Validation of a Low-Cost Hyperspectral Imager for Coral Surveys A Review of Existing Coral Health Assessment Methodologies

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A Journey Through SISSTEM.

My SISSTEM journey began when I was just 16, a high school student wandering through a college fair, unsure of what to expect or where my path would lead. Then, amidst the crowd, I noticed a man at the University of Aruba booth, his warm smile instantly puts me at ease. That man was Dr. Eric Mijts, and without knowing it, he would become a defining part of my academic journey.

"Den ki idioma?" he asked, and from that moment, everything felt a little less daunting. I told him about my love for science but admitted I had no idea what to do next. He introduced me to the SISSTEM program, which was set to begin the following year. Suddenly, the uncertainty in my mind settled, and for the first time, I could see a clear path ahead. And my mom was also very happy.

Years later, here I am, reflecting on this incredible chapter of my life, or perhaps just the first part of it. Through SISSTEM and the Academic Foundation Year, I have met some of the most remarkable people. They've given me friendships that transcend age, backgrounds, and perspectives, teaching me more about what it means to be Aruban and how diverse yet united we are in our shared hope for a better future. The road wasn't always easy (trust me on that), but I wouldn't trade this experience for anything. Staying in Aruba, choosing to learn, grow, and advocate for a more sustainable future was one of the best decisions I've ever made.

SISSTEM opened doors to opportunities I never imagined. I became part of the UAUCU program, where I learned from brilliant minds with different cultural and academic backgrounds. It was here that I first started my own research, laying the foundation for my thesis. I also found my passion for environmental advocacy, joining MAGEC and later Synergy, where we work toward a greener, more sustainable Aruba. Beyond that, I took part in projects like the Surfside Science Project, worked at Plastic Beach Party, experienced the Erasmus+ program in Belgium, and joined the Overseas Countries and Territories Youth Network. And amid it all, I somehow became a pro at cat and house-sitting for my teacher, who knew my skill set would expand to expert feline care? None of this, however, would have been possible had I left my island, and for that, I will always be grateful. These experiences shaped me, prepared me for the unknown, and helped me grow in ways I never expected.

Finally, I want to express my deepest gratitude to everyone who has been part of this journey. To the SISSTEM team, thank you for your guidance and patience. To my family and friends, Abi, Ale, Belle, Andrew, Joel, Marc, Jason, Siguerd, and so many others, you have been with me through every high and low, and I am endlessly grateful.

So, was it worth it?

Yes, yes it was.

Validation of a Low-Cost Hyperspectral Imager for Coral Surveys

A Review of Existing Coral Health Assessment Methodologies

Raydeline Wever

Introduction

“The health of coral reefs has been an issue worldwide for several years, made more prominent by incidences of bleaching”, this is the first sentence of the research paper done by Fitt et al in 2000. A quarter of a century later, coral bleaching is still on the rise and the health of corals keeps crashing. Coral reefs are particularly vulnerable to the impacts of climate change, with rising ocean temperatures being a primary stressor (Huisman, 2023). Corals have a symbiotic relationship with algae called zooxanthellae, which live within their tissues and provide them with nutrients through photosynthesis (Hoegh-Guldberg, 1999). Zooxanthellae algae help with the growth of the coral by supplying energy and contributing to the formation of calcium carbonate which are the building blocks of reef structures. Zooxanthellae also produce the pigments that give corals their vibrant colors (Huisman, 2023). However, when exposed to high temperatures, corals experience physiological stress, leading to the expulsion of zooxanthellae, leaving the translucent tissue of the coral exposing the underneath white skeleton, a process called bleaching. Without these algae, corals struggle to meet their energy needs and become more vulnerable and susceptible to diseases, often resulting in mass coral mortality and the degradation and loss of entire reef ecosystems (Brown et al., 1996). In addition to rising ocean temperatures, ocean acidification weakens coral skeletons, reducing their ability to recover from bleaching events (Huisman, 2023). Other human-induced factors, such as coastal development, overfishing, and pollution, further contribute to disturbing coral reefs, exacerbating their decline.

Coral reefs are among the most diverse, productive, and beautiful ecosystems on the planet (Hoegh-Guldberg, 1999). They provide crucial ecosystem services including habitat for a wide range of marine species, supporting local communities and livelihoods through fisheries and tourism, while also acting as natural barriers that protect our shorelines from erosion and storm surges by reducing wave action. They serve as habitats for approximately 25% of all marine species, including fish, crustaceans, and mollusks, making them vital for sustaining ocean biodiversity.

