Tech-Enhanced Coral Reef Restoration: An IoT-Based Monitoring Study on Redang Island, Terengganu

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Abstract
Coral reef ecosystems are among the most biologically diverse and economically valuable habitats on Earth, yet they are increasingly threatened by climate change, unsustainable tourism, and anthropogenic stressors. This study presents a comprehensive *Coral Rehabilitation and Sustainability Strategy* for Pulau Redang, Malaysia, integrating ecological restoration, community engagement, and policy support frameworks. Through a mixed-methods approach involving in situ coral transplantation, long-term reef monitoring, and stakeholder collaboration, the project aims to restore 1250 square meter of degraded coral reef within a one-year implementation period. This research examines the development and implementation of a Tech-Based Monitoring of Coral Farming Restoration System on Redang Island, Terengganu. Utilizing IoT technology and real-time sensor data collection, the system monitors key water parameters—pH, temperature and salinity—crucial for coral health. Through experimental development and field observation, the system demonstrated effectiveness in supporting coral reef restoration efforts. The integration of IoT sensors significantly improved coral growth monitoring, providing a scalable, data-driven approach to marine conservation. Findings from pilot restoration sites demonstrate a 68% post-transplant survival rate for branching *Acropora* species and 72% for massive *Porites* species after 12 months. Water quality analysis confirms that nutrient levels and sedimentation rates are within tolerance thresholds for coral recovery. Community engagement through eco-volunteering and local training has contributed to enhanced reef stewardship and social ownership. The proposed strategy establishes a replicable model which using IOT-Based Monitoring for integrated coral rehabilitation combining ecological science, social inclusion, and sustainable marine management. Long-term success will depend on the institutionalization of reef stewardship programs, stable funding streams, and periodic scientific assessment.

Keywords: Coral Reef Monitoring IoT; Coral Restoration; Environmental Conservation.

1.0 Introduction
Marine parks and marine reserves have been instituted at various locales globally to facilitate the conservation, recreation, education, and management of coastal resources. Due to their capacity to sustain and augment the adjacent aquatic biota, including coral reefs and algae, these entities play a crucial role in the aquatic ecosystem. Referred to as the "marine rainforests," these ecosystems encompass less than 1% of the oceanic substrate yet sustain approximately 25% of all marine biodiversity (Alex Smith, 2024).

Coral reefs fulfil numerous essential functions that underpin the sustenance of underwater life. They offer feeding, spawning, and nursery habitats for various aquatic organisms. Moreover, coral reefs are essential for protecting shorelines from erosive waves, enhancing nutrient cycles, helping with carbon and nitrogen fixation, and acting as homes for nearly a quarter of various biological species. The Malaysian government has declared 42 islands as marine parks, including 13 in Terengganu. As for Terengganu, there are four most prominent groups of marine parks which are Redang Islands, Perhentian Islands, Kapas Islands, and Tenggol Islands. According to Che Din et al. (2022), the four prominent marine park islands of Terengganu namely Perhentian, Redang, Kapas, and Tenggol which are located in the South China Sea off Peninsular Malaysia's east coast, manage to attract significant numbers of domestic and international tourists.

Global warming, primarily induced by anthropogenic activities such as unregulated tourism and unsustainable fishing practices, constitutes one of the principal drivers of the climate change. Coral bleaching is one of the phenomena which harm the coral. It will course expulsion of coral’s pigment algae, causing coral reef to become pale and cause death to coral. A prevention act is needed to avoid damage to coral reefs. Large-scale coral bleaching events, caused by above average sea surface temperatures, have now affected nearly every major coral reef ecosystem on the planet (Wilkinson & C. R. (Ed.) ,2002). Coral reef ecosystems is vulnerable to damage (Grimsditch & Salm, 2006; Hoegh-Guldberg & Bruno, 2010; Pratchett, 2013).

