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Ayla Oasis Lagoons: A Model for Ecological Sustainability and Marine Conservation in Aqaba, Jordan

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Abstract: The Ayla Oasis in Aqaba, Jordan, is a major tourism and residential development project in Aqaba, Jordan, containing three artificial lagoons. This study explores the ecological sustainable development of Ayla Lagoons, focusing on the seawater and bottom sediment quality, and the bottom habitat, in addition to coral conservation and restoration initiatives. The flushing time, averaging 3.7 days for the Upper Lagoon and 2.4 days for the Middle Lagoon, plays a crucial role in maintaining water quality. These measures secure the well-being of all visitors and residents, while also preserving the marine biodiversity. The Upper, Middle, and Tidal Lagoons exhibit physiochemical properties in alignment with seawater characteristics of the Gulf of Aqaba. Sediment quality analysis shows organic carbon levels and grain size distribution vary among lagoons, indicating expected different energy conditions and a healthy environment. The lagoons support a diverse range of species, with a total of 2343 fish individuals belonging to 22 species across 17 families recorded. The comprehensive analysis of the Ayla Oasis lagoons' seawater and sediment quality revealed a dynamic and resilient ecosystem. Ayla's coral conservation and restoration initiative within its lagoons feature 166 reef balls, 5 coral nurseries, and 2 metal structures, all designed to foster marine biodiversity. The project demonstrates the effectiveness of Ayla Oasis' environmental resilience and monitoring strategies, showcasing a commitment to sustainable management and environmental stewardship. These efforts reflect Ayla's ongoing dedication to protecting and preserving the marine ecosystem, ensuring the long-term health of its coral reefs and surrounding marine life.

Keywords: artificial lagoons; Ayla Oasis; sustainability; marine ecosystem; coral restoration; marine ecology; Gulf of Aqaba; seawater quality; sediment quality; marine bottom habitat survey

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1. Introduction

Urban development along the Red Sea coast during the last decades has caused numerous disruptions to marine ecology [1–4]. The tidal zones of the Red Sea contain numerous habitats, such as coral reefs and seagrass beds, which support a highly rich, productive, and diverse ecosystem [2,5,6]. Hence, uncontrolled and unregulated continuous human coastal activities exert stresses on the coastal areas that place the sensitive ecosystems at a great risk [7,8].

Artificial lagoons, as semi-enclosed shallow water bodies connected with coastal zones, are primarily designed to increase the waterfront areas for attracting tourists and facilitating marine activities [9,10]. They are, however, critically sensitive to water pollution under conditions of lacking water exchange and flushing times, which should ideally not exceed 5–7 days for the entire lagoon and its corresponding hydrodynamic turnover, as well as possible leaked discharges from land [11–13]. Water—and bottom sediment—quality indicators of such lagoons, are important factors within the lagoon ecosystem. They are characterized by their delicate response to changes in temperature and/or salinity of their water body because of their limited areas and shallow depth [14–16]. Moreover, physical, chemical, and biological processes are linked to each other which controls temporal variability and spatial distribution of nutrients in lagoons [12,14,17]. Thus, planning and implementation of coastal management strategies in coastal lagoons is significantly required for maintaining bathing beaches and preservation of the overall ecological condition of the lagoon and its connected water body ecosystem [18,19].

However, when securing healthy ecological conditions, these lagoons not only facilitate touristic water activities, but also create diverse habitats that support a wide array of marine species, while also serving as a platform for innovative conservation strategies [20–22].

The progressive coastal developments in Aqaba, Jordan, depending on the tourist industry, have grown in the last three decades [23,24]. The Ayla Oasis, a revolutionary development project located in Aqaba, Jordan, has succeeded since its establishment in 2010, coupled with the integration of artificial lagoons into sustainable coastal resort design. It is a large-scale venture aimed at enhancing tourism in the region, featuring luxury hotels, residential units, golf courses, and various recreational facilities [25,26]. The project aims to attract both local and international visitors seeking leisure and relaxation in a safe, beautiful, and ecologically friendly coastal setting [25]. This multifaceted project not only offers an array of tourism facilities but also prioritizes the ecological integrity of its marine environments. The artificial lagoons at Ayla Oasis are more than just appealing features; they are a cornerstone of the development's commitment to environmental stewardship and sustainable practices [26,27].

Ayla Lagoon's design model is based on a seawater pumping system from the Gulf of Aqaba into the lagoons, to keep a suitable flushing rate, which subsequently secures "close to ambient" in-lagoon water quality that is safe for human tourism, and thereafter minimal impact on the adjacent ambient water of the GoA [28]. The pumping system at Ayla Lagoons is the key factor in maintaining the oligotrophic status of water and sediment quality, minimizing eutrophication which has adverse impacts on the ecosystem in general and on more delicate species like corals in particular, both in the lagoon and the GoA seawater [29,30].

Ayla Oasis adopted a marine monitoring program that carefully tracks seawater and sediment quality, in addition to fish and ecological habitats [31]. This program is essential for the ongoing assessment and management of the lagoons, ensuring their role as bathing beaches and waterfront destinations [32]. Through continuous monitoring, the program provides the data-driven insights necessary to guide effective conservation efforts and to maintain the ecological balance within these artificial environments [33].

Another key component of Ayla's ecological sustainability is the coral restoration and preservation project [34]. This initiative involves the establishment of coral nurseries and the deployment of reef balls, which are instrumental in fostering the growth and resilience of coral communities [35]. These nurseries and structures not only aid in the recovery of damaged reefs but also serve as living laboratories for coral biology research, contributing to the global effort to preserve coral ecosystems [36–38]. Furthermore, the project highlights the importance of education and public awareness in marine conservation [39].

Despite sustainable seafront developments consistently posing challenges, particularly in the context of preserving natural habitats [40–42], Ayla Oasis's environmental policy maintained healthy water and sediment quality in lagoons through the provisioning of adequate flushing conditions and minimal discharge or runoff of pollutants such as sewage and nutrients into the lagoons [26–30].

In this study, we present the ecological conditions of Ayla Oasis lagoons and its sustainable development, where recreational and ecological responsibility coexist cordially. Through its innovative design and commitment to marine conservation, Ayla Oasis provides a blueprint for future developments, flagging the way towards a more sustainable and environmentally conscious world.

2. Study Site

Three artificial inland lagoons, spanning a total area of 750,000 m^2, are located strategically within the Ayla project (Figure 1), namely: the Upper Lagoon (UL), Middle Lagoon (UL), and Tidal Lagoon (TL). With these lagoons, Ayla Oasis extended a seafront of 235 m along the Gulf of Aqaba to an additional 17 km of lagoons' waterfront. The UL and ML are positioned in the north and center of the development, respectively. The UL sits at an elevation of 6.0 m above sea level, while the ML is at an elevation of 3.0 m above sea level. Both lagoons have approximate water volumes of 374,000 m^3 and 246,500 m^3, respectively, with consistent depths of approximately 1.95 m. TL directly connected to the Gulf of Aqaba (GoA) and maintains a water surface at sea level. It boasts a significantly larger water depth of approximately 5.2 m and a substantial water volume of about 1,525,000 m^3.