Coral reefs, however, do not exist in isolation since they are closely interconnected with seagrass beds and mangrove forests, forming an ecological triad often referred as the Power of Three (Guannel et al., 2016). They play crucial roles in marine biodiversity, coastal protection, and climate resilience. Seagrasses act as carbon sinks, improve water clarity by trapping sediments, and serve as nurseries for juvenile fishes and invertebrates while mangrove forests function as natural barriers against coastal erosion and provide habitat for marine organisms, many of which later migrate to coral reefs (Carlson et al., 2021). Coral reefs, in turn, support biodiversity and protect coastlines by attenuating wave energy, preventing erosion of mangroves and seagrass beds. Unfortunately, these valuable ecosystems are under severe pressure and are facing threats from rising climate change, pollution, and anthropogenic activities therefore needing robust monitoring methods to track ecosystem health (Huisman, 2023).

Without healthy coral reefs, coastal communities face increased vulnerability to extreme weather events and economic losses due to the decline of fisheries and tourism. Despite their ecological and economic importance, coral reefs are declining at an unprecedented rate, traditional monitoring methods often detect bleaching too late. Early detection of bleaching events is crucial for implementing timely interventions and improving conservation strategies. Advancing coral health monitoring technology can help mitigate coral loss and support long-term survival of these ecosystems.

Problem Statement

Traditional coral health monitoring methods rely heavily on divers capturing RGB (red, green, and blue) imagery to visually assess the conditions of the coral reefs (Teague et al., 2020). While this method is widely used, it has significant limitations. One major drawback is that RGB imaging lacks spectral resolution and can only detect the bleaching after it has progressed to an advanced stage, typically when 70% or more of the zooxanthellae have already been expelled from the corals. By this point, the damage is already severe, limiting the time available for conservation efforts to respond effectively (Hedley et al., 2016). Additionally, the reliance on human divers makes coral surveys labor-intensive, costly, and subject to environmental constraints such as water clarity and depth (Roche et al., 2016). An alternative approach that has gained attention in recent years is hyperspectral imaging (HSI). Unlike RGB imaging, which only captures only three broad color bands, HSI collects data across hundreds of narrow spectral bands, providing a more detailed and accurate analysis of how light interacts with a subject. The use of spectral data provides a more accurate differentiation between live coral, macroalgae, and other photoactive organisms. In addition, it allows us to assess the health of corals by measuring the intensity of spectral signatures associated with pigments like chlorophyll (Teague et al., 2020; Hedley et al., 2016). This helps to identify if corals are experiencing stress or a decline in their normal health, such as bleaching. However, despite its potential, HSI technology remains expensive and may be inaccessible for widespread coral monitoring, especially for research and conservation purposes in developing regions. A low-cost hyperspectral imager could make this technology more accessible and practical for large-scale coral monitoring, especially in developing regions. The feasibility of such a system, however, needs to be validated. If successful, a low-cost hyperspectral imaging system could provide a powerful new tool for monitoring coral health, supporting conservation efforts, and enabling earlier interventions to protect vulnerable coral reefs.

Research Objective & Limitations

The primary objective of this research is to develop a proof-of-concept for a low-cost hyperspectral imager by adapting existing designs and evaluating their feasibility for coral health monitoring and bleaching detection. This involves reviewing existing methodologies, constructing the imaging hardware, assessing its capability to capture spectral data, and evaluating whether it can detect spectral differences in surrogate samples that mimic coral bleaching conditions.

Limitations include the absence of underwater validation and potential spectral accuracy constraints as in-situ testing is not yet planned. Instead, alternative validation methods will be used, such as using photoactive terrestrial organisms, calcium carbonate samples, and artificially pigmented test samples to explore the simulation of different spectral differences. Another limitation is that no coding or software integration will be included in this proof-of-concept stage, and it will be solely focused on hardware development. Finally, if needed, local stakeholders may be consulted for the exploration possibilities for custom lenses to improve image quality and performance, however, this aspect remains exploratory, and the final imager may still just rely on off-the-shelf optical components. Despite these limitations, this study provides the foundation for future refinements that could eventually lead to a practical system for early coral bleaching detection.

