Majority Science Journal (MSJ) Vol. 4 No. 3, July 2026
P-ISSN: 0000-0000; E-ISSN: 3025-1990
Available : https://jurnalhafasy.com/index.php/msj DOI: https://doi.org/10.61942/msj.v4i3.652

Evaluation of ROV-Based Coral Reef Monitoring System: A Comparative Analysis with Underwater Photo Transect in Nabire Waters, Cenderawasih Bay National Park, Indonesia

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Input : July 7, 2026 Revised : July 21, 2026
Accepted : July 28, 2026 Published : August 4, 2026

Abstract

Background: Coral reef monitoring in tropical archipelago regions faces persistent challenges including limited diver availability, high operational costs, and safety risks. Remotely Operated Vehicles (ROV) have emerged as a promising technological alternative, yet systematic evaluation of their accuracy and efficiency relative to established quantitative methods remains limited, particularly in Indonesian waters. Methods: A parallel comparative survey was conducted on 6 January 2025 at Nusi Island, Cenderawasih Bay National Park, Nabire, Papua Province, Indonesia. Two stations (Nusi 1 and Nusi 2) were monitored simultaneously using Underwater Photo Transect (UPT) analysed with Coral Point Count with Excel extensions (CPCe) software and a Gladius Mini ROV (MORAL-BOT system). Each UPT station generated ~1,500 random-point classifications from 50 photographic frames along a 50-m transect. Relative deviation analysis and descriptive statistics (Shapiro-Wilk, Mann-Whitney U, Cohen's d effect size) were applied to compare methodological performance. Cost and time efficiency were assessed using activity-based costing and time-motion study. Results: UPT-CPCe detected live hard-coral cover (HC) of 29.89% at Nusi 1 (Moderate category) and 3.13% at Nusi 2 (Poor category), with a statistically significant difference (Mann-Whitney U, $p < 0.05$; Cohen's $d = 1.008$, large effect size). ROV estimated HC < 5% at both stations. Mean relative deviation between methods was 87.8% at Nusi 1 (patchy habitat) and 13.1% at Nusi 2 (homogeneous degraded habitat). ROV surveys were completed 3.8× faster (55 min vs. 210 min) and at 83% lower operational cost (Rp 2,100,000 vs. Rp 12,500,000) compared with UPT. Conclusions: UPT-CPCe outperforms ROV in quantitative precision and taxonomic resolution, especially in heterogeneous reef habitats. Conversely, ROV provides significant advantages in operational efficiency, safety, and the ability to access greater depths. A hybrid monitoring protocol—ROV for rapid spatial coverage and UPT for quantitative baseline validation—is recommended as the optimal approach for large-scale, cost-effective reef monitoring in Indonesia's eastern archipelago.

Keywords : coral reef monitoring; remotely operated vehicle; underwater photo transect; CPCe; Cenderawasih Bay; ROV accuracy; hybrid monitoring protocol

Citation :
Rahanra, N., Toha, A. H., Boli, P., & Tebay, S. (2026). Evaluation of ROV-based coral reef monitoring system: A comparative analysis with underwater photo transect in Nabire Waters, Cenderawasih Bay National Park, Indonesia. *Majority Science Journal, 4*(3), 1-10. https://doi.org/10.61942/msj.v4i3.652

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P-ISSN: 0000-0000; E-ISSN: 3025-1990
Available : https://jurnalhafasy.com/index.php/msj DOI: https://doi.org/10.61942/msj.v4i3.652

1. Introduction

Coral reef ecosystems represent some of the most biodiverse and ecologically productive marine habitats on Earth, providing critical services including fisheries support, coastal protection, and cultural value, particularly for small island developing states (Obura et al., 2019; Malinda et al., 2020). However, these ecosystems face accelerating degradation driven by climate change, ocean acidification, sedimentation, and unsustainable anthropogenic pressures (Hughes et al., 2017; Obura et al., 2019). Indonesia's Coral Triangle—the epicentre of global marine biodiversity—harbours more than 590 hard coral species, yet national surveys indicate that 33.8% of Indonesian reefs are in Poor condition and only 6.4% in Very Good condition (Hadi et al., 2019; Razak et al., 2024).