Therefore, various environmentally and unfriendly human activities as well as global climate change have caused coral reef ecosystems to suffer damage, resulting in a decrease in the state of good coral life cover, while the damaged areas are increasing (Sadili et al., 2015). In order to maintain the sustainability of the coral reef ecosystem in Redang Island, conservation efforts are needed with the aim of preserving the condition and sustainability. The method of coral transplantation is to obtain the donor coral colonies. In order to get donor coral plants, it is very crucial to select healthy donor coral plants which is to be used as coral seeds or nubbins. This paper is aim to assess the feasibility and impact of coral transplantation as a conservation method for the restoration and sustainability of coral reef ecosystems in Redang Island, Malaysia.

2.0 Methodology

This study adopted the development of an IoT-based coral monitoring system, with field validation conducted at Redang Island, Terengganu. Redang Island is part of the Terengganu Marine Park and features diverse coral reef ecosystems. The island's protected status and the establishment of marine biodiversity made it an ideal location for field validation of the coral monitoring system. The study site was selected based on accessibility, coral coverage, water depth, and representative reef conditions. One conservation effort that can be done is the coral transplant activity introduced by Edwards & Clarck (1998) and modified by Rani et al. (2017) using the Coral

Transplantation Technique Model Paku-Natural Substrate. Coral transplantation, a restoration technique involving the cutting and replanting of live corals to aid natural reef recovery, is employed as per Sadili et al. (2015). The Malaysia Tidal Garden Association (MTGA), an NGO established by the Redang Island community in December 2021 for ecological preservation, conducts this project at the Redang Island Marine Park Center in Terengganu, as indicated in Figure 1.

Figure 1: Map of Pulau Redang

2.1 Phase 1: Process of transplant

In order to produce healthy coral nubbins as many as possible, the Department of Fisheries (DOF) has dedicated a specific area of healthy donor coral which is to be used as nubbins. Figure 2 (a) shows a coral transplant by taking healthy donors in an area that has been designated to be used as coral seeds or nubbins. The size of the donor is chosen depending on the overall condition of the available donors. Figure 2 (b) shows the donors are taken and will be cut into pieces. The donors are placed in the container filled with seawater and are brought to the land for further process. The water in this container needs to be changed frequently to ensure that the corals are not exposed to pollution and debris.

Figure 2 :(a) Donor collecting (b) The donors which are used as seed for breeding

Figure 3 (a) shows the donors are cut into fragments. To ensure that the fragments will sustain their healthy lives, the cutting size must not be too small. As such, the fragments will have high durability and will not die after they are being placed on the nursery table. The method and degree of cutting are also very important to ensure that the coral can grow naturally. The equipment used is a grinder. Figure 3 (b) shows the cutting process of the fragment. The fragments are placed in small pots using special adhesive. Each pot is marked with a special marker and is given a unique number.

Figure 3 : (a) The process of cutting the coral mother into small pieces using a grinder (b) The process of cutting the donors into fragments.

Figure 4 (a) shows the process of hardening the adhesive pot fragment. Simultaneously, the fragments are put in the basket as not to expose them to the air for too long and become very stressful. Figure 4 (b) shows the process of transferring the fragments to the underwater nursery tables. The fragments are carefully arranged according to the numbers on the markers.

Figure 4: (a) The process of placing the pots. (b) The process of transferring pots to underwater nursery site.

Figure 5 (a) shows each table is set with 200 pots and approximately 2,000 pots for 10 nursery tables. Figure 5 (b) shows the nubbins monitoring activity that had successfully germinated after 3 months.

Figure 5: (a) A table that has been completed through the nursery process (b) Coral Monitoring

Once the nursery process has been completed, the key water parameters, i.e turbidity, light intensity, temperature, and salinity need to be observed. These parameters are critical for the growth of the coral health. According to Castillo, K.D., 281 (2014) coral skeletons are composed of calcium carbonate, and the stability of the water parameters are essential for corals to effectively build and maintain these skeletons.

The water parameters strongly affect coral metabolism and their symbiotic algae. Changes in these factors can destabilize symbiosis and cause bleaching. Corals grow best between 23–29°C, and even small temperature increases can trigger bleaching. Johansen, J.L.,Glob. Change Biol., 17 (2011) emphasized water parameters are the most important elements that influence the metabolisms of both cnidarian host and symbiotic algae, as shown during several stress laboratory settings and the metabolic performance of the associated marine organism.

