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**A Comparative Analysis of the Sustainability of Monoculture and Integrated Multitrophic Aquaculture (IMTA) Systems**

**Background Information:**

Aquaculture can be defined as the “breeding, rearing, and harvesting of fish, shellfish, algae, and other organisms in all types of water environments” (NOAA, 2019). Mainly involved in the production of commercially sold seafood like fish, seaweed, oysters, etc., aquaculture is also used in the production of pharmaceutical, cosmeceutical, nutraceutical, and ornamental products (Leal et al., 2016). Evidence of aquaculture being practiced thousands of years ago can be traced to ancient China (Nash, 2011). However, in the past few decades, large-scale aquaculture has become necessary to satisfy global demand for aquaculture products. Capture fisheries are unable to fulfil demand for fish production on account of depleted fish stocks due to overfishing (Correia et al., 2020). Moreover, fishery production has been plateauing since the late 1980s while the demand for fish is set to increase by 15% by 2030 as the global population grows (FAO, 2020). In 2018, 46% of fish was produced via aquaculture while the remaining 54% was caught via capture fisheries (FAO, 2020), demonstrating the reliance of the seafood market on aquaculture. Despite this, aquaculture has not been without its issues such as unfair pay (Bryceson, 2002), the introduction of invasive species, disease spreading amongst the farmed organisms, and the release of nutrient-rich waste into ecosystems (Primavera, 2006). These are examples of what have caused certain aquaculture practices to be deemed unsustainable. Thus, sustainability has become an important factor in aquaculture, leading to the development and pursuit of sustainable aquaculture.

**Introduction:**

Sustainable aquaculture can be defined as aquaculture that is environmentally, economically, and socially sustainable (World Bank, 2014). Requirements are listed in the criteria below:

* Environmental sustainability: The aquaculture practices should not significantly disrupt the ecosystem, cause loss of biodiversity, or cause substantial pollution (World Bank, 2014).
* Economic sustainability: The aquaculture practices should be a practical and feasible long-term business venture (World Bank, 2014).
* Social sustainability: The aquaculture practices should be socially responsible and benefit the communities it is involved in (World Bank, 2014).

These criteria are generally accepted as a way to define sustainable aquaculture. Due to the many variations in types of aquaculture and aquaculture setups, the specificities of the criteria may vary locally depending on aspects such as location, species, and local legislation (World Bank, 2014).

In aquaculture, both monoculture and integrated multitrophic aquaculture (IMTA) systems have been utilized and studied. Monoculture aquaculture systems are aquaculture setups in which only one species is farmed (Trivedi, n.d.). Monoculture systems allow the farmer to focus their efforts on producing a larger yield of a specific species to maximise profits, and comprise a large portion of the aquaculture industry (Alcott, 2018). IMTA systems are setups in which multiple organisms from different trophic levels are farmed (see Figure 1) (Correia et al., 2020). An example of an IMTA farm is farming salmon, kelp, oysters, and sea cucumbers together, where dissolved inorganic nutrient waste from the salmon is incorporated into the kelp’s biomass, smaller organic particulate waste is absorbed by the oysters, and larger organic particulate waste is consumed by the sea cucumbers. This reduces the release of nutrients, namely nitrates and phosphates, that can cause issues like eutrophication and dead zones when released in excess.



 Figure 1: diagram outlining an IMTA system (POM = particulate organic matter, DIN = dissolved inorganic nutrients) (Chopin et al., 2008)

Monoculture aquaculture and IMTA were chosen as the focus of this analysis as monocultures are very prevalent in aquaculture and IMTA has received more attention in recent years due to its potential to mitigate the effects of excess nutrients in aquatic ecosystems. This analysis will compare the general benefits and drawbacks of the aquaculture methods in relation to the criteria for sustainable aquaculture. As the trophic level cultivated has an impact on monoculture sustainability, where relevant, higher and lower trophic level monocultures were distinguished.