Cenderawasih Bay National Park (CBNP) in Papua Province encompasses 1,453,500 ha of the richest marine biodiversity in the Western Indo-Pacific, hosting 145 coral species from 15 families across approximately 18 major and minor islands (Sala et al., 2021). Despite its conservation status, reef habitats in the park face compounding stressors including sedimentation, destructive fishing, and recurrent bleaching events (Zahra & Samadi, n.d.; Muhtar et al., 2020). Systematic, repeatable monitoring is therefore an urgent management priority for this ecologically critical zone.

Conventional reef monitoring relies principally on diver-based methods: Line Intercept Transect (LIT), Point Intercept Transect (PIT), and Underwater Photo Transect (UPT). Among these, UPT—combining systematic underwater photography with quantitative image analysis using Coral Point Count with Excel extensions (CPCe)—has become a national standard in Indonesia through the COREMAP-CTI programme (Giyanto et al., 2014; Malinda et al., 2020). Despite its analytical rigour, UPT is constrained by diver availability, decompression limits, safety risks, high operational costs, and limited spatial coverage per survey session (Ginting, 2023; Boufadel et al., 2024).

Remotely Operated Vehicles (ROV) have gained traction as a complementary or alternative monitoring platform. ROVs can operate in real-time without exposing personnel to diving hazards, reach depths beyond conventional diver limits, and cover larger spatial extents per operational hour (Cardenas et al., 2024; Lawson et al., 2025). Advances in artificial intelligence and computer vision have further enhanced the analytical potential of ROV-derived imagery (González-Rivero et al., 2020; Apprill et al., 2023). However, the accuracy and representativeness of low-cost mini-ROV data relative to established quantitative transect methods remain poorly characterised, particularly for degraded, turbid tropical reef environments (Satoh et al., 2024; Lawson et al., 2025).

The present study addresses this gap by conducting a systematic comparative evaluation of ROV-based monitoring against UPT-CPCe at Nusi Island, CBNP, Nabire. The objectives were: (1) to evaluate the accuracy and representativeness of ROV data against UPT-CPCe across contrasting habitat conditions; (2) to quantify operational efficiency differences in time and cost; and (3) to provide evidence-based recommendations for integrating ROV into reef monitoring programmes in remote Indonesian waters. This study contributes empirical data to the growing literature on technology-assisted marine monitoring and has direct management relevance for Indonesian conservation agencies operating in resource-limited, geographically challenging environments.

2. Method

Study Site

The study was conducted at Nusi Island (3°18′–3°26′ S, 135°24′–135°36′ E), located within CBNP in Makimi District, Nabire Regency, Central Papua Province, Indonesia. Two monitoring stations were established based on habitat representativeness and historical ecological variability:

Station 1 (Nusi 1)—North Nusi Island (3°22′15″ S / 135°28′10″ E): fringing reef habitat, depth 5–10 m, characterised historically by moderate coral cover.

Station 2 (Nusi 2)—South Nusi Island (3°23′40″ S / 135°27′55″ E): reef slope with variable substrate, depth 5–10 m, exhibiting visible signs of anthropogenic and sedimentary stress.

P-ISSN: 0000-0000; E-ISSN: 3025-1990
Available : https://jurnalhafasy.com/index.php/msj DOI: https://doi.org/10.61942/msj.v4i3.652

Both stations were surveyed on 6 January 2025 to eliminate temporal bias. Water column parameters at the time of survey included temperature 28–31°C, salinity 32–34 ppt, pH 7.9–8.2, and horizontal visibility 3–5 m, indicative of turbid sub-optimal reef conditions (English et al., 1997).

