Turf Algae Monitoring on Artificial Reefs Using Underwater Photography and ImageJ

Yashinta Widiana Jatmiko
Department of Marine Science, Brawijaya University, Indonesia
yashintawidiana@student.ub.ac.id

Aulia Lanudia Fathah
Master Program of Environmental Management & Development, Brawijaya University, Indonesia
aulialanudiaf@gmail.com

Muhammad Naufal Eka Putra
Department of Marine Science, Brawijaya University, Indonesia
naufaleka@student.ub.ac.id

Berlania Mahardika Putri
Master Program of Environmental Science, Universitas Gadjah Mada, Indonesia
berlaniamahardika@gmail.com

Andik Isdianto
Department of Marine Science, Brawijaya University, Indonesia
andik.isdianto@ub.ac.id (corresponding author)

Received: 21 September 2025 | Revised: 13 January 2026 and 21 February 2026 | Accepted: 23 February 2026

 DOI: https://doi.org/10.48084/etasr.14991

ABSTRACT

Coral reefs are vital ecosystems that support marine biodiversity and protect shorelines, but face increasing threats from human activities. Artificial reefs have emerged as a restoration tool to enhance ecological functions and provide habitats for benthic organisms. Turf algae, which are among the first to colonize artificial reefs, play a critical role but can inhibit coral recruitment and biodiversity when their growth becomes excessive. This study introduces a data-driven methodology for monitoring turf algae cover, applied at Damas Beach, East Java, using underwater photography and the ImageJ software. The measured turf-algae cover ranged from 12.0% to 33.9% across reef units. Turf algae were higher on sediment-free surfaces, consistent with sediment burial likely associated with lower early algal colonization. These results demonstrate that an ImageJ-based photo-analysis workflow can quantify turf-algae cover consistently and support long-term monitoring of artificial reefs.

Keywords-artificial reef monitoring; imagej software for reef monitoring; long-term reef management; marine ecosystem restoration; turf algae quantification

I. INTRODUCTION

Coral reefs represent critical coastal ecosystems that play an essential role in maintaining marine biodiversity and serving as natural barriers against environmental pressures [1]. However, they are increasingly threatened by human activities such as destructive fishing, pollution, and climate change, leading to the degradation of natural reefs. In response, Artificial Reefs (ARs) have been widely deployed for ecosystem restoration, aiming to restore ecological functions, enhance biodiversity, and support benthic communities. ARs help rehabilitate damaged coral ecosystems by providing habitats for benthic organisms, including turf algae, which are often the first to colonize hard substrates such as concrete [2].

Although turf algae are essential in the early stages of reef colonization, their excessive growth can inhibit coral recruitment and reduce biodiversity, challenging the long-term success of ARs [3]. Accurately measuring turf algae coverage is crucial to understanding their role in reef succession. However, reliable and reproducible methods for quantifying turf algae cover, especially in southern Java, remain limited. This study addresses this gap by developing a data-driven methodology to measure turf algae cover on ARs at Damas

Beach, using underwater photography and the ImageJ software. This approach provides precise quantification while minimizing the observer bias common in traditional visual assessments [4].

This study aimed to establish a robust framework for assessing the ecological success of ARs in tropical coastal restoration projects [5]. By enhancing turf algae monitoring accuracy, this methodology offers a reliable, reproducible tool for long-term ecological assessments, contributing to the growing body of knowledge in reef restoration and supporting future research that incorporates key environmental variables influencing turf algae dynamics. Ultimately, this study aims to help manage ARs to ensure their success in supporting biodiversity and ecosystem recovery.

II. MATERIALS AND METHODS

A. Study Site

Damas Beach, located in Karang Gandu Village, Trenggalek Regency, East Java, was chosen for its role in AR restoration. This site spans 5.5 hectares along a 2 km coastline. In 2017, 25 ARs made from concrete material were installed, with 16 remaining intact by 2024, indicating their structural integrity and ecological value. Data collection was focused on these remaining reef units, as shown in Figure 1 [6].

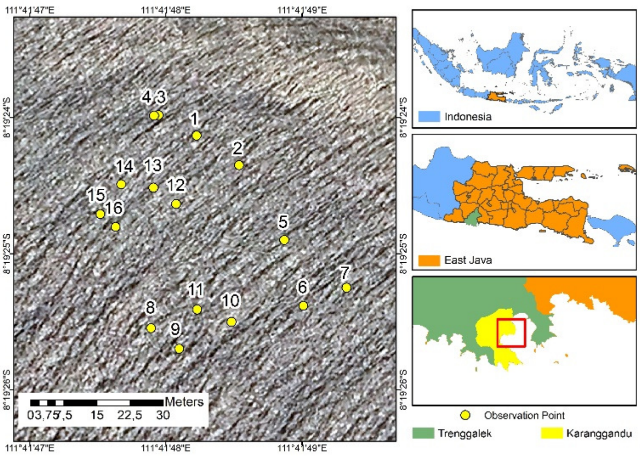

Fig. 1. Observation points.