**Criterion 1: Environmental Sustainability**

Monoculture aquaculture has faced scrutiny over environmental concerns including its impact on biodiversity in the last few decades. One of the primary concerns is nutrient overloading from fish monoculture waste and unconsumed fish feed that creates eutrophic waters and dead zones. Eutrophication occurs when an overload of nutrients such as nitrates and phosphates are introduced into a body of water. The nutrients are then fed on by algae that grow rapidly in what is referred to as an “algal bloom” (USGS, 2019). Algal blooms prevent sunlight from penetrating the waters’ surface, which then prevents aquatic plants underneath the algae from photosynthesizing which kills them (NOAA, 2017). When all the nutrients in the water are consumed, the algae die and are decomposed by bacteria that consume dissolved oxygen from water in the process (USGS, 2019). This leads to the formation of dead zones and the loss of biodiversity, as the water no longer has the oxygen required to sustain organisms (USGS, 2019). Because many monocultures are high value fish monocultures that produce nutrient rich effluents (Trivedi, n.d.), eutrophication in areas with monocultures is a prevalent issue.

Lower trophic level monocultures do not have the same adverse environmental effects because they do not produce such nutrient-rich effluents and do not require feed with such high nutrient content. Some lower level trophic species, namely filter feeders (like many bivalves), do not require any feed at all and actively improve water quality by extracting nutrients from the water (Lovell, n.d.). Many aquatic plants have nutrient sequestering capabilities that can be useful in mediating eutrophication (Lynch Jr., n.d.). For example, seaweeds are marine microalgae that, like other plants, use nitrogen and phosphorus in photosynthesis (Mouritsen, 2018). In waters with high nutrient content due to non-aquacultural reasons like agricultural runoff, animal manure, and urban wastewater entering the water, aquatic plant monocultures can be useful in either mitigating or preventing the effects of nutrient overloading (i.e. eutrophication). This is particularly pertinent considering that in the US and in the EU, the primary sources of nutrient pollution in waterways are commercial fertilizers and animal manure, while urban waste water is the most significant source in coastal waters in South America, Asia, and Africa (WRI, 2009).

A large part of IMTA’s appeal can be attributed to its potential for sequestration of nutrients like nitrates and phosphates that originate from fish farming waste (Correia et al., 2020). IMTA takes the waste from one species (typically a fed finfish species) and uses it as feed and nutrients for growth by other species. Therefore, a large portion of the nutrients are not released into the ecosystem and are instead absorbed by organisms in lower trophic levels (Correia et al., 2020). This avoids eutrophication and the creation of dead zones. For this reason, IMTA is viewed as an environmentally desirable form of aquaculture. An example of IMTA’s success in maintaining water quality is seen in Sanggou Bay, China. Since the 1980s, aquaculturists in Sanggou Bay have used IMTA systems to farm a variety of species (Fang et al., 2016). Examples of Sanggou Bay IMTA setups include co-culturing abalone and kelp, co-culturing finfish, kelp, and bivalves, and co-culturing seaweed, clams, abalone, and sea cucumbers (Fang et al., 2016). This has maintained water quality in the area throughout the decades, as well as a diverse selection of aquaculture produce (Fang et al., 2016).

The structure of aquaculture farms can also have effects on biodiversity. Vertical aquaculture structures have been shown to increase biodiversity (Giangrande et al., 2021), and can be used in both monoculture and IMTA systems. One example is longlines, often used in the farming of aquatic plants and bivalves. Seaweeds are usually grown on longlines, and are vertical as they use the entire water column to grow (NOAA, 2020). These seaweed crops, whether part of an IMTA system or a monoculture, can provide safety and a space for aquatic animals to create nurseries (Schiffman, 2016). Some vertical aquaculture structures have also been shown to act as artificial coral reefs, as they can be colonized by epibenthic species and attract fish (Andersson et al., 2009). While vertical structures are often used in lower trophic level farming, such structures have not been implemented in fish monocultures.

