A Multi-Criteria Decision Analysis of Species Selection for Integrated Multi-Trophic Aquaculture on Bonaire

Balancing Ecological, Biological, and Economic Criteria for System Design under Changing Environmental Conditions

Master's Thesis MSc Marine Sciences

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Abstract

This thesis assessed the potential for developing an Integrated Multi-Trophic Aquaculture (IMTA) system on Bonaire by identifying the most suitable combinations of fed, extractive, and ecosystem-restoring species under current and projected coastal environmental conditions. To achieve this, physicochemical seawater characteristics around Bonaire were quantified using global oceanographic datasets, and environmental tolerance ranges for candidate shrimp, seaweed, and mangrove species were compiled through an extensive literature review. These datasets were integrated into multi-criteria suitability matrices (MCSMs) that combined ecological, biological, and economic criteria.

Results showed that Bonaire's coastal waters are warm, saline, slightly alkaline, and well oxygenated, conditions favourable for tropical aquaculture. Under present-day conditions, the combination of *Penaeus monodon*, *Ulva lactuca*, and *Rhizophora mangle* provides the highest overall suitability, balancing productivity, environmental compatibility, and ecological value. Under projected climate scenarios, *Avicennia germinans* becomes the more resilient mangrove species, owing to its broader tolerance to salinity and pH. These results show that species performing well under current conditions may not remain suitable in the future, underscoring the need for adaptive IMTA designs.

Despite limitations such as reliance on literature-derived data, coarse-resolution environmental datasets, and simplified climate projections, the applied framework demonstrates the feasibility of IMTA development on Bonaire. The findings provide a transferable, science-based approach for balancing biological performance, environmental sustainability, and economic viability, supporting blue economy objectives and sustainable aquaculture expansion in small island contexts.

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Introduction

The growing global population continues to increase the demand for food. Aquaculture, the controlled cultivation of aquatic organisms such as finfish, crustaceans, molluscs, and aquatic plants, now supplies more than 50% of the seafood consumed worldwide (FAO, "The State Of World Fisheries And Aquaculture 2024", 2024; Khanjani et al., 2022; Ahmed & Thompson, 2018). Aquaculture is the fastest-growing sector in food production, expanding at an average annual rate of around 5-6%, compared with under 2% for terrestrial livestock production (FAO, "The State Of World Fisheries And Aquaculture 2024", 2024). This rapid growth is often referred to as the "blue revolution" (Khanjani et al., 2022; Hossain et al., 2022). Aquaculture is widely recognized as an important strategy for food security and poverty reduction, as it contributes to at least 7 of the 17 United Nations Sustainable Development Goals (UNSDGs). Especially UNSDG 14 is relevant, as it focuses on the conservation and sustainable use of oceans, seas, and marine resources (Explaining IMTA — ASTRAL Project, z.d.). By providing alternative sources of seafood, aquaculture can contribute to this goal by reducing fishing pressure on wild stocks and creating job opportunities in coastal communities (Hossain et al., 2022).

Over the 20-year period from 2000 to 2020, overall aquaculture production increased by 204%. Specifically, aquatic animal farming increased by 191%, and algae production grew more than threefold, totalling 36.5 million tons in 2022. In that same year, global aquaculture production also surpassed total capture production (harvesting aquatic animals from natural environments) for the first time (FAO, "The State Of World Fisheries And Aquaculture 2024", 2024). Despite the already immense growth, aquaculture production needs to increase fivefold over the next 50 years to keep up with the growing global population (Junda, 2018). This rapid expansion of aquaculture poses challenges to surrounding ecosystems and raises concerns about environmental impacts. First of all, excess feed and faeces produced by aquaculture organisms can cause significant nutrient loading in both marine and coastal ecosystems (eutrophication) (Hossain et al., 2022). These nutrients can induce exponential growth of phytoplankton or bacteria, leading to oxygen depletion in the water column (Khanjani et al., 2022; Liu et al., 2024). Secondly, pharmaceuticals, such as antibiotics and pesticides, are commonly used to control disease outbreaks and enhance productivity in aquaculture systems. The release of these compounds into surrounding water bodies can damage ecosystems and threaten human health (Liu et al., 2024; Martinez-Porchas & Martinez-Cordova, 2012). Thirdly, coastal aquaculture can lead to habitat changes when mangroves and wetlands are converted into farming sites, resulting in biodiversity loss (Khanjani et al., 2022). Besides these challenges, the availability of coastal space for aquaculture may become problematic in the future. Global sea-level rise is predicted to convert approximately 20% of coastal wetlands into marine areas, rendering them unable to support aquaculture (Hossain et al., 2022).

The challenges conventional aquaculture faces highlight the need for innovative, sustainable solutions. One promising alternative to traditional monoculture practices is Integrated Multi-Trophic Aquaculture (IMTA), which combines species from different trophic levels so that the waste from one species becomes a resource for another, promoting nutrient recycling and reducing environmental impacts (Hossain et al., 2022; Khanjani et al., 2022). In IMTA systems, species are typically divided into two functional groups: fed species, which are given external feed and produce nutrient-rich effluents, and extractive species, which absorb or filter these nutrients from the water. This ecological balance mimics natural food webs and reflects a shift from traditional monoculture to circular, ecosystem-based aquaculture (Khanjani et al., 2022; Hossain et al., 2022).

The potential of IMTA is particularly relevant in regions where local food resources are limited and dependence on imported food is high. The island of Bonaire is one such region. Although IMTA has been successfully introduced in various parts of the world, its suitability for Bonaire's specific environmental conditions remains unknown (Hossain et al., 2022; Explaining IMTA — ASTRAL Project, z.d.). In addition, the use of ecosystem-restoring species in IMTA systems has also not yet been studied, despite its potential to support marine ecosystem recovery. This knowledge gap is especially relevant for Bonaire, where limited local food production and growing pressure on marine ecosystems underscore the need for innovative, sustainable aquaculture solutions (Post & Hengsdijk, 2023; Meesters et al., 2025).

Therefore, the aim of this thesis is to assess the potential for developing an Integrated Multi-Trophic Aquaculture system on Bonaire. This leads to the following research question:

Which combinations of fed, extractive, and ecosystem-restoring species are most suitable for IMTA development on Bonaire, given current and projected coastal seawater conditions?

In order to answer this research question, the following sub-questions were formulated:

1. What are the current physicochemical characteristics of Bonaire's coastal seawater?
2. Which candidate fed, extractive, and ecosystem-restoring species are best suited for cultivation in an IMTA system on Bonaire?
3. How might projected climate change scenarios affect the long-term viability and resilience of IMTA species on Bonaire?

1. Background

1.1 Bonaire

Bonaire is a small island in the southern Caribbean, located approximately 80 km north of Venezuela (Fig. 1.1). The climate is subtropical, characterized by arid conditions and year-round warm temperatures. Its surrounding waters are warm and oligotrophic, housing coral reefs that support a great diversity of marine life (Openbaar Lichaam Bonaire, 2014; Van Oosterhout et al., 2023).

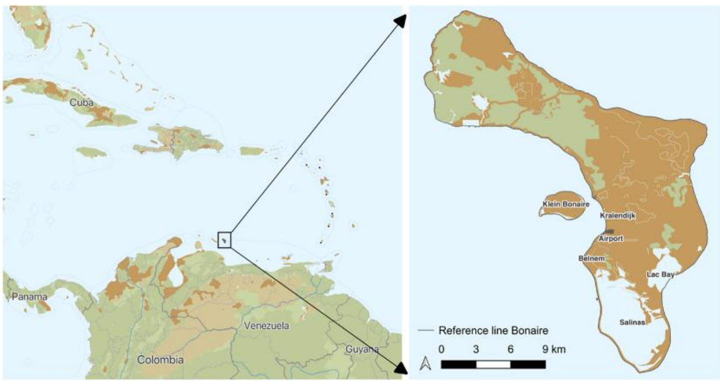


Figure 1.1. Bonaire, located in the Caribbean Sea (Van Oosterhout et al. (2023)

The island's limited size and lack of natural resources have led to a high reliance on imported products. Most food, particularly fresh produce, is imported and sold at high prices. The lack of a diversified local economy makes the island especially vulnerable to external shocks, such as the 2014 Venezuelan border closure and the COVID-19 pandemic. Both instances disrupted food supply chains and led to spikes in food prices, underscoring Bonaire's economic vulnerability and the need for local solutions. Strengthening local food production could improve Bonaire's resilience and reduce its dependency on imports. Because imported goods are costly, locally produced food can also be price-competitive, while the tourism sector could provide a consistent demand for high-quality products (Post & Hengsdijk, 2023; Van Oosterhout et al., 2023).

Although local policy strategies emphasize greater self-sufficiency in food production, past initiatives have frequently failed or proved non-scalable. Fisheries remain important for providing a source of local protein, yet no commercial aquaculture currently exists on Bonaire. The development of IMTA could therefore represent an alternative solution. Such a system has the potential to strengthen Bonaire's food security, reduce reliance on imported products, and make productive use of land that is unsuitable for agriculture or grazing (Openbaar Lichaam Bonaire, 2014; Post & Hengsdijk, 2023).

1.2 IMTA

Integrated Multi-Trophic Aquaculture (IMTA) builds on the principle of ecological complementarity, where species at different trophic levels are cultivated together to optimize resource use and minimize waste (Hossain et al., 2022). This bio-inspired approach imitates the natural roles and interactions of organisms in ecosystems, recreating natural food webs (Explaining IMTA — ASTRAL Project, z.d.). Rather than relying on a single species, IMTA uses multiple organisms to increase economic sustainability (Khanjani et al., 2022). The concept aligns closely with blue economy principles by promoting the responsible use of ocean resources while safeguarding ecosystem health (Explaining IMTA — ASTRAL Project, z.d.). Because IMTA is adaptable, its structure and species composition can be altered to different environmental conditions, production scales, and market demands.

1.2.1 Definition and mechanisms

The origins of IMTA can be traced back to traditional polyculture practices in Asia, where farmers discovered, through trial and error, that aquaculture "wastes" could serve as valuable resources (Troell et al., 2009). Modern IMTA applies this principle in designed systems that connect feed and extractive species through nutrient and energy flows. Depending on the system's design, this exchange between species can occur through gravity-fed flow, pumping systems, or shared water bodies (Khanjani et al., 2022).

In practical terms, IMTA systems are designed so that water carrying waste products from the fed species flows toward the extractive species (Khanjani et al., 2022). Fed species produce outputs such as uneaten feed, faeces, and dissolved inorganic nutrients, including ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), and carbon dioxide (CO_2). These outputs, which are usually considered pollutants, are utilized as resources by extractive species (Nardelli et al., 2018). Through this process, a functional connection is established between trophic levels: the fed species act as higher-trophic organisms providing essential inputs for lower-trophic organisms (Nardelli et al., 2018). This exchange of water, nutrients, and energy forms a feedback loop that not only supports nutrient recycling but can also recirculate 'clean' water back to the fed species, reducing water demand and effluent discharge (Khanjani et al., 2022; Samocha et al., 2015) (Fig. 1.2).

Extractive species can be categorized according to the type of waste they process. Organic extractive species primarily filter or trap suspended solids and organic matter, enabling the breakdown and recycling of particulate waste. Inorganic extractive species assimilate dissolved inorganic nutrients through photosynthesis, reducing eutrophication and improving water quality (Khanjani et al., 2022; Nardelli et al., 2018) (Fig. 1.2).

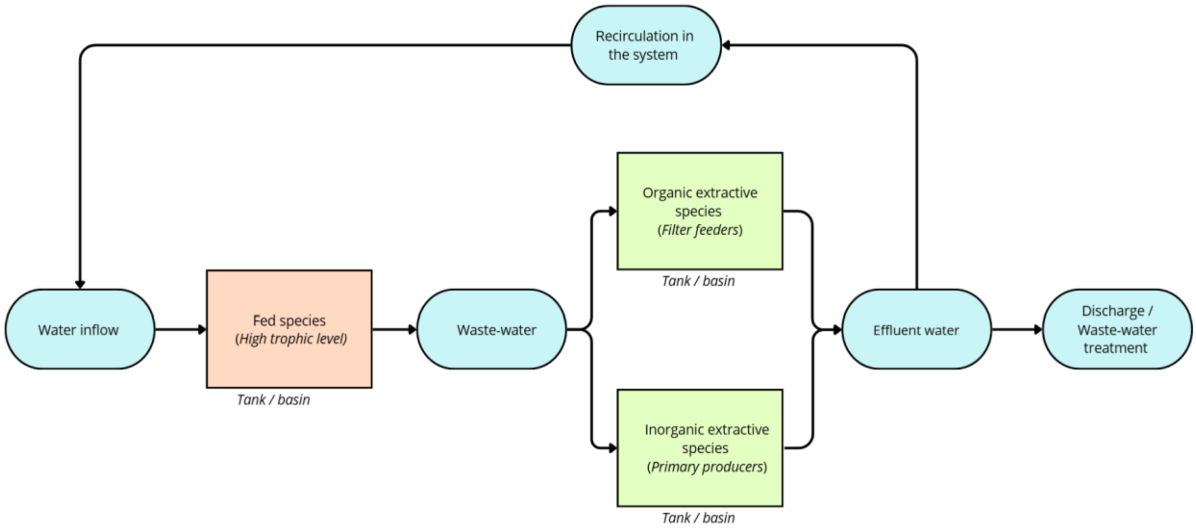


Figure 1.2. Schematic representation of an Integrated Multi-Trophic Aquaculture (IMTA) system. Fed species produce wastewater (uneaten feed, faeces, and dissolved nutrients), which are utilized by extractive species (organic and inorganic). Effluent water can either be recirculated within the system or discharged. Created by the author in Canva.

The design of an IMTA system is adaptable and context-dependent. It can be applied in marine or freshwater environments, whether inshore or offshore, or on land, using flow-through or recirculating aquaculture technologies (Khanjani et al., 2022; Explaining IMTA — ASTRAL Project, z.d.). Sea-based IMTA systems are typically open or semi-open setups in the ocean, where water flows freely between the cultured organisms and the surrounding environment. These systems rely on natural water exchange to transport nutrients from fed species to extractive species, and are often combined with existing coastal aquaculture (Khanjani et al., 2022; Buck et al., 2018). In contrast, land-based IMTA systems are closed or semi-closed facilities in which water movement and nutrient flows are controlled through tanks and pipelines. This allows for better regulation of environmental conditions, more efficient waste capture, and reduced risk of ecological contamination, though it generally requires higher infrastructure and energy inputs. In land-based systems, species may either be co-cultured within the same tanks or maintained in separate but connected units. The latter approach is more common, as it allows greater control over environmental conditions and prevents issues such as predation and interspecific competition. In these systems, nutrient recycling occurs without direct physical interaction between species (Khanjani et al., 2022; Batır et al., 2024). For Bonaire, land-based IMTA offers an advantage since much of the land is unsuitable for conventional agriculture (Post & Hengsdijk, 2023). This would make productive use of otherwise underutilized land while reducing pressure on wild fish stocks and harming marine ecosystems. This thesis, therefore, focuses on a land-based IMTA system with separate but connected tanks.

The control of water quality is another important aspect of IMTA design. Fed species excrete ammonium, in the ionized (NH_4^+) and un-ionized (NH_3) form, the latter being toxic to aquatic organisms. During nitrification, ammonium is converted to nitrite and nitrate, both of which can be toxic to aquatic organisms at high levels (Shpigel et al., 2019; Nardelli et al., 2018). Extractive species play a vital role in nitrogen removal. They preferentially absorb nitrogen as ammonium but switch to nitrite and nitrate when ammonium levels are depleted (Hossain et al., 2022; Nardelli et al., 2018). Similar attention is required for phosphorus management in IMTA. Even low concentrations of soluble phosphorus can drive eutrophication, which is why certain standard levels need to be maintained in systems with effluent runoff (Global Seafood Alliance, 2020). Suspended solids from feed and faeces also form challenges in these systems, as high concentrations can reduce water quality and increase the oxygen demand, thereby threatening the growth and survival of the fed species (Hossain et al., 2022).

1.2.2 Advantages and challenges

IMTA has multiple ecological advantages. Extractive species, often being photosynthetic organisms, can take up CO_2. This way, carbon gets stored in the biomass, which, if harvested, can remove CO_2 from the system (Khanjani et al., 2022). In addition, IMTA minimizes waste outputs by recycling nutrients within the system (Troell et al., 2009). Economically, IMTA generates multiple income streams by producing both fed and extractive species within the same system. This diversification provides "natural crop insurance", protecting farmers against possible disease losses or market fluctuations affecting a single species (Khanjani et al., 2022; Correia et al., 2020*;* Hossain et al., 2022). Extractive species cultured in IMTA systems could also serve as a partial food source for the fed species, thereby reducing total feed costs (Bolton et al., 2008; Samocha et al., 2015; Khanjani et al., 2022). The combination of high water-use efficiency and the potential for year-round production in stable climates makes IMTA particularly attractive in resource-limited regions (Hossain et al., 2022). From a social perspective, IMTA can contribute to local development by creating employment opportunities in farming, product processing, trade, and improving food security. IMTA can also improve public acceptance of aquaculture by demonstrating environmental responsibility and sustainability (Hossain et al., 2022; Khanjani et al., 2022).

Despite these advantages, several challenges remain. First, IMTA systems can be fragile. Failure of a single component compromises the entire system due to its dependence on interactions across multiple levels. A collapse in the extractive species crops, for example, could reduce nutrient recycling efficiency (Khanjani et al., 2022). The artificial and confined environment of intensive IMTA also makes the cultured species vulnerable to stress and disease outbreaks, particularly under conditions of overcrowding or poor water management (Khanjani et al., 2022*;* Ahmed & Thompson, 2018). Secondly, IMTA systems often depend on imported inputs such as feed, larvae, or seeds, leaving them susceptible to external price increases and supply shortages (Khanjani et al., 2022). Thirdly, IMTA systems may pose ecological risks to local ecosystems by potentially introducing exotic species if aquaculture organisms escape into the surrounding environment (Ahmed & Thompson, 2018).