B. Observation Points and Data Collection

Underwater images were collected for each AR unit by imaging five faces of the cube (top and four lateral faces) and collected during 15–17 August 2024. For each face, the camera was held parallel to the AR surface (nadir orientation for the top face) and kept consistent across units to minimize perspective distortion. The camera-to-surface distance was adjusted so that the target AR face (nominal 60×60 cm) was fully visible in the image with minimal cropping, corresponding to an approximate working distance of 0.5–0.8 m, depending on diver positioning and water conditions.

A separate scale bar was not placed in each image because all AR units had identical fixed dimensions. Spatial calibration in ImageJ used the known AR edge length (60 cm) as the reference scale. Turf-algae metrics were quantified within a manually delineated Region Of Interest (ROI) corresponding to the visible boundaries of each AR face, and the percentage of cover was computed relative to the ROI of the AR face rather than the full image frame. The images were acquired using an Olympus Tough TG-6 camera at 4000×3000 pixels (~12 MP) in sRGB (24-bit). Acquisition settings were documented from EXIF metadata (typical example: f/2.8, 1/320 s, ISO 100, focal length 4 mm [25 mm equivalent], flash disabled) to support reproducibility. Figure 2 shows an underwater observation.

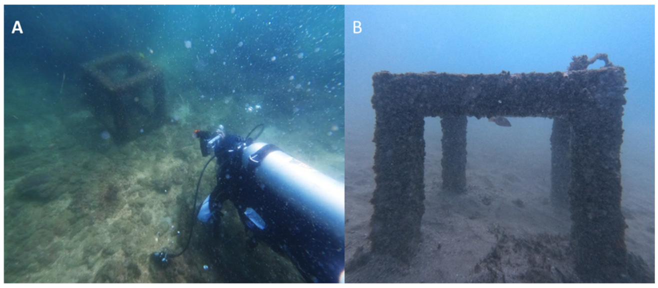

Fig. 2. Underwater observation: A: Field survey activity around the AR structure during data collection; B: AR condition showing the sediment accumulation on the seabed.

C. Turf Algae Quantification Using ImageJ

ImageJ, a widely used open-source software for precise biological analyses [7], was employed to quantify turf algae cover on ARs using a cover percentage method. Manual digitization within a reef-face ROI (with optional threshold overlay for guidance) distinguished turf algae from other substrates. Underwater photography integrated with digital analysis offers advantages for long-term reef monitoring [8].

1. Step 1: Set scale per image using the known artificial reef (AR) edge length (60 cm) via Analyze → Set Scale (Figure 3).
2. Step 2: Define the analyzable reef surface as a ring-shaped ROI (outer minus inner), creating two ROIs (Outer and Hole) combined in ROI Manager using XOR to generate AR_ROI (Figure 3).
3. Step 3: Apply minimal color/contrast adjustments in ImageJ to improve interpretability under green-tinted underwater lighting using Image → Adjust → Brightness/Contrast, aiding consistent manual delineation (no automated filtering) (Figure 4).
4. Step 4: Optional diagnostic – split RGB channels via Image → Color→ Split Channels to enhance visibility, especially for strongly green-tinted images. This step supports consistent visual interpretation, but is not mandatory (Figure 4).
5. Step 5: Apply an optional threshold overlay in ImageJ (Image → Adjust → Threshold) to highlight candidate turf patches. Threshold values are adjusted per image for visual aid only, not for classification (Figure 5).

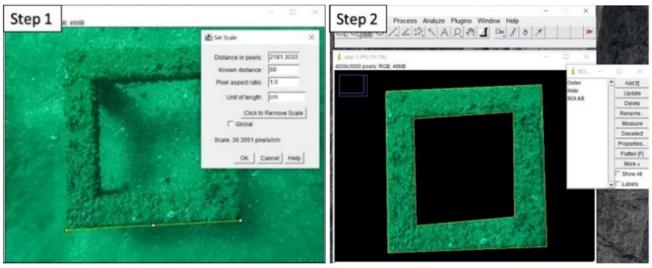

Fig. 3. Steps 1-2: Set the image scale using the 60-cm AR edge, then define the ring-shaped reef-face ROI (outer minus inner using XOR).