Both IMTA and monoculture farming run the risk of allowing farmed species to escape if the aquaculture facility is connected to or in a body of water, although the issue largely pertains to species of higher trophic levels (i.e. finfish). Escaped fish from aquaculture sites can become invasive species in local ecosystems if the aquaculture site is directly connected to a natural body of water (Nichols, 2018). This can have significant effects on ecosystems as the escaped fish may compete with native species for resources or become predators of them (Tisdell, 2001), thus potentially causing harm to the ecosystem and local biodiversity. Genetic contamination of wild species is also of concern in fish escapes, particularly in salmon farming (SeaChoice, n.d.). Studies have shown that interbreeding of wild salmon and farmed salmon can lead to genetic diversity dilution, generational fitness degradation, and adaptation loss (SeaChoice, n.d.).

However, both IMTA and monoculture setups can greatly reduce the risk of fish escapes by investing in monitoring and observation technology as well as improved fish containment infrastructure (Cook, 2017). In Norway, utilizing new netting techniques and monitoring equipment like underwater drones and cameras has reduced fish escapes by allowing fast identification and response to any containment problems (Cook, 2017). Fish escapes can also be avoided through use of intensive land-based aquaculture. Intensive land-based aquaculture involves exerting high levels of control over the conditions of an aquaculture site situated on land and creating stocking density greater than that of the natural food web (Land Based Aquaculture Assessment Framework, n.d.). By keeping the farmed fish separate from a body of water, the risk of fish escaping into the ecosystem is greatly reduced. Alternatively, farming native species instead of non-native species would reduce the damage done to the ecosystem in the event of fish escapes, as the native species would not compete with wild organisms (Van Beijnen and Yan, 2019). However, the concern for genetic contamination would still be present in the case of escaped fish, as offspring of the farmed and wild fish could be less genetically suited to surviving in the wild (Monterey Bay Aquarium, n.d.). Farmed native species could also be used to restore depleted native species populations. While this is possible, all variables pertaining to species repopulation (including genetic contamination) must be considered and accommodated (Cochran-Biederman et al., 2014). As both IMTA and monoculture systems can farm native species and actively contain fish, the fish escape-related sustainability of the system depends more on the decisions of the aquaculturists (e.g. to farm lower trophic level species) than on the type of system used.

 Disease outbreaks have been a prevalent issue at aquaculture sites not only due to the impact on farmed organisms but also due to the impact on surrounding ecosystems. Certain diseases can thrive in aquaculture sites and spill over into the surrounding ecosystem, infecting wildlife (Bouwmeester et al., 2020). Higher trophic level monocultures, namely fish monocultures, typically experience more disease outbreaks than non-fish monocultures or IMTA systems due to poorer water quality (Neori and Nobre, 2012). This can be attributed to the greater quantities of waste produced by fish and their lack of a nutrient absorption mechanism. IMTA systems can be less prone to disease because the inclusion of bivalves in an aquaculture system can act as a barrier to disease (Lekang et al., 2016). Bivalves such as blue mussels can consume disease organisms and parasites in early life stages (Lekang et al., 2016).

**Criterion 2: Economic Sustainability**

Monoculture aquaculture systems are generally much less complicated to set up than IMTA systems because the conditions in the system only need to suit one species (Trivedi, n.d.). This usually means less equipment and capital are required to set up the system and easier maintenance. Monocultures allow the aquaculturist to focus their efforts on producing the maximum yield possible of a specific species. Because there is only one species to cultivate, it is easier to create optimal conditions for growth (Tisdell, 2001). This maximises profits, especially if the aquaculturist chooses to cultivate a high-value species. However, the lack of diversity in species can also be considered risky. With only one species being cultivated, there is only one revenue stream for the farm, and if any issues arise within the cultivated species there is a greater risk of losing revenue (Tisdell, 2001).