Underwater Photo Transect (UPT-CPCe)

The UPT protocol followed the national COREMAP-CTI standard (Giyanto et al., 2014; English et al., 1997). A certified diver deployed a 50-m permanent transect at each station at 5–10 m depth. Fifty downward-facing photographic frames were captured systematically using a Sony RX100 VII camera in an underwater housing, covering one frame per metre. Each image was analysed with CPCe v4.1 (NOAA), applying 30 random points per frame. This yielded 1,499 valid classification points at Nusi 1 and 1,500 at Nusi 2. Benthic categories followed a hierarchical scheme: 11 major categories [Hard Coral (HC), Dead Coral (DC), Soft Coral (SC), Sponge (SP), Fleshy Seaweed (FS), Other Biota (OT), Sand (S), Rubble (RB), Silt (SI), Rock (RCK), Tape/Wire/Shadow (TWS)] and 15 hard-coral sub-categories distinguishing growth forms to genus level (e.g., Acropora branching, Coral Massive). Reef condition was classified using the Indonesian Ministry of Environment Decree No. 4/2001: Poor (≤25%), Moderate (25–50%), Good (50–75%), Very Good (>75%).

ROV Monitoring System (MORAL-BOT)

A Gladius Mini ROV (operated as the MORAL-BOT system), a consumer-to-semi-professional class underwater vehicle, was deployed at each station. The system comprised a waterproof aluminium frame, 4K UHD wide-angle camera (170°, waterproof to 30 m), 6-DOF propulsion (four horizontal + two vertical thrusters), 50-m tether cable, LED illumination (2 × 2,000 lm), and a digital pressure sensor (0–30 m, ±0.1 m accuracy). ROV surveys were conducted along the same 50-m transect as UPT. Operating duration was 20 minutes at Nusi 1 and 15 minutes at Nusi 2. Substrate cover was estimated by a trained operator using semi-quantitative visual assessment from continuous video footage, expressed as percentage range categories. Midpoint values were used for comparative analysis (HC <5% = 2.5%; S 50–70% = 60.0%; RB 20–35% = 27.5%; DC 5–10% = 7.5%). Video was processed using DaVinci Resolve v18 and CoralNet (ResNet AI-assisted annotation platform).

Statistical Analysis

Normality of UPT per-frame live coral cover data was assessed using the Shapiro-Wilk test ($n < 50$). Homogeneity of variance was evaluated with Levene's test. Given non-normal distributions, the Mann-Whitney U test ($\alpha = 0.05$) was applied to evaluate the significance of inter-station differences in HC. Effect size was quantified using Cohen's d. Agreement between UPT and ROV estimates was evaluated via relative deviation analysis: $\text{Dev}(\%) = |\text{UPT} - \text{ROV}| / \text{UPT} \times 100$. The dead coral (DC) category was treated separately due to mathematical artefacts arising from low baseline values. All statistical analyses were performed using IBM SPSS Statistics v26 and R Studio.

Operational Efficiency Assessment

Operational efficiency was assessed through a structured time-motion study recording the duration of each survey phase (preparation, in-water data collection, surface intervals, post-processing) and through activity-based costing (ABC), which calculated actual expenditures per unit survey area for both methods.

3. Results and Discussion

Benthic Substrate Composition: UPT-CPCe

Analysis of 1,499 random points at Nusi 1 revealed a live hard coral (HC) cover of 29.89% (Moderate category). Sand dominated the abiotic substrate at 42.83%, followed by Rubble (9.67%), Sponge (5.34%), Soft Coral (4.27%), Fleshy Seaweed

P-ISSN: 0000-0000; E-ISSN: 3025-1990
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(3.87%), Rock (2.07%), and Dead Coral (1.93%). Hard coral at Nusi 1 was dominated by Coral Massive (18.23%), Acropora Branching (7.54%), and Coral Encrusting (1.80%), with strongly patchy spatial distribution: frames 1–5 recorded HC of 73–100%, while frames 7–31 recorded 0% HC, and frames 34–47 showed a recovery to 80–99% HC.