Literature Review

Traditional Methods for Coral Health Assessment and Their Limitations

Coral reef monitoring has long relied on traditional survey methods that involve in-situ observations, imaging techniques, and remote sensing (Teague et al., 2020). These methods have contributed significantly to understanding coral health but still have some limitations.

1. Diver-based surveys:
Diver-based observations are one of the most common approaches to coral monitoring where trained divers document coral conditions using standardized techniques such as:

- <u>Belt Transects (BT):</u>
  Sampling quadrats along the transect line at predetermined intervals, recording coral health, bleaching, and disease for long-term monitoring.
- <u>Line Intercept Transects (LIT):</u>
  Recording corals directly interacting with the transect line to assess species distribution, population dynamics, and health. Multiple transects are needed for comprehensive data (English et al., 1997).
- <u>Point Count Transects (PCT):</u>
  A random sampling approach where random points along the transect are pre-selected for analysis. It is faster than LIT and often combined with quadrats but requires multiple transects for accurate data in diverse coral environments (Teague et al., 2020).

Even though these are widely used methods for assessing corals they can still have some limitations and drawbacks. Some limitations include:

- Human interpretation can be biased and subjective, leading to variability in data collection therefore requiring highly skilled experts for coral and disease identification (Page et al., 2016).
- Large-scale reef assessments can be time-consuming and labor-intensive. (Hoegh-Guldberg et al., 2007).
- There can be physical limitations like depth, environmental conditions, and visibility, as well as risks like dangerous animals (Teague et al., 2020).

2. Underwater photography & RGB imaging:
Underwater photographic surveys are the primary method for modern reef monitoring, allowing rapid assessment of large areas. A key advantage is that there will be permanent digital records, reducing reliance on field experts and enabling repeat analyses. Some techniques include:

- <u>Quadrat Photography:</u>
  High-resolution digital cameras replace manual counting, improving accuracy and enabling long-term monitoring. Data is analyzed in the lab, reducing diver time underwater.
- <u>Photogrammetry & Structure from Motion (SfM):</u>
  This method uses overlapping images processed through Structure from Motion (SfM) software to create 3D reef models. It can measure reef structure, coral cover, and species distribution (Teague & Scott, 2017). While limited by traditional RGB cameras, it can be enhanced by integrating additional visual data layers.

Some limitations of underwater photography are:

- Limited spectral sensitivity since they are RGB cameras and only capture visible light with a wavelength ranging from 400-700 nm, making it difficult to differentiate between bleached and non-bleached corals before pigment loss is visible (rgb.com, 2025; Baker et al., 2008). Typically, around 50% or more of the total symbiotic algae will be lost before being visible to the human eye (Fitt et al., 2000).
- Images might suffer from color attenuation, low contrast and blurred details due to water conditions (Zhou et al., 2021).

3. Remote sensing:
Remote sensing techniques, like satellite and airborne sensors, make large-scale reef monitoring is more accessible and cost-effective. Satellites such as Landsat, Sentinel-2, and MODIS capture spectral data to track coral bleaching events (Hedley et al., 2016). However, it does have its limitations:

- Incomplete remote sensing coverage may lead to inaccuracies in estimations of the coverage of different benthic types (Foo & Asner, 2019).
- Optical data is affected by depth and turbidity.
- Lack of fine spectral resolution for detailed assessment (Hedley et al., 2016).

4. Remotely operated vehicles (ROVs):
ROVs are unmanned vehicles that could be underwater UUVs, that could replace the human element of underwater surveys decreasing the costs and risks while also improving replicability (Teague et al., 2020). Aerial vehicles (UAV/drones) can also be used as an alternative to satellites as they can provide higher-resolution reef images at lower costs. The drones are equipped with multispectral or RGB cameras that have been used for mapping coral bleaching events and reef damage (Casella et al., 2016). The main issues of unmanned vehicles are battery life and water clarity (Teague et al., 2020). With all the limitations mentioned above, the need for advanced spectral imaging techniques that can provide early-stage coral bleaching detection with higher precision and spectral resolution is emergent. This is where hyperspectral imaging can be an option for a possible alternative solution.