Salinity and temperature are two major abiotic factors that directly affect the survival and growth of marine life (Alderdice D. Fish Physiology. Volume 11. Elsevier; Amsterdam, The Netherlands: 1988). Sudden changes in salinity can disrupt coral physiology and lead to death. Climate change is causing changes in seawater temperature and salinity, which affect coral growth and survival.

Coral reefs are highly biodiverse and economically important. Other water quality factors, such as alkalinity, calcium, and magnesium, also support coral health. Coral reefs are considered the most biodiverse ecosystems in the world, and are economically important for marine fisheries and ecotourism (Mar. Sci. 2012). In addition to these key parameters, other water quality factors like alkalinity, calcium, and magnesium levels also play a role in supporting coral health by influencing the parameters stability and calcium carbonate deposition (Glob. Change Biol., 17 (2011).

2.2 Phase 2 Prototype System Development

The IoT-based coral monitoring system comprises of several key hardware components integrated into a waterproof housing unit. The system included:

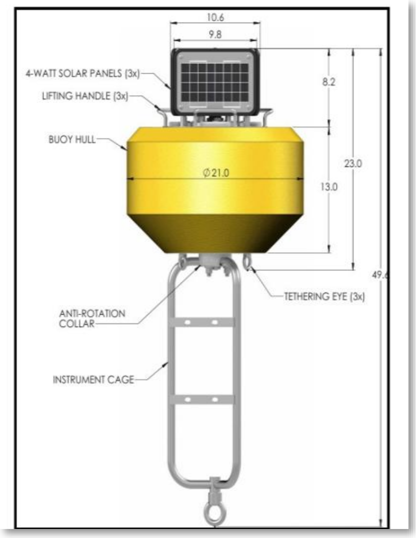
i. Microcontroller unit (MCU) for data processing and system control
ii. Multiple environmental sensors for measuring water quality parameters including temperature, turbidity, salinity and light intensity,
iii. Underwater camera module for visual coral health assessment
iv. Power management system with rechargeable batteries and solar charging capability
v. Wireless communication module for data transmission
vi. GPS module for precise location tracking

A prototype IoT-based coral monitoring system was developed for remote environmental monitoring of coral reef conditions. The system was built around an Arduino microcontroller platform integrated with multiple sensors within a waterproof housing unit. The core hardware components included:

i. Arduino microcontroller serving as the central processing unit for data acquisition, processing, and system control
ii. Temperature sensor for monitoring water temperature variations
iii. Salinity sensor for measuring dissolved salt concentration
iv. Turbidity sensor for assessing water clarity and suspended particle concentration
v. Light intensity sensor for measuring available light penetration, critical for coral photosynthesis
vi. Waterproof enclosure to protect electronic components from marine environment
vii. Power supply system with rechargeable batteries
viii. Wireless communication module for remote data transmission to cloud/server
ix. GPS module for geolocation tracking

The system operates by continuously collecting real-time data from the marine environment. If any parameter exceeds preset thresholds, notifications are triggered, and an actuator mechanism works to restore the environment to acceptable conditions. Data collected by the sensors is transmitted reliably through an online platform for monitoring and management. Wireless Sensor Networks (WSN) and IoT applications were incorporated for data acquisition, logging, and real-time analysis. According to Nielsen (2019), mobile device integration in IoT networks further reduces energy consumption and operational costs. Figure 6 (a) show A Tech-Based Monitoring of Coral Reef Restoration System device and tools for protype development. The prototype is to monitor the growth and development of coral nubbins, providing valuable insights into their progress and health.

Figure 6: (a) Device and tools for prototype development



(b) Buoys Prototype

Using remote sensing within a monitoring program potentially addresses many of the caveats highlighted above. Remote sensing covers many technologies, from satellites to airborne sensors, unmanned aerial systems, boat-based systems and autonomous underwater vehicles. In comparison to the sampling of physical areas achievable by field survey, habitat mapping and environmental stress assessment by remote sensing, especially by satellites, is highly cost-effective. While mapping reef composition from a satellite inherently cannot provide the level of accuracy and detail than could a field survey at that same point, the statistical power for inferring large scale patterns benefits in having complete a real coverage. Estimations of the statistical power of airborne data for mapping live coral (by Mumby et al.) implied that 20 s of airborne acquisition time were equal to 6 days of field survey.