1.2.3 Water quality

The development of an IMTA that uses seawater requires assessing local water quality, as water parameters strongly influence the growth and survival of cultured organisms. For fed species, the most critical factors include temperature, salinity, pH, and dissolved oxygen (Yusoff et al., 2024). Among these physicochemical parameters, dissolved oxygen is especially important, as oxygen deficiency directly affects respiration, metabolism, and growth. Suboptimal values of these parameters can also induce stress, reduce feeding efficiency, and increase susceptibility to disease (Yusoff et al., 2024; Hossain et al., 2022).

In contrast, extractive species are often photosynthetic organisms with different environmental requirements. While they also rely on suitable ranges of temperature, salinity, and pH, dissolved oxygen is less critical, as they generate oxygen through photosynthesis (Yusoff et al., 2024; Mohamed et al., 2023). Even if effluent water from the fed species has reduced oxygen levels due to respiration and decomposition, this typically does not limit their growth. Instead, the productivity of extractive species is more closely linked to nutrient availability, such as nitrate or phosphate (Yusoff et al., 2024; Huong et al., 2025). Because the surrounding waters of Bonaire are oligotrophic and naturally nutrient-poor, these resources are typically scarce in the marine environment. This is not an issue for the IMTA system, however, as nutrient-rich effluents serve as a nutrient source for the extractive species (Van Oosterhout et al., 2023).

1.2.4 Climate change

Due to its geography and topography, the Caribbean region is among the world's most vulnerable hotspots to climate change (Van Oosterhout et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) projects that the region will experience rising sea surface temperatures, ocean acidification, and shifts in precipitation patterns. These changes are expected to place additional pressure on small islands such as Bonaire, which has been recognized as particularly susceptible to anthropogenic stressors, including climate change (Van Oosterhout et al., 2023).

Recent climate events illustrate this vulnerability. The year 2024 was recorded as the warmest year to date in the Dutch Caribbean, with exceptionally high air temperatures. This was largely driven by the El Niño event that occurred between 2023 and the spring of 2024, ranking among the five strongest on record. Although conditions transitioned back to neutral later in the year 2024, sea surface temperatures in the Tropical North Atlantic still reached exceptional highs (NOAA et al., 2024).

For aquaculture and IMTA development on Bonaire, these projected and observed changes in environmental conditions have direct consequences. Rising sea surface temperatures, ocean acidification, declining dissolved oxygen levels, and changes in salinity could induce stress and hinder growth and survival in IMTA species (Van Oosterhout et al., 2023; Yusoff et al., 2024). This underlines the importance of selecting candidate species that are not only compatible with current physicochemical conditions but are also resilient to the anticipated impacts of climate change. Ensuring such resilience will be crucial for long-term success and sustainability of IMTA systems on Bonaire.

1.3 Selection of candidate species for IMTA on Bonaire

The successful design of an IMTA system depends on the careful selection of the species involved (Khanjani et al., 2022). For candidate species, preference should initially be given to native and regionally occurring species to minimise ecological risks (Lightner, 1999). However, many of Bonaire's native species have not been used in aquaculture and lack data on growth performance, husbandry requirements, and market value, making them uncertain choices for IMTA development. For this reason, globally established species with proven performance in aquaculture and IMTA systems will also be considered. For this thesis, candidate species were categorized into three species groups based on their ecological roles within the system: fed species, inorganic extractive species, and ecosystem-restoring species.

Within these groups, shrimp are considered as potential fed species, seaweeds as inorganic extractive species, and mangroves as ecosystem-restoring species (due to their role in habitat formation and coastal protection (Mangrove Maniacs Bonaire, 2021) with additional water-quality benefits (Fig. 1.3). However, mangroves also function as extractive organisms by trapping organic matter and absorbing dissolved nutrients (Kumara et al., 2023; De-León-Herrera et al., 2014*)*. They are classified separately from extractive species to provide a clear distinction between the groups in the IMTA system.

These taxa are selected based on multiple criteria that reflect both system performance and ecological relevance. For the fed and extractive components, shrimp and seaweed species are selected for their documented compatibility with IMTA systems. These groups have been widely studied and successfully combined in various IMTA setups, demonstrating efficient nutrient recycling, high productivity, and complementary trophic functions. Their selection is further supported by the availability of well-established physiological data for cultivation in controlled, tank-based environments, which aligns with the system design proposed in this research (Huong et al., 2025; Laramore et al., 2018; Explaining IMTA — ASTRAL Project, z.d.; Neori et al., 2004). In contrast, the inclusion of mangrove species as an ecosystem-restoration component was primarily driven by local ecological considerations. Mangroves are native to Bonaire and provide critical ecosystem services. Their integration into the IMTA system offers an opportunity to enhance water-quality regulation and support ongoing mangrove restoration initiatives on the island (Mangrove Maniacs Bonaire, 2021). Each group contributes differently to the overall system, yet all are interconnected through nutrient and energy flows (Fig. 1.3). Together, these species provide complementary ecological functions (production, nutrient recycling, and restoration), forming the foundation for a sustainable, context-specific IMTA system for Bonaire. Each species group (shrimp, seaweed, and mangrove) faces distinct challenges related to their environmental tolerances, disease susceptibility, and market demand. These challenges, along with specific ecological functions and cultivation requirements of each species group, are discussed in the following sections.

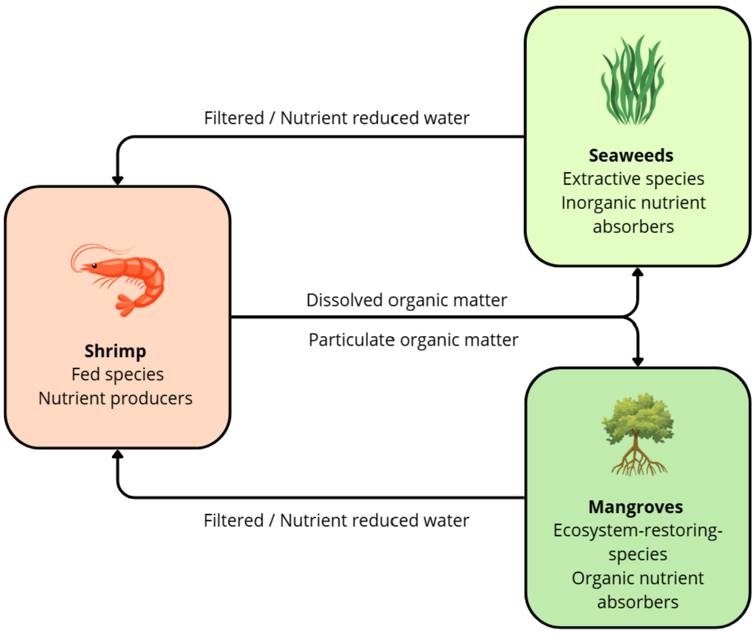


Figure 1.3. Schematic representation of nutrient and energy flows between candidate species groups in a land-based IMTA system for Bonaire. Created by the author in Canva.

1.3.1 Shrimp

Shrimp are an important aquatic commodity globally, representing the most widely traded seafood product, with worldwide production reaching approximately 5.6 million tons in 2023 (Global Seafood Alliance, 2023; Kumara et al., 2023). This economic significance highlights their suitability as a core species in IMTA designs, where they can combine high market value with ecological functionality.

Shrimp play a key role in IMTA systems as fed species. From an ecological perspective, they occupy the higher trophic level, where they serve as the primary drivers of nutrient input that sustains the lower-trophic-level organisms. Within an IMTA framework, shrimp are externally fed and subsequently release waste in the form of uneaten feed, faecal matter, and dissolved inorganic nutrients. Their feeding and excretion stimulate microbial activity, promoting the decomposition of organic matter and transforming particulate waste into dissolved nutrients. This microbial activity increases the availability of bioavailable nitrogen and phosphorus for primary producers (seaweeds and mangroves). Such interactions mirror those in natural estuarine food webs, where benthic detritivores enhance nutrient availability and support coastal productivity (Khanjani et al., 2022; Hossain et al., 2022).

The suitability of specific shrimp species depends strongly on environmental tolerances such as temperature, salinity, and pH (Yusoff et al., 2024). Species that can thrive under the physicochemical conditions of Bonaire's coastal waters are more likely to perform successfully in a local IMTA system. Dissolved oxygen tolerance is another factor influencing shrimp selection, as species differ in their sensitivity to low oxygen levels. Shrimp species should be able to tolerate the oxygen concentrations of Bonaire's coastal waters, ensuring normal growth and physiological performance under these natural conditions (Yusoff et al., 2024). Disease management is another critical aspect in determining suitability. Nearly 20 viral pathogens have been identified in penaeid shrimp, of which White Spot Syndrome Virus (WSSV), Yellow Head Virus (YHV), Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV), and Taura Syndrome Virus (TSV) are considered to be the most pathogenic. These viruses have caused major disease outbreaks and economic losses worldwide, with WSSV and YHV particularly affecting Asia, and TSV and IHHNV impacting shrimp production across the Americas (Briggs et al., 2004; De Alaiza et al., 2022). The introduction of non-native species has been linked to the spread of these viruses across aquaculture regions, underscoring the importance of robust biosecurity measures. To mitigate these risks, specific-pathogen-free (SPF) or pathogen-resistant (SPR) shrimp strains are commonly used in aquaculture and should be prioritized for IMTA development (Briggs et al., 2004; Lightner, 1999*)*. Feed Conversion Ratio is also a key parameter for evaluating species suitability, as it indicates how efficiently feed is converted into biomass. It is defined as the amount of feed required to produce a unit of shrimp biomass. Species with lower FCR values contribute to more efficient production and reduced waste generation, whereas those with higher FCRs may release more nitrogen, phosphorus, and organic matter. In aquaculture, preference is usually given to species with a lower FCR (Yusoff et al., 2024). However, for this IMTA design, a higher FCR is favourable, as it increases nutrient outflow for extractive species. In general, species with a longer history of domestication tend to exhibit lower FCRs than less domesticated species, reflecting improved feed efficiency through selective breeding and optimized culture practices.

Among shrimp species, those in the family Penaeidae are the most widely farmed worldwide in aquaculture and IMTA systems (Ghaffari et al., 2014; Waiho et al., 2024). For this study, three penaeid species were considered as potential candidates for Bonaire: *Litopenaeus vannamei* (Whiteleg Shrimp), *Penaeus monodon* (Tiger Shrimp), and *Penaeus schmitti* (Southern White Shrimp). The Whiteleg and Tiger Shrimp are the most commercially important species globally and have demonstrated compatibility with extractive species in IMTA systems (Ghaffari et al., 2014; Waiho et al., 2024). However, neither is native to the Caribbean, raising ecological and environmental concerns (Khafage et al., 2019; Liao & Chien, 2011). As a regional alternative, *P. schmitti*, which occurs naturally in nearby Venezuelan water, raises fewer concerns and has been cultured under controlled conditions, although not yet within IMTA systems (Alio et al., 1999). Although several shrimp species occur naturally in Bonaire's coastal waters, none have been commercially cultivated or hold significant market value, which is why they have not been selected as candidate species. Other native species, such as small finfish, crabs, or locally occurring crustaceans, have also been considered for this research. Theoretically, they could serve as fed species within an IMTA framework. However, these organisms have not yet been tested in such systems and lack established culture protocols, performance data, or commercial markets.

1.3.2 Seaweeds

Seaweeds form the base of the trophic structure in IMTA systems, serving as primary producers that utilize dissolved inorganic nutrients released by fed species *(Khanjani et al., 2022; Hossain et al., 2022)*. Through photosynthesis, they assimilate ammonium, nitrate, and phosphate, converting these 'wastes' into oxygen and biomass. Their high nutrient demand makes them grow suboptimal in oligotrophic waters like those surrounding Bonaire, but within an IMTA system, this becomes an advantage, as they efficiently absorb the nutrient-rich effluents produced by fed species (Nardelli et al., 2018; Mohamed et al., 2023*)*. Seaweeds also increase oxygen concentrations, stabilize water pH, and store carbon in their biomass. The efficiency of these ecological services depends largely on species-specific traits, such as nutrient uptake rates, growth performance, and environmental tolerance. Optimal performance requires that seaweed species thrive under the temperature, salinity, and pH conditions of Bonaire's coastal waters (Khanjani et al., 2022; Nardelli et al., 2018). Seaweeds generally exhibit lower susceptibility to pathogens than animal aquaculture species, largely due to their simple structure and natural antimicrobial defences. Despite the lower susceptibility, they are not entirely disease-free, and it still remains important to select seaweed species with strong pathogen resistance. Certain bacterial infections and epiphytic algal growth can still affect productivity (González et al., 2021; Vinuganesh et al., 2022).

Globally, species from the *Ulva* (Chlorophyta) and *Gracilaria* (Rhodophyta) genera are among the most frequently used in IMTA systems due to their high nutrient assimilation capacity and rapid growth. Seaweeds are also commercially significant, with global production values at USD 17.14 billion in 2023 and projected to reach 34.56 billion by 2032, driven by expanding applications in food, animal feed, nutraceuticals, pharmaceuticals, cosmetics, and biofuels (Commercial Seaweed Market Size, Share | Forecast [2032], z.d.; Khanjani et al., 2022 & Neori et al., 2004)

Several seaweed species occur naturally within Bonaire's coastal environment, including *Ulva lactuca* (sea lettuce) and *Gracilaria foliifera* (| Dutch Caribbean Species Register, z.d.). *Ulva lactuca* is particularly promising because it is indigenous to Bonaire, thrives in nutrient-rich, warm-water conditions, and has already been successfully incorporated into subtropical IMTA systems (Nardelli et al., 2018; Laramore et al., 2022). *Gracilaria foliifera* has potential for agar production but has not yet been tested under IMTA conditions. While prioritizing native species reduces ecological risk, selecting suitable seaweed species for IMTA must also consider nutrient uptake efficiency, growth performance, and economic potential (Osman et al., 2017). Therefore, in addition to native species, *Gracilaria tikvahiae* represents a regionally adapted candidate. Although not indigenous to Bonaire, it is native to the wider Caribbean and Western Atlantic, and its environmental tolerances are therefore likely to match Bonaire's conditions (Rocha et al., 2018). It has been successfully cultured in shrimp-based IMTA systems and holds strong market value in the global agar industry (Osman et al., 2017); Kim et al., 2017; Samocha et al., 2015). Another benefit that these species have is their ability to grow unattached to any substrate, making them suitable for aquaculture setups (Bolton et al., 2008)

1.3.3 Mangroves

Mangroves function as ecosystem-restoring species within this IMTA system, providing ecological services that complement nutrient cycling and water-quality regulation. They are halophytic trees and shrubs adapted to saline, waterlogged, and low-oxygen environments, typically occurring in intertidal zones (Kumara et al., 2023; Rahman et al., 2020). In these areas, mangroves contribute to coastal protection, sediment stabilization, and carbon storage, while supporting diverse marine life by providing shelter and nursery habitats (Van Der Geest et al., 2025). Beyond direct nutrient uptake, mangrove root zones host complex microbial communities that drive processes such as nitrification, denitrification, and organic matter mineralization. These microbial interactions transform dissolved and particulate wastes from fed species into forms that can be reabsorbed or removed from the system, effectively closing the nutrient loop. In this way, mangroves function not only as nutrient sinks but also as filters that stabilize the water quality (Kumara et al., 2023; Rahman et al., 2020).

While mangroves are not commercially valuable like the other IMTA components, their integration adds an important ecological restoration dimension. Studies in South and Southeast Asia, where mangroves have been incorporated into shrimp pond systems (often referred to as silvo-aquaculture), have demonstrated that mangroves can assimilate nitrogen and phosphorus from effluent water, enhance sediment stability, and improve overall water quality (De-León-Herrera et al., 2014; Moroyoqui-Rojo et al., 2012). These findings highlight their potential role in IMTA systems designed not only for production but also for environmental restoration.

In the context of Bonaire, the inclusion of mangroves in IMTA development is particularly relevant due to the island's vulnerable coastal ecosystems and increasing anthropogenic pressures (Van Oosterhout et al., 2023). Mangrove restoration is already an active conservation effort on Bonaire, where seedlings are collected, cultivated in nurseries within the mangrove forest, and later planted into degraded coastal areas (Mangrove Maniacs Bonaire, 2021). Mangrove species reproduce through vivipary, meaning their seeds germinate while still attached to the parent tree, developing into buoyant seedlings known as propagules. Once detached, these propagules disperse through tidal currents, allowing them to be naturally collected from the water for restoration purposes. However, propagules that remain in the natural environment face high mortality rates due to drying out, stranding in unsuitable substrates, or being washed away before they can establish roots (Duke & Allen, 2006; Allen & U.S. Department of Agriculture, 2002). Cultivation of propagules in controlled nurseries greatly increases survival rates and promotes stronger early-stage growth (Duke & Allen, 2006). While this approach has been successfully applied in traditional nurseries, it has not yet been explored within an IMTA context. Integrating mangroves into IMTA systems could serve as an innovative extension of ongoing restoration efforts, functioning as a controlled nursery environment where propagules grow under nutrient-rich conditions. They can then be transplanted into priority restoration areas, thereby helping the mangrove rehabilitation efforts on Bonaire.

Only native species are suitable for this purpose, as they help maintain local biodiversity. Three mangrove species occur naturally on Bonaire: *Rhizophora mangle* (Red Mangrove), *Avicennia germinans* (Black Mangrove), and *Laguncularia racemosa* (White Mangrove) (Van Der Geest et al., 2025; Dutch Caribbean Species Register, z.d.). Among these, *R. mangle* and *A. germinans* dominate local mangrove forests, accounting for approximately 99% of Bonaire's mangrove cover (Mangrove Maniacs Bonaire, 2021). Both species are highly valued for their ecological roles but face ongoing habitat degradation, making them priority candidates for restoration-based integration into IMTA systems. When selecting the most suitable mangrove species for IMTA, their tolerance to seawater parameters (temperature, salinity, and pH) is important, as preference will go to the most resilient species. Mangroves also exhibit a high degree of pathogen resistance, but fungal infections and leaf blight can occasionally occur under poor water conditions (Duke & Allen, 2006; Allen & U.S. Department of Agriculture, 2002; Alleman & Hester, 2011). So, when selecting species, preference should be given to mangroves with strong physiological resistance to disease and environmental stress, reducing the likelihood of pathogen introduction within the IMTA system.