Advances in Hyperspectral Imaging and Its Application in Environmental Monitoring

Hyperspectral Imaging (HSI) is a remote sensing technique that captures and analyzes data across a wide range of the electromagnetic spectrum. Unlike RGB or multispectral imaging, which captures limited spectral bands, HSI collects continuous spectral information across numerous bands, enabling precise material identification based on unique spectral features (Goetz et al., 1985). HSI has been used in various scientific fields, including agriculture, forestry, water resources, and biodiversity monitoring (Shah, 2024; Govender et al., 2007; Clark, 1999). Advancements in hyperspectral sensor technology, data processing, and machine learning techniques have made it more accessible for environmental applications. In the marine environment, hyperspectral imaging has been utilized for detecting and classifying different underwater substrates, such as sand, rock, coral, and seagrass beds. It has been used for mapping seagrass and coral reef health and monitoring harmful algal blooms (Velloth et al., 2015). The ability of HSI to differentiate between live coral, dead coral, and macroalgae is particularly useful for early coral bleaching detection (Hedley et al., 2016). HSI enables more precise assessments by detecting changes in pigments like chlorophyll-a, which degrades before visible bleaching occurs (Holden & LeDrew, 1998). However, traditionally hyperspectral imaging systems are bulky and expensive optical elements, including lenses, spectrometers, and filters (Makarenko et al., 2022). These macroscopic components also do not allow it to process data fast in real-time, and in high-resolution. However, recent studies show new technological advancements may lead to the miniaturization and cost reduction of hyperspectral sensors, making them more viable for field applications (Hakala et al., 2012; Makarenko et al., 2022; Baston & Qian, 2015; Stuart et al., 2019). Several advancements that can contribute to the minimization of costs and bulkiness include:

- <u>Replacement of bulky and expensive optical elements with metasurfaces:</u>
  The metasurfaces in the Hyplex system are designed using artificial intelligence and are compatible with CMOS sensors (Makarenko et al., 2022). The CMOS is an acronym for Complementary Metal Oxide Semiconductor image sensors that convert light into electrical signals (global.canon, 2025).
- <u>Use conventional monochrome cameras:</u>
  Hyplex utilizes standard monochrome cameras instead of specialized and expensive spectrometers (Makarenko et al., 2022).
- <u>On-chip computational hyperspectral imaging:</u>
  Broadband filtering materials are integrated directly into the imaging sensor, which allows data cubes with full spatial and temporal resolution to be captured (Baston & Qian, 2015). This simplifies the optical design by eliminating the need for external filters and enhances light throughput.
- <u>Integrated design for LiDAR:</u>
  The design aims to combine active hyperspectral imaging and laser scanning into the same instrument (Hakala et al., 2012).

These are some of the advancements, however, future research should still aim to refine cost-effective hyperspectral imagers by improving spectral resolution while maintaining affordability. Innovations in custom lens manufacturing and filter design may also enhance the feasibility of low-cost hyperspectral solutions for marine applications.

Research Gaps

Despite advancements in hyperspectral imaging and low-cost sensor technologies, several research gaps remain in this research:

- <u>Affordability and accessibility:</u>
  Most hyperspectral imaging systems remain too expensive for widespread use in coral reef monitoring. This research investigates a cost-effective imager design that can be replicated by researchers in resource-limited settings.
- <u>Validation of low-cost hyperspectral imaging for coral health assessment:</u>
  While HSI has been successfully applied to agriculture, water quality monitoring, and forestry, there is limited research on the performance of low-cost hyperspectral imagers in coral reef environments. This study evaluates the feasibility of a low-cost alternative for early-stage bleaching detection.
- <u>Simulation of spectral data collection on land:</u>
  Given the logistical challenges of in-situ testing in marine environments, this research explores land-based experimental setups that can effectively simulate coral spectral properties.

Methodology

Research Design

This study follows a proof-of-concept framework, where the main goal is to assess the feasibility of building an affordable and effective hyperspectral imaging system for early coral health assessment. The research methodology consists of a four-phase approach:

1. Literature review & theoretical foundation.
2. Hyperspectral imager hardware development.
3. Optical and spectral simulation.
4. Validation and feasibility assessment.

Each phase contributes to addressing research gaps in cost-effective coral monitoring using hyperspectral imaging.