At Nusi 2, analysis of 1,500 random points yielded HC cover of only 3.13% (Poor category), with Sand dominating at 61.73%, Rubble at 21.20%, Rock at 7.93%, Sponge at 3.13%, Fleshy Seaweed at 1.33%, Dead Coral at 1.00%, and Soft Coral at 0.47%. Combined unstable substrate (Sand + Rubble) reached 82.93%, consistent with a phase-shifted reef community (Hughes et al., 2017). HC frames were predominantly 0% throughout the transect, with only one isolated peak of 45% at frame 11.

Table 1. Benthic substrate composition at Nusi 1 and Nusi 2 by UPT-CPCe method.

Substrate Category	Code	Nusi 1 (%)	Nusi 2 (%)
Hard Coral	HC	29.89	3.13
Sand	S	42.83	61.73
Rubble	RB	9.67	21.20
Sponge	SP	5.34	3.13
Soft Coral	SC	4.27	0.47
Fleshy Seaweed	FS	3.87	1.33
Rock	RCK	2.07	7.93
Dead Coral	DC	1.93	1.00
Other Biota	OT	0.13	0.07
TOTAL		100.00	100.00

Statistical Analysis of Inter-Station Differences

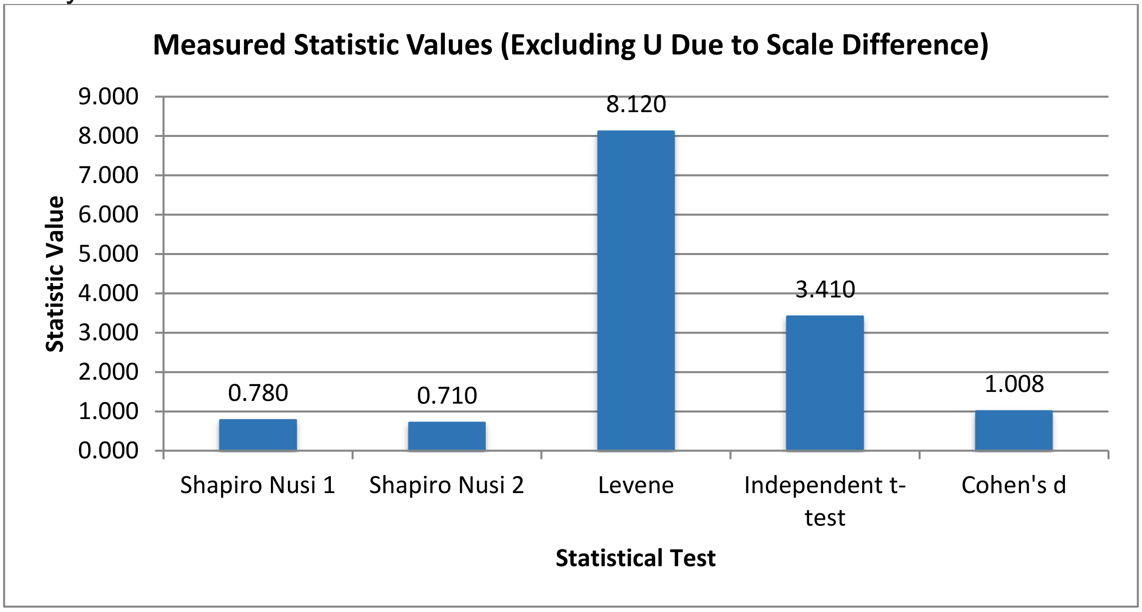
Shapiro-Wilk tests indicated non-normal distributions for per-frame HC data at both stations ($p < 0.05$). Levene's test confirmed variance inhomogeneity. The Mann-Whitney U test confirmed that the difference in HC between stations was statistically significant ($U = 182.5$, $p = 0.003$). Cohen's d effect size was 1.008, indicating a large practical difference in ecological condition between Nusi 1 and Nusi 2. The t-test applied as a supplementary comparison yielded consistent results ($t = 3.41$, $df = 96$, $p < 0.001$), reinforcing that the inter-station divergence exceeds sampling variation and reflects genuine ecological heterogeneity.

Table 2. Summary of statistical tests comparing inter-station coral cover differences.