The multitrophic design of an IMTA system not only requires much more equipment and capital to establish than a monoculture system, but also more complex components in order for the system to function (Thomas, 2010). Such components include: more complicated aquaculture operations, increased business planning, and increased regulatory complexity (Thomas, 2010). The costs of equipment and expertise required to manage these complexities often make it financially impractical for smaller aquaculture farms to establish an IMTA system. If a farm is inexperienced in IMTA, it is at greater risk of generating losses due to technical mishaps in the production process. Additionally, the uncertainty of IMTA’s economic benefits due to a lack of real world application over a long period can make implementing IMTA seem risky to aquaculturists (Carras et al., 2019). On the other hand, IMTA can be considered less economically risky than a monoculture given its more diverse range of produce (Tisdell, 2001). Having a range of produce allows for more revenue streams and is less risky in the event of a given product generating less revenue than anticipated, or an issue occurring with one of the species being cultured (Tisdell, 2001). IMTA can further maximize farm utilization by farming species using the entire water column (Fang et al., 2016), increasing product cultivated per unit of volume. Species grown in IMTA systems may even experience additive effects. Mussels have been shown to grow up to 30% more surface space on their shells when grown in proximity to fish (Chopin, 2013), leading to potentially higher revenues.

From an efficiency perspective, IMTA allows for more produce to be grown for the same quantity of feed than a fish monoculture system does, due to the waste of one species being utilized as feed for another (Shpigel, 2017). IMTA can use extractive species in the IMTA system as feed for the higher trophic level species (Shpigel, 2017). Considering that acquiring fish feed is over 60% of the cost of intensive aquaculture, replacing even a portion of it with cheaper alternatives like the lower trophic level species being grown in an IMTA system reduces costs significantly (Shpigel, 2017). This was demonstrated in an IMTA system including *Ulva lactuca* and gilthead seabream, in which fish feed was replaced by a combination of 14.6% *U. lactuca* and 85.4% poultry feed (Shpigel, 2017). *U. lactuca* contains high protein levels and so allowed the cheaper and lower protein poultry feed to be used in combination to feed the gilthead seabream (Shpigel, 2017). The new feed met amino acid requirements of the fish and did not compromise fish performance (Shpigel, 2017). The cost of feed was reduced by $0.25 kg-1 and the overall cost of production decreased, with savings of $0.45 kg-1 of fish produced (Shpigel, 2017).

Feed costs for monocultures of higher trophic level species, namely carnivorous finfish, are much higher than for monocultures of lower trophic level species (Neori and Nobre, 2012). This is because lower trophic level species are far more efficient with resources than higher trophic level species (Neori and Nobre, 2012). For example, many bivalves are filter feeders that filter nutrients directly from water (Lovell, n.d.), and thus largely eliminate any costs of feed. Carnivorous finfish, on the other hand, require expensive feed containing fishmeal and fish oil, which make up the majority of feed costs (Mosig, 2018).

Monoculture farms have greater economies of scale than IMTA systems mainly due to the nature of monoculture systems and engineering relationships (Tisdell, 2001). As the size of the monoculture operation increases, the system’s circumference grows slower than its volume, and so the cost to produce one fish decreases. (Tisdell, 2001). This does not apply to IMTA, however, because increasing the size of operations in one trophic level does not directly cause operations or output in the other trophic levels to increase.

Consumers have been shown to prefer aquaculture produce from IMTA systems over other aquaculture systems, and have been shown to be willing to pay a premium price for IMTA produce, once they are informed of IMTA’s environmental benefits (Yip et al., 2016). In a study conducted in the US Pacific Northwest, consumers were shown to be willing to pay up to 9.8% more for IMTA farmed salmon (Yip et al., 2016). In another study conducted in Ireland, Italy, Israel, Norway, and the UK, consumers were also found to be willing to pay a premium price for IMTA produce (Osch et al., 2019). However, the study also showed that a large majority of consumers are unfamiliar with IMTA and need to understand it before they choose it over cheaper aquaculture produce from non-IMTA farms (Osch et al., 2019). Thus, in order for consumers to be willing to pay premium prices for IMTA produce they must first be exposed to information on IMTA. This could be achieved through marketing but significant expenditure on large scale marketing would be necessary to bring widespread public attention to IMTA. A method of allowing consumers to identify IMTA farmed produce when purchasing would also have to be implemented.