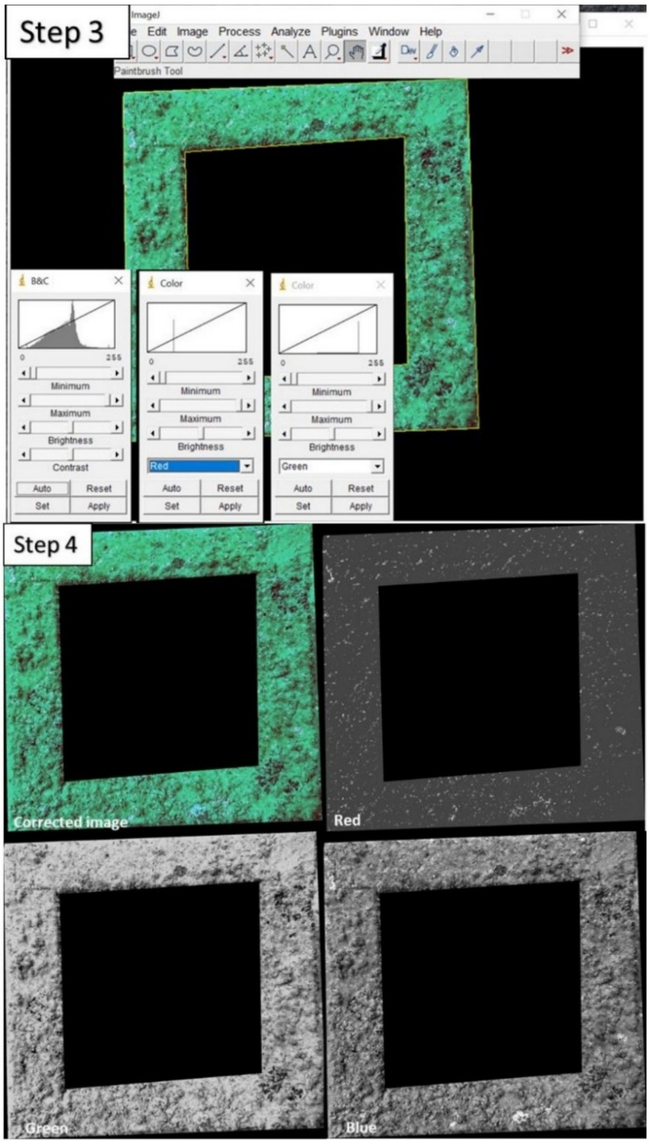

Fig. 4. Steps 3-4. Adjust brightness/contrast and split RGB channels to improve visual interpretation prior to delineation.

6. Step 6: Manually digitize turf-algae patches within the AR_ROI, tracing patches showing filamentous texture and a greenish-brown appearance. Each patch is added as a separate ROI in ROI Manager. Ambiguous areas are excluded. All turf ROIs are merged to create TURF_ROI_Final, which is intersected with AR_ROI to ensure accuracy (Figure 5).
7. Step 7: Generate a binary mask for documentation/QC using Edit → Selection → Create Mask. Approximately 15% of images are reprocessed by the same analyst, and a subset is digitized by a second analyst to assess consistency (Figure 6).

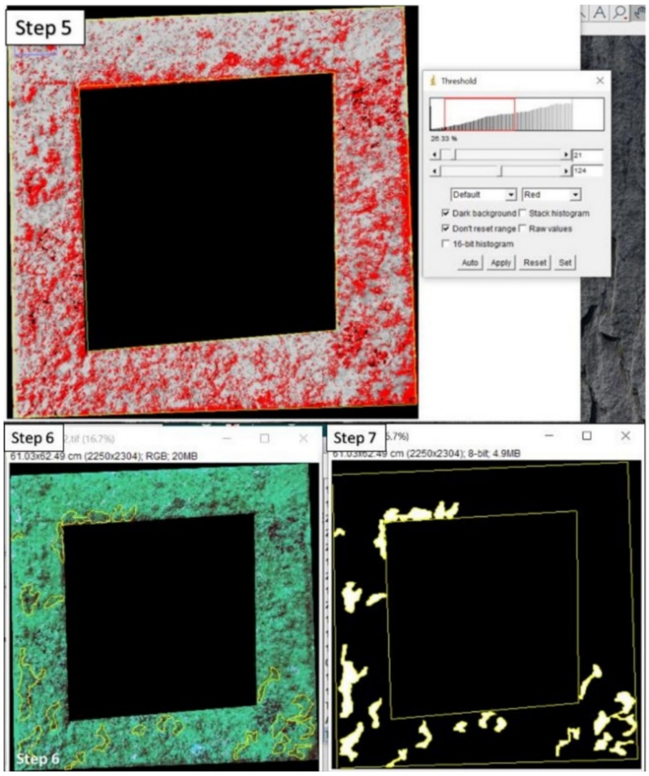

Fig. 5. Steps 5-7. Use Threshold as a visual aid, manually digitize turf-algae patches, then convert the selection to a binary mask to measure Area_Turf.