2. Methods

This study used a multi-step approach, integrating environmental data analysis, a literature review, and multi-criteria decision modelling to assess the suitability of candidate shrimp, seaweed, and mangrove species for the development of Integrated Multi-Trophic Aquaculture (IMTA) on Bonaire. First, long-term oceanographic datasets were processed to characterize the current physicochemical conditions of Bonaire's coastal waters (Section 2.1). These conditions were then compared with species-specific environmental tolerance ranges collected from peer-reviewed literature (Section 2.2.1-2.2.2). Then, a multi-criteria decision analysis framework (Section 2.2.3) was used to evaluate species suitability by combining ecological, biological, and economic criteria. Finally, projected climate impacts were incorporated to assess potential shifts in suitability under future scenarios (Section 2.3).

2.1 The physicochemical characteristics of Bonaire's coastal seawater

To characterize physicochemical conditions of Bonaire's coastal seawater, data collection and visualization were conducted for all key water quality parameters (Section 1.2.3). Long-term datasets were collected from publicly available oceanographic monitoring programs (Table 1.2), providing both historical and current information derived from satellite observations and *in situ* measurements. These datasets were processed and visualized to generate representative climatological patterns for parameters relevant to IMTA development: temperature, salinity, dissolved oxygen, pH, and nutrient concentrations.

2.1.1 Sea surface temperature

Sea surface temperature (SST) data was retrieved from the World Ocean Atlas (WOA23, 1955-2022), a product of the National Oceanic and Atmospheric Administration (NOAA) (Table 2.1), which gathers global *in situ* measurements (shipboard casts, buoys, Argo floats) and interpolates them on a 1° x 1° latitude-longitude grid at standard depth levels []. Data were extracted for the grid cell nearest to Bonaire's coast (12.15° N, 68.27° W; note that WOA uses a 0-360° longitude convention, corresponding to 291.73° E). To complement the climatological WOA SST data, monthly SST records (1982-2022) were obtained from the Optimum Interpolation Sea Surface Temperature (OISST) v2.1 dataset, which integrates satellite and *in situ* observations []. OISST data were accessed via de NOAA ERDDAP server for the grid cell at 12.15° N, -68.27° W, representing conditions near Bonaire's coast. All data were downloaded in NetCDF format and processed using R (version 4.3.1) with the packages 'ncdf4', 'tidyverse', 'lubridate', 'rerddap', and 'ggplot2'. Longitude and latitude indices for Bonaire were identified, and temperature values were extracted from the surface layer (depth index 1), representing sea-surface conditions. Time variables, originally expressed as numeric timestamps (days since 01/01/1970), were converted into standard calendar dates (YYYY-MM-DD). Monthly and annual means were computed to show interannual SST trends, while climatological monthly averages were used to depict the typical seasonal cycle near Bonaire.

2.1.2 Dissolved oxygen

For dissolved oxygen (DO), seasonal climatology data from WOA23 were also used. They were spatially subset to a regional bounding box encompassing Bonaire (11.7°-12.7° N, 68.8°-67.8° W) and vertically restricted to the upper 50 meters of the water column. Within this box, all grid cells were extracted at each standard depth level and averaged to produce a single vertical DO profile per season (Q1-Q4). Concentrations were converted from µmol kg^{-1} to mg L^{-1} using a molecular-weight conversion factor (1 µmol kg^{-1} = around 0.0319988 mg L^{-1}). The resulting multi-decadal seasonal profiles (1955-2017) represent typical background oxygen conditions in the region and were visualized as seasonal depth profiles using 'ggplot2'.

2.1.3 Sea surface salinity

Sea surface salinity (SSS) data, collected from CMEMS (Table 2.1), were processed and analysed in R (version 4.3.1) using the packages 'ncdf4', 'tidyverse', 'lubridate', and 'ggplot2'. The NetCDF files were imported, and variables corresponding to longitude, latitude, time, and sea surface salinity were extracted. The dataset was set to the grid cell nearest to Bonaire's coast (approximately 12.15 ° N, 68.27 ° W) and limited to the surface layer (0.49 m depth), which represents the shallowest available model level in the CMEMS reanalysis. This layer was selected because it is closest to the sea surface conditions and therefore most relevant to IMTA. Time variables, originally expressed as numeric timestamps (seconds since 01/01/1970), were converted to standard calendar dates (YYYY-MM-DD). For each month, mean salinity values were calculated, followed by the calculation of annual means and monthly climatological averages across 2015-2022. Seasonal and interannual patterns in salinity were visualized using 'ggplot2', including an annual mean trend plot and climatological seasonal cycle plot. This workflow provided an analysis of nearshore salinity for Bonaire.

2.1.4 pH

pH data were extracted from the GLODAPv2.2016b Mapped Climatologies (Table 2.1), a gridded dataset that provides mean carbonate system variables derived from ship-based seawater chemistry measurements []. This dataset combines thousands of *in situ* observations of dissolved inorganic carbon, total alkalinity, nutrients, and related variables, which are then interpolated on a 1° x 1° latitude-longitude grid. Among the variables available, the parameter 'pHtsinsitutp' was selected. This variable represents pH measured at the actual temperature and pressure of the seawater sample (*in situ*), rather than being standardized to fixed laboratory conditions. Temperature and pressure strongly influence the chemical equilibrium of dissolved carbonates in seawater, which, in turn, affects pH. Therefore, using the 'pHtsinsitutp' variable provides a more realistic depiction of the pH conditions truly experienced by marine organisms in Bonaire's coastal waters. Data was downloaded in the NetCDF format and analysed in R (version 4.3.1) using the packages 'ncdf4', 'raster', 'dplyr', and 'ggplot2'. Longitude, latitude, and depth variables were extracted from the NetCDF file, and the grid cell closest to Bonaire's coast was identified (approximately 12.15° N, 68.27° W). The vertical profile of the pH variable was then extracted for this location and restricted to the upper 50 meters of the water column. The extracted data were collected into a tidy data frame, filtered to remove missing or invalid values, and visualized as a vertical pH profile (pH vs. depth). This profile provides a representation of the mean pH conditions (1972-2013) near Bonaire.

2.1.5 Nitrate and phosphate

Seasonal climatologies of nitrate (NO_3^-) and phosphate (PO_4^{3-}) were obtained from the World Ocean Atlas 2023 (WOA23, 1955-2022) (Table 2.1). These datasets provide global distributions of nutrient concentrations derived from *in situ* oceanographic measurements, interpolated onto a 1° x 1° latitude-longitude grid at standard depth levels. For both nitrate and phosphate, data were spatially set to a regional bounding box surrounding Bonaire (11.7°-12.7° N, 68.8°-67.8° W) and vertically restricted to the upper 50 meters of the water column, corresponding to the productive surface layer relevant to IMTA. Data were downloaded in NetCDF format and analysed using R (version 4.3.1) with the packages 'ncdf4', 'dplyr', and 'ggplot2'. Longitude, latitude, and depth dimensions were extracted, and the seasonal climatology files corresponding to each other (Q1: Jan-Mar, Q2: Apr-Jun, Q3: Jul-Sep, Q4: Oct-Dec) were loaded. Within each seasonal dataset, all grid cells within the defined spatial domain were averaged to produce a single mean nutrient profile per season. Concentrations originally reported in µmol kg^{-1} were converted to mg L^{-1} using molecular weight conversion factors of 0.0620 for nitrate and 0.0950 for phosphate. Mean concentrations were calculated for each standard depth level (0-50 meters), and seasonal profiles were collected into a single dataset for visualization. The resulting seasonal vertical profiles (mean concentration vs depth) showed mean nutrient distributions for Bonaire's coastal waters. Data visualization was performed in 'ggplot2' using line and point plots, with color-coded seasonal groupings to show vertical and seasonal variability in nutrient concentrations.

Table 2.1 Overview of seawater parameters, data sources, and visualization approaches used for Bonaire's coastal water characterization.

Parameter	**Dataset Source**	**Visualization**	**Temporal coverage**
Sea Surface Temperature (SST)	World Ocean Atlas (WOA), National Oceanic and Atmospheric Administration (NOAA)	Climatological monthly cycle plots; Monthly time-series (2015-2022); Annual mean trends	1972 – 2022
Sea Surface Salinity (SSS)	Copernicus Marine Environment Monitoring Service (CMEMS)	Climatological seasonal cycle plots; Annual mean trends	2015 – 2022
pH	Global Ocean Data Analysis Project v2 (GLODAPv2)	Vertical profile plots (mean values with depth)	1972 – 2013
Dissolved Oxygen (DO)	World Ocean Atlas (WOA)	Annual mean vertical profile; Seasonal depth profiles	1955 – 2022
Nitrate (NO_3^-)	World Ocean Atlas (WOA)	Seasonal depth profiles	1955 – 2022
Phosphate (PO_4^{3-})	World Ocean Atlas (WOA)	Seasonal depth profiles	1955 – 2022

2.2 Species' suitability

2.2.1 Species tolerance ranges

To assess the suitability of the candidate species for IMTA on Bonaire, a literature-based analysis was first conducted to determine the environmental tolerance ranges of the candidate shrimp, seaweed, and mangrove species, and to compare them with the physicochemical characteristics of Bonaire's coastal waters. Data were gathered for three shrimp species (Litopenaeus vannamei, Penaeus monodon, and Penaeus schmitti), three seaweed species (Ulva lactuca, Gracilaria foliifera, and Gracilaria tikvahiae), and two mangrove species (*Rhizophora mangle* and *Avicennia germinans*) (see Section 1.3).

The tolerance ranges for each environmental parameter (temperature, salinity, pH, and dissolved oxygen) were obtained from peer-reviewed studies. The reported minimum and maximum values were first averaged within each study to obtain a single mean value per parameter and species. When multiple studies were available for a given parameter, all were included to capture the full range of variability. Study-level means were then averaged across the studies to get an overall mean tolerance value per parameter.

This approach prioritized data quality over quantity, while acknowledging the possible limited availability of tolerance data. The number of studies, regional classification, and research methods were listed for each parameter and species. Preference was given to studies from (sub)tropical regions comparable to Bonaire's environmental conditions, as well as to more recent publications (post-2000). When such data were unavailable, older or geographically broader studies were included to ensure sufficient coverage.

2.2.2 Comparison of tolerance ranges with the physicochemical characteristics of Bonaire's coastal seawater

The collected environmental tolerance ranges for the candidate species were compared to the physicochemical characteristics of Bonaire's coastal seawater, determined in Section 2.1. They were then visualized using grouped bar charts created in Microsoft Excel. For each species and parameter, the means per study were averaged across studies to obtain an overall mean. To represent variability, propagated standard errors (SE) were calculated, reflecting uncertainty arising from using multiple sources. The mean values were depicted as bars, and the standard error (SE) was depicted as error bars.

The following formulas were applied in Microsoft Excel:

- Mean per study: =AVERAGE(min,max)
- Overall mean: =AVERAGE(range_of_study_means)
- Standard deviation: =STDEV.S(range_of_study_means)
- Standard error: =SD/SQRT(COUNT(range_of_study_means))

2.2.3 Multi-Criteria Suitability Matrix

To evaluate the relative suitability of candidate shrimp, seaweed, and mangrove species for IMTA on Bonaire, a weighted multi-criteria decision-making (MCDA) approach based on the Analytical Hierarchy Process (AHP) was applied to develop multi-criteria suitability matrices (MCSMs). These matrices integrate information from peer-reviewed literature and oceanographic datasets, providing a structured analysis of the combined scientific knowledge. Ecological, biological, and economic factors were combined into a single scoring framework to capture the multi-dimensional nature of IMTA suitability.

This approach used a set of ecological, biological, and economic criteria, each assigned a relative weighting according to its importance for aquaculture performance and system functioning. This matrix-based method has been widely applied in aquaculture to balance trade-offs between environmental suitability and production potential []. A multi-criteria framework was selected over simpler single-criterion approaches because IMTA suitability depends on the interaction of diverse ecological and economic factors, and no single parameter alone can represent this.

2.2.3.1 Criteria selection

Suitability criteria were selected based on their relevance to aquaculture performance, environmental compatibility, and market potential, as discussed in Section 1.3. Core criteria that were applied to all three groups' species were: native occurrence on Bonaire; previous use in IMTA practices; pathogen resistance; and environmental suitability for temperature, salinity, and pH. For shrimp species, two additional criteria were included: the effluents (measured in FCR) and dissolved oxygen tolerance.

For mangrove species, an additional specific criterion was their impact on the ecosystem, reflecting their dual role in aquaculture integration and habitat restoration. For both shrimp and seaweed species, the market potential criterion was added to assess the economic viability of IMTA []. Information for all criteria was obtained through a literature analysis of peer-reviewed aquaculture studies.

2.2.3.2 Scoring system

Each species was scored for each criterion on a three-point ordinal scale: Yes/High = 2, Medium = 1, No/Low = 0. Scores reflected either species traits reported in literature or the degree of match between species' environmental tolerance ranges and the physicochemical characteristics of

Bonaire's seawater. This ordinal scoring approach represented a simplified adaptation of AHP's quantitative assessment principle, translating qualitative knowledge and literature-based evidence into numerical scores suitable for multi-criteria comparison [].

- Binary traits (Yes/Medium/No): For the criteria native occurrence and prior use in IMTA, species scored 2 if present/true and 0 if absent/false. In cases where a species had not been used in IMTA, but had been used in other aquaculture practices, an intermediate score of 1 was given.
- Performance-related traits (High/Medium/Low): For growth rate, pathogen resistance, market potential, effluent and ecosystem impacts, a score of 2 was given to species with high performance for these criteria; 1 was given for moderate performance; and 0 for poor or negligible performance.
- Environmental ranges (Yes/Medium/Low): For temperature, salinity, pH, and dissolved oxygen, each species was scored based on the degree of overlap between its environmental tolerance range and the physicochemical characteristics of Bonaire's coastal seawater. A score of 2 was assigned when the species' environmental tolerance range entirely aligned with the physicochemical characteristics. A score of 1 was given when the tolerance range partially overlapped, and a score of 0 was given when the tolerance ranges fell entirely outside the ranges of Bonaire's conditions. For the dissolved oxygen criterion, only the minimum tolerance value was used to assign a score, since dissolved oxygen acts as a limiting factor at low concentrations but not at high levels.

2.2.3.3 Weighting system

Following the MCDA and AHP frameworks, all criteria were assigned weights reflecting their relative importance for the overall objective of selecting suitable IMTA species for Bonaire. To assign these specific weights, a literature-based frequency analysis was conducted. Relevant aquaculture and IMTA studies (n = 20) were reviewed to determine which criteria were mentioned most frequently as critical to species suitability. For each criterion, the number of studies mentioning it was counted, and the relative frequencies were calculated using the following calculation (n_i = the number of studies that mention the criterion; $\sum n_i$ = the total number of mentions across all criteria)

$$R_i = \frac{n_i}{\sum n_i}$$

The total weight across all criteria equalled 1.0. This gave a set of proportional weights reflecting the relative importance of each factor, as supported by the literature.

The environmental suitability was treated as an aggregate criterion, representing the combined influence of key abiotic parameters: temperature, salinity, pH, and dissolved oxygen. This structure was used to prevent overrepresentation of these environmental factors and to acknowledge that species performance depends on the combined effects of these parameters, rather than on a single isolated factor. In literature, these parameters are most often also mentioned together as part of water quality assessments. The aggregate environmental weight was subdivided among the three environmental criteria (four for shrimp species) using the same frequency-based method described above. Each sub-criterion was assigned a relative weight (w_i) based on its frequency in the reviewed literature. The contribution to the total score was calculated as (W_i = final weight of an individual environmental sub-criterion; w_i = the relative proportion of each environmental parameter, within the aggregate criterion; W_{env} = the aggregate weight of the entire environmental criterion):

$$W_{sub,i} = w_i \times W_{env}$$

This ensured that environmental factors accounted for a percentage of the total suitability score while maintaining the internal weights for temperature, salinity, pH, and dissolved oxygen.

2.2.3.4 Total suitability score and ranking

To create multi-criteria suitability matrices (MCSM), the scores for all criteria (0 = No/Low, 1 = Medium, 2 = Yes/High) for each candidate species of shrimp, seaweed, and mangroves were multiplied by their assigned criterion weight. The products were then summed across all criteria to calculate the Overall Weighted Score (OWS).

$$OWS = \Sigma\,(Score\ per\ criterion\ \times\ Weight)$$

The resulting scores were naturally constrained between 0 (least suitable) and 2 (most suitable). This ensured that values were directly comparable among the candidate species without the need for additional normalization. The final ranking of candidate species' suitability was based on their OWS, with the highest-scoring species assigned rank 1 (most suitable), followed by lower-ranking species in descending order of suitability.

2.3 Long-term viability and resilience

To evaluate how projected climate change may affect the long-term viability and resilience of the candidate IMTA species on Bonaire, the environmental components (temperature, salinity, pH, dissolved oxygen) of the multi-criteria suitability matrices were recalculated using projected future seawater conditions. Non-environmental criteria were held constant, as they are not directly affected by climate projections.

Projections of future sea surface temperature, salinity, pH, and dissolved oxygen were obtained from the IPCC Sixth Assessment Report (AR6) (Calvin et al., 2023), which develops Shared Socio-economic Pathways (SSPs) that represent a range of greenhouse gas emission trajectories. Two contrasting scenarios were selected: SSP1-2.6, a “best-case” pathway with strong global cooperation and sustainable developments, and SSP5-8.5, a “worst-case” pathway with continued reliance on fossil fuels and high emissions. Table 2.2 shows the projected water parameters for these scenarios. Exact numbers for the Caribbean area were not provided in the AR6 report, but these values represent global parameter projections.

Table 2.2. Projected ocean parameters under the IPCC SSP1-2.6 and SSP5-8.5 climate change scenarios (Calvin et al., 2023)

Parameter	*SSP1-2.6*	*SSP5-8.5*
Temperature (°C)	+1 to +1.8	+3 to +4
Salinity (PSU)	+0.2 to +0.4	+0.5 to +1.0
pH	-0.04 to -0.1	-0.28 to -0.32
Dissolved oxygen (mg L^{-1})	-1 to -4 %	-5 to -7 %

2.3.1 Climate change scenarios

Future seawater parameters were recalculated using the physicochemical characteristics from Section 2.1. This was done using the delta-change method (also known as the change-factor approach). This widely used technique in climate impact assessments estimates future conditions by applying projected climate model changes directly to historical observations, thereby preserving the statistical characteristics of the original dataset while aligning it with expected trends.