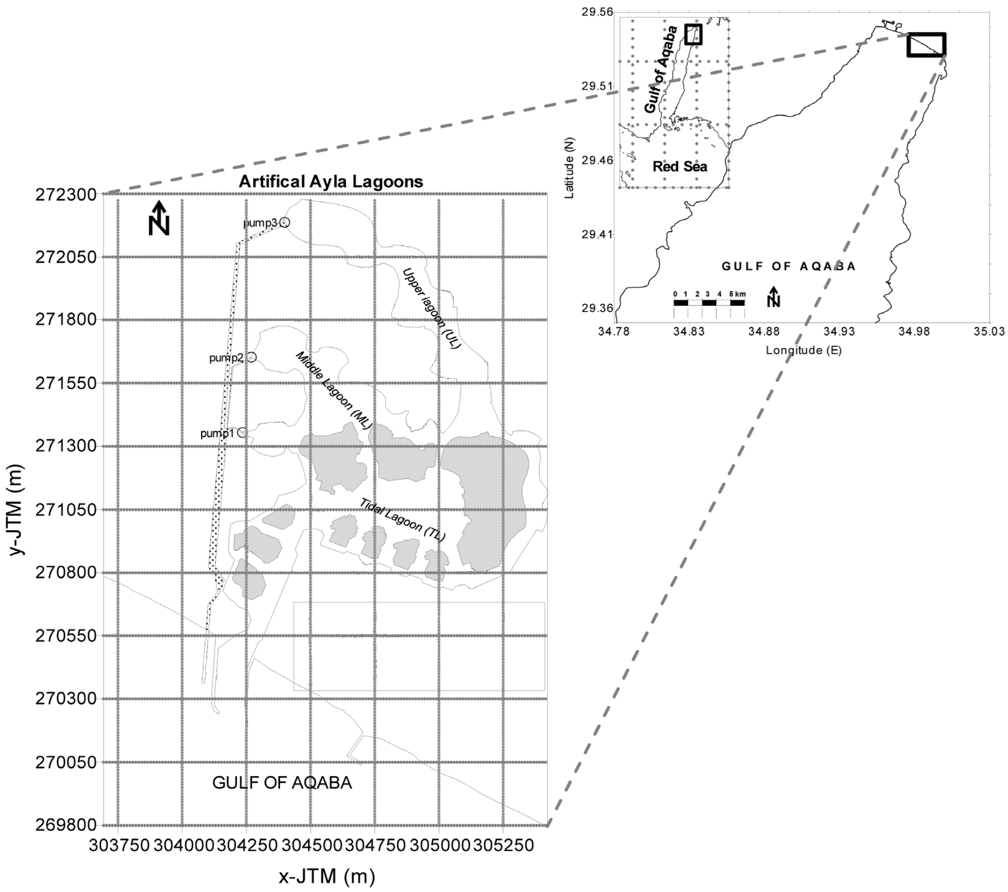

Figure 1. Map of study area of the Ayla Oasis lagoons in the northern Gulf of Aqaba (adopted from Manasrah 2015 [29]).

Being well-designed for water exchange, maintaining good water quality through regular flushing, both UL and ML lagoons meet the ideal hydraulic criteria for an artificial lagoon. UL has a flushing time of 3.7 days, while ML has a flushing time of 2.4 days which falls within the recommended range of 5–7 days (General Guidelines for Good

Quality Artificial Beaches and Lagoons, and Case Stories, by Mangor, DHI, Denmark, https://www.dhigroup.com/), which contributes strongly to achieving significant dilution, avoiding stagnation and maintaining overall water health, which is crucial for supporting natural marine life and recreational use.

3. Methods

3.1. Seawater Quality

Surface water (at 0.5 m depth) and bottom sediment samples as well as habitat surveys of fish and marine species, were collected from well determined sites across each lagoon (Figure 2), in addition to the entry of Tidal Lagoon as well as the offshore opposite to it as reference zone.

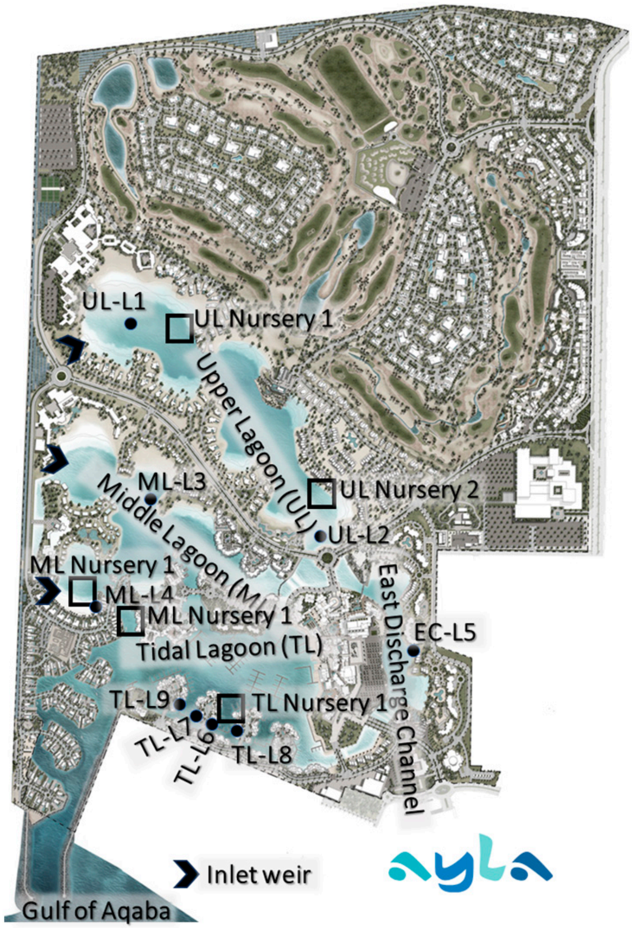

Figure 2. Locations of coral nurseries and beef balls' installations across the Upper Lagoon (UL), Middle Lagoon (ML), Tidal Lagoon (TL), and the East Discharge Channel within the Ayla Oasis.