Literature Review & Theoretical Foundation

A comprehensive literature review was conducted above to understand already existing technologies and their applications towards coral health assessment. This included an analysis of:

- Traditional coral monitoring techniques like RGB imaging, satellite remote sensing, and underwater spectrometry and their limitations.
- Advancements in hyperspectral imaging and its relevance for early coral stress detection.
- Cost-effective imager development, including recent trends in miniaturization and affordability.

Hyperspectral Imager Hardware Development

The hardware development process focuses on designing a low-cost, compact hyperspectral imaging (HSI) system. This process, however, is subject to change if and when a step is unfeasible, or changes are made since this is purely theoretical. The key design choices include:

1. Optical design and sensor selection:

- <u>Spectrographic-based approach 1:</u>
  One possible route is using a holographic grating spectrograph such as the Specim ImSpector V10E since it has an already established performance and has potential for integrating with various cameras (Abd-Elrahman et al., 2011). The spectral range should be 400 - 1000 nm, and the spectral resolution should be 2.8 nm. When selecting a camera to pair with a spectrograph, key factors like spectral response range, spatial and radiometric resolution, and frame rate should be considered. The system, in the Abd-Elrahman et al. paper, uses the Imperx IPX-2M30H-L digital camera with a Charge-Coupled Device (CCD) sensor.
- <u>Spectrographic-based approach 2:</u>
  Another spectrographic setup uses a Raspberry Pi NoIR Camera Module V2.1, which features an 8 MP Sony IMX219 CMOS sensor with a pixel size of 1.12 µm × 1.12 µm and no infrared filter making it suitable for capturing both visible and near-infrared wavelengths (Pechlivani et al., 2023). The camera captures high-quality images and is connected to a Raspberry Pi 4 single-board computer with 8 GB of RAM, which manages image processing and storage. This design achieves a spectral range of 379-937 nm which captures about 290 wavebands, which offers a spectral resolution of 1.92 nm per band.
- <u>Metasurface-based approach:</u>
  A more compact and emerging alternative involves using AI-designed nanophotonic metasurfaces that filter light directly at the sensor level (Makarenko et al., 2022). These systems often use open-source tools like ALFRED for spectral pattern optimization and a Raspberry Pi for control and processing. A conventional monochrome camera can be used as the imaging sensor, with emphasis on matching the pixel size to the metasurface sub-pixel array and ensuring sufficient frame rate.

2. Lens and light source considerations:

- <u>Lens for spectrograph-based systems:</u>
  Lens choice should be based on field of view, light sensitivity (f-number), and compatibility with the spectrograph's opening. The Abd-Elrahman et al. study used a Schneider-Kreuznach Xenoplan lens, though off-the-shelf C-mount lenses may offer a more affordable option.
- <u>Lens for metasurface-based systems:</u>
  Any standard imaging lens compatible with the selected monochrome camera can be used to focus light onto the metasurface (Makarenko et al., 2022).

The selection criteria are based on conventional photography, like the field of view and light sensitivity.

- Lighting setup:
  - Passive hyperspectral imaging depends on ambient natural light, making it simpler but less controllable (Pechlivani et al., 2023).
  - Active hyperspectral imaging uses controlled light sources, such as broadband LEDs or supercontinuum lasers, which improves spectral consistency but can significantly increase cost and power requirements.

Optical and Spectral Simulation

Since in-situ measurements are not going to be done at this stage, the imager's performance is evaluated through simulations of alternative photoactive terrestrial organisms that mimic coral properties. As was mentioned earlier, these setups include: the exploration of photoactive terrestrial organisms that undergo color or pigmentation changes in response to environmental stress like plants, leaves, algae, and fungi; calcium carbonate samples that replicate coral skeletal structures like seashells or coral skeletons (if allowed); and artificially pigmented surfaces to reflect specific wavelengths similar to coral tissues mimic coral properties like using fluorescent dyes or ultraviolet paints (Bergamonti et al., 2011).