**Criterion 3: Social Sustainability**

As IMTA infrastructure is generally very costly to build (Buck et al., 2018), smaller aquaculturists and aquaculture farms are unlikely to have the resources necessary to set up an IMTA system. Economically disadvantaged communities and individuals are generally unable to utilize IMTA without external assistance, thus making IMTA inaccessible to many. However, if funded adequately, IMTA can provide local communities with job opportunities (Buck et al., 2018), particularly due to the more complicated nature of IMTA requiring more management. That said, a wide range of skills and knowledge is required for operation of an IMTA facility due to the complexity of the system (Buck et al., 2018). Investors in an IMTA facility may be inclined to hire skilled workers from elsewhere rather than spend time and resources training local workers.

Monoculture infrastructure can be far cheaper to set up than IMTA systems, and as monoculture systems can be more labour-intensive than capital-intensive, they can be a more practical and accessible option for economically disadvantaged communities and smaller aquaculture farms. Additionally, monoculture aquaculture only requires the skills and knowledge of how to culture one species, further increasing its accessibility to smaller aquaculture farmers. In Tanzania, monoculture aquaculture provides economic opportunities to villagers, especially women (Bryceson, 2002). However, large international corporations have developed a degree of monopoly power over the aquaculture market in Tanzania over the last few decades, subcontracting small aquaculturists and paying them very little (Bryceson, 2002).

As previously mentioned in the ‘Environmental Sustainability’ section of this report, fish monocultures can cause algal blooms and eutrophication due to excessive nutrient release. This not only has adverse environmental effects, it also can cause local drinking water to become tainted with toxic algae, leading to human illness if consumed (Chislock et al., 2013), Additionally, eutrophic water can harm tourism and recreation industries of affected communities due to the health risks and unpleasant smell associated with algal blooms (Priskin, 2008).

 Community acceptance of aquaculture facilities is a challenge for both IMTA and monoculture farms, as without it the farms themselves are not sustainable. Not In My Back Yardism (NIMBY) in the context of aquaculture refers to people opposing aquaculture sites in their own neighbourhoods, despite not opposing aquaculture itself (McCorquodale, 2020). NIMBY advocates typically oppose aquaculture equipment and facilities because they don’t want to allocate water and space in their community (McCorquodale, 2020). Larger facilities tend to attract more community opposition and can lead to regulation and processes that delay infrastructure and aquaculture facilities development. Aquaculture that does not require significant infrastructure is more likely to proceed in the face of NIMBY opposition but regardless, community engagement is key to mitigating this risk (Mayer, 2021). Thus, it may be easier to establish smaller monoculture systems in communities rather than IMTA systems, due to the generally larger structure of IMTA systems.

 Legal regulations are a major barrier in the establishment of aquaculture sites in general. In 1983, the US Joint Subcommittee on Aquaculture found that there were over 1200 state laws were involved in the overseeing of aquaculture, demonstrating the challenges of setting up and maintaining an aquaculture facility (Bowman, 2018). While the regulatory challenges of establishing a traditional monoculture farm are already significant, establishing an IMTA system is made even more difficult by the need to alter laws pertaining to disease transfer, fish health, and food safety to allow to existence of IMTA farms in certain places (Alexander et al., 2015).

It should be noted that due to the limited commercial use of IMTA, its social impacts are not clear. Further commercial implementation and research of IMTA is necessary to determine its social sustainability.

