, the profitability for owner-entrepreneurs is often inequitable, and working conditions may be substandard, with issues such as gender discrimination and the use of unregulated child labour. Additionally, food safety concerns should ideally be addressed at the farm level, yet small-scale and rural farms frequently lack the necessary infrastructure, such as refrigeration, to implement proper safety measures and controls.

Principle 3, The integration of aquaculture with other sectors may seem less applicable at the farm scale; however, more efficient use of on-site and surrounding resources can still be achieved, as demonstrated in various examples from Asia. Integrated aquaculture at the farm level presents opportunities for synergistic interactions with other sectors, such as agriculture, thereby avoiding or minimising conflicts over resource use. However, in many Western countries, the integration of aquaculture with other coastal activities or the implementation of multitrophic aquaculture is often hindered by regulatory frameworks. In some cases, such practices are even prohibited, particularly in coastal marine areas. This regulatory environment can isolate individual aquaculture farms from other activities, thereby increasing the potential for conflicts with other users of coastal zones and aquatic resources.

Watershed/Aquaculture Zone Scale

Planning for an EAA at the watersheds/ aquaculture scale is relevant to common ecosystem and social issues such as diseases, trade in seed and feeds, climatic and landscape conditions, urban/rural development, etc. Assessment of an EAA at this scale will include,

1) Aquaculture should be included in regional governance frameworks, such as the overall framework of integrated coastal zone management or integrated watershed, land–water resource management planning and implementation. Assessments should consider existing scenarios, user competition and conflicts for land and water uses, and comparisons of alternatives for human development.
2) Impacts of aquaculture on regional issues such as escapes, disease transmission, and sources of contamination to/from aquaculture.
3) Social considerations such as comprehensive planning for all the possible beneficial multiplier effects of aquaculture on jobs and the regional economy, as well as considerations of aquaculture's impacts on indigenous communities.

Regarding Principle 1, while the environmental impacts of a single farm could be marginal, more attention needs to be paid to the ecosystem effects of collectives or clusters of farms and their aggregate, potentially cumulative contribution at the watershed/zone scale, for example, the development of eutrophication because of excessive nutrient outputs. Evaluations and monitoring of the overall effects of aquaculture (plus other sectors) at this scale are rare; a good example of this approach is the Modelling Of growing fish farms-Monitoring (MOM) system in Norway (Ervik *et al.*, 1997) and some pilot initiatives in Ireland (Ferreira *et al.*, 2007). Similarly, strategic environmental impact assessments are not common, while individual farm-oriented EIA is the norm and the basis of environmental regulations within the sector. A very relevant issue is that introductions of alien species or alien genotypes take place at this scale, which often has relevant impacts on biodiversity in whole watersheds. Similarly, disease outbreaks take place first at the farm scale but often need control and management at the watershed scale. Such management and mitigation necessarily require the watershed approach.

When aquaculture activities are not well planned and regulated, they can increase inequality at the watersheds scale and in the aquaculture zone region, therefore violating **Principle 2**. For example, some benefits can be felt upstream (which would be the case when there is more water and better quality) but not downstream. Aquaculture can create opportunities for a broad range of resource users; however, often, the sector does not offer equitable access to resources and benefits, failing to recognise that different stakeholders have different abilities/opportunities to access these. Increasing equity and well-being simultaneously will not always be possible, and over time, the balance between the two will change, and regional and local scale initiatives, especially those that promote well-being and equity, are often ignored. Ultimately, the transfer of benefits from regional, national, and other scales should get to locals in which aquaculture takes place.

Regarding Principle 3, in general, at the watershed/zone scale, the integration of aquaculture into other sectors' performance and development is difficult, and it does not happen in general. Perhaps Asia has been a special case where integration as a process seems to start at the farm scale without much planning for integration at the watershed. Although recommended and with theoretical potential, freshwater aquaculture use is seldom planned and developed in conjunction with irrigation and water resources enhancement (Haylor and Bhutta, 1997; Brugère, 2006). Watershed/zone scale activities and initiatives most often are not subsidiary to the wider context of the watershed, coastal zone and other integrated management policies and programmes, particularly those extending beyond administrative borders.