However, in aquatic environments, light undergoes absorption where the water molecules absorb light with longer wavelengths (red) more rapidly than with shorter wavelengths (blue-green) (Liu et al., 2020). The absorption affects the intensity and spectral composition of light as it penetrates deeper into the water column. Light attenuation can distort the spectral reflectance measurements of corals or other benthic features at different depths. Some water molecules and particles suspended in the water like sediments or pollutants that cause turbidity, might also scatter light, redirecting the light and causing diffusion. This scattering can blur images and alter the apparent color of submerged objects like corals or other benthic objects. Therefore, to account for color distortion caused by absorption and scattering, adjustments in spectral calibration will be considered. To replicate the underwater light environment during these terrestrial experiments, optical filters or computational correction models can be used (Wetzstein et al., 2011):

1. Optical filtering:

- Bandpass filters:
  These filters transmit specific wavelength ranges while blocking others, allowing simulation for selective absorption characteristics of water. For instance, using filters that attenuate red wavelengths can replicate the rapid absorption of red light in water.
- Dichroic filters:
  These filters reflect certain wavelengths while transmitting others, enabling the creation of lighting conditions that resemble the underwater spectral environment.

2. Computational correction methods:

- Semi-analytical models:
  These models can predict how light interacts with water by incorporating factors like absorption coefficients and scattering properties (Niu et al., 2024).
- Radiative transfer models:
  These models simulate the transmission of light through water, allowing for the adjustment of spectral data to account for depth-related changes in light quality (Li et al., 2017).

These can help refine the accuracy of spectral data collected on land for future underwater applications.

Validation and Feasibility Assessment

The final step involves assessing the technical feasibility and cost-effectiveness of the hyperspectral imager:

- Accuracy evaluation:
  The spectral response of the imager is compared to standard hyperspectral imaging benchmarks.
- Cost analysis:
  A cost breakdown is conducted to assess the affordability of the prototype compared to commercial hyperspectral sensors.
- Future improvements:
  - Recommendations for miniaturization and improved spectral resolution are outlined.
  - The potential for integration with drones or underwater vehicles is discussed.

Conclusion

The literature review highlights the pressing need for enhanced coral reef monitoring due to significant threats like coral bleaching, which are escalating despite decades of awareness. Traditional coral health assessment methods, relying on diver-based surveys and RGB imaging, are limited by subjectivity, high labor demands, and their inability to detect coral stress in its early stages due to a lack of sufficient spectral sensitivity. While RGB imaging only captures broad bands of visible light, making early detection of pigment loss challenging, hyperspectral imaging (HSI) emerges as a powerful alternative by acquiring detailed spectral information across numerous narrow bands. This capability holds the potential for earlier and more precise detection of coral stress by analyzing specific spectral signatures related to coral pigments. However, the widespread adoption of HSI for coral monitoring has been hindered by the high cost and bulkiness of conventional HSI systems. Recent technological advancements, including the development of metasurfaces and integration with conventional monochrome cameras, offer promising methods for creating more affordable and compact HSI solutions. Despite these advancements, a significant research gap remains in validating the effectiveness and feasibility of low-cost HSI systems specifically for the unique challenges of coral health monitoring.

The proposed research methodology, employing a proof-of-concept framework, directly addresses the limitations of current monitoring techniques and the existing research gap. By focusing on the hardware development of a low-cost hyperspectral imager, and exploring both spectrographic and potentially metasurface-based designs, this study aims to tackle the affordability barrier. Recognizing the logistical challenges of immediate underwater testing, the methodology includes optical and spectral simulation using photoactive terrestrial organisms to mimic coral properties, allowing for an initial evaluation of the imager's spectral capabilities. The planned validation and feasibility assessment, encompassing accuracy evaluation and cost analysis, are crucial steps in determining the potential of such a system for practical coral monitoring. This approach, while acknowledging limitations like the absence of initial underwater validation, provides a necessary foundation for future refinements. For the practical implementation of a low-cost hyperspectral imager for coral health monitoring, several future directions are essential. Firstly, improving the spectral resolution and accuracy of the low-cost imager while maintaining its affordability should be a primary focus. Subsequently, comprehensive in-situ underwater validation in diverse reef environments will be critical to assess its performance under real-world conditions. Exploring the integration of the HSI system with autonomous platforms such as UAVs and ROVs/UUVs could enable large-scale and remote monitoring capabilities, reducing the reliance on divers and expanding spatial coverage. The development of user-friendly software and data processing pipelines, potentially incorporating machine learning algorithms for automated coral health assessment, will be crucial for making the technology accessible to a broader range of users. Investigating the use of custom-designed, low-cost optics could further optimize the imager's performance for underwater spectral imaging. Finally, collaboration with local marine researchers and conservation stakeholders will be vital to ensure the practical utility and adoption of the developed technology in addressing real-world coral reef conservation needs.

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