For each seawater parameter (temperature, salinity, pH, and dissolved oxygen), the present-day values were first defined by their observed minimum (a0), mean (μ0), and maximum (b_0) (Section 2.1). Scenario-specific changes (Δ) were derived from the published climate projections for the two

IPCC scenarios described above. Positive Δ values represent projected increases (e.g., temperature rise), while negative Δ values represent decreases (e.g., pH decline). The following calculations were used to determine the future parameter values for the IPCC scenarios:

- Future means:

$$\mu 1 = \mu 0 + AVERAGE\ (\Delta low, \Delta high)$$

- Future minima and maxima:

$$a1 = a0 + \Delta low, b1 = b0 + \Delta high$$

For variables projected as percentage changes (e.g. dissolved oxygen), multiplicative deltas (δ) were applied for proportional change:

$$\mu 1 = \mu 0 \times \left(1 + AVERAGE\ (\delta low, \delta high)\right)$$

$$a1 = a0 \times (1 + \delta low)$$

$$b1 = b0 \times (1 + \delta high)$$

Grouped bar charts were generated in Microsoft Excel to visualize shifts in species' environmental suitability under each scenario by comparing tolerance ranges with projected future conditions (see Section 2.2.2).

2.3.2 Suitability matrices for future scenarios

For all candidate species, two additional MCSMs were developed for the SSP1-2.6 and SSP5-8.5 scenarios, using the same scoring system and weighting systems as described in Section 2.2.3. By maintaining the AHP-derived weighting structure, the scenario-based analyses remained directly comparable to the baseline assessment, allowing changes in suitability to be attributed solely to shifts in environmental parameters, rather than changes in decision priorities. This approach isolates the influence of climate-driven environmental changes on the overall suitability of the candidate species. Environmental suitability sub-scores were recalculated using the scenario-specific parameter values, and updated Overall Weighted Scores (OWS) were generated. Species were re-ranked (1 = most suitable, 2 = moderately suitable, 3 = least suitable) for each scenario.

3. Results

3.1 The physicochemical characteristics of Bonaire's coastal seawater

The physicochemical characteristics of Bonaire's coastal seawater, representing the environmental parameters relevant for IMTA development, were assessed using long-term oceanographic datasets (Table 2.1). The results are presented below, organized per parameter. A summary of the results is given in the Appendix (Section 1, Table 1).

3.1.1 Sea surface temperature

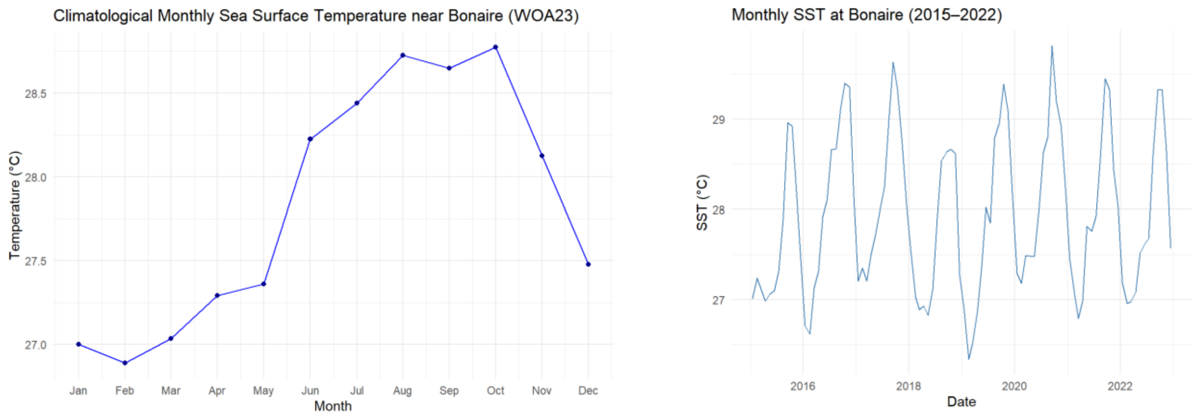


Figure 3.1 and 3.2. Climatological and recent monthly sea surface temperature (SST) near Bonaire. (3.1) Climatological monthly mean SST from WOA (1972-2022). (3.2) Monthly SST time series from OISST (2015-2022), showing seasonal fluctuations and interannual variability.

Climatological monthly sea surface temperature (SST) near Bonaire (according to WOA23; Fig. 3.1) showed values ranging between 27 °C in February and 28.9 °C in October. Interannual SST variability between 2015-2022 (according to OISST; Fig. 3.2) revealed a recurring seasonal cycle, with observed values ranging from 26.7 °C (in early 2018) to peaks above 29.5 °C (during 2020 and later years). This dataset confirmed consistent annual fluctuations with a mean SST across this period of 28.1 °C.

3.1.2 Sea surface salinity

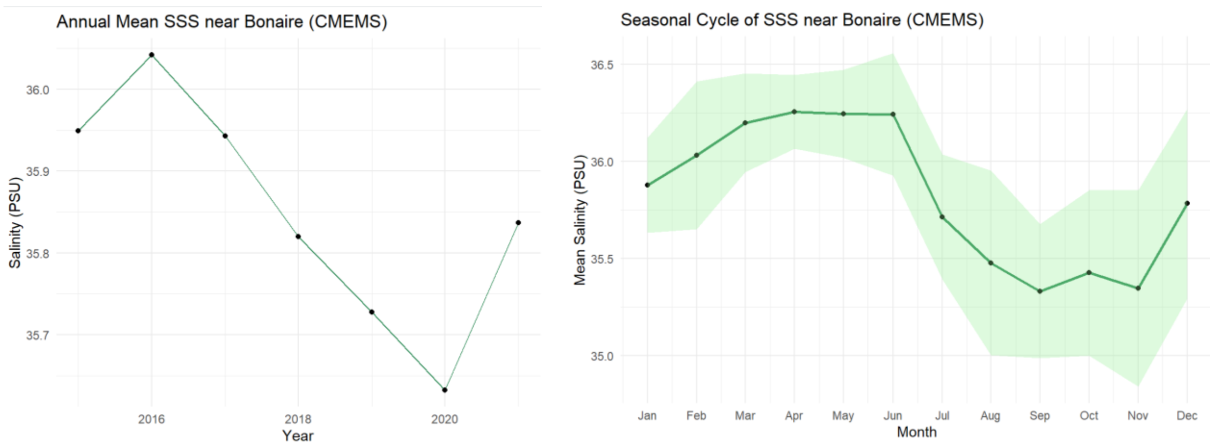


Figure 3.3 and 3.4. Annual mean and seasonal cycle of sea surface salinity (SSS) near Bonaire. (B1) Annual mean SSS from CMEMS (2015-2022). (B2) Seasonal cycle of mean monthly SSS with associated variability (shaded area).

Annual mean sea surface salinity (according to CMEMS; Fig 3.3) ranged between 35.7 and 36.1 PSU during 2015-2022, with an overall mean of around 35.9 PSU. The seasonal cycle of sea surface salinity (Fig. 3.4) was characterised by higher values during February-June (36.0 – 36.2 PSU), declining to around 35.5 PSU between July and October, before recovering towards December.

3.1.3 pH

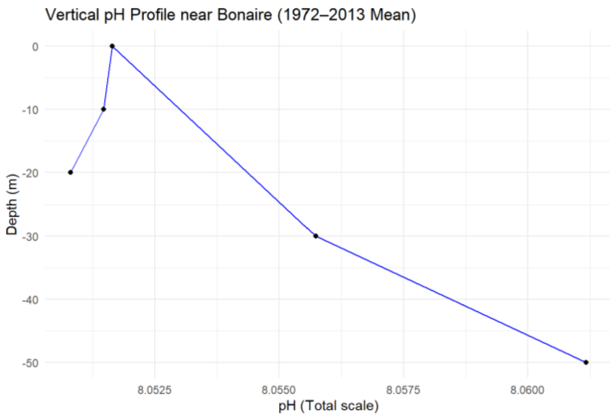


Figure 3.5. Vertical pH profile near Bonaire. Climatological mean vertical profile of pH from GLODAPv2 (1972-2013).

The vertical pH profile (from GLODAPv2; Fig. 3.5) showed surface values between 8.052 and 8.055, with a mean of 8.054. The pH increased slightly with depth, reaching 8.060 at -50 meters. This dataset represents mean conditions (1972-2013), so no temporal trends could be determined.

3.1.4 Dissolved oxygen

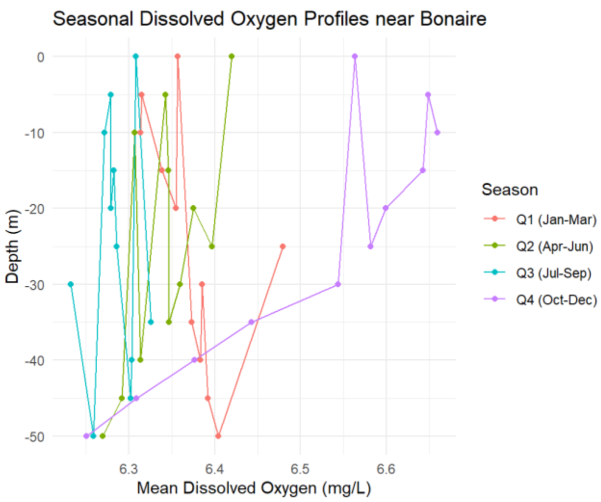
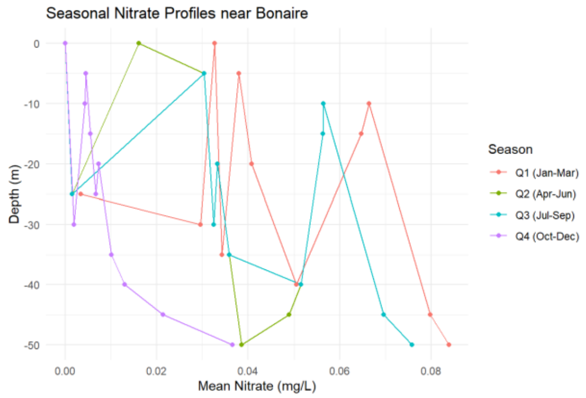


Figure 3.6. Seasonal vertical profiles of dissolved oxygen (DO) near Bonaire. Mean seasonal DO concentrations (mg/L) by depth, based on WOA data (1955-2022). Seasons: Q1 = Jan-Mar; Q2 = Apr-Jun; Q3 = Jul-Sep; Q4 = Oct-Dec.

Seasonal vertical profiles (from WOA, Fig. 3.6) showed relatively uniform surface DO concentrations, ranging from 6.3 to 6.6 mg/L, with a mean of 6.4 mg/L. Slight seasonal differences were observed: values reached up to 6.6 mg/L in Q4 (Oct-Dec), while Q1-Q3 remained closer to 6.3 – 6.4 mg/L.

3.1.5 Nitrate and phosphate



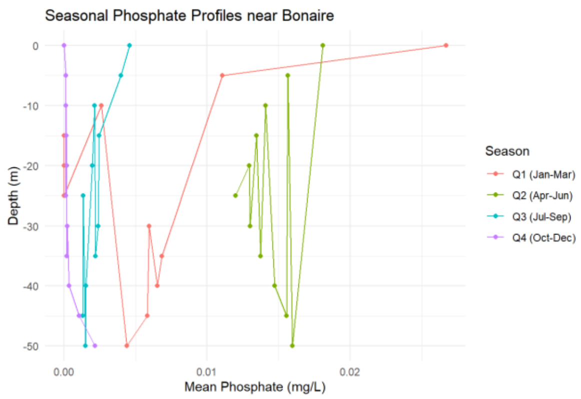


Figure 3.7 and 3.8. Seasonal vertical profiles of nitrate and phosphate near Bonaire. (E1) Seasonal vertical nitrate profiles (mg/L). (E2) Seasonal vertical phosphate profiles (mg/L). Data from WOA (1955-2022). Seasons: Q1 = Jan-Mar; Q2 = Apr-Jun; Q3 = Jul-Sep; Q4 = Oct-Dec.

Seasonal nitrate profiles (WOA; Fig. 3.7) showed surface concentrations ranging from 0.00 to 0.05 mg/L, with a mean of 0.02 mg/L. Phosphate concentrations (WOA; Fig. 3.8) were similarly low, ranging from 0.00 mg/L (surface waters during Q3-Q4) to around 0.02 mg/L (Q1-Q2), with a mean of around 0.01 mg/L.

3.2 Species' suitability

3.2.1 Environmental tolerance ranges

The environmental tolerance ranges for three shrimp species (*Litopenaeus vannamei*, *Penaeus monodon*, *Penaeus schmitti*), three seaweed species (*Ulva lactuca*, *Gracilaria foliifera*, *Gracilaria tikvahiae*), and two mangrove species (*Rhizophora mangle* and *Avicennia germinans*) were collected from the literature (Appendix Section 2). For reference, the reported minimum and maximum tolerance values are shown, along with their research locations and methods. For each parameter and species, a single mean range across studies is shown in a summary table.

These mean ranges were compared with the physicochemical characteristics of Bonaire's current coastal seawater (Fig. 3.1-3.6; Appendix Section 1). Figures 3.9–3.11 show the tolerance ranges for the candidate species of shrimp, seaweed, and mangrove. These figures can be used to determine whether the species' tolerance ranges align with Bonaire's coastal seawater characteristics.

3.2.1.1 Shrimp species' tolerance ranges

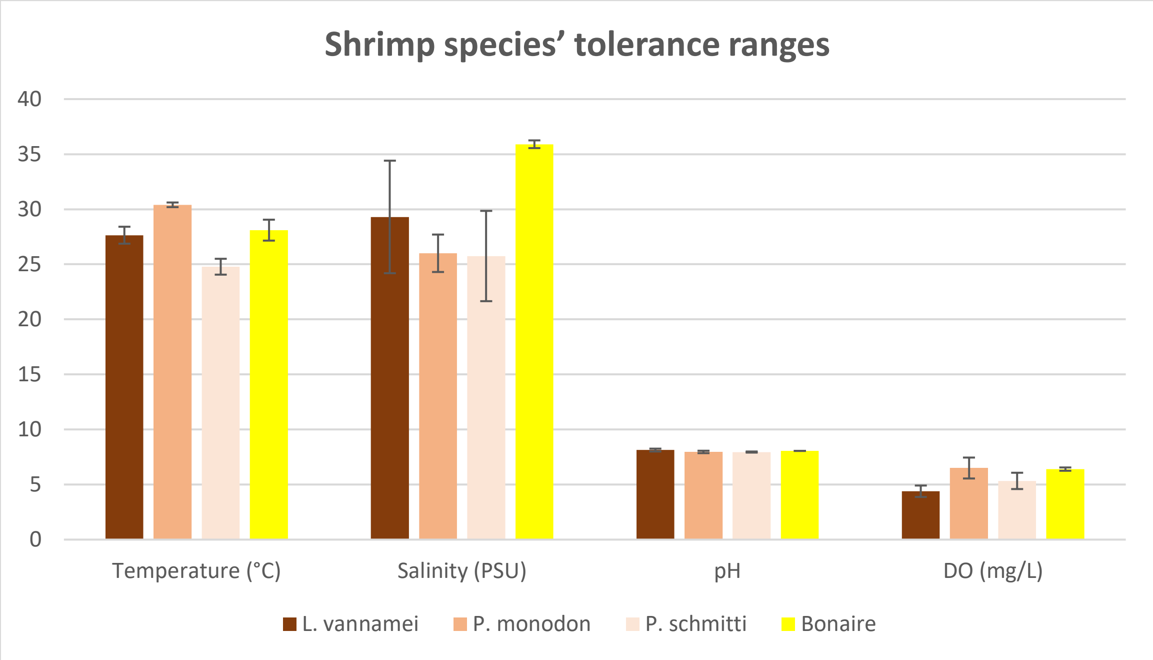


Figure 3.9. Comparison of shrimp species' tolerance ranges with present-day seawater conditions at Bonaire. Mean values (bars) with error bars for Litopenaeus vannamei, Penaeus monodon, and Penaeus schmitti were compared with mean and range values for Bonaire's seawater (yellow bars). Parameters shown: temperature (°C), salinity (PSU), pH, and dissolved oxygen (mg L^{-1}).

For candidate shrimp species, tolerance ranges were evaluated for temperature, salinity, pH, and dissolved oxygen (Fig. 3.9). Bonaire's seawater temperature (26.7-29.5 °C) fell completely within the reported tolerance ranges for *L. vannamei* and *P. monodon*. *P. schmitti* has a temperature tolerance of 21.5-28.1 °C, which only partially overlapped with Bonaire conditions. Surface pH (8.052-8.055) also matched the reported tolerance ranges for all shrimp species. Dissolved oxygen concentrations (6.3-6.6 mg L^{-1}) consistently exceeded the minimum thresholds reported in the literature. By contrast, Bonaire's salinity values (35.5-36.2 PSU) only partially overlapped with the tolerance range for *L. vannamei*, and exceeded the upper tolerance limits for *P. monodon* and *P. schmitti* (Appendix Section 2A, Tables A. 1. a – A. 12. b).