The global scale

Under **Principle 1**, core issues at a global scale include pressures on small pelagic fisheries for fishmeal to feed aquaculture; concerns for the unknown biogeochemical consequences of global net transport for elements such as nitrogen, phosphorus, and carbon (N, P, C) mostly from the southern hemisphere to the northern hemisphere, partly driven by aquaculture. Other relevant concerns are those related to the global environmental costs of aquaculture in terms of energy, water usage, carbon production, etc. Some relevant tools for the comparison of footprints of food sectors in general are being developed (Bartley *et al.*, 2007). Climate change will affect aquaculture development in the ecosystem context, and it is important to consider such effects at global scales (e.g. effects related to fish meal production) and also by regions considering particularities of each (droughts, floods etc.).

Following **Principle 2** on the global scale can be challenging. There is a need to improve the well-being of all relevant stakeholders within the context of transnational aspects of production, markets, and other decision-making (e.g. promoting global common standards and social policies/practices for international companies with activities in different countries). However, inequity can grow amongst producers (countries, regions) with very different capacities and technological development, particularly regarding the compliance of global standards. Opportunities on the global scale could compromise regional and local opportunities. On the positive side, the global scale offers an opportunity for the enforcement of food safety procedures to comply with global market demands.

The development of aquaculture in the context of other sectors, following **Principle 3**, becomes relevant at the global scale, when positioning food fish within the global food sector. Fish and aquatic proteins are increasing in human diets, and aquaculture is rapidly increasing its relevance to fulfil such demand. In parallel and consequently, competition with other food and energy sectors for vegetable proteins (feeds) is increasing (e.g. use of corn for biofuels), and competition for freshwater use with other food sectors will increase, especially under climate change scenarios. Therefore, there is a clear need for aquaculture to be integrated with other sectors, particularly other food sectors and those using aquatic spaces and aquatic resources on a global scale. The increasing requirements of protein for feeding the human population could be a main driver.

Table 1: **Summary of guiding principles, scales and major issues**

PRINCIPLES	**1**	**2**	**3**
SCALES	Aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation beyond their resilience.	Aquaculture should improve human well-being and equity for all relevant stakeholders.	Aquaculture should be developed in the context of other sectors, policies and goals.
Farm	Better/best management practices implemented at this scale. Large intensive farms may significantly alter local/site ecosystem functions. Farmed species escape and diseases take place and can be controlled at this scale. Integrated aquaculture can be an opportunity to mitigate environmental impacts.	Returns to local farmers are often unfair. Aquaculture can offer family improvement options and employment opportunities. Working conditions are not always adequate. Food safety can often be a concern at this scale, especially for small farmers.	Use of on-site and immediate surrounding resources more common in Asian countries (e.g. integrated agriculture aquaculture)
Watershed/zone	The environmental effects of farms are rarely being evaluated. Limited knowledge to define ecosystem resilience capacity. Diseases and	Unplanned/unregulated aquaculture activities could increase inequity. Often different stakeholders have different abilities/ opportunities to access	Lack of support and/or regulations for integrated aquaculture and multitrophic aquaculture. Local-scale activities most often are not subsidiary to the wider context

PRINCIPLES	1	2	3
	the establishment of alien species take place at this scale and could be prevented and mitigated.	resources and benefits from aquaculture. Increasing equality and well-being simultaneously will not always be possible. Transfer of benefits from regional, national, and other scales should get to the local scale. Local-scale initiatives promoting well-being and equity are often ignored.	of the watershed, coastal zone management policies and Programmes. Integration between different sectors is not facilitated from an ecosystem perspective.
Global	Increasing pressure on small pelagic fisheries for fishmeal to feed aquaculture. Unknown biochemical consequences of N, P, and C transport among regions partially driven by aquaculture. Climatic change affects aquaculture development in the ecosystem context.	Improving the well-being of relevant stakeholders within the context of trans-national aspects of production, and markets is a challenge and an opportunity. Food safety is globally enforced due to global markets. The development of global opportunities can compromise regional and local opportunities.	Fish and aquatic proteins are increasingly present in world diets, and aquaculture is rapidly becoming more relevant. Competition with other food and energy sectors for vegetable proteins (feeds) is also increasing. Competition for freshwater use with other food sectors will increase.

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