Seawater samples were collected monthly during the first week of each month at around 12 PM (midday) using Nisken bottles and were then transferred to a 1 L polyethylene bottle in duplicate. Immediately after sampling, all samples were kept in an ice box, upon return to the laboratory. For hydrocarbon samples, the water samples were collected from the sea surface in 1 L brown glass bottles pre-cleaned with n-hexane. Water samples for nutrient analysis were filtered through 0.45 µm cellulose acetate filter upon arrival to the labs and then kept at ca. 0 °C until the time of analysis. The filter paper and the filtrate after being dried at 50–60 °C was used to estimate total suspended solids (TSS). Inorganic nutrients ammonium, nitrate, nitrite, phosphate, and silicate were analyzed spectrophotometrically according to Grasshoff (1999) [43]. Chlorophyll a in water samples is measured fluorometrically using the method of Elizabeth and Gary (1992) using acetone

(95%) as the extraction agent [44]. pH values were measured in situ using a portable pH meter. Temperature, salinity, and oxygen readings were recorded using a CTD for conductivity, temperature, and pressure (SBE 19pluseV2 SEACAT PROFILER (Sea-Bird Scientific, Bellevue, WA, USA) [45]).

3.2. Bottom Sediment Quality

Bottom surface sediment samples were collected by Van Veen Grab sampler by SCUBA divers from the first 10 cm of the lagoon bed. Sediment samples were first rinsed with distilled water and dried to a constant weight of 60 °C in a well-ventilated oven. Particle size analysis (PSA) analyses were conducted using a set of calibrated analytical sieves (US standard sieves), while total organic carbon (TOC) is measured by titration with ferrous ammonium sulphate solution (Gaudette et al., 1974) using Buret (volumetric measuring glassware) [46].

3.3. Bottom Habitat Survey

The benthic habitat and fish community structure were conducted using the point intercept method, following the approach outlined by Reef Chick's worldwide recognized habitat survey method [47]. Target areas were surveyed using 100 m-long transects, each transect comprised four 20 m segments, with a 5 m gap between each segment, resulting in a complete transect line measuring 100 m. Substrate composition was examined along these segments, including hard coral (HC), rock (RC), soft coral (SC), rubble (RB), recently killed coral (RKC), sand (SD), nutrient indicator algae (NIA), silt/clay (SI), sponge (SP), other (OT), and seagrass (SG). These were divided into categories that reflect their impact on reef health: live coral cover (HC + SC), available substrate (RC), disturbance Indicators (RKC + RB + SI), and pollution indicators: (NIA + SP).

3.4. Coral Conservation

Coral conservation initiatives at Ayla Lagoons have involved a comprehensive approach to coral conservation, located within the lagoons, including nurseries, metal structures, and strategically placed reef balls. Over the course of the project, several significant achievements have been reached, such as the transplantation of corals onto reef balls, systematic relocation efforts, and the establishment of coral nurseries. The project has followed a well-defined timeline, with detailed observations and future strategies guiding its progress.

The coral nursery aspect of the project involves the careful cultivation of coral fragments or larvae, which were collected from live corals during their reproductive events. These fragments were then raised in dedicated nurseries until they reached maturity, at which point they were transplanted back into their natural habitat [48]. These carefully raised corals were intended for replanting in their original habitat, contributing significantly to the restoration and conservation of the coral reef ecosystem [49].

The first reef ball was placed in the Ayla Upper Lagoon in 2015, with the initial transplantation from Ayla coral nursery to Ayla reef ball occurring in 2016. Careful monitoring by the Ayla diving team revealed successful coral growth, leading to the expansion of the project. In 2017, a second coral nursery was established in the Middle Lagoon, accompanied by an increase in the number of reef balls. As of 2022, a total of 166 reef balls have been strategically distributed across the lagoon area, available in three distinct sizes—large (90 cm), medium (50 cm), and small (30 cm). Additionally, the lagoon as of 2024, Ayla Lagoons contains five coral nurseries, and two metal structures.

Table 1 represents the map of Ayla Oasis in Figure 2.

Table 1. The distribution of coral nurseries, reef balls of various sizes (large, medium, small), and metal structures across different lagoon locations, including the Upper Lagoon, Middle Lagoon, East Discharge Channel, and Tidal Lagoon for coral restoration.

Lagoon	Coral Nursey	Reef Balls				Metal Structures
		L	M	S	Location	
Upper Lagoon	2	4	2	--	UL-L1	2
		11	10	20	UL-L2	--
Middle Lagoon	2	15	10	10	ML-L3	--
		1	3	1	ML-L4	--
East Discharge Channel	0	42	--	--	EC-L5-SE	--
		8	7	7	EC-L5	--
Tidal Lagoon	1	2	2	--	TL-L6	--
		2	2	1	TL-L7	--
		--	2	--	TL-L8	--
		1	1	2	TL-L9	--

4. Results

4.1. Seawater Quality

The analysis of water quality indicators in the Ayla Lagoons for the year 2022 demonstrates that, despite some fluctuations, all measured values remain within ambient levels, reflecting healthy and stable environmental conditions across the Upper Lagoon (UL), Middle Lagoon (ML), and Tidal Lagoon (TL). Table S1 presents a summary of water quality indicators across lagoons, showing the maximum (Max), average (Avg), minimum (Min), and standard deviation (SD) values for various water quality parameters measured in the Upper, Middle, and Tidal lagoons.

The analysis of water temperature showed distinct seasonal variations, with temperatures peaking in the summer months and cooling during the winter. The UL exhibited temperatures ranging from 17.28 °C in January to 28.1 °C in August, and the ML showed a similar trend, with temperatures ranging from 17.34 °C to 27.99 °C. The TL, however, showed slightly more variation, with temperatures ranging from 17.14 °C to 27.94 °C. The reference site consistently had higher temperatures in the winter months, ranging from 21.34 °C to 27.37 °C.

The analysis of salinity levels showed consistent salinity values, with slight variations throughout the year. The UL exhibited salinity ranging from 40.745 psu to 41.205 psu, reflecting minor seasonal fluctuations. The ML showed a similar range, with values between 40.7 psu and 41.17 psu, indicating stable conditions across this lagoon. The TL had slightly more variability, with salinity levels ranging from 40.72 psu to 41.17 psu. The reference site consistently had lower salinity levels, ranging from 40.57 psu to 40.72 psu, highlighting the differences between the lagoon systems and the external environment.

A moderate positive correlation between temperature and salinity across the lagoons was revealed, with the correlation coefficient (r) estimated around 0.5 to 0.7, indicating that as temperature increases, salinity also tends to increase, especially during the summer months. This relationship is reflected in the seasonal variation, where higher temperatures in the summer (mean values of temperature around 26–28 °C) correspond with slightly elevated salinity levels (mean salinity around 41.0 psu). Conversely, during the winter months, lower temperatures (around 17–21 °C) coincide with lower salinity levels (mean salinity value around 40.7 psu). This seasonal pattern suggests that temperature-driven evaporation is a key factor influencing salinity, particularly in the semi-enclosed lagoon systems, where the effect is more pronounced compared to the reference site, which exhibits a more stable salinity due to better exchange with the open sea.

pH levels showed stable and consistent values throughout the year, with minimal fluctuations in accordance with the reference site. All lagoons exhibited a similar trend, with pH levels ranging from 8.29 to 8.35, from 8.295 to 8.355, and from 8.26 to 8.36, for UL, ML, and TL, respectively. The reference site also maintained stable pH values between 8.27 and 8.36.