Inter-observer agreement was assessed by independently reprocessing the same AR faces by two observers following the identical ImageJ workflow. Table I shows side-by-side values.

TABLE I. INTER-OBSERVER RESULT FOR AR-FACE MEASUREMENTS USING THE IMAGEJ PROTOCOL.

AR_Surface	Observer 1	Observer 2
1_Side_3	876.27	874.52
2_Upper side	574.07	572.35
2_Side_3	14.18	13.62
3_Upper side	512.00	510.97
6_Upper side	278.29	275.88
9_Side_1	680.62	675.18
10_Side_1	634.07	630.90
10_Side_3	760.32	758.03
12_Upper side	1350.87	1345.47
12_Side_2	408.53	406.48
13_Upper side	1269.20	1266.03
14_Upper side	1372.47	1360.11

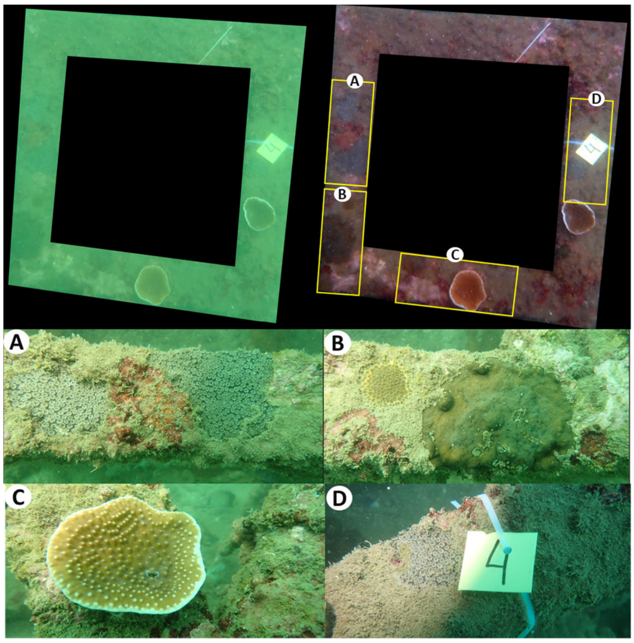

Fig. 6. Example raw and color-corrected underwater images. A-D indicate zoomed-in areas, highlighting turf algae and other benthic organisms visible on the AR surface.

D. Calculation of Artificial Reef Exposed Surface Area (AR_{ESA})

The ARs used in this study were designed to provide maximum surface area for colonization. The exposed surface area of each reef was calculated by measuring the physical dimensions of the reef structure [9], which included the column, upper beam, and lower beam areas, as illustrated in Figure 7.

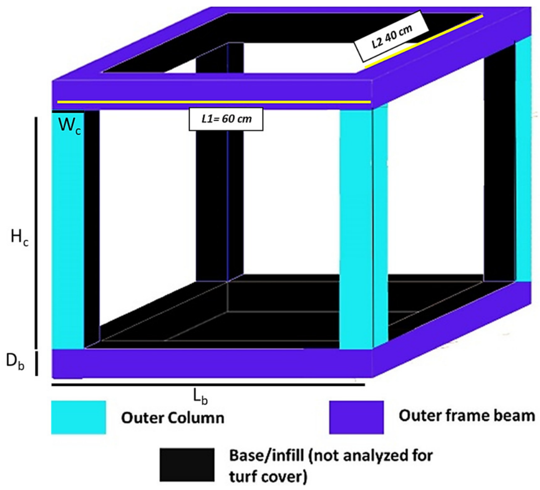

Fig. 7. AR calculation.

$$AR_{ESA} = C_{ESA} + UF_{ESA} + LF_{ESA} \quad (1)$$

$$C_{ESA} = (H_c \times W_c) \times 8 \quad (2)$$

$$UF_{ESA} = (L_1 \times D_b) \times 6) + (L_2 \times D_b) \times 2) \quad (3)$$

$$LF_{ESA} = ((L_b \times D_b) \times 4)) \quad (4)$$

where AR_{ESA} is the Artificial Reef Exposed Surface Area (cm^2), C_{ESA} is the Column Exposed Surface Area (cm^2), $UF_{ESA}$is the Upper Frame Beam Exposed Surface Area (cm^2), LF_{ESA} is the Lower Frame Beam Exposed Surface Area (cm^2), H_c is the exposed column height (cm), W_c is the exposed column width (cm), L_1 is the exposed length of the long upper-beam segment (60 cm), L_2 is the exposed length of the short upper-beam segment (40 cm), L_b is the length of a lower-beam side (cm), and D_b is the width of a lower-beam side (cm).