3.2.1.2 Seaweed species' tolerance ranges

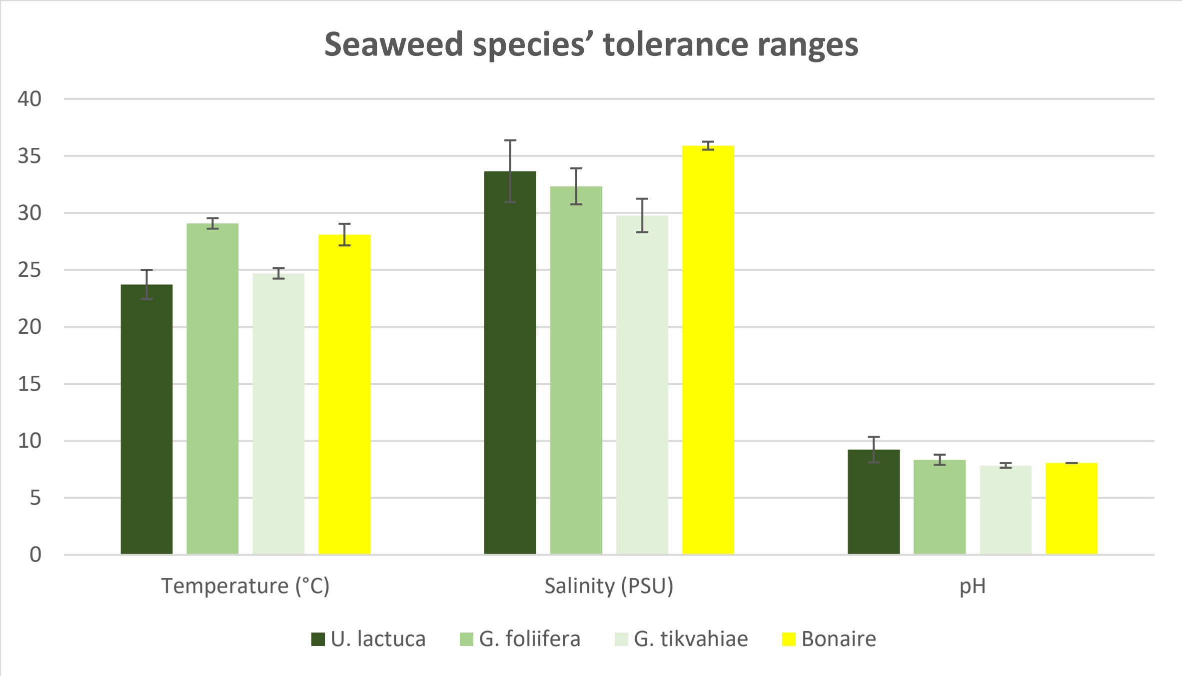


Figure 3.10. Comparison of seaweed species' tolerance ranges with present-day seawater conditions at Bonaire. Mean values (bars) with error bars for Ulva lactuca, Gracilaria foliifera, and Gracilaria tikvahiae were compared with mean and range values for Bonaire's seawater (yellow bars). Parameters shown: temperature (°C), salinity (PSU), and pH.

For candidate seaweed species, tolerance ranges were evaluated for temperature, salinity, and pH (Fig. 3.10). Bonaire's seawater temperature (26.7-29.5 °C) was within the reported tolerance ranges for *G. foliifera* and *G. tikvahiae*. For *U. lactuca*, the temperature tolerance range lay only partially within Bonaire's range. Surface pH (8.052-8.055) fell within the reported ranges of all three species. In contrast, Bonaire's salinity levels (35.5-36.2 PSU) exceeded the tolerance ranges reported for *G. foliifera and G. tikvahiae*, whilst the tolerance range for *U. lactuca* only partially overlapped (Appendix Section 2B, Tables B.1.a – B.9.b).

3.2.1.3 Mangrove species' tolerance ranges

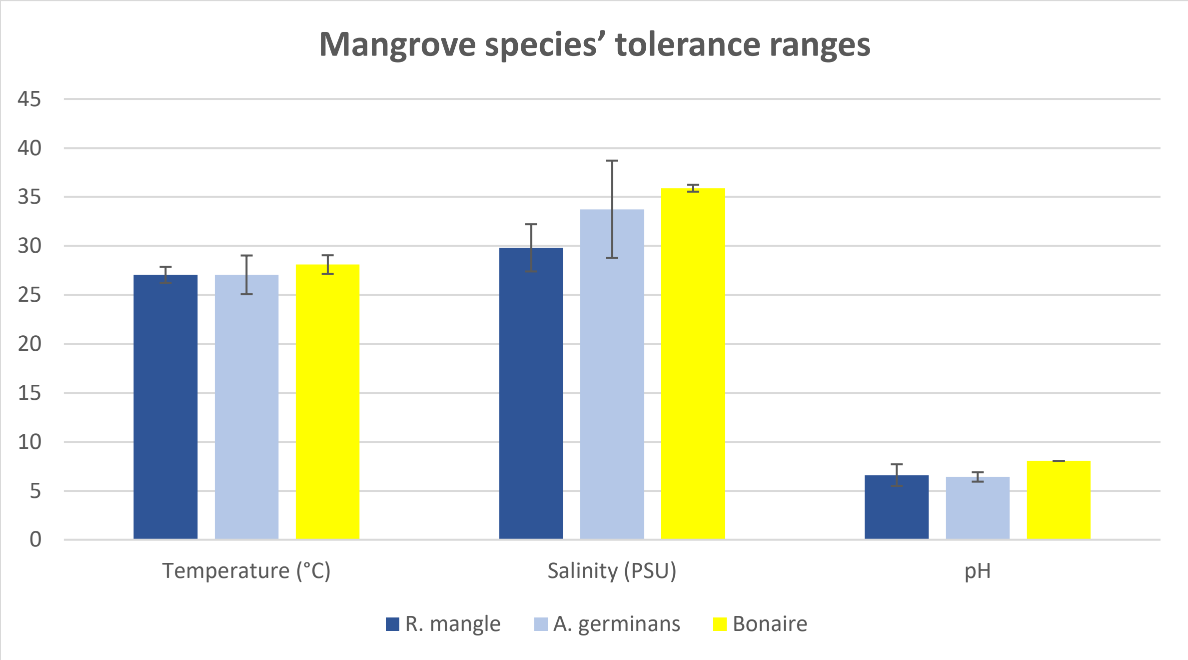


Figure 3.11. Comparison of mangrove species ' tolerance ranges with present-day seawater conditions at Bonaire. Mean values (bars) with error bars for Rhizophora mangle and Avicennia germinans were compared with mean and range values for Bonaire's seawater (yellow bars). Parameters shown: temperature (°C), salinity (PSU), and pH.

For candidate mangrove species, tolerance ranges were evaluated for temperature, salinity, and pH (Fig. 3.11). Bonaire's seawater temperature (26.7-29.5 °C) was within the tolerance ranges reported for both *R. mangle* and *A. germinans*. However, Bonaire's pH levels (8.052-8.055) showed no overlap with the tolerance ranges for both species. Salinity conditions (35.5-36.2 PSU) exceeded the upper tolerance limit for *R. mangle*, but fell completely within the ranges of *A. germinans* (Appendix Section 2C, Tables C.1.a – C.6.b).

3.2.2 Species suitability matrices

Information on the selected suitability criteria for the MCSMs was collected through a literature review. The outcomes of this literature analysis for all candidate species are presented in Section 3 of the Appendix. Here, the evidence summary, references, and complementing scores (Section 2.2.3.2) are all presented. For *G. foliifera*, there was no literature available for two of the criteria (pathogen resistance and market potential), which is depicted as 'X' in the table (Appendix Section 3B, Table E.2). This value therefore scored the same as 'Low/No = 0' in the scoring system.

The weights for the MCSMs were determined using a literature-based frequency analysis of 20 studies. The relevant studies and the number of relevant aquaculture and IMTA studies per criterion for each species group are presented in Section 4 of the Appendix. The weights are depicted in Tables 3.1-3.3.

Table 3.1. Assigned weights for shrimp species suitability criteria

Suitability criteria	*Weight*
Native species	0,06
IMTA use	0,13
Growth rate	0,18

Pathogen Resistance	0,11
Market value	0,18
Effluent/feed	0,16
Environmental suitability (aggregate)	0,18
Environmental suitability sub-criteria	*Weight*
Temperature	0,29
Salinity	0,26
pH	0,22
Dissolved oxygen	0,22

Table 3.2. Assigned weights for seaweed species suitability criteria

Suitability criteria	*Weight*
Native species	0,075
IMTA use	0,150
Growth rate	0,215
Pathogen resistance	0,129
Market value	0,215
Environmental suitability (aggregate)	0,215
Environmental suitability sub-criteria	*Weight*
Temperature	0,38
Salinity	0,33
pH	0,29

Table 3.3. Assigned weights for mangrove species suitability criteria

Suitability criteria	*Weight*
Native species	0,075
IMTA use	0,150
Growth rate	0,215
Pathogen resistance	0,129
Ecosystem impacts	0,215
Environmental Suitability (aggregate)	0,215
Environmental suitability sub-criteria	*Weight*
Temperature	0,38
Salinity	0,33
pH	0,29

Together, the physicochemical characteristics of Bonaire's coastal seawater (Appendix Section 1), the data collected from the literature analyses (Appendix sections 2 & 3), and the scoring and weighting systems (Appendix section 4) formed the basis for developing multi-criteria suitability matrices. Tables 3.4-3.6 present the MCSMs for the candidate shrimp, seaweed, and mangrove species, showing, for each group, which species rank highest in IMTA suitability on Bonaire.

Table 3.4. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Shrimp Candidate Species.

Criteria	***L. vannamei***	***P. monodon***	***P. schmitti***	**Weight**
Native species	0	0	0	0,06
IMTA use	2	2	1	0,13
Growth rate	1	2	0	0,18
Pathogen resistance	2	1	0	0,11
Market potential	2	2	0	0,18
Effluent/feed	1	1	2	0,16
ES Temperature	2	2	1	0,29

ES Salinity	1	0	0	0,26
ES pH	2	2	2	0,22
ES Dissolved oxygen	2	2	2	0,22
Environmental suitability (ES) aggregate	1,72	1,46	1,17	0,18
Overall weighted score	1,4896	1,5128	0,6606	
Rank (1=best)	2	1	3	

Among the candidate shrimp species, *Penaeus monodon* had the highest OWS (1.5128), ranking first in suitability for IMTA on Bonaire, due to its high growth rates. However, the OWS differed only slightly from that of Litopenaeus vannamei (1.4896) due to its pathogen-resistant larvae and suitable environmental tolerances. Ranking last was *P. schmitti* (OWS = 0.6606), which proved the least suitable for IMTA on Bonaire due to low growth rates, poor pathogen resistance, and limited market potential (Table 3.4).

Table 3.5. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Seaweed Candidate Species. X = No information was found in literature for this criterion (score equals 0).

Criteria	***U. lactuca***	***G. foliifera***	***G. tikvahiae***	**Weight**
Native species	2	2	0	0,075
IMTA use	2	1	2	0,15
Growth rate	2	0	2	0,215
Pathogen resistance	1	X	1	0,129
Market potential	2	X	2	0,215
ES temperature	1	2	2	0,38
ES salinity	1	0	0	0,33
ES pH	2	2	2	0,29
Environmental suitability (ES) aggregate	1,29	1,34	1,34	0,215
Overall weighted score	1,7164	0,5881	1,5771	
Rank (1=best)	1	3	2	

Among the candidate seaweed species, *U. lactuca* ranked first with an OWS of 1.7164, due to native occurrence, high growth rates, and good market potential. The OWS of *G. tikvahiae* was not far behind (1.5771), ranking second with scores similar to *U. lactuca* and an even higher ES aggregate. *G. foliifera* scored significantly lower (OWS = 0.5881) due to its low growth rates and lack of literature information (Table 3.5).

Table 3.6. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Mangrove Candidate Species.

Criteria	***R. mangle***	***A. germinans***	**Weight**
Native species	2	2	0,075
IMTA use	1	1	0,15
Growth rate	2	1	0,215
Pathogen resistance	2	2	0,129
Ecosystem impacts	2	2	0,215
ES Temperature	2	2	0,38
ES Salinity	0	2	0,33
ES pH	0	0	0,29

Environmental suitability (ES) aggregate	0,76	1,42	0,215
Overall weighted score	1,5814	1,5083	
Rank (1=best)	1	2	

Among the candidate mangrove species, *R. mangle* achieved the highest OWS (1.5814). However, this score differs only slightly from *A. germinans*, with an OWS of 1.5083. Both species showed very similar scores, except that R. mangle had higher growth rates and A. germinans was more tolerant of saline conditions (Table 3.6).

3.3 Long-term viability and resilience

3.3.1 Environmental tolerance ranges

To assess the potential impact of climate change on the suitability of IMTA, candidate species' tolerance ranges (Appendix Section 2) were compared with projected seawater conditions for Bonaire under two IPCC climate scenarios: SSP1-2.6 (low-emission) and SSP5-8.5 (high-emission) (Appendix Section 1, Table 1). Environmental parameters included temperature, salinity, pH, and dissolved oxygen. Figures 3.12–3.14 present results for shrimp, seaweed, and mangrove species under projected future scenarios.

3.3.1.1 Shrimp species' tolerance ranges – Bonaire IPCC

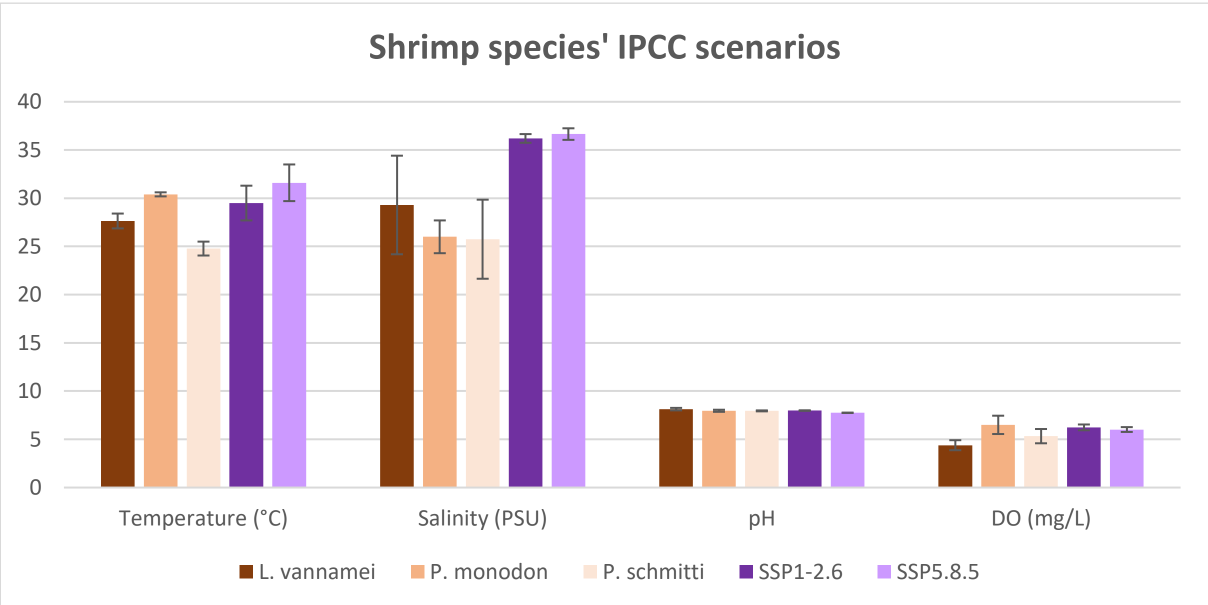


Figure 3.12. Comparison of shrimp species' tolerance ranges with projected future seawater conditions at Bonaire under IPCC scenarios. Mean values (bars) with error bars for Litopenaeus vannamei, Penaeus monodon, and Penaeus schmitti were compared with projected mean seawater conditions for Bonaire under low-emission (SSP1-2.6) and high-emission (SSP5-8.5) scenarios (purple bars). Parameters shown: temperature (°C), salinity (PSU), pH, and dissolved oxygen (mg L^{-1}).

Under SSP1-2.6 and SSP5-8.5, projected sea surface temperatures (27.7-31.1 °C) still aligned with the reported tolerance ranges for *P. monodon*, and only partially overlapped for *L. vannamei*. *P. schmitti* had no overlap in temperature ranges under the SSP5-8.5 scenario. Despite decreases, dissolved oxygen concentrations remained well above the threshold for all three species, and salinity suitability remained unchanged. The increase in pH under the SSP5-8.5 scenario caused the tolerance ranges of *L. vannamei* and *P. schmitti* to only partially overlap (Fig. 3.12; Appendix Section 2A, Tables A. 1. a – A. 12. b).

3.3.1.2 Seaweed species' tolerance ranges – Bonaire IPCC

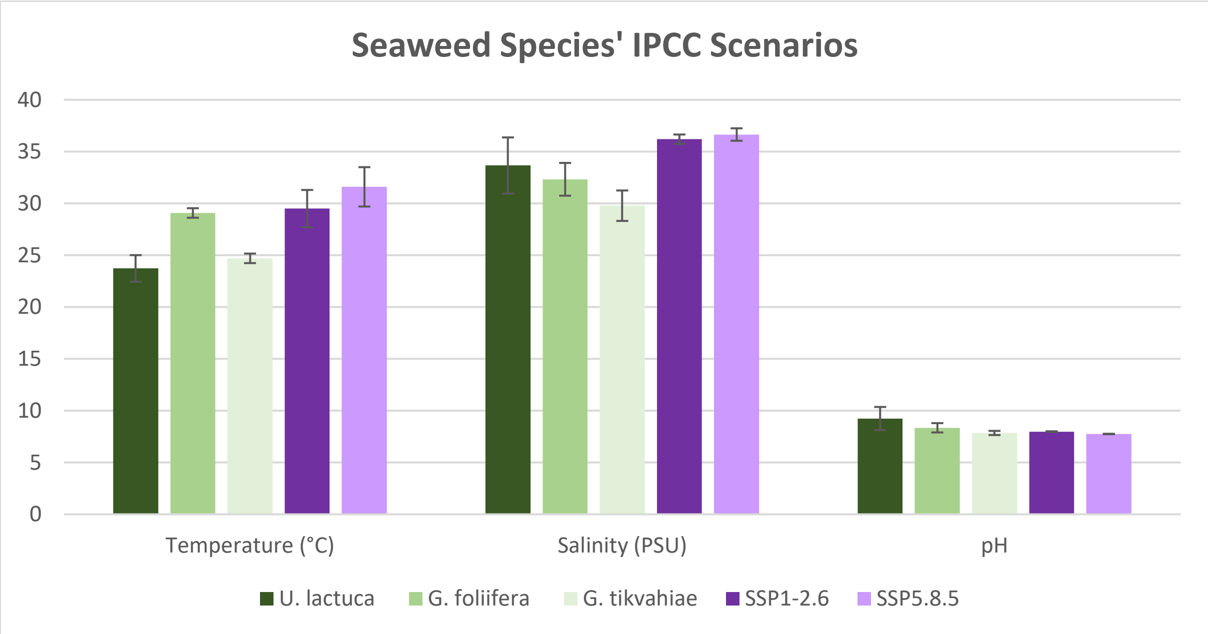


Figure 3.13. Comparison of seaweed species' tolerance ranges with projected future seawater conditions at Bonaire under IPCC scenarios. Mean values (bars) with error bars for Ulva lactuca, Penaeus monodon, and Penaeus schmitti were compared with projected mean seawater conditions for Bonaire under low-emission (SSP1-2.6) and high-emission (SSP5-8.5) scenarios (purple bars). Parameters shown: temperature (°C), salinity (PSU), and pH.