The analysis of ammonium (NH4+) concentrations showed that most values were within reasonable limits, staying below 1 μM. The UL had consistently lower ammonium levels, with values ranging from 0.21 to 0.67 μM, indicating the effective management of water quality in this zone. The ML and TL exhibited slightly higher variable concentrations, ranging from 0.22 to 0.805 μM, and between 0.26 and 0.86 μM, respectively, possibly reflecting a slight accumulation of ammonium as water traveled downstream through the lagoons. The reference site showed similar fluctuations, with levels between 0.2 and 0.77 μM, indicating variations in external environmental factors. Overall, the system maintained ammonium concentrations within acceptable ranges, with occasional peaks that warrant further monitoring.

The analysis of nitrate (NO3-) concentrations showed that nitrate levels remained well within acceptable limits. The UL and ML showed a decreasing trend throughout the year exhibiting nitrate concentrations ranging from 0.195 to 0.57 μM, and between 0.21 and 0.47 μM, respectively, indicating consistent management of nitrate levels. The TL had slightly lower concentrations overall, ranging from 0.22 to 0.44 μM, reflecting stable conditions. The reference site showed minor fluctuations, with nitrate levels between 0.22 and 0.43 μM.

Nitrite (NO2-) concentrations were at the lowest levels and indicated healthy conditions throughout the year. The lagoons exhibited a gradual increase in nitrite levels towards the end of the year, peaking in December at 0.22 μM for the UL, 0.175 μM for ML, and at 0.17 μM for TL. The reference site had the most stable nitrite levels, peaking at 0.15 μM in December.

Phosphate ($PO4^{3-}$) concentrations showed that all values were at their lowest level, indicating healthy conditions throughout the year. Phosphate values exhibited relatively stable phosphate.

Silicate (SiO_2) concentrations showed a range of values, reflecting natural fluctuations throughout the year. The UL exhibited silicate concentrations ranging from 1.365 μM in March to a peak of 2.07 μM in April, indicating seasonal variations that could be linked to biological activity or external inputs. The ML had slightly higher fluctuations, with a peak in May at 2.28 μM and the lowest concentration in January at 1.305 μM. The TL showed similar variability, with concentrations ranging from 1.23 μM in June to 2 μM in September. The reference site displayed relatively stable levels, with values between 1.13 μM in January and 1.97 μM in April.

Chlorophyll a (Chl a) concentrations revealed seasonal variations with distinct peaks in certain months. The UL exhibited fluctuating Chl a levels, with a notable peak of 0.995 μg/L in December, indicating a possible increase in algal activity. The ML also showed variability, with a peak of 0.83 μg/L in December, reflecting a similar trend. The TL maintained more stable Chl a concentrations, ranging from 0.2 μg/L to 0.48 μg/L, with less pronounced peaks. The reference site displayed the lowest overall Chl a levels, with concentrations ranging from 0.2 μg/L to 0.43 μg/L, indicating relatively stable conditions.

Hydrocarbon (HC) levels were uniformly low across all lagoons and the reference site, indicating minimal pollution and a healthy environment.

Figure 3 provides a monthly overview of the water quality indicators and ecological health of the Ayla Oasis lagoons during 2023, highlighting the importance of continuous monitoring to understand the dynamics of these aquatic ecosystems.

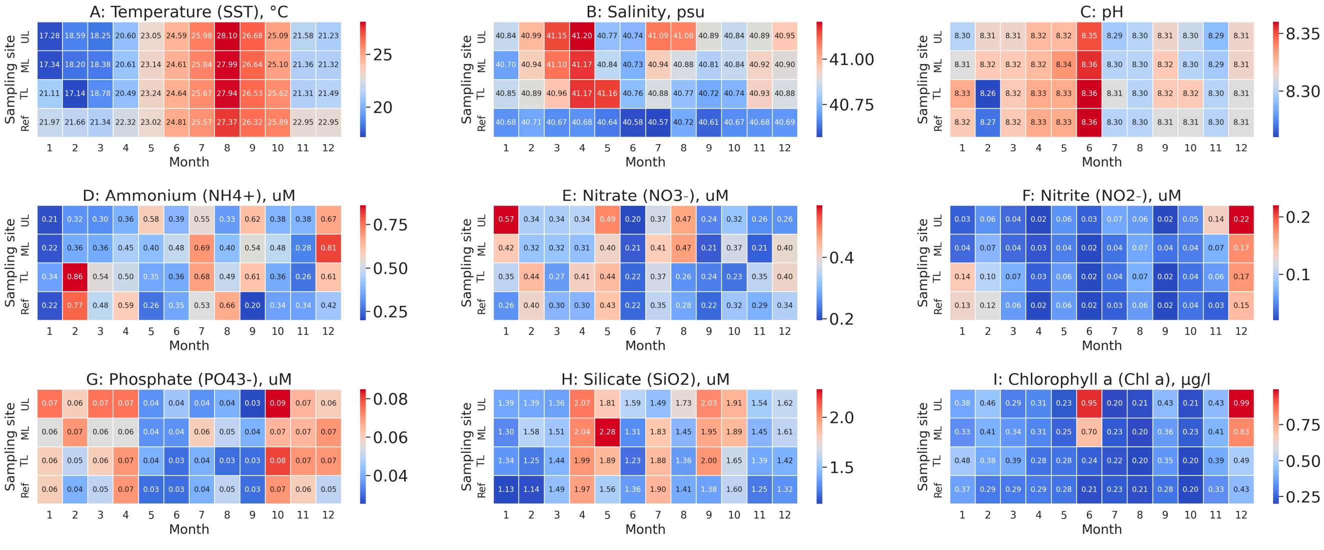

Figure 3. Monthly variations in key water quality indicators across the Upper Lagoon (UL), Middle Lagoon (ML), and Tidal Lagoon (TL), compared to a reference site (Ref). The indicators measured include (**A**) Temperature, (**B**) Salinity, (**C**) pH, (**D**) Ammonium (NH4), (**E**) Nitrate (NO3), (**F**) Nitrite (NO2), (**G**) Phosphate ($PO4^3$), (**H**) Silicate (SiO2), and (**I**) Chlorophyll a (Chl a).

4.2. Bottom Sediment Quality

The sediment quality analysis of the Ayla Lagoons further attests to their environmental health and sustainability. The spectrum of organic carbon concentrations, ranging from 0.605 to 1.067 g/kg, signifies a moderate to significant presence of organic material within the sediment layers (Figure 4).