Surface area was calculated for exposed (non-buried) structural faces only; the base/infill and fully buried faces were excluded.

E. Percentage of Turf Algae Coverage

The percentage of turf algae coverage was calculated using the percent cover method, which is a quantitative approach to estimating the proportion of an area covered by a particular object or organism within the observation field. In this study, the observation field consisted of artificial cube-shaped reef structures (60×60 cm). Visual images captured within the frame were analyzed using the ImageJ software, where the area covered by turf algae was identified through image conversion and thresholding processes, then measured after scale calibration [10].

$$PercentCover = \frac{A\_turf}{A\_exposed} \times 100$$

where A_{turf} is the turf algae area (cm²) measured in ImageJ and $A_{exposed}$ is the exposed reef surface area (cm²) of the same face.

F. Artificial Reef Physical Condition

Sediment burial was assessed for each AR unit by measuring sediment thickness (cm) using a representative side view. The image scale was set using the known AR dimension (60 cm), and the exposed frame height above the sediment ($H_{exposed}$) was measured. Sediment thickness was calculated as $burial(cm) = 60 - H_{exposed}$. Units were classified as Low (<10 cm), Medium (10–29 cm), or High (≥30 cm) based on burial. Units missing burial data were excluded from analyses. Current speed was measured with the Flowatch FL-03 flowmeter (accuracy ±2%) and water clarity using a standard Secchi disk.

III. RESULTS AND DISCUSSION

A. Condition of Artificial Reef

The surface area of ARs plays a key role in supporting turf algae colonization; however, sediment accumulation has the clearest association with turf algae cover. Reef units with minimal sedimentation consistently exhibited higher cover, underscoring the importance of sediment-free surfaces for optimal algae growth [11]. Figure 8 shows the condition ARs.

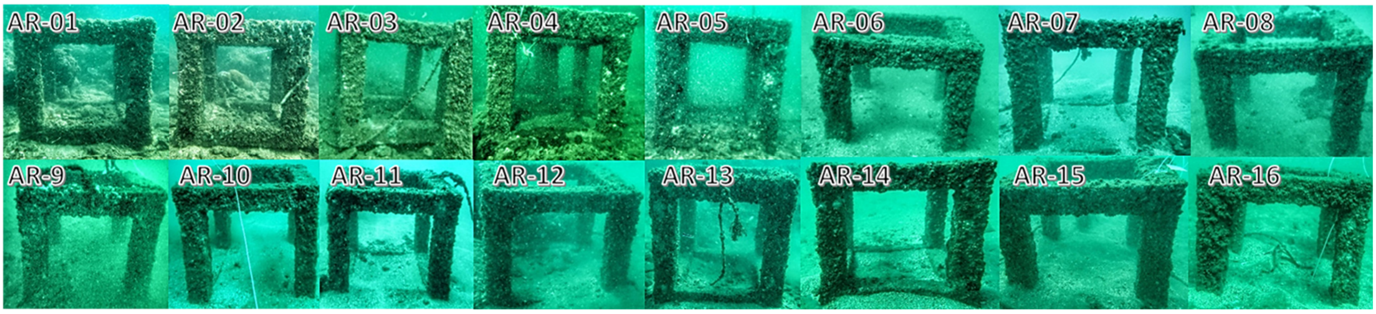

Fig. 8. Sediment burial categories (cm) for the 16 AR units: Low (<10 cm, including 0 cm/no sediment) = AR-01, AR-02, AR-03, AR-04, AR-05, AR-13, AR-14 (7 units; 43.75%); Medium (10–29 cm) = AR-07, AR-11 (2 units; 12.5%); High (≥30 cm) = AR-06, AR-08, AR-09, AR-10, AR-12, AR-15, AR-16 (7 units; 43.75%).