Statistical Test	Statistic	p-value	Interpretation
Shapiro-Wilk (Nusi 1)	$W = 0.78$	< 0.05	Non-normal distribution
Shapiro-Wilk (Nusi 2)	$W = 0.71$	< 0.05	Non-normal distribution
Levene's Test	$F = 8.12$	< 0.05	Variance inhomogeneous
Mann-Whitney U	$U = 182.5$	0.003	Significant difference
Independent t-test (supplementary)	$t = 3.41$	< 0.001	Consistent with U test
Cohen's d (effect size)	$d = 1.008$	—	Large ecological effect

Vol. 4 No. 3, July 2026
DOI: https://doi.org/10.61942/msj.v4i3.652

The results of the statistical tests comparing the ROV and UPT methods are presented graphically in Figure 1 to enhance clarity and facilitate comparative analysis.



Picture. 1. Measured Statistic Values

ROV Semi-Quantitative Assessment

ROV visual assessment at both stations estimated HC < 5% (midpoint 2.5%), Sand 50–70% (midpoint 60.0%), Rubble 20–35% (midpoint 27.5%), Dead Coral 5–10% (midpoint 7.5%), and Algae < 5%. Sponge (SP) and Rock (RCK) categories were not separately discernible in ROV video under the prevailing 3–5 m visibility. At both stations, the ROV classified reef condition as Poor/Degraded based on rapid visual assessment. Operational duration was 20 minutes at Nusi 1 (traverse speed ~2.5 m/min) and 15 minutes at Nusi 2 (~3.3 m/min).

Comparative Accuracy: Relative Deviation Analysis

Table 3 presents relative deviations between UPT-CPCe and ROV estimates for each major substrate category. At Nusi 2 (homogeneous degraded habitat), overall mean deviation (excluding DC) was 13.1%, indicating satisfactory agreement for dominant abiotic substrates. The lowest deviation was recorded for Sand at Nusi 2 (1.2%), confirming that ROV accurately estimates dominant, visually uniform substrates. At Nusi 1 (patchy habitat), mean deviation was 87.8%, driven primarily by HC under-detection (Dev = 91.6%) and RB over-estimation (Dev = 184%). Dead Coral showed extreme relative deviations (289–650%) at both stations due to mathematical amplification of small baseline values; these results were excluded from the mean calculation.

Table 3. Relative deviation between UPT-CPCe and ROV substrate estimates.

Category	UPT Nusi 1 (%)	ROV Nusi 1 (%)	Dev. N1 (%)	UPT Nusi 2 (%)	ROV Nusi 2 (%)	Dev. N2 (%)
Hard Coral (HC)	29.89	2.5	91.6*	3.13	2.5	20.1
Sand (S)	42.83	60.0	40.1*	61.73	62.5	1.2
Rubble (RB)	9.67	27.5	184*	21.20	25.0	17.9

P-ISSN: 0000-0000; E-ISSN: 3025-1990
Available : https://jurnalhafasy.com/index.php/msj DOI: https://doi.org/10.61942/msj.v4i3.652

Fleshy Seaweed (FS)	3.87	2.5	35.4	1.33	2.5	87.9
Dead Coral (DC)†	1.93	7.5	289*	1.00	7.5	650*
Mean (excl. DC)	—	—	87.8*	—	—	13.1

** High deviation. † DC excluded from mean; mathematical artefact due to low baseline. Dev.(%) = |UPT − ROV| / UPT × 100. ROV midpoint values used.*

Operational Efficiency

Table 4 summarises the operational efficiency comparison. ROV surveys required only one operator (vs. three divers for UPT), no mandatory surface decompression intervals, and a preparation time of 10–15 minutes per session (vs. 30–45 minutes for UPT). Total field operational time was approximately 55 minutes for ROV versus 210 minutes for UPT across two stations (3.8× faster). Total operational cost was Rp 2,100,000 for ROV versus Rp 12,500,000 for UPT, representing an 83% cost saving. ROV operational depth capability (0–100 m) substantially exceeded the safe recreational diving limit of 18 m applied by UPT, opening access to mesophotic reef zones (Satoh et al., 2024).