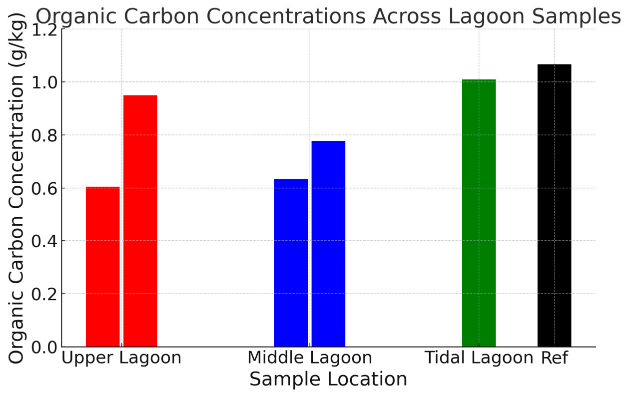

Figure 4. Organic carbon concentrations (g/kg) measured at two different sites within the Upper Lagoon (red) and Middle Lagoon (blue), and at single sites in the Tidal Lagoon (green) and the reference location (black) in the Gulf of Aqaba.

The grain size distribution from the three lagoons implies a sediment distribution pattern in each (Figure 5). The Upper and Middle lagoons show a similar trend with a gradual increase in grain size up to a certain point (0.25 mm), suggesting a mix of fine and coarse sediments with a dominance of medium-sized grains. This could indicate a stable environment with a balanced energy flow capable of supporting a diverse range of sediment sizes.

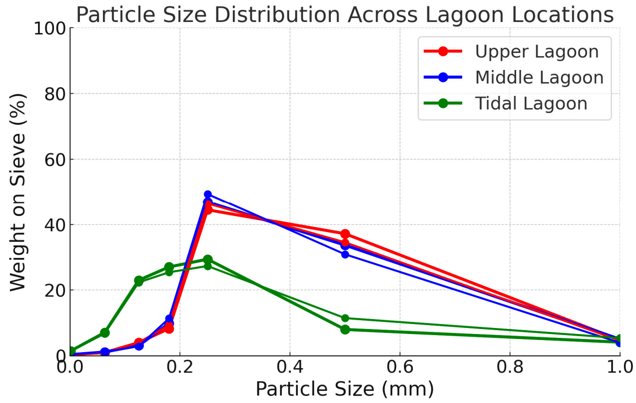

Figure 5. The Grain size distribution from the three Ayla Lagoons.

In contrast, the Tidal Lagoon starts with larger grains at the smallest particle size and then shows a rapid decrease in size (Figure 5). This might suggest a more dynamic environment with higher energy conditions that reduce the sediment size more quickly, possibly due to stronger water currents or wave action.

4.3. Bottom Habitat Survey

A comprehensive survey of the bottom substrate composition was conducted across various lagoon areas, revealing distinct patterns in substrate types (Figure 6). In the Upper Lagoon, sand overwhelmingly dominates, constituting 98% of the substrate, while the Middle Lagoon displays a similar prevalence of sand (91%) with a minor presence of seagrass. In contrast, the Tidal Lagoon exhibits significant sand coverage (91%), alongside notable rock formations (6%) and seagrass (3%). These findings underscore the varying ecological compositions and habitat complexities across the surveyed areas.

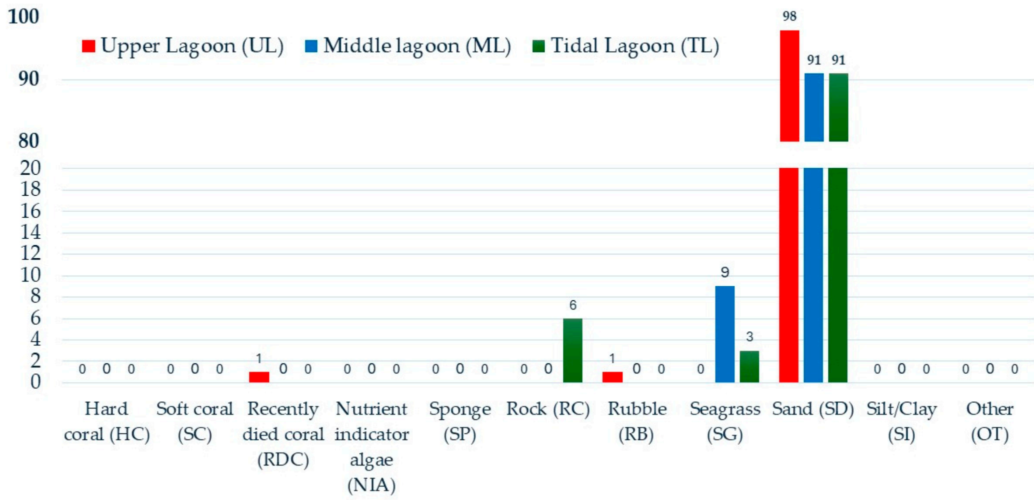

Figure 6. The mean percent cover of various bottom substrate types, including sand, seagrass, rock, and other categories, in the Upper Lagoon (UL), Middle Lagoon (ML), and Tidal Lagoon (TL).

Invertebrates were also observed among species, with the collector urchin and sea cucumber displaying contrasting distribution patterns across the Upper, Middle, and Tidal lagoons. The giant clam demonstrates substantial variations in abundance across zones, suggesting habitat-specific preferences.

The assessment of fish communities elucidates the rich diversity within the Ayla Lagoon ecosystem (Figure 7). A total of 2343 fish individuals belonging to 22 species across 17 families were recorded. The Upper Lagoon is characterized by the dominance of

Atherinomorus lacunosus, while the Middle Lagoon presents higher diversity, with *Diplotus noct* emerging as the most abundant species. Conversely, the Tidal Lagoon showcases a distinct distribution pattern, prominently featuring *Sphyraena flavicauda*. Sparidae emerges as a dominant family in both the Middle and Tidal lagoons, reflecting the varied habitat preferences of fish species within different zones. Despite disparities, the Middle Lagoon exhibits the highest species richness and a more balanced distribution, while the Tidal Lagoon maintains significant biodiversity with relatively equitable species distribution.

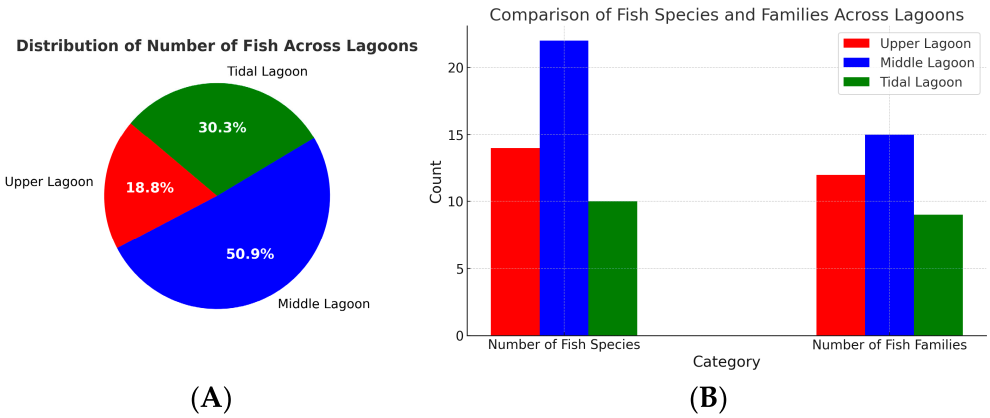

Figure 7. (**A**) Distribution of fish in Ayla Lagoons, (**B**) comparison of fish species and families across Ayla Lagoons.