Under SSP1-2.6, there was no change in temperature suitability for any of the three species. However, under SSP5-8.5, the temperature ranges of *G. foliifera* and *G. tikvahiae* now only partially overlap. There were also no changes in salinity suitability for any of the species under both scenarios. However, the decrease in pH did affect *G. foliifera*, whose tolerances only partially overlap under both scenarios (Fig. 3.13; Appendix Section 2B, Tables B. 1a–B. 9 b).

3.3.1.3 Mangrove species' tolerance ranges – Bonaire IPCC

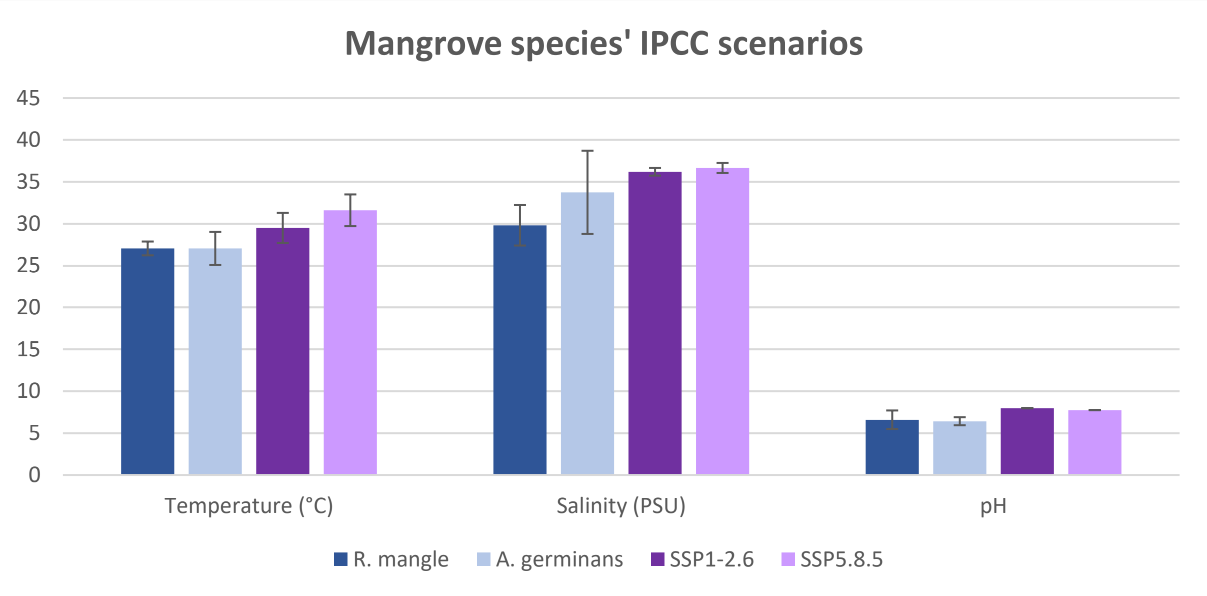


Figure 3.14. Comparison of mangrove species' tolerance ranges with projected future seawater conditions at Bonaire under IPCC scenarios. Mean values (bars) with error bars for Rhizophora mangle and Avicennia germinans were compared with projected mean seawater conditions for Bonaire under low-emission (SSP1-2.6) and high-emission (SSP5-8.5) scenarios (purple bars). Parameters shown: temperature (°C), salinity (PSU), and pH.

For *R. mangle*, the temperature suitability only partially overlaps Bonaire's seawater conditions under both climate change scenarios. *A. germinans* only has this lower temperature suitability under the SSP5-8.5 scenario. Besides this, an interesting development for *A. germinans* is that under this 'worst-case' scenario, its suitability for pH actually increases under the more acidic conditions of the projected seawater (Appendix Section 2C, Tables C.1.a – C.6.b).

3.3.2 Species suitability matrices

To extend the suitability analysis beyond present-day conditions, Multi-Criteria Suitability Matrices (MCSMs) were also applied under future climate scenarios. Using projected seawater parameters for SSP1-2.6 and SSP5-8.5, environmental suitability scores were recalculated while keeping the same weighting scheme as in the present-day assessment. Overall Weighted (OWS) again ranged from 0 (least suitable) to 2 (most suitable), enabling direct comparison of species rankings across scenarios. Species-specific tolerable ranges, scenario-adjusted values, and supporting references are shown in the Appendix (A1-A6).

3.3.2.1 IPCC SSP1-2.6

Table 3.7. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Shrimp Candidate Species under SSP1-2.6

Criteria	*L. vannamei*	*P. monodon*	*P. schmitti*	Weight
Native species	0	0	0	0,06
IMTA use	2	2	1	0,13
Growth rate	1	2	0	0,18
Pathogen resistance	2	1	0	0,11
Market potential	2	2	0	0,18
Effluent/feed	1	1	2	0,16

ES Temperature	1	2	1	0,29
ES Salinity	1	0	0	0,26
ES pH	2	2	2	0,22
ES Dissolved oxygen	2	2	2	0,22
Environmental suitability (ES) aggregate	1,72	1,46	1,17	0,18
Overall weighted score	1,4374	1,5128	0,6606	
Rank (1=best)	2	1	3	

Under the projected SSP1-2.6 scenario, only the OWS (1.4374) for *L. vannamei* decreased slightly compared to the present-day conditions (Tables 3.4 & 3.7). This was due to the higher temperature in this scenario. However, for the overall suitability ranking, nothing changed: P. monodon still ranked highest, followed by L. vannamei and P. schmitti, which ranked lowest.

Table 3.8. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Seaweed Candidate Species under IPCC SSP5-8.5

Criteria	***U. lactuca***	***G. foliifera***	***G. tikvahiae***	**Weight**
Native species	2	2	0	0,075
IMTA use	2	1	2	0,15
Growth rate	2	0	2	0,215
Pathogen resistance	1	X	1	0,129
Market potential	2	X	2	0,215
ES Temperature	1	2	2	0,38
ES Salinity	1	0	0	0,33
ES pH	2	1	2	0,29
Environmental suitability (ES) aggregate	1,29	1,34	1,34	0,215
Overall weighted score	1,7164	0,5257	1,5771	
Rank (1=best)	1	3	2	

Under the projected SSP1-2.6 scenario, rankings also stayed the same for the candidate seaweed species, with U. lactuca as the most suitable species and G. foliifera as the least. The only change in scores occurred with G. foliifera, where a slight decrease in score (0.5257) was caused by changes in pH under this climate change scenario (Tables 3.5 & 3.8).

Table 3.9. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Mangrove Candidate Species under IPCC SSP1-2.6

Criteria	***R. mangle***	***A. germinans***	**Weight**
Native species	2	2	0,075
IMTA use	1	1	0,15
Growth rate	2	1	0,215
Pathogen resistance	2	2	0,129
Ecosystem impacts	2	2	0,215
ES Temperature	1	2	0,38
ES Salinity	0	2	0,33
ES pH	0	0	0,29
Environmental suitability (ES) aggregate	0,38	1,42	0,215
Overall weighted score	1,4997	1,5083	

Rank (1=best)	2	1	

The rankings for the candidate mangrove species changed under the SSP1-2.6 scenario. The OWS of *A. germinans* did not change under these projected conditions, but that of *R. mangle* did. The projected increase in temperature led to a decrease in the score (1.4997). Therefore, under SSP1-2.6, *A. germinans* is now the best option for IMTA suitability on Bonaire (Tables 3.6 & 3.9).

3.3.2.2 IPCC SSP5-8.5

Table 3.10. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Shrimp Candidate Species under IPCC SSP5-8.5

Criteria	***L. vannamei***	***P. monodon***	***P. schmitti***	**Weight**
Native species	0	0	0	0,06
IMTA use	2	2	1	0,13
Growth rate	1	2	0	0,18
Pathogen resistance	2	1	0	0,11
Market potential	2	2	0	0,18
Effluent/feed	1	1	2	0,16
ES Temperature	1	2	0	0,29
ES Salinity	1	0	0	0,26
ES pH	1	2	1	0,22
ES Dissolved oxygen	2	2	2	0,22
Environmental suitability (ES) aggregate	1,21	1,46	0,66	0,18
Overall weighted score	1,3978	1,5128	0,5688	
Rank (1=best)	2	1	3	

Under the SSP5-8.5 scenario, the OWS of *L. vannamei* continues to decrease (1.3978) due to increasing temperatures and decreasing pH. These parameters now also affect the suitability of *P. schmitti*, scoring lower than under the present-day and SSP1-2.6 scenarios (0.5688). The OWS of *P. monodon* does not change (1.5128), therefore remaining the species with the highest suitability for IMTA on Bonaire (Tables 3.4, 3.7 & 3.10).

Table 3.11. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Seaweed Candidate Species under IPCC SSP5-8.5

Criteria	***U. lactuca***	***G. foliifera***	***G. tikvahiae***	**Weight**
Native species	2	2	0	0,075
IMTA use	2	1	2	0,15
Growth rate	2	0	2	0,215
Pathogen resistance	1	X	1	0,129
Market potential	2	X	2	0,215
ES Temperature	1	1	1	0,38
ES Salinity	1	0	0	0,33
ES pH	2	1	2	0,29
Environmental suitability (ES) aggregate	1,29	0,67	0,96	0,215
Overall weighted score	1,7164	0,4441	1,4954	
Rank (1=best)	1	3	2	

The OWS for *U. lactuca* has not changed under the SSP5-8.5 scenario (1.7164) compared to the present-day and SSP1-2.6 scenario. The species, therefore, remains the most suitable candidate for IMTA on Bonaire. *G. foliifera* showed another decrease in OWS (0.4441) due to increases in temperature, which also caused G. tikvahiae to become slightly less suitable compared to the previous scenarios (1.4954) (Tables 3.5, 3.8 & 3.11).

Table 3.12. Multi-Criteria Suitability Matrix and Overall Weighted Scores for Mangrove Candidate Species under IPCC SSP5-8.5

Criteria	***R. mangle***	***A. germinans***	**Weight**
Native species	2	2	0,075
IMTA use	1	1	0,15
Growth rate	2	1	0,215
Pathogen resistance	2	2	0,129
Ecosystem impacts	2	2	0,215
ES Temperature	1	1	0,38
ES Salinity	0	2	0,33
ES pH	0	2	0,29
Environmental suitability (ES) aggregate	0,38	1,62	0,215
Overall weighted score	1,4997	1,5513	
Rank (1=best)	2	1	

Under the SSP5-8.5 scenario, the OWS of R. mangle remains unchanged compared to the SSP1-2.6 scenario. However, the OWS score for A. germinans slightly increases under this scenario (1.5513), suggesting it is better adapted to the decrease in pH. This increase in score reaffirms that A. germinans is the most suitable species for IMTA on Bonaire under climate change conditions (Tables 3.6, 3.9 & 3.12).

4. Discussion

The aim of this study was to evaluate the suitability of different fed, extractive, and ecosystem-restoring species for the development of Integrated Multi-Trophic Aquaculture (IMTA) systems on Bonaire, under both present-day and projected future seawater conditions. The goal was to identify species combinations that are environmentally compatible, biologically resilient, and economically viable. To achieve this, candidate shrimp, seaweed, and mangrove species were systematically compared using multicriteria suitability matrices that integrated environmental suitability with biological traits and market considerations. This combined focus moved beyond purely ecological assessment and provided a framework directly applicable to aquaculture planning, reflecting the interdisciplinary nature of IMTA, in which operational feasibility, ecological resilience, and commercial potential must all align for long-term success. The results of the MCSMs revealed clear differences among candidates within the species groups, with some consistently emerging as the most promising options, and others becoming more suitable under climate change conditions.

Results from the first sub-question provided the environmental baseline against which species suitability was assessed. Bonaire's coastal waters were characterized as warm, saline, slightly alkaline, and well oxygenated, with consistently low levels of nitrate and phosphate (Fig. 3.1-3.8). These physicochemical conditions offer both opportunities and constraints for aquaculture: relatively stable temperature and pH are beneficial, but high salinity values narrow the range of suitable species.

Similarly, the oligotrophic characteristics underscore the importance of nutrient effluents from the fed species to support the efficient growth of extractive species. This environmental context formed the foundation for species evaluations, ensuring that suitability assessments were based on the specific conditions of Bonaire's coastal water.

In present-day conditions, *Penaeus monodon* ranked highest in suitability within the shrimp group due to its combination of high growth rates, previous integration in IMTA systems, and established global market value. Within the seaweed group, *Ulva lactuca* emerged as the most promising candidate, due to its high productivity, market potential, and its native occurrence on Bonaire. Among the mangrove species, *Rhizophora mangle* was the most suitable, due to its growth rates, pathogen resistance, and positive ecosystem impacts. Collectively, these findings point to *P. monodon*, *U. lactuca,* and *R. mangle* as the most robust species combination for an IMTA system on Bonaire under current climate conditions.

To evaluate how projected climate change may affect the long-term viability and resilience of IMTA species on Bonaire, the results obtained with the MCSM analysis were recalculated using projected future environmental conditions. The weighting structure used in these future-scenario assessments was intentionally kept consistent with the present-day analysis, following the AHP-based weighting framework. This ensured that any differences in species rankings under SSP1-2.6 and SSP5-8.5 could be attributed solely to changes in environmental conditions rather than changes in decision priorities. Under SSP1-2.6 and SSP5-8.5, suitability rankings remained unchanged for the candidate shrimp and seaweed species. This indicates that *P. monodon* and *U. lactuca* are not only the most suitable candidates for Bonaire now, but also under projected climate change conditions.

This study is subject to several limitations. Firstly, most oceanographic datasets ended in 2022, meaning the most recent environmental changes could not be incorporated into the analysis. In addition, the oceanographic data used in this study were compiled from several publicly available global products (Table 2.1), each of which differs slightly in sampling frequency, spatial resolution, and methodological approach. Data extraction was performed on a 1° latitude-longitude grid (approximately 100 km), which, while suitable for capturing broad regional patterns, significantly limits the spatial precision of the results and may not fully represent fine-scale variability in Bonaire's nearshore environment. This limitation is particularly relevant in coastal systems, where small-scale hydrodynamics can cause substantial departures from regional averages. Temporal resolution also introduces potential uncertainties. For example, dissolved oxygen and nutrient data are based on multi-decadal climatologies (1955-2017 and 1955-2022), and pH values were derived from mapped data ending in 2013. These long-term averages smooth out interannual and decadal variability, potentially masking shorter-term changes or recent trends. A further source of uncertainty stems from data gaps in the underlying observational records, particularly in the Caribbean region, where *in situ* sampling is sparse. Many of the climatological fields used in this study rely heavily on spatial and temporal interpolation to fill these gaps, which can introduce artefacts and potentially smooth out localised variability. Despite these limitations, the chosen datasets remain the most comprehensive and accessible options available for Bonaire's marine environment, providing a robust baseline for evaluating relative species suitability. Nevertheless, future work would benefit from higher-resolution, site-specific observational data to improve spatial and temporal precision.

Secondly, the future scenario analysis applied a delta-change method, which captures changes in long-term mean conditions rather than seasonal or interannual variability. It is important to note that this represents a simplified climate signal: the approach does not explicitly account for extremes, seasonal shifts, or short-term fluctuations, all of which can strongly influence aquaculture performance and species physiology.

Thirdly, this research relied on literature-based data rather than experimental data conducted under Bonaire's specific environmental conditions. While this approach allowed for a broad range of studies, it also introduced several limitations. For some species, tolerance data were scarce, reducing the robustness of the species' suitability assessment. The available literature varied in both regional relevance and methodological consistency, with some studies conducted in tropical conditions, such as Bonaire, and others in temperate or laboratory settings. Data availability was also uneven among species. Considerably more information is available for *U. lactuca* than for *G. tikvahiae* and *G. foliifera*, and for certain parameters, only 2 or 3 studies could be identified. Moreover, reported tolerance ranges for the same species occasionally differed between studies, reflecting differences in experimental design, local adaptation, or strain-specific variability.

Additionally, the way the criteria were weighted directly influenced the resulting species rankings, and alternative weighting schemes could produce different outcomes. For example, a stronger emphasis on market potential might favour species with high economic returns but lower environmental tolerance. This sensitivity is inherent to multi-criteria decision-making and highlights the importance of carefully justifying weight assignments. For this thesis, 20 studies were evaluated for the literature-based frequency analysis. However, adding more studies to this analysis could potentially change the weighting outcomes. Future applications of this framework would benefit from a more participatory weighting process involving aquaculture practitioners, policymakers, and local stakeholders to ensure the criteria reflect real-world priorities and trade-offs.

Finally, other uncertainties in the weighting of the MCSM analyses should be acknowledged. Species performance can vary depending on farming practices, genetic strains, or local adaptation. Market dynamics may also shift, for example, changes in consumer demand for seaweed products or global fluctuations in shrimp prices, which could alter the attractiveness of farmed species. Furthermore, the tolerance data used in the thesis were derived from datasets and the literature, rather than from Bonaire-specific trials, introducing uncertainty about how the species will perform under local conditions.

The species combination that was identified in this study should be regarded as a starting point for future research. Shrimp, seaweed, and mangrove species actively modify seawater conditions within an IMTA system, altering the pH, nutrient concentrations, oxygen dynamics, and waste profiles (Nardelli et al., 2018*;* Yusoff et al., 2024). As a result, the optimal functioning of such a system requires extensive pilot-scale testing with different ratios and *in situ* monitoring of nutrient fluxes, oxygen balance, and waste accumulation before scaling up to a fully operational industrial system on Bonaire. While this thesis focused on identifying a single top-performing seaweed and mangrove species, future designs could explore the inclusion of multiple extractive species to enhance functional diversity and resilience. Feasibility considerations, however, suggest starting with the most suitable candidates and expanding only once performance has been validated under local conditions. Future adaptations of the system could also explore integrating other trophic groups, such as filter feeders, abalone, or microbial Biofloc technology, to further enhance nutrient cycling and water quality, although these were beyond the scope of this thesis.