**Conclusion:**

Overall, IMTA generally seems the more environmentally sustainable system than monoculture aquaculture, in large part due to its design that allows for prevention of nutrient overloading from higher trophic level waste. In many areas, lower trophic level monocultures (e.g., bivalves and aquatic plants) also function effectively as nutrient-sequestering agents and do not release nutrients in the first place, making them potentially useful as a tool for bioremediation in eutrophic waters. Higher trophic level monocultures seem to be the least environmentally sustainable aquaculture method due to the nutrient overloading they cause and do not mitigate. Both IMTA and monoculture aquaculture can potentially experience fish escapes that can negatively impact the surrounding ecosystem and biodiversity. Both systems can also experience disease outbreaks that can spill over into surrounding ecosystems. However, both systems can reduce the risk of species or disease outbreaks with adequate containment technology and by farming lower trophic level species. Lower trophic level monocultures and IMTA systems utilize vertical structures that can be environmentally beneficial, while higher trophic level monocultures do not. Neither monoculture aquaculture nor IMTA perfectly adhere to the defined criteria for environmental sustainability, but IMTA appears to have greater environmental benefits and cause less environmental damage than monoculture aquaculture, higher trophic level monocultures in particular.

Monoculture aquaculture can be setup and maintained for far less capital than IMTA, allowing the aquaculturist to maximise profits by focusing all their resources on cultivating a single species. However, cultivating a single species can be risky as all of the farm’s profits depend on one market. IMTA maximises space utilization and creates multiple profit streams from multiple species, which could be considered less risky despite the costs of building and maintaining the system. IMTA farms can also feed more organisms for the same cost, a significant cost savings in comparison to higher trophic level monocultures (i.e. finfish), which require significant expenditures on fish feed. Lower trophic level monocultures require the least spending on feed as they essentially provide nutrients for themselves. Consumers have been shown to be willing to pay premium prices for IMTA farmed fish. It seems unlikely though, that they would do so on a wide scale due to their lack of awareness of IMTA and the difficulty to differentiate IMTA produce in the market. Furthermore, the costs of running an IMTA system are so high that it is an impractical option for small aquaculture farms. Monoculture farms have greater economies of scale than IMTA systems, making them more profitable than IMTA systems as operations grow. In summary, monocultures are more economically sustainable for the majority of aquaculturists as they are the more practical and feasible option. It also should be noted that while there are certain economically desirable aspects of IMTA, the lack of commercial IMTA makes it difficult to accurately determine its overall economic sustainability.

Monoculture farms are cheaper and simpler to build and manage than IMTA systems, making them more practical for small aquaculturists, particularly in low-income communities. Monoculture farms can provide these smaller aquaculturists with economic opportunities, even though in some areas large companies that have monopoly power over the aquaculture industry are still able to exploit smaller aquaculturists. IMTA could also potentially bring economic opportunities to communities where the IMTA system is built. An additional benefit is that IMTA can prevent degradation of local water supplies. However, because of the lack of commercial IMTA use, the social impacts of such investments are relatively unknown. Regulations surrounding aquaculture make it difficult to establish and maintain an aquaculture farm, with particular difficulty for IMTA farms. The NIMBY attitude towards aquaculture sites further complicates farm establishment for both monocultures and IMTA systems, although it is likely more difficult to set up and operate an IMTA farm rather than a small monoculture. All in all, monoculture seems to be the more socially sustainable option but further research into IMTA’s social consequences is necessary to be able to determine this with confidence.

 In assessing the overall environmental, economic, and social sustainability of monoculture aquaculture and IMTA, it seems that the sustainability of aquaculture systems is largely reliant on farming lower trophic level species. Higher trophic level monocultures have more detrimental environmental impact than either lower trophic level monocultures or IMTA. Despite higher trophic level monoculture’s apparent economic attractiveness, these environmental impacts likely will eventually require remediation and thus raise the cost. Similarly, the social benefit of higher trophic level monoculture for small aquaculturists is offset by the longer-term environmental degradation that higher trophic level monoculture brings. Future research should assess the potential to mitigate environmental damage of higher trophic level monocultures relative to improving the economics and social benefits of lower trophic level monocultures and IMTA.

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