4.4. Coral Conservation

The coral conservation and restoration project, initiated in 2015 in Ayla Oasis lagoons, marked a significant achievement with the establishment of the first coral nursery in the Upper Lagoon (Figure 8), which has now become a thriving habitat for various marine species.

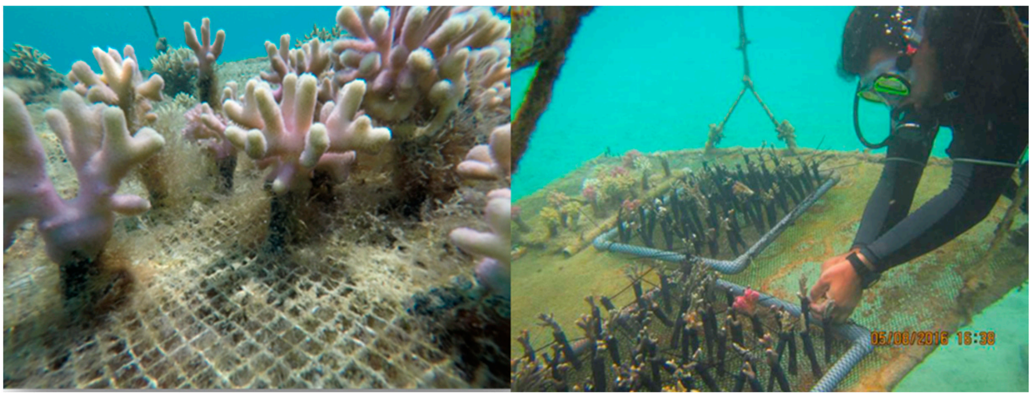

Figure 8. Coral nurseries in Ayla Lagoons showcasing attaching coral fragments that were being cultivated on metal or mesh frames to support coral growth.

The project successfully promoted the growth of multiple coral species, contributing to the overall ecological balance within the artificial lagoons, as shown in Figure 9. This pioneering effort demonstrates the potential for artificial environments to support biodiversity in the lagoons, providing both conservation benefits and valuable insights for future restoration projects.

In January 2015, corals were transplanted onto 62 reef balls distributed in two locations, labeled as UL-L1 and UL-L2 (Figure 2). In September 2021, 15 reef balls were transferred from Upper Lagoon and distributed at Tidal Lagoon (TL). In addition to 2 metal structures and 4 reef balls exist at location (UL-L1), 43 out of 47 reef balls were relocated to UL-L2, to protect corals near the swimming area and water sports at UL-L1.

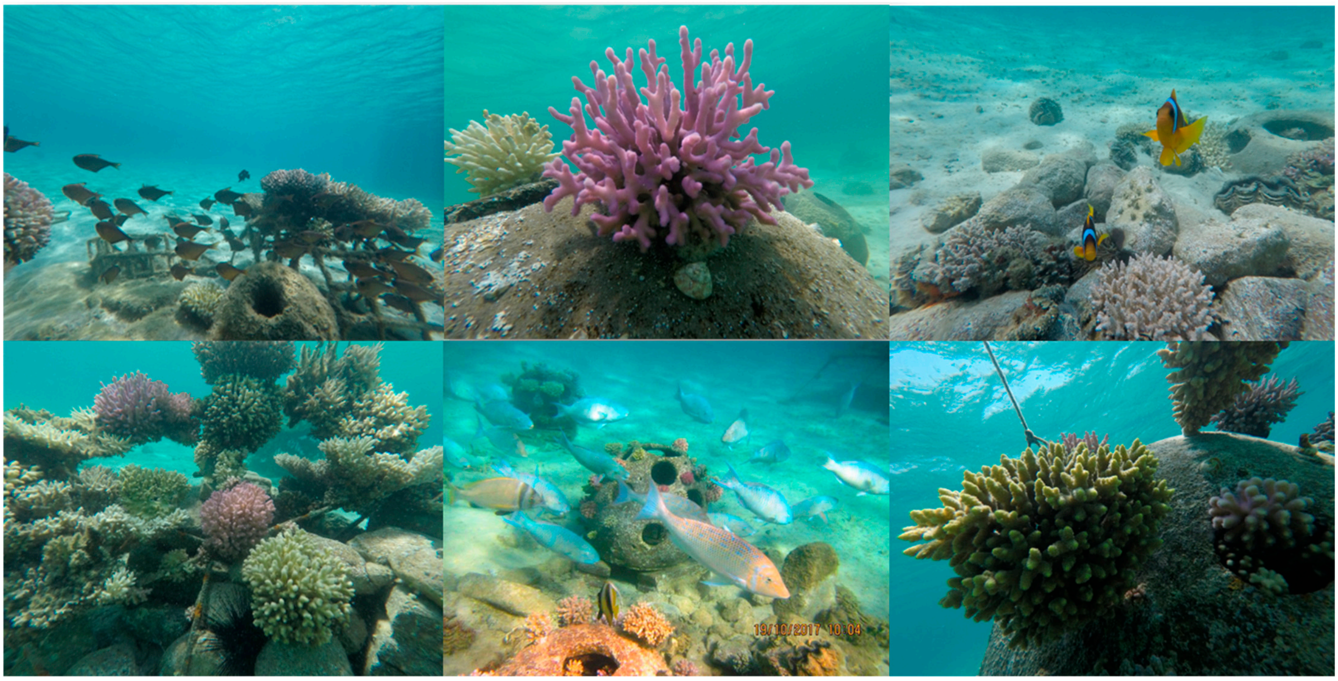

Figure 9. Marine ecosystem in Ayla Lagoons, a result of the Ayla Lagoons coral conservation and restoration project, which successfully established coral nurseries, reef balls, and metal structures to support coral growth and biodiversity. Featured in the photo are branching coral colonies of *Stylophora pistillata*, *Pocillopora verrucosa*, and *Acropora* species.

Location UL-L2 near the upper discharge weir showed the best conditions for marine life, with high water circulation, while translocated corals at location UL-L2 faced sensitivity issues, and the adaptation process was prolonged. Approximately 35% of corals did not survive, while the remaining 65% requires an additional year for full restoration.