The combination of *P. monodon*, *U. lactuca,* and *R. mangle* emerged as the most promising IMTA assemblage under current conditions, whereas *A. germinans* appeared better adapted to future climate scenarios. This outcome illustrates that a species performing well under current environmental conditions may not necessarily remain suitable under projected climate change.

Trade-offs must also be carefully considered in the future design system. *P. monodon*, while highly productive and commercially valuable, is a non-native species (Khafage et al., 2019) and therefore poses potential ecological risks, particularly if it were to escape or transmit disease in natural ecosystems. Likewise, higher feed conversion ratios can increase nutrient availability for extractive species but also reflect lower shrimp performance or greater feed requirements, raising production costs (Yusoff et al., 2024). These examples illustrate the importance of balancing biological performance with ecological compatibility, biosecurity, and market considerations.

The findings in this thesis align with and extend published IMTA research. Globally, *P. monodon* is a dominant shrimp species in aquaculture due to its large size, high quality, and its suitability for integration into IMTA systems (Waiho et al., 2024). Similarly, *U. lactuca* has been successfully used in subtropical IMTA systems and already has an established market (Laramore et al., 2022). The strong performance of *R. mangle* under present-day conditions makes it well-suited for integration into IMTA systems in Bonaire's current coastal setting. In contrast, A. germinans demonstrated greater resilience under projected future scenarios, reflecting its broader tolerance to salinity and temperature fluctuations. This suggests that A. germinans may become increasingly advantageous for IMTA integration as ocean conditions shift due to climate change. Together, these findings contribute to the growing body of research on mangrove inclusion in IMTA and emphasize the importance of species-specific selection to ensure system sustainability under both current and future environmental conditions.

5. Conclusions

This thesis set out to answer the question: *Which combinations of fed, extractive, and ecosystem-restoring species are most suitable for IMTA development on Bonaire, given current and projected coastal environmental conditions?* By characterizing local seawater conditions and generating multi-criteria suitability matrices that integrated ecological, biological, and economic criteria, the study identified species combinations that are both environmentally compatible and commercially promising.

The findings demonstrate that IMTA is both feasible and potentially resilient on Bonaire when species are carefully matched to local environmental conditions. Under present-day conditions, a system centred on *Penaeus monodon*, *Ulva lactuca,* and *Rhizophora mangle* provides the strongest balance between productivity, environmental compatibility, and ecological function. However, under projected climate change scenarios, *Avicennia germinans* emerges as the most suitable mangrove species due to its greater tolerance to elevated salinity and pH. These results show that species performing well under current conditions may not remain suitable in the future, underscoring the need for adaptive IMTA designs. Despite methodological constraints (reliance on literature-derived tolerance data, subjective weighting, simplified climate projections), the multi-criteria framework proved valuable for aquaculture planning under uncertainty.

Overall, this study provides a science-based foundation for IMTA development on Bonaire and contributes to broader discussions on climate-smart aquaculture in small island contexts. The findings present a transferable framework for balancing biological performance, environmental suitability, and economic value, supporting both sustainable food production and blue economy principles. Future research should validate these findings through pilot-scale trials, refine weighting schemes with stakeholder input, and incorporate more detailed climate models to strengthen long-term projections.

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Appendix

1. Physicochemical characteristics of Bonaire's coastal seawater

Table 1

Parameter	*Present – min*	*Present – max*	*SSP1-2.6 – min*	*SSP1-2.6 – max*	*SSP5-8.5 – min*	*SSP5-8.5 – max*	*Reference*
Temperature (°C)	26.7	29.5	27.7	31.3	29.7	33.5	(+ Fig. 3.1, 3.2); IPCC
Salinity (PSU)	35.5	36.2	35.7	36.6	36.0	37.2	(+ Fig. 3.3, 3.4); IPCC
pH	8.052	8.055	7.955	8.012	7.735	7.772	(+ Fig. 3.5); IPCC
Dissolved oxygen (mg L^{-1})	6.3	6.6	6.24	6.34	5.99	6.14	(+ Fig. 3.6); IPCC

2. Environmental criteria data

A. Candidate shrimp species

Litopenaeus vannamei – temperature

Table A.1.a. Reported temperature tolerance ranges per study

Reference (year)	*Min (°C)*	*Max (°C)*	*Region*	*Study type*
Ponce-Palafox et al., (1997)	28.0	30.0	Sinaloa, Mexico	Experimental
Topuz & Kır, (2023)	25.0	30.0	Turkey	Experimental
Wyban et al., (1995)	23.0	30.0	Waimanalo, Hawaii	Experimental
Barraza-Guardado et al., (2015)	28.1	31.3	Mexico	Field
De Alaiza Garcia Madrigal et al. (2020)	22.0	29.0	Brazil	Experimental

Table A.1.b Summary of averaged temperature ranges

Species	*Parameter*	*Range (°C)*	*No. of studies*	*Calculation method*
L. vannamei	Temperature	25.0-30.0	5	Mean of reported min & max (Table A.1.a)

Litopenaeus vannamei – salinity

Table A.2.a Reported salinity tolerance ranges per study

Reference (year)	*Min (PSU)*	*Max (PSU)*	*Region*	*Study type*
Ponce-Palafox et al., 1997	33.0	40.0	Sinaloa, Mexico	Experimental
Sadek &Nabawi, 2021	5.0	15.0	Egypt	Experimental
Pan et al., 2007	28.0	31.0	Qingdao, China	Experimental
Barraza-Guardado et al., 2015	38.0	40.0	Mexico	Field
De Alaiza Garcia Madrigal et al., 2020	31.0	32.0	Brazil	Experimental

Table A.2.b Summary of averaged salinity ranges

Species	*Parameter*	*Range (PSU)*	*No. of studies*	*Calculation method*
L. vannamei	Salinity	27.0-32.0	5	Mean of reported min & max (Table A.2.a)

Litopenaeus vannamei – pH

Table A.3.a Reported pH tolerance ranges per study

Reference (year)	*Min*	*Max*	*Region*	*Study type*
Pan et al., 2007	8.1	8.6	Qingdao, China	Experimental
Barraza-Guardado et al., 2015	8.1	8.2	Mexico	Field
De Alaiza Garcia Madrigal et al. (2020)	7.8	8.0	Brazil	Experimental

Table A.3.b Summary of averaged pH ranges

Species	*Parameter*	*Range*	*No. of studies*	*Calculation method*
L. vannamei	pH	8.0-8.3	3	Mean of reported min & max (Table A.3.a)

Litopenaeus vannamei – dissolved oxygen

Table A.4.a Reported dissolved oxygen tolerance ranges per study

Reference (year)	*Min (mg L^{-1})*	*Max (mg L^{-1})*	*Region*	*Study type*
Nonwachai et al., 2011	2.0	4.0	Chanthaburi, Thailand	Experimental
Barraza-Guardado et al., 2015	2.8	6.4	Mexico	Field
De Alaiza Garcia Madrigal et al. (2020)	4.4	4.5	Brazil	Experimental
Galang et al. (2019)	3.5	7.5	Bali, Indonesia	Experimental

Table A.4.b Summary of averaged dissolved oxygen ranges

Species	*Parameter*	*Range (mg L^{-1})*	*No. of studies*	*Calculation method*
L. vannamei	DO	3.2-5.6	4	Mean of reported min & max (Table A.4.a)

Penaeus monodon – temperature

Table A.5.a Reported temperature tolerance ranges per study

Reference (year)	*Min (°C)*	*Max (°C)*	*Region*	*Study type*
Thakur & Lin, 2003	26.8	34.5	Thailand	Experimental
Shaari et al., 2011	29.6	31.6	Palau Pinang, Malaysia	Field
Sahu et al., 2012	25.0	35.0	Orissa, India	Field

Table A.5.b Summary of averaged temperature ranges

Species	*Parameter*	*Range (°C)*	*No. of studies*	*Calculation method*
P. monodon	Temperature	27.1-33.7	3	Mean of reported min & max (Table A.5.a)

Penaeus monodon – salinity

Table A.6.a Reported salinity tolerance ranges per study

Reference (year)	*Min (PSU)*	*Max (PSU)*	*Region*	*Study type*
Chaitanawisuti et al., 2013	25.0	35.0	X	Experimental
Ye et al., 2009	20.0	35.0	China	Experimental
Thakur & Lin, 2003	20.0	20.0	Thailand	Experimental
Shaari et al., 2011	20.0	30.0	Palau Pinang, Malaysia	Field

Sahu et al., 2012	20.0	35.0	Orissa, India	Field

Table A.6.b Summary of averaged salinity ranges

Species	*Parameter*	*Range (PSU)*	*No. of studies*	*Calculation method*
P. monodon	Salinity	21.0-31.0	5	Mean of reported min & max (Table A.6.a)

Penaeus monodon – pH

Table A.7.a Reported pH tolerance ranges per study

Reference (year)	*Min*	*Max*	*Region*	*Study type*
Noor-Hamid et al., 1994	7.5	8.0	Iloilo, Philippines	Experimental
Thakur & Lin, 2003	7.0	9.4	Thailand	Experimental
Shaari et al., 2011	7.7	8.5	Palau Pinang, Malaysia	Field
Sahu et al., 2012	7.3	8.3	Orissa, India	Field

Table A.7.b Summary of averaged pH ranges

Species	*Parameter*	*Range*	*No. of studies*	*Calculation method*
P. monodon	pH	7.4-8.6	4	Mean of reported min & max (Table A.7.a)

Penaeus monodon – dissolved oxygen

Table A.8.a Reported dissolved oxygen tolerance ranges per study

Reference (year)	*Min (mg L^{-1})*	*Max (mg L^{-1})*	*Region*	*Study type*
Thakur & Lin, 2003	4.4	12.0	Thailand	Experimental
Shaari et al., 2011	4.6	8.2	Palau Pinang, Malaysia	Field
Sahu et al., 2012	4.8	5.0	Orissa, India	Field

Table A.8.b Summary of averaged dissolved oxygen ranges

Species	*Parameter*	*Range (mg L^{-1})*	*No. of studies*	*Calculation method*
P. monodon	DO	4.6-8.4	3	Mean of reported min & max (Table A.8.a)

Penaeus schmitti – temperature

Table A.9.a Reported temperature tolerance ranges per study

Reference (year)	*Min (°C)*	*Max (°C)*	*Region*	*Study type*
Barbieri, 2010	23.0	28.0	Brazil	Experimental
De Alaiza Garcia Madrigal et al. (2020)	22.0	29.0	Brazil	Experimental
Bochini et al. (2014)	19.4	27.3	Brazil	Field

Table A.9.b Summary of averaged temperature ranges

Species	*Parameter*	*Range (°C)*	*No. of studies*	*Calculation method*
P. schmitti	Temperature	21.5-28.1	3	Mean of reported min & max (Table A.9.a)

Penaeus schmitti – salinity

Table A.10.a Reported salinity tolerance ranges per study

Reference (year)	*Min (PSU)*	*Max (PSU)*	*Region*	*Study type*
Rosas et al., 1997	15.0	25.0	Cuba	Experimental
Barbieri, 2010	10.0	25.0	Brazil	Experimental
De Alaiza Garcia Madrigal et al., 2020	31.0	32.0	Brazil	Experimental
Bochini et al. (2014)	33.0	35.0	Brazil	Field

Table A.10.b Summary of averaged salinity ranges

Species	*Parameter*	*Range (PSU)*	*No. of studies*	*Calculation method*
P. schmitti	Salinity	22.0 – 29.0	4	Mean of reported min & max (Table A.10.a)

Penaeus schmitti – pH

Table A.11.a Reported pH tolerance ranges per study

Reference (year)	*Min*	*Max*	*Region*	*Study type*
Barbieri, 2010	8.0	8.0	Brazil	Experimental
De Alaiza Garcia Madrigal et al. (2020)	7.8	8.0	Brazil	Experimental

Table A.11.b Summary of averaged pH ranges

Species	*Parameter*	*Range*	*No. of studies*	*Calculation method*
P. schmitti	pH	7.9-8.0	2	Mean of reported min & max (Table A.11.a)

Penaeus schmitti – dissolved oxygen

Table A.12.a Reported dissolved oxygen tolerance ranges per study

Reference (year)	*Min (mg L^{-1})*	*Max (mg L^{-1})*	*Region*	*Study type*
Rosas et al., 1997	4.5	5.0	Cuba	Experimental
Barbieri, 2010	6.8	6.8	Brazil	Experimental
De Alaiza Garcia Madrigal et al. (2020)	4.4	4.5	Brazil	Experimental

Table A.12.b Summary of averaged dissolved oxygen ranges

Species	*Parameter*	*Range (mg L^{-1})*	*No. of studies*	*Calculation method*
P. schmitti	DO	5.2-5.4	3	Mean of reported min & max (Table A.12.a)

B. Environmental tolerance data for seaweed species

Ulva lactuca – temperature

Table B.1.a Reported temperature tolerance ranges per study

Reference (year)	*Min (°C)*	*Max (°C)*	*Region*	*Study type*
Nardelli et al., 2018	22.4	29.2	Brazil	Experimental
Laramore et al., 2022	21.7	29.7	Florida, USA	Experimental
Huo et al., 2024	12.6	25.8	California, USA	Experimental
Drawbridge et al., 2024	12.7	26.2	California, USA	Experimental
Msuya & Neori, 2008	21.0	25.0	X	Experimental
Chamily et al. (2024)	27.6	28.8	Bangladesh	Field

Neori et al., 2000	18.2	31.3	X	Experimental

Table B.1.b Summary of averaged temperature ranges

Species	*Parameter*	*Range (°C)*	*No. of studies*	*Calculation method*
U. lactuca	Temperature	19.4-28.0	7	Mean of reported min & max (Table B.1.a)

Ulva lactuca – salinity

Table B.2.a Reported salinity tolerance ranges per study

Reference (year)	*Min (PSU)*	*Max (PSU)*	*Region*	*Study type*
Laramore et al., 2022	24.6	33.9	Florida, USA	Experimental
Drawbridge et al., 2024	34.0	35.0	California, USA	Experimental
Chamily et al. (2024)	29.4	30.4	Bangladesh	Field
Neori et al., 2000	41.0	41.0	X	Experimental

Table B.2.b Summary of averaged salinity ranges

Species	*Parameter*	*Range (PSU)*	*No. of studies*	*Calculation method*
U. lactuca	Salinity	32.0-35.0	4	Mean of reported min & max (Table B.2.a)

Ulva lactuca – pH

Table B.3.a Reported pH tolerance ranges per study

Reference (year)	*Min*	*Max*	*Region*	*Study type*
Laramore et al., 2022	6.9	7.9	Florida, USA	Experimental
Huo et al., 2024	7.8	8.2	California, USA	Experimental
Drawbridge et al., 2024	7.9	8.8	California, USA	Experimental
Msuya & Neori, 2008	7.5	8.5	X	Experimental
Chamily et al. (2024)	7.4	7.8	Bangladesh	Field
Neori et al., 2000	8.5	8.9	X	Experimental

Table B.3.b Summary of averaged pH ranges

Species	*Parameter*	*Range*	*No. of studies*	*Calculation method*
U. lactuca	pH	7.7-8.4	6	Mean of reported min & max (Table B.3.a)

Gracilaria foliifera – temperature

Table B.4.a Reported temperature tolerance ranges per study

Reference (year)	*Min (°C)*	*Max (°C)*	*Region*	*Study type*
Raikar et al., 2001	25.0	32.5	India / Japan	Experimental
Lapointe & Ryther, 1979	23.0	34.0	Florida, USA	Experimental
Vinuganesh et al. (2022)	30.0	30.0	India	Experimental

Table B.4.b Summary of averaged temperature ranges

Species	*Parameter*	*Range (°C)*	*No. of studies*	*Calculation method*
G. foliifera	Temperature	26.0-32.2	3	Mean of reported min & max (Table B.4.a)

Gracilaria foliifera – salinity

Table B.5.a Reported salinity tolerance ranges per study

Reference (year)	*Min (PSU)*	*Max (PSU)*	*Region*	*Study type*
Raikar et al., 2001	30.0	35.0	India / Japan	Experimental
Lapointe & Ryther, 1979	26.0	33.0	Florida, USA	Experimental
Vinuganesh et al. (2022)	35.0	35.0	India	Experimental

Table B.5.b Summary of averaged salinity ranges

Species	*Parameter*	*Range (PSU)*	*No. of studies*	*Calculation method*
G. foliifera	Salinity	30.0-34.0	3	Mean of reported min & max (Table B.5.a)

Gracilaria foliifera – pH

Table B.6.a Reported pH tolerance ranges per study

Reference (year)	*Min*	*Max*	*Region*	*Study type*
Lapointe & Ryther, 1979	8.4	9.2	Florida, USA	Experimental
Vinuganesh et al. (2022)	7.7	8.1	India	Experimental

Table B.6.b Summary of averaged pH ranges

Species	*Parameter*	*Range*	*No. of studies*	*Calculation method*
G. foliifera	pH	8.1-8.7	2	Mean of reported min & max (Table B.6.a)

Gracilaria tikvahiae – temperature

Table B.7.a Reported temperature tolerance ranges per study

Reference (year)	*Min (°C)*	*Max (°C)*	*Region*	*Study type*
Samocha et al., 2015	18.0	33.0	Texas, USA	Experimental
Lapointe et al., 1984	20.0	30.0	Florida, USA	Experimental
Gorman et al., 2017	20.0	29.0	New York, USA	Experimental
Lapointe & Ryther, 1978	12.0	34.0	Florida, USA	Experimental
Ryther et al., 1981	16.0	35.0	Florida, USA	Experimental

Table B.7.b Summary of averaged temperature ranges

Species	*Parameter*	*Range (°C)*	*No. of studies*	*Calculation method*
G. tikvahiae	Temperature	17.2-32.2	5	Mean of reported min & max (Table B.7.a)

Gracilaria tikvahiae – salinity

Table B.8.a Reported salinity tolerance ranges per study

Reference (year)	*Min (PSU)*	*Max (PSU)*	*Region*	*Study type*
Samocha et al., 2015	30.4	34.8	Texas, USA	Experimental
Lapointe et al., 1984	26.0	29.0	Florida, USA	Experimental
Lapointe & Ryther, 1978	20.0	34.0	Florida, USA	Experimental
Ryther et al., 1981	30.0	34.0	Florida, USA	Experimental