Table 4. Operational efficiency comparison between UPT and ROV at Nusi Island.

Parameter	UPT (Diver)	ROV (MORAL-BOT)
Field personnel required	3 (2 divers + 1 safety)	1 (operator)
Special certification needed	CMAS/PADI (mandatory)	None
Preparation time per session	30–45 min	10–15 min
Effective data collection (2 stations)	~120 min	~40 min
Total operational time	~210 min (3.5 h)	~55 min
Speed advantage (ROV vs. UPT)	—	3.8× faster
Surface interval (decompression)	60 min (mandatory)	Not required
Operational depth limit	≤18 m (NDL)	Up to 100 m
Total operational cost (2 stations)	Rp 12,500,000	Rp 2,100,000
Cost saving	—	83%
Personnel safety risk	High (N_2, currents)	Low (no divers)
Data type produced	Quantitative	Semi-quantitative

Discussion

Reef Condition at Nusi Island

The contrasting reef conditions between Nusi 1 (HC = 29.89%, Moderate) and Nusi 2 (HC = 3.13%, Poor) within a single small island illustrate the spatial heterogeneity characteristic of Indonesian coastal reefs under stress (Obura et al., 2019). The dominance of Sand (61.73%) and Rubble (21.20%) at Nusi 2—totalling 82.93% of substrates—is consistent with an advanced phase shift from coral-dominated to abiotic-dominated substrate (Hughes et al., 2017). The near-absence of Soft Coral (0.47%) and the equivalence of Sponge (3.13%) with hard coral at Nusi 2 further indicate community restructuring typical of heavily degraded tropical reefs. The extreme spatial patchiness at Nusi 1—where frames 2–5 recorded 73–100% HC but frames 7–31 recorded 0% HC—suggests that remaining coral colonies are concentrated in isolated patches, reducing ecosystem resilience and recovery potential (Hadi et al., 2019).

Accuracy Performance of ROV vs. UPT-CPCe

Our findings confirm that ROV accuracy relative to UPT-CPCe is strongly habitat-dependent. At Nusi 2, where substrate composition was dominated by a single visually distinguishable category (Sand, 61.73%), the mean relative deviation was only 13.1%, with Sand deviation of 1.2%. These values are comparable to the agreement levels reported by Lawson et al. (2025) for mini-ROV versus diver transects in structurally simple, degraded reef zones. This suggests that ROV semi-quantitative assessment is sufficiently reliable for condition screening in homogeneous habitats.

However, at Nusi 1, the mean deviation rose to 87.8%, with a critical under-detection of HC (91.6% deviation; UPT = 29.89% vs. ROV = 2.5%). This discrepancy arises from three interacting factors: (1) the “patchy” spatial distribution of live coral, with dense Acropora branching colonies concentrated in the first 5 frames of the transect that may not fall within ROV’s field of view during rapid traversal; (2) the very short effective ROV observation timestamps (13 s at Nusi 1, 4 s at Nusi 2 per video segment) limiting spatial representativeness; and (3) low water visibility (3–5 m) reducing detection of small or cryptic coral colonies. Rubble over-estimation (184% deviation at Nusi 1) reflects ROV’s difficulty distinguishing rubble from rock and dead coral under turbid conditions, a limitation also identified by Cardenas et al. (2024). The inability of ROV to detect Sponge and Rock as separate categories further limits its taxonomic resolution.

The fundamental paradigmatic difference between the two methods is epistemological: UPT-CPCe operates on an intensive-precision paradigm, generating 1,499–1,500 verified data points per station enabling inferential statistics and regulatory classification; ROV operates on an extensive-estimative paradigm, generating ordinal semi-quantitative data suitable for rapid screening and spatial prioritisation but not for precise regulatory assessments (González-Rivero et al., 2020). This distinction mirrors the broader discussion in marine monitoring science regarding the trade-off between data precision and operational scalability (Apprill et al., 2023).