Coral nursery 1 at Upper Lagoon in 2022 and 2016 experienced an increase in corals. However, at coral nursery at UL-L1, the intensity of the nursery decreased in 2023 following the use of corals for transplantation to the new location at Tidal Lagoon. A second nursery was established in late 2024. Metal structure project location UL-L1 images of 2016, 2017, and 2022 revealed the increase in corals. Another metal structure at the Upper Lagoon location UL-L2 showed an increase in coral from 2016, 2022, and 2023.

At location UL-L1 at the Upper Lagoon, reef balls project RF1 consists of four reef balls of size L that show growth of corals, which displays robust healthy conditions, indicating a successful ecosystem in this specific area. The thriving conditions at location UL-L1 can be attributed to its proximity to the water inlet weir, where temperatures are suitable, and water flow is higher compared to other areas. These favorable conditions contribute to the overall health and vitality of the coral reef at this specific location.

At the location UL-L2, the 43 reef ball—11 of size L, 12 of size M, and 20 of size S—witnessed coral bleaching, possibly due to stress and change of conditions, such as temperature, light, or nutrients. This stress leads to the expulsion of symbiotic algae living in their tissues, causing the corals to turn completely white.

Middle Lagoon coral nurseries and reef balls developed from 2017 to 2024 by the placement of 40 reef balls in 2017. The subsequent year witnessed the transplantation of corals onto the reef balls. Since then, a commendable 85% survival rate and robust conditions observed in 2022. In 2023, a notable decrease of 12% in coral survival rates was recorded. Currently, ML consists of 2 coral Nurseries, 37 reef Balls [15 of size L, 12 of size M, &10 of size S in Fish shape at location ML-L3, and 3 reef balls [1 of size L, 1 of size M, 1S] at location ML-L4.

At the East Discharge Channel, the installation and transplantation of reef balls started from 2018 to 2023 with placement of 64 reef balls (42 reef balls of size L, 22 reef balls [8 of size L, 7 of size M, 7 of size S] at location EC-L5 beside Beach 10 (Mama Gaia), accompanied by the successful transplantation of corals within the same year. The subsequent years witnessed the sustained health and robust condition of the coral reefs.

In 2018, reef balls installation and successful coral transplantation were carried out as follows: a total of 64 reef balls were installed at Beach 10, while the corals proceeded in good condition.

Finally, at the Tidal Lagoon (TL), a total of 15 reef balls were distributed in September 2021 and are observed to be in good condition across four locations: TL-L6 (three sizes L, one size S), TL-L7 (six sizes L, one size M), TL-L8 (three size M), and TL-L9 (three sizes L, one size S). In 2024, a coral nursery was established to support the restoration of corals in TL.

On the other hand, another ecological success of Ayla Lagoons in preserving healthy and ambient conditions is the natural growth of corals along the water inlet wall adjacent to the weir that supplies the UL with water pumped from the Gulf of Aqaba (Figure 10). This observation highlights ambient conditions of the coral ecosystem, offering a unique perspective on the self-sustaining qualities of Ayla Lagoons.

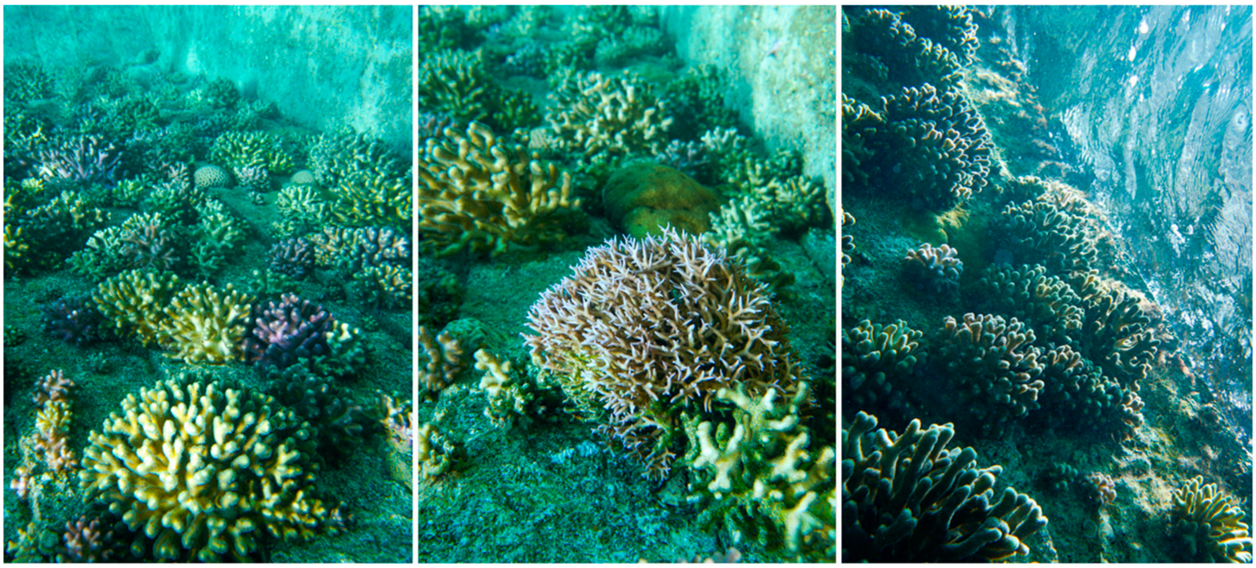

Figure 10. Natural coral growth along the water inlet wall adjacent to the weir supplies the Upper Lagoon with water from the Gulf of Aqaba showcasing the self-sustaining qualities of the coral ecosystem maintained within the lagoons.

5. Discussion

The detailed ecological analyses of the Ayla Lagoons affirm their sustainability and resilience [50]. These findings not only highlight the lagoons' compliance with ecological requirements but also showcase their role as a healthy marine ecosystem that supports diverse habitats, fosters biodiversity, and offers a sustainable model for coastal resort development [51]. The flushing time for both UL and ML lagoons is well-designed for effective water exchange, ensuring good water quality through regular flushing and significant dilution. This supports also both natural marine life and recreational use.

The annual monitoring program conducted by the "Marine Science Station", an institute affiliated with the University of Jordan, has been consistently evaluating the seawater and bottom sediment quality, as well as bottom habitat of the Ayla Oasis lagoons.

The 2023 analysis of the Ayla Oasis lagoons' seawater quality (Figure 3) reveals a healthy ecosystem across all three lagoons and demonstrated consistent levels of key indicators. The Middle Lagoon, despite its transitional nature with variable salinity and temperature, exhibits a well-balanced ecosystem. Meanwhile, the Tidal Lagoon and the offshore reference site have consistently met the ecological baseline set for healthy marine environments.