3.0 Result and Discussion

Table 1 shown there are two types of family coral species have been cultured in the areas and about 530 fragments had been transplanted.

Table 1: Coral Species List and Transplantation Summary

Family	Genus/Species	Morphological Type	Common Name	Transplant Count
Acroporidae	*Acropora formosa*	Branching	Staghorn coral	120
Pocilloporidae	*Pocillopora damicornis*	Bushy	Cauliflower coral	80
			Total Transplants	200 fragments

By using IOT based monitoring system, the water quality mostly remained within coral tolerance thresholds which was within the range of temperature between 27–30°C and the turbidity was <5 NTU. The light intensity is >3000 lux. The salinity is between 32-35 ppt (Port per thousand). As such ,table 2 shows the results after 12 months, the mean for all the coral survival rates were quite high which exceeded above 60%.

Table 2 : Coral Transplant Survival Summary (After 12 Months)

Species	Initial Count	Survivors	Survival (%)
Acropora formosa	120	82	68
Pocillopora damicornis	80	50	63

Studies indicated that while some corals exhibit resilience to changing conditions (Goulet et al., 2017; Keshaymurthy et al., 2022), fast-growing species remain vulnerable to rapid temperature increases, leading to mortality and degradation of reef structures. Climate change continues to impose significant threats to coral reefs globally. Therefore, the integration of IoT technologies enhances the resilience and sustainability of coral restoration projects, enabling a more adaptive response to environmental changes (Edmunds & Burgess, 2020).

4.0 Conclusion

The Pulau Redang Coral Rehabilitation and Sustainability Strategy successfully demonstrates that localized, community-integrated restoration can yield measurable ecological recovery within one year. The model balances scientific inventions rigor with practical implementation through partnerships, adaptive monitoring, and stakeholder ownership. Ecological restoration is increasingly used around the globe to address the dramatic declines in the extent and function of many ecosystems due to rising anthropogenic and climate-change driven impacts (Young, 2000; Aronson and Alexander, 2013; Perring et al., 2015).

The integration of technology in coral restoration offers promising advancements in monitoring and scalability. By combining low-tech and high-tech approaches, restoration efforts can be tailored to different contexts, from hotel resorts to community-based projects. These innovations not only improve the efficiency of restoration but also engage a broader range of stakeholders, from local communities to global ecotourism markets. Continued development and implementation of these technologies are essential for the sustainable management and recovery of coral reef ecosystems worldwide. With consideration of which remote sensing technology is most mature and developed, current technologies are matched to key restoration steps, with suggestions of potential future studies that will advance the use of remote sensing in coral reef restoration (Foo, et al., 2019).

Advancements in technology are transforming coral restoration monitoring, offering new tools and methods to improve the effectiveness and scalability of restoration efforts. By combining low-tech, autonomous, and IoT-based systems, restoration practitioners can better assess coral health and adapt strategies to ensure the long-term survival of these vital ecosystems. According to Nielsen (1992), the use of smartphones or mobile devices in IoT applications can reduce energy consumption in terms of data generation, manufacturing and consumption costs.

Continued innovation and integration of these technologies are essential for the future of coral reef conservation. New technologies with applications in reef science and conservation are emerging at an ever-faster rate and are simultaneously becoming cheaper and more accessible. Technology alone cannot save reefs, but it can potentially help scientists and conservation practitioners study, mitigate, and even solve key challenges facing coral reefs (Elizabeth et al ,2019). In future, monitoring systems will be designed with automatic corrective actions to monitor and maintain water quality parameters.

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Author Contributions
H.Madiah: Data Collection, Data Validation; **S.D.Johari:** Introduction, Methodology, Writing, Original Draft Preparation; **N.M.Mat Hashim :** Writing, Data Collection; **S.Mohd Ali:**Supervision, Review & Editing; **F.Mat Yasim** :Supervision, Review: **N.Mahmood :** Supervision& Review

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest in the manuscript.

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