Table B.8.b Summary of averaged salinity ranges

Species	Parameter	Range (PSU)	No. of studies	Calculation method
G. tikvahiae	Salinity	26.6-33.0	4	Mean of reported min & max (Table B.8.a)

Gracilaria tikvahiae – pH

Table B.9.a Reported pH tolerance ranges per study

Reference (year)	Min	Max	Region	Study type
Samocha et al., 2015	7.4	7.9	Texas, USA	Experimental
DeBusk & Ryther (1984)	8.0	8.1	Florida, USA	Experimental

Table B.9.b Summary of averaged pH ranges

Species	Parameter	Range	No. of studies	Calculation method
G. tikvahiae	pH	7.7-8.0	2	Mean of reported min & max (Table B.9.a)

C. Environmental tolerance data for mangrove species

Rhizophora mangle – temperature

Table C.1.a Reported temperature tolerance ranges per study

Reference (year)	Min	Max	Region	Study type
Moroyoqui-Rojo et al., 2012	24.0	32.7	Sinaloa, Mexico	Experimental
De-León-Herrera et al., 2014	27.3	27.3	Mexico	Experimental
Allen & U.S. Department of Agriculture, 2002	21.0	30.0	X	X

Table C.1.b Summary of averaged temperature ranges

Species	Parameter	Range (°C)	No. of studies	Calculation method
R. mangle	Temperature	24.1-30.0	3	Mean of reported min & max (Table C.1.a)

Rhizophora mangle – salinity

Table C.2.a Reported salinity tolerance ranges per study

Reference (year)	Min	Max	Region	Study type
Moroyoqui-Rojo et al., 2012	32.1	32.8	Sinaloa, Mexico	Experimental
De-León-Herrera et al., 2014	32.0	32.0	Mexico	Experimental
Allen & U.S. Department of Agriculture, 2002	15.0	35.0	X	X

Table C.2.b Summary of averaged salinity ranges

Species	Parameter	Range (PSU)	No. of studies	Calculation method
R. mangle	Salinity	26.4-33.3	3	Mean of reported min & max (Table C.2.a)

Rhizophora mangle – pH

Table C.3.a Reported pH tolerance ranges per study

Reference (year)	Min	Max	Region	Study type
De-León-Herrera et al., 2014	7.7	7.7	Mexico	Experimental
Thibodeau & Nickerson (1986)	5.5	5.5	Bahamas	Field

Table C.3.b Summary of averaged pH ranges

Species	Parameter	Range	No. of studies	Calculation method
R. mangle	pH	6.6	2	Mean of reported min & max (Table C.3.a)

Avicennia germinans – temperature

Table C.4.a Reported temperature tolerance ranges per study

Reference (year)	Min	Max	Region	Study type
De-León-Herrera et al., 2014	27.3	27.3	Mexico	Experimental
Villavicencio et al., 2024	28.0	37.0	Brazil	Experimental
Suárez & Medina, 2005	16.3	30.5	Venezuela	Experimental
Find Trees & Learn | UA Campus Arboretum, z.d	20.0	30.0	X	X

Table C.4.b Summary of averaged temperature ranges

Species (year)	Parameter	Range (°C)	No. of studies	Calculation method
A. germinans	Temperature	22.9-31.1	4	Mean of reported min & max (Table C.4.a)

Avicennia germinans – salinity

Table C.5.a Reported salinity tolerance ranges per study

Reference (year)	Min	Max	Region	Study type
De-León-Herrera et al., 2014	32.0	32.0	Mexico	Experimental
Alleman & Hester, 2010	24.0	72.0	Louisiana, USA	Experimental
Matto et al., 2023	15.0	45.0	Guyana	Experimental
Suárez & Medina, 2005	10.0	40.0	Venezuela	Experimental

Table C.5.b Summary of averaged salinity ranges

Species	Parameter	Range (PSU)	No. of studies	Calculation method
A. germinans	Salinity	20.0-47.0	4	Mean of reported min & max (Table C.5.a)

Avicennia germinans – pH

Table C.6.a Reported pH tolerance ranges per study

Reference (year)	Min	Max	Region	Study type
De-León-Herrera et al., 2014	7.7	7.7	Mexico	Experimental
Matto et al., 2023	5.2	6.6	Guyana	Experimental
Find Trees & Learn | UA Campus Arboretum, z.d	5.3	7.8	X	X
Thibodeau & Nickerson (1986)	5.5	5.5	Bahamas	Field

Table C.6.b Summary of averaged pH ranges

Species	Parameter	Range	No. of studies	Calculation method
A. germinans	pH	5.9-6.9	4	Mean of reported min & max (Table C.6.a)

3. Functional and economic criteria data

A. Candidate shrimp species

Litopenaeus vannamei

Table D.1 Suitability criteria for L. vannamei

Criterion	*Score*	*Evidence summary*	*References*
Native species	No	The species is native to the East Pacific.	Liao & Chien, 2011
IMTA use	Yes	The species has been used in IMTA systems before.	Huong et al., 2025; Laramore et al., 2018; Samocha et al. (2015)
Growth rate	Medium	The species had a mean growth rate of 0.82 g/week (min = 0.4 g/week; max = 1.7 g/week), across multiple studies, indicating a medium growth rate.	Appelbaum et al., 2002; De Alaiza Garcia Madrigal et al., 2020; Liao & Chien, 2011; Peixoto et al. (2003); Paquotte et al. (1998); Da Silveira et al. (2020)
Pathogen resistant	Yes	The species is known carriers for multiple diseases, including WSSV, IHHNV & TSV. However, the species has many Specific-Pathogen-Free larvae available.	Briggs et al., 2004; Albalat et al., 2022; Asmild et al., 2023; Lightner, 1999
Market potential	High	The species has a high market demand. It's the most grown crustacean in global aquaculture. Most countries in Central and South America have replaced all farming with *L. vannamei*. In 2024, around 83% off all shrimp aquaculture worldwide produced *L. vannamei.*	Albalat et al., 2022; De Alaiza et al., 2022; Waiho et al., 2024
Feed	Medium	The species showed a mean FCR of 1.65 (min = 0.73; max = 3.4) across multiple studies, indicating a moderate feed conversion efficiency with some degree of feed loss.	Aalimahmoudi et al. (2016); De Alaiza Garcia Madrigal et al. (2020); Weldon et al., 2021; Bachruddin et al., 2018; Soares et al., 2021

Penaeus monodon

Table D.2 Suitability criteria for P. monodon

Criterion	*Score*	*Evidence summary*	*References*

Native species	No	The species is native to the Indo-Pacific and the East coast of Africa.	Khafage et al., 2019
IMTA use	Yes	The species has been used in IMTA systems before.	Arriesgado et al., 2022; Kumara et al., 2023
Growth rate	High	The species had a mean growth rate of 1.8 g/week (min = 0.77 g/week; max = 2.52 g/week), across multiple studies, indicating a high growth rate.	Duy et al., 2012; Suwoyo et al., 2024; Chakraborti et al. (1986); Smith et al. (2002)
Pathogen resistant	Medium	The species is known carriers for multiple diseases, including WSSV, YHV & IHHNV. The species has a limited amount of Specific Free Larvae available.	Briggs et al., 2004; Waiho et al., 2024; Lightner, 1999
Market potential	High	This species has a high market demand. *P. monodon* is the second most produces crustacean worldwide, with *L. vannamei* on the first place. The species is more for niche markets. However, due to its bigger size and good quality, it has market demand and sells for high prices.	Waiho et al., 2024; Asmild et al., 2023
Feed	Medium	The species showed a mean FCR of 1.99 (min = 0.97; max = 5.3) across multiple studies, indicating a moderate feed conversion efficiency with some degree of feed loss.	Burford & Lorenzen, 2003; Thakur & Lin, 2003; Mohanty, 2001; Niu et al., 2015; Supriatna ; et al. (2019); Catacutan (1991); Smith et al. (2002)

Penaeus schmitti

Table D.3 Suitability criteria for P. schmitti

Criterion	*Score*	*Evidence summary*	*References*
Native species	No	The species occurs in the Caribbean Sea, including the waters of Venezuela. However, the species has not been recorded for Bonaire specifically.	Alio et al., 1999 & Gusmão et al., 2005
IMTA use	Medium	The species has not been used in IMTA systems before, but it has been cultivated in aquaculture before.	Ramos et al., 1995; Griffith & Wigglesworth, 1993
Growth rate	Low	The species had a mean growth rate of 0.4 g/week (min = 0.1 g/week; max = 0.8 g/week), across multiple studies, indicating a low growth rate.	De Alaiza Garcia Madrigal et al., 2020; Artiles, 2002

Pathogen resistant	Low	The species is known carriers for multiple diseases, including TSV and IHHNV. There is no literature available on Specific-Pathogen-Free larvae for this species.	Briggs et al., 2004; Lightner, 1999
Market potential	Low	The species has limited domestication and commercial-scale farming experience. Previous cultivation attempts have largely been left abandoned, partly to make way for *L. vannamei*. *P. schmitti* therefore has a low market potential.	De Alaiza Garcia Madrigal et al., 2020; De Alaiza et al., 2022
Feed	High	The species showed a mean FCR of 7.83 (min = 2.3; max = 11.5) 2.3-9 ; 8.5-11.5 relatively high (2.3 – 11.5) across multiple studies, indicating low feed conversion efficiency and substantial feed losses during culturing.	Ceballos et al. (2011) ; De Alaiza Garcia Madrigal et al. (2020)

B. Candidate seaweed species

Ulva lactuca

Table E.1 Suitability criteria for U. lactuca

Criterion	*Score*	*Evidence summary*	*References*
Native species	Yes	The species is native to Bonaire.	Dutch Caribbean Species Register, z.d
IMTA use	Yes	The species has been used in IMTA systems before.	Laramore et al., 2022; Nardelli et al., 2018; Drawbridge et al. (2024); Huo et al. (2024)
Growth rate	High	The species had a mean growth rate of 9.7% day^{-1} (min = 3.38% day^{-1} ; max = 21.36% day^{-1}), across multiple studies, indicating a high growth rate.	Nardelli et al., 2018; Drawbridge et al., 2024; Ale et al. (2010)
Pathogen resistant	Medium	The species is fairly resistant to pathogens when cultured under good aquaculture conditions. It's prone to opportunistic bacterial or fungal infections, but has a complex microbiome that helps resist infection. It requires careful microbial balance and good water quality exchange to avoid disease outbreaks.	Van Der Loos et al., 2024; Simon et al., 2022; González et al., 2021; Simon et al., 2022
Market potential	High	The species has a good market potential. It's emerging as a sustainably, nutritious and commercially valuable seaweed. It has applications in human food, animal feed and health products. The global market value for U. lactuca was estimated at 1.46 billion in 2025, and is projected to keep growing.	Laramore et al., 2022; Putra et al., 2025; Doshi, 2025

Gracilaria foliifera

Table E.2 Suitability criteria for G. foliifera

Criterion	*Score*	*Evidence summary*	*References*

Native species	Yes	The species is native to Bonaire.	Dutch Caribbean Species Register, z.d
IMTA use	Medium	The species has not been used in IMTA systems before, but it has been cultivated in aquaculture before.	Osman et al., 2017
Growth rate	Low	The species had a mean growth rate of 1.94% day^{-1} (min = 0.65% day^{-1} ; max = 4.0% day^{-1}) in two studies, indicating a low growth rate.	Rosenberg & Ramus, 1982; Vinuganesh et al., 2022
Pathogen resistant	X	There is no literature available on the pathogen resistance of this species.	X
Market potential	X	There is no literature available on the market potential of this species.	X

Gracilaria tikvahiae

Table E.3 Suitability criteria for G. tikvahiae

Criterion	*Score*	*Evidence summary*	*References*
Native species	No	The species is native to the West-Atlantic, with a distribution from Nova Scotia to the Caribbean, but has not been recorded on Bonaire.	Rocha et al., 2018
IMTA use	Yes	The species has been used in IMTA systems before.	Samocha et al., 2015
Growth rate	High	The species had a mean growth rate of 13.8% day^{-1} (min = 4.51% day^{-1} ; max = 27.8% day^{-1}), across multiple studies, indicating a high growth rate.	Samocha et al., 2015; Kim & Yarish, 2014; Lapointe & Ryther, 1978
Pathogen resistant	Medium	The species is susceptible to specific diseases, but fairly resistant under good aquaculture conditions. The main concern for this species are harmful epiphytes.	Friedlander & Critchley, 2024; Capo et al., 1999
Market potential	High	The species has a good market potential. It is economically significant as a human food source, animal feed and as an agar-producing seaweed.	Wu et al., 2023; Samocha et al., 2015

C. Candidate mangrove species

Rhizophora mangle

Table F.1 Suitability criteria for R. mangle

Criterion	*Score*	*Evidence summary*	*References*
Native species	Yes	The species is native to Bonaire.	Van Der Geest et al., 2025; Dutch Caribbean Species Register, z.d.
IMTA use	Medium	The species has not been used in IMTA systems before, but it has been used in silvo-fishery before.	Moroyoqui-Rojo et al., 2012; De-

			León-Herrera et al., 2014
Growth rate	High	The species growth varies greatly with site, salinity and age of the plant, but the growth rate falls between 15 cm $year^{-1}$ to 150 cm $year^{-1}$, based on multiple studies, indicating a high growth rate.	De-León-Herrera et al., 2014; De Oliveira Lima et al., 2018; Duke & Allen, 2006; Allen & U.S. Department of Agriculture, 2002
Pathogen resistant	High	The species is generally resistant to pathogens, with disease occurring mainly only occurring under environmental stress. The species can be susceptible to: leaf fungal infections, root rot, wood boring insects.	Duke & Allen, 2006; Allen & U.S. Department of Agriculture, 2002
Ecosystem impact	High	The species has positive ecosystem impacts: carbon storage, habitat provision, coastline protection.	Van Der Geest et al., 2025; Duke & Allen, 2006

Avicennia germinans

Table F.2 Suitability criteria for A. germinans

Criterion	*Score*	*Evidence summary*	*References*
Native species	Yes	The species is native to Bonaire.	Van Der Geest et al., 2025; Dutch Caribbean Species Register, z.d.
IMTA use	Medium	The species has not been used in IMTA systems before, but it has been used in silvo-fishery before.	De-León-Herrera et al., 2014
Growth rate	Medium	The species growth varies greatly with site, salinity and age of the plant, but the growth rate falls between 24 cm $year^{-1}$ to 79 cm $year^{-1}$, based on multiple studies, indicating a medium growth rate.	De-León-Herrera et al., 2014; Villavicencio et al., 2024; (Find Trees & Learn | UA Campus Arboretum, z.d.)
Pathogen resistant	High	The species is naturally resistant to many pathogens. Root rot or fungal infestation can occur, but propagules in seawater are better protected against this.	Pickens & Hester, 2010; Alleman & Hester, 2011

Ecosystem impact	High	The species has positive ecosystem impacts: carbon storage, habitat provision, coastline protection.	Van Der Geest et al., 2025; Find Trees & Learn | UA Campus Arboretum, z.d.

4. Criterion weights

A. References Criterion Weights

Table 4.A References used for the literature-based frequency analysis

no.	reference
1	Hossain et al. (2022)
2	Khanjani et al. (2022)
3	Neori et al. (2004)
4	Bolton et al. (2008)
5	Correia et al. (2020)
6	Troell et al. (2009)
7	Harini et al. (2024)
8	Arriesgado et al. (2022)
9	Kumara et al. (2023)
10	Huong et al. (2025)
11	S. Laramore et al. (2018)
12	Rahman et al. (2020)
13	Rusco et al. (2024)
14	S. E. Laramore et al. (2022)
15	Nardelli et al. (2018)
16	Samocha et al. (2015)
17	Huo et al. (2024)
18	Drawbridge et al. (2024)
19	Neori et al. (2000)
20	De-León-Herrera et al. (2014)

Table 4.A References used for the literature-based frequency analysis – environmental aggregate

no.	reference
1	Neori et al. (2004)
2	Bolton et al. (2008)
3	Correia et al. (2020)
4	Troell et al. (2009)
5	Harini et al. (2024)
6	Arriesgado et al. (2022)
7	Kumara et al. (2023)
8	Huong et al. (2025)
9	S. Laramore et al. (2018)

10	Rahman et al. (2020)
11	Rusco et al. (2024)
12	S. E. Laramore et al. (2022)
13	Nardelli et al. (2018)
14	Samocha et al. (2015)
15	Huo et al. (2024)
16	Drawbridge et al. (2024)
17	Neori et al. (2000)
18	De-León-Herrera et al. (2014)

B. Candidate shrimp species

Criterion	*No. of studies*	*Normalized weight (∑ = 1.0)*
Native species	7	0.06
IMTA use	14	0.13
Growth rate	20	0.18
Pathogen resistance	12	0.11
Market value	20	0.18
Feed	18	0.16
Environmental suitability (aggregate)	20	0.18

Environmental sub-criterion	*No. of studies*	*Normalized weight (∑ = 1.0)*
Temperature	17	0.29
Salinity	15	0.26
pH	13	0.22
Dissolved oxygen	13	0.22

C. Candidate seaweed species

Criterion	*No. of studies*	*Normalized weight (∑ = 1.0)*
Native species	7	0.075
IMTA use	14	0.150
Growth rate	20	0.215
Pathogen resistance	12	0.129
Market value	20	0.215
Environmental suitability (aggregate)	20	0.215

Environmental sub-criterion	*No. of studies*	*Normalized weight (∑ = 1.0)*
Temperature	17	0.38
Salinity	15	0.33
pH	13	0.29

D. Candidate mangrove species

Criterion	*No. of studies*	*Normalized weight (∑ = 1.0)*
Native species	7	0.075
IMTA use	14	0.150
Growth rate	20	0.215

Pathogen resistance	12	0.129
Ecosystem impacts	20	0.215
Environmental suitability (aggregate)	20	0.215

Environmental sub-criterion	*No. of studies*	*Normalized weight (∑ = 1.0)*
Temperature	17	0.38
Salinity	15	0.33
pH	13	0.29