Notably, the peak concentration of organic carbon in sediments (Figure 4) observed in Tidal Lagoon (TL) may suggest a zone of intensified biological activity, prompting a need for further investigation. Nevertheless, this peak is consistent with the average range of organic carbon content previously documented in the sediments of the Gulf of Aqaba, as per our annual monitoring records. On the other end, the lower concentration found in UL and ML potentially denotes a sector with reduced biological deposition or heightened efficiency in carbon degradation, reflecting a more stable marine environment conducive to water entertainment activities. The grain size distribution patterns highlight environmental differences among the lagoons (Figure 5). The Upper and Middle lagoons show stable conditions with a mix of fine and medium grains, supporting balanced energy flow, while the Tidal Lagoon exhibits a more dynamic environment with higher energy levels that quickly reduce sediment size.

Ayla Lagoons demonstrate a rich and diverse habitat ecosystem, shaped by the interplay of substrate composition and biological communities, highlighting the importance of preserving these unique ecological zones (Figure 6). The existence of habitat ecosystems within the Ayla Lagoons is characterized by distinct and varied ecological compositions across different zones. The substrate analysis reveals a predominance of sand, particularly in the Upper and Middle lagoons, with minimal seagrass presence, while the Tidal Lagoon introduces additional complexity through rock formations and a small seagrass population. These substrate differences contribute to the observed variations in fish and invertebrate communities. The fish community assessment highlights significant biodiversity, with 22 species recorded across the three zones (Figure 7). The Upper Lagoon is dominated by *Atherinomorus lacunosus*, the Middle Lagoon displays higher species richness with *Diplodus noct* as the most abundant species, and the Tidal Lagoon features a distinct distribution pattern with *Sphyraena flavicauda*. The presence of the Sparidae family in both the Middle and Tidal lagoons underscores the habitat preferences of different fish species, contributing to the overall ecological diversity of the area. Invertebrate populations further emphasize the complexity of the ecosystem, with marked differences in abundance and distribution across the lagoons. The varying presence of species across the different zones indicates habitat-specific preferences and the potential influence of substrate composition on invertebrate distribution.

The Ayla Lagoons' coral conservation and restoration project exemplified a mixture of environmental conservation, community engagement, and innovative sustainability practices (Figure 8). Through the strategic placement of reef balls, the establishment of coral nurseries, and the continuous monitoring and adaptation of coral growth and transplantation initiatives, Ayla Lagoons has successfully demonstrated its commitment to the ecological requirements and the long-term sustainability of the unique coral ecosystems thriving within its distinctive aquatic milieu. This project achieved notable targets, including the careful transplantation of corals onto reef balls, systematic relocation processes, and the establishment of coral nurseries. In addition to their crucial role in cultivating coral fragments, nurseries were also used for education and awareness, where one reef ball was used by a school student to experience coral preservation as a school project.

The possibility of creating coral reef ecosystems in artificial lagoons represents a major advancement in global marine conservation. Our study proves that artificial lagoons, such as those in Ayla Oasis, can successfully replicate conditions necessary for coral growth and resilience. This approach has global potential, particularly for regions where natural habitats are under threat from climate change and human activity. On the other hand, artificial lagoons offer controlled conditions that are instrumental for studying coral ecosystems. Having variables such as temperature, salinity, and nutrient levels regulated, scientific research experiments on coral biology and stress responses can be precisely conducted. This approach is fundamental for advancing conservation strategies and could enhance biodiversity, provide coastal protection, and create opportunities for eco-tourism and community engagement. By showcasing the potential of artificial lagoons, this study underscores their critical role in marine conservation and sustainable development, offering a scalable solution to safeguard coral ecosystems worldwide.

The natural coral growth in Ayla Lagoons highlights the effectiveness of the lagoon's ecological management and its broader implications for similar coastal developments. This natural proliferation validated the potential for artificial habitats to sustain marine biodiversity when supported by proper environmental stewardship. It also emphasizes that while human intervention is vital, the inherent resilience of nature can lead to unexpected positive outcomes. Lessons from Ayla Lagoons can guide future projects, enhancing the sustainability and ecological health of coastal ecosystems.

6. Conclusions

The Ayla Oasis in Aqaba stands as an outstanding example of sustainable coastal development coexisting with environmental excellence, achieving a balance between human activity and natural ecosystems. Since their commissioning, its artificial lagoons have been carefully designed and managed to minimize their impact on the surrounding marine environment while providing significant recreational and economic benefits.

The extensive monitoring of water quality, sediment composition, and biological communities has consistently revealed that the lagoons support a diverse ecosystem, with conditions closely mirroring those of the adjacent Gulf of Aqaba. The establishment of coral nurseries, and the deployment of reef balls at Ayla Lagoons and creation of new habitats that support a wide array of marine life, are evidence to the ecological success of Ayla Oasis Lagoons.

The stability of key water quality parameters indicates a well-functioning ecosystem and adaptation to seasonal and anthropogenic changes and demonstrates the lagoons' capacity for resilience in the face of environmental fluctuations. This resilience shows a balance between organic content and particle size distribution, essential for maintaining diverse and productive benthic habitats. Furthermore, the diversity of fish and invertebrate populations within the lagoons underscores the ecological success of the project.

Ayla Oasis continues its efforts to adhere to regulations concerning water quality, public safety and services, environmental information and education, and environmental management. Ayla Oasis was eligible to obtain the International Certificate "Blue Flag", which is one of the environmental education programs of the Foundation for Environmental Education, within its lagoons [52]. By 2024, the "Blue Flag" was raised in four locations: at B12 Beach Club, La Plage Beach at the Hyatt Regency Hotel, the Ayla Marina, and Mama Gaia Beach Club.

Ayla Oasis, with its artificial lagoons, has proven its success as a development project, achieving ecological sustainability. It also demonstrates the possibility of creating successful artificial environments when careful planning, continuous monitoring, and a commitment to conservation are fulfilled. This project serves as an inspiring model for future developments, highlighting the importance of preserving our marine environments while pursuing economic growth and human recreation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17031279/s1, Table S1: summary of water quality indicators across lagoons, showing the maximum (Max), average (Avg), minimum (Min), and standard deviation (SD) values for various water quality parameters measured in the Upper, Middle, and Tidal lagoons; Figure S1: progression of coral growth success in Ayla Upper Lagoon's coral nursery from 2020 to 2023; Figure S2: coral growth progression on a metal structure 1 at Upper Lagoon location UL-L1 from 2016 to 2022; Figure S3: coral growth progression on a Metal Structure 2 at Upper Lagoon location UL-L1 from 2016 to 2022; Figure S4: development of corals at the 4 Reef Balls (size L) at Upper Lagoon location UL-L1 from 2022 to 2023; Figure S5: coral nursery at Middle Lagoon in 2022; Figure S6: reef Balls at Middle Lagoon location ML-L3 from 2020 to 2023; Figure S7: reef Balls at Middle Lagoon location ML-L4 from 2020 to 2023; Figure S8: reef balls at East Discharge Channel location EC-L5 from 2020 to 2023; Figure S9: reef balls at Tidal Lagoon Locations TL-L6, TL-L7, TL-L8. TL-L9 from 2020 to 2023.

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