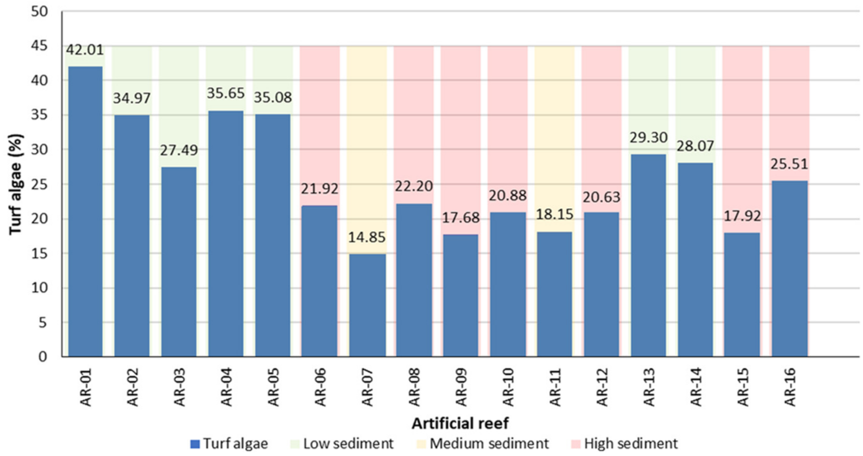

Fig. 9. Turf algae percentage cover across reef units (Reefs 1–16).

B. Turf Algae Coverage and Variability

Turf algae coverage ranged from 12.0% to 33.9%, with the highest on Reef 1 (3,388 cm²) and the lowest on Reef 7 (863 cm²), as presented in Table II. AR_{ESA} varies among units because it represents exposed (non-buried) outer faces measured from images; sediment burial reduced exposed dimensions used in the geometric calculation. This across-reef variation is consistent with an association between substrate condition in shaping turf algae dynamics.

TABLE II. CONDITION OF ARTIFICIAL REEFS

AR	Exposed area of AR (cm²)	Turf algae cover (cm²)	Cover %	Sediment burial (cm)
1	10,000	3,388	33.9	0 (Low)
2	10,000	2,820	28.2	0 (Low)
3	10,000	2,217	22.2	0 (Low)
4	10,000	2,360	23.6	6 (Low)
5	10,000	2,829	28.3	0 (Low)
6	6,404	1,137	17.8	30 (High)
7	7,183	863	12.0	29 (Medium)
8	5,889	1,060	18.0	45 (High)
9	6,545	937	14.3	37 (High)
10	6,877	1,162	16.9	33 (High)
11	6,080	1,054	17.3	29 (Medium)
12	6,900	1,152	16.7	33 (High)
13	10,000	2,363	23.6	0 (Low)
14	10,000	2,264	22.6	0 (Low)
15	6,815	972	14.3	35 (High)
16	10,000	1,407	14.1	34 (High)

Seven reef units were classified as Low (<10 cm, including 'no sediment'): Reefs 1, 2, 3, 4, 5, 13, and 14. These units exhibited higher turf algae cover, reinforcing the importance of cleaner, sediment-free surfaces for optimal colonization [12]. This aligns with previous studies showing that minimal sediment enhances light penetration and algal attachment efficiency [13]. Overall, most units at Damas Beach face sedimentation pressure that likely reduces ecological performance by limiting benthic growth.

C. Environmental Factors Influencing Turf Algae Growth

Turf algae growth is commonly associated with local light availability, near-bottom flow, and water quality, with sediment acting as a proximate stressor that can reduce the exposed substrate usable for algal attachment. Water clarity at the study site averaged 3.03±0.31 m (moderate), suggesting that light penetration to the reef depth was still possible.

Current speed averaged 0.13±0.13 m/s (low). These conditions may co-vary with sediment settling and water clarity, which in turn may relate to benthic communities; however, their effects were not tested as causal drivers in this study. Figure 9 shows per-reef percent cover (ARs 1–16), whereas units exposed to persistent sediment loads exhibit lower cover (pattern consistent with prior observations of macroalgae-coral dynamics) [14].

Taken together, these results indicate that managing sediment deposition and maintaining adequate light/flow are potential management-relevant factors to support turf algae on ARs. Excessive sediment can shade the substrate and physically hinder filament attachment, suppressing cover even where hard surfaces are available [15]. Conversely, on cleaned or naturally sediment-free surfaces, colonization proceeds more quickly and yields higher cover, aligning with the quantitative differences among sediment categories reported here.