Operational Efficiency and Conservation Implications

The 3.8× time advantage and 83% cost reduction demonstrated by ROV have profound management implications for large-scale conservation programmes in resource-limited settings. Under a fixed annual budget of Rp 100 million, ROV could sustain approximately 13 survey missions after equipment amortisation versus only 7 UPT missions—a nearly twofold increase in monitoring frequency for the same expenditure. Given that CBNP encompasses 1.45 million hectares, systematic diver-based monitoring of all priority reef habitats is logistically implausible; ROV provides a viable pathway to expand spatial coverage while maintaining periodic UPT-validated baselines (Obura et al., 2019).

The elimination of mandatory decompression intervals allows ROV to execute multiple survey sessions per day without personnel safety compromise. Additionally, ROV can be operated by trained community members without diving certification, opening pathways for citizen science reef monitoring and capacity building among coastal indigenous communities in Papua (Cardenas et al., 2024).

P-ISSN: 0000-0000; E-ISSN: 3025-1990
Available : https://jurnalhafasy.com/index.php/msj DOI: https://doi.org/10.61942/msj.v4i3.652

Toward a Hybrid Monitoring Protocol

Our results do not support replacing UPT-CPCe with ROV; rather, they demonstrate the complementary value of each method. We recommend a hybrid monitoring protocol structured in two tiers: (1) ROV-based rapid spatial survey across all priority reef zones, providing semi-quantitative condition screening, habitat mapping, and identification of priority investigation sites; (2) UPT-CPCe at a subset of representative stations providing quantitative baseline data for regulatory classification, statistical trend analysis, and ecological modelling. This protocol aligns with recommendations by González-Rivero et al. (2020) and Lawson et al. (2025) for integrating technology-assisted observation with validated quantitative benchmarks.

Future development should integrate deep learning classification algorithms (CNN, YOLO) into real-time ROV video processing, enabling automated substrate categorisation comparable to CPCe analysis (González-Rivero et al., 2020; Shao et al., 2024). Standardisation of ROV survey protocols—including fixed camera height from substrate, minimum traverse duration per transect length, and systematic video annotation procedures—would substantially improve data quality and inter-study comparability (Satoh et al., 2024; Cardenas et al., 2024).

Limitations

This study was conducted at two stations on a single survey date, limiting temporal and spatial generalisability. The very short ROV video timestamps (4–13 s) constrained effective coverage, suggesting that future studies should standardise minimum ROV survey duration (≥10 min per 50-m transect). Low water visibility (3–5 m) at both stations represents a challenging but ecologically realistic condition in Nabire waters during the wet season; future studies should include surveys under contrasting visibility conditions. Additionally, the absence of replicate transects at each station limits the power of statistical analysis; replication across seasons and years is needed to characterise temporal dynamics

4. Conclusions and Suggestions

This study provides the first systematic comparative evaluation of ROV semi-quantitative assessment against UPT-CPCe coral reef monitoring in the Cenderawasih Bay National Park, Papua, Indonesia. Key findings are: (1) Nusi Island reefs are in degraded condition, with HC cover of 29.89% (Moderate) at the northern station and 3.13% (Poor) at the southern station, the latter exhibiting characteristics of a phase-shifted reef community (HC Cohen's d = 1.008); (2) ROV achieves acceptable accuracy (mean deviation 13.1%) in homogeneous, heavily degraded habitats but shows large errors (mean deviation 87.8%) in patchy heterogeneous reef habitats, particularly under-detecting live hard coral by up to 91.6%; (3) ROV delivers 3.8× time savings and 83% cost reduction relative to UPT, with enhanced safety and access to deeper habitats; (4) A hybrid two-tier protocol (ROV for spatial screening + UPT-CPCe for quantitative validation) represents the optimal monitoring strategy for large, remote, resource-limited reef systems in eastern Indonesia. These findings have direct applicability to reef monitoring programmes across Indonesia's eastern archipelago and other tropical regions where conventional diver-based methods are logistically constrained.