D. Technological Advances in Monitoring Turf Algae

Integrating underwater photography with ImageJ enables precise, repeatable quantification of turf algae on ARs. The workflow—calibration, thresholding, and segmentation—minimizes observer bias and yields consistent percent-cover metrics suitable for long-term comparisons across sites and seasons [16]. In this study, the same pipeline underpins both the per-reef analysis (Figure 3-5) and the sediment-class comparison (Figure 7), ensuring that engineering or management inferences are grounded in standardized measurements rather than subjective estimates.

Key advantages of this method include:

- Precision and Repeatability: Standardized digital segmentation improves accuracy and auditability over time.
- High Spatial Resolution: High-throughput frame processing supports routine inspections aligned with deployment/maintenance cycles.
- Objectivity: The output integrates directly with substrate status (e.g., sediment classes), allowing data-driven thresholds for intervention.

By standardizing monitoring, ImageJ enhances objectivity, enables comparisons across reef locations, and ensures reproducible long-term results, improving reef health tracking and turf algae dynamics for better reef restoration and management decisions.

E. Broader Implications for Reef Restoration and Management

This data-driven workflow links substrate conditions to algal outcomes, providing a basis for AR operations. Managers can set performance targets for sediment loads and algae cover, aligning monitoring with restoration goals [17]. Integrating ImageJ-based 2D cover with 3D photogrammetry (SfM) extends assessments to surface complexity and microhabitat structure [18]. These indicators can be integrated into small-area conservation programs, strengthening the effectiveness of monitoring when resources are limited [19].

IV. CONCLUSION

This study establishes a practical, data-driven workflow for monitoring turf algae on ARs using underwater photography and ImageJ. Across 16 reef units at Damas Beach, cover percentage ranged from 12.0% to 33.9%. Turf algae cover differed among sediment categories (Low <10 cm, including no sediment; Medium 10-29 cm; High ≥ 30 cm). Maintaining sediment-free surfaces may help maintain higher turf algae on AR modules. Sediment burial was associated with lower turf colonization at an early stage, which is important for understanding the dynamics of biota succession in AR, including its implications for coral recruitment. Standardizing image acquisition and segmentation provides precise, repeatable indicators, suitable for routine maintenance and long-term assessments.

Limitations include single-site design, small sample size, and lack of seasonal replication and environmental covariates (e.g., light, flow). Future studies should expand monitoring across seasons and sites, integrate environmental measurements, and combine 2D cover with 3D photogrammetry to capture surface complexity. Linking these to coral recruitment and benthic community trends will help identify sediment thresholds for management actions and set performance targets for restoration. The ROI and manual delineation protocol can be extended to other biota classes (CCA, sponges, coral recruits) with clear classification rules and inter-observer reliability testing.

ACKNOWLEDGMENT

This study was carried out as independent research. The authors received no external funding and had no financial support for data collection, analysis, or publication. The authors thank all of their colleagues and local stakeholders who provided helpful comments and logistical assistance during fieldwork.

REFERENCES

[1] S. A. Bitterwolf, B. G. Reguero, C. D. Storlazzi, and M. W. Beck, "Shifting sands: The influence of coral reefs on shoreline erosion from short-term storm protection to long-term disequilibrium," *Nature-Based Solutions*, vol. 6, Dec. 2024, Art. no. 100174, https://doi.org/10.1016/j.nbsj.2024.100174.

[2] M. Francescangeli *et al.*, "Artificial reef based ecosystem design and monitoring," *Ecological Engineering*, vol. 221, Dec. 2025, Art. no. 107752, https://doi.org/10.1016/j.ecoleng.2025.107752.

[3] G. Syafruddin, Estradivari, A. M. A. Pratama, I. Yasir, S. C. A. Ferse, and R. Ambo-Rappe, "Sediment, substrate, and structure: Factors shaping algal turf dynamics in urban Indonesian reefs," *Regional Studies in Marine Science*, vol. 86, Sept. 2025, Art. no. 104172, https://doi.org/10.1016/j.rsma.2025.104172.

[4] A. Alshahrani, H. Ali, E. Saif, M. Alsayed, and F. Alshareef, "Classification of Coral Reef Species using Computer Vision and Deep Learning Techniques," *Engineering, Technology & Applied Science Research*, vol. 14, no. 5, pp. 16478–16485, Oct. 2024, https://doi.org/10.48084/etasr.8044.

[5] B. Ozanam, P. Romans, and R. Lami, "Choosing the right substrate to restore coral reefs through artificial reef construction: a mini-review," *Blue Biotechnology*, vol. 2, no. 1, Nov. 2025, Art. no. 24, https://doi.org/10.1186/s44315-025-00047-5.

[6] A. P. R. Sirait, O. M. M. Luthfi, and A. Isdianto, "Physical Characteristics of Artificial Reef Post Deployed on 2017 in Trenggalek Damas Beach," *Journal of Marine and Coastal Science*, vol. 10, no. 1, Feb. 2021, Art. no. 58, https://doi.org/10.20473/jmcs.v10i1.25607.

[7] B. P. Harvey *et al.*, "Feedback mechanisms stabilise degraded turf algal systems at a CO2 seep site," *Communications Biology*, vol. 4, no. 1, Feb. 2021, Art. no. 219, https://doi.org/10.1038/s42003-021-01712-2.

[8] Y. K. Wong, Z. Zheng, M. Zhang, D. J. Suggett, and S. K. Yeung, "CoralSCOP-LAT: Labeling and analyzing tool for coral reef images with dense semantic mask," *Ecological Informatics*, vol. 91, Nov. 2025, Art. no. 103402, https://doi.org/10.1016/j.ecoinf.2025.103402.

[9] S. Rouse, J. S. Porter, and T. A. Wilding, "Artificial reef design affects benthic secondary productivity and provision of functional habitat,"

Ecology and Evolution, vol. 10, no. 4, pp. 2122–2130, Feb. 2020, https://doi.org/10.1002/ece3.6047.

[10] J. M. Mwaura, D. Murage, J. F. Karisa, L. M. Otwoma, and H. O. Said, "Artificial reef structures and coral transplantation as potential tools for enhancing locally-managed inshore reefs: a case study from Wasini Island, Kenya," *Western Indian Ocean Journal of Marine Science*, vol. 21, no. 2, pp. 83–94, Feb. 2023, https://doi.org/10.4314/wiojms.v21i2.8.

[11] A. Duran *et al.*, "Long sediment-laden algal turf likely impairs coral recovery on Florida's coral reefs," *Coral Reefs*, vol. 43, no. 4, Aug. 2024, Art. no. 1109–1120, https://doi.org/10.1007/s00338-024-02532-6.

[12] D. J. Pondella, J. T. Claisse, and C. M. Williams, "Theory, practice, and design criteria for utilizing artificial reefs to increase production of marine fishes," *Frontiers in Marine Science*, vol. 9, Oct. 2022, Art. no. 983253, https://doi.org/10.3389/fmars.2022.983253.

[13] H. F. Mohamed, A. Abd-Elgawad, R. Cai, Z. Luo, L. Pie, and C. Xu, "Microbial community shift on artificial biological reef structures (ABRs) deployed in the South China Sea," *Scientific Reports*, vol. 13, no. 1, Mar. 2023, Art. no. 3456, https://doi.org/10.1038/s41598-023-29359-5.

[14] A. Isdianto *et al.*, "Observation of Coral Reef and Macroalgae Competition in the Sempu Strait, Malang," *Journal of Ecological Engineering*, vol. 24, no. 10, pp. 174–184, Oct. 2023, https://doi.org/10.12911/22998993/170246.

[15] C. S. Rogers and C. E. Ramos-Scharrón, "Assessing Effects of Sediment Delivery to Coral Reefs: A Caribbean Watershed Perspective," *Frontiers in Marine Science*, vol. 8, Jan. 2022, Art. no. 773968, https://doi.org/10.3389/fmars.2021.773968.

[16] C. T. Rueden *et al.*, "ImageJ2: ImageJ for the next generation of scientific image data," *BMC Bioinformatics*, vol. 18, no. 1, Dec. 2017, Art. no. 529, https://doi.org/10.1186/s12859-017-1934-z.

[17] A. Becker, M. D. Taylor, H. Folpp, and M. B. Lowry, "Managing the development of artificial reef systems: The need for quantitative goals," *Fish and Fisheries*, vol. 19, no. 4, pp. 740–752, July 2018, https://doi.org/10.1111/faf.12288.

[18] I. M. Carneiro *et al.*, "Precision and accuracy of common coral reef sampling protocols revisited with photogrammetry," *Marine Environmental Research*, vol. 194, Feb. 2024, Art. no. 106304, https://doi.org/10.1016/j.marenvres.2023.106304.

[19] M. S. Mills, M. Ungermann, G. Rigot, J. Den Haan, J. X. Leon, and T. Schils, "Coral reefs in transition: Temporal photoquadrat analyses and validation of underwater hyperspectral imaging for resource-efficient monitoring in Guam," *PLOS ONE*, vol. 19, no. 3, Mar. 2024, Art. no. e0299523, https://doi.org/10.1371/journal.pone.0299523.