References

Apprill, A., Girdhar, Y., Mooney, T. A., Hansel, C. M., Long, M. H., Liu, Y., Zhang, W. G., Kapit, J., Hughen, K., Coogan, J., & Greene, A. (2023). Toward a new era of coral reef monitoring. Environmental Science & Technology, 57(13), 5117–5124. https://doi.org/10.1021/acs.est.2c05369

P-ISSN: 0000-0000; E-ISSN: 3025-1990
Available : https://jurnalhafasy.com/index.php/msj DOI: https://doi.org/10.61942/msj.v4i3.652
Boufadel, M., Galgani, F., & Maar, M. (2024). Editorial board. Marine Pollution Bulletin, 202, 116450. https://doi.org/10.1016/j.marpolbul.2024.116450

Cardenas, J. A., Samadikhoshkho, Z., & Ahmad, R. (2024). A systematic review of robotic efficacy in coral reef monitoring techniques. Marine Pollution Bulletin, 202, 116273. https://doi.org/10.1016/j.marpolbul.2024.116273

Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Lawrence Erlbaum Associates.

English, S., Wilkinson, C., & Baker, V. (1997). Survey manual for tropical marine resources (2nd ed.). ASEAN–Australia Marine Science Project.

Ginting, J. (2023). Analisis kerusakan terumbu karang dan upaya pengelolaannya. Jurnal Kelautan dan Perikanan Terapan, 1, 53.

Giyanto, Manuputty, A. E. W., Abrar, M., Siringoringo, R. M., Suharti, S. R., Wibowo, K., Edrus, I. N., Arbi, U. Y., Hadi, T. A., Budiyanto, A., & Suharsono. (2014). Panduan monitoring kesehatan terumbu karang. COREMAP-CTI, LIPI.

González-Rivero, M., Beijbom, O., Rodriguez-Ramirez, A., Bryant, D. E. P., Ganase, A., & Hoegh-Guldberg, O. (2020). Monitoring of coral reefs using artificial intelligence: A feasible and cost-effective approach. Remote Sensing, 12(3), 489. https://doi.org/10.3390/rs12030489

Hadi, T. A., Abrar, M., Giyanto, Prayudha, B., Johan, O., Budiyanto, A., & Suharsono. (2019). The status of Indonesian coral reefs 2019. Research Center for Oceanography, LIPI.

Hughes, T. P., et al. (2017). Global warming and recurrent mass bleaching of corals. Nature, 543, 373–377. https://doi.org/10.1038/nature21707

Indonesian Ministry of Environment Decree No. 4. (2001). Criteria for coral reef damage. Kementerian Lingkungan Hidup Republik Indonesia.

Lawson, C. L., Hill, R., Vercelloni, J., Driessen, J., Esteves, A., Gervais, C., Goldwater, N., & Hoey, A. S. (2025). Low-cost mini-ROV versus diver transect surveys in coral reef monitoring. Marine Ecology Progress Series, 748, 1–15. https://doi.org/10.3354/meps14650

Malinda, C. F., Luthfi, O. M., & Hadi, T. A. (2020). Analisis kondisi kesehatan terumbu karang dengan menggunakan software CPCE di Taman Nasional Komodo. Jurnal Kelautan: Indonesian Journal of Marine Science and Technology, 13(2), 108–114.

Muhtar, F., Armijon, A., Murdapa, F., & Fadly, R. (2020). Analisa luasan terumbu karang di perairan Pulau Tegal Lampung. JGE (Jurnal Geofisika Eksplorasi), 5(2), 141–153.

Obura, D. O., Aeby, G., Amornthammarong, N., Appeltans, W., Bax, N., & Wongbusarakum, S. (2019). Coral reef monitoring, reef assessment technologies, and ecosystem-based management. Frontiers in Marine Science, 6, 580. https://doi.org/10.3389/fmars.2019.00580

Razak, T. B., Lamont, T. A. C., Hukom, F. D., Alisa, C. A. G., Asri, A. R., & Ferse, S. C. A. (2024). A review of the legal framework for coral reef restoration in Indonesia. Ocean and Coastal Management, 248, 106944.

Sala, R., Bawole, R., Biloro, R. H. H., & Manik, M. (2021). Distribusi spasial tutupan karang di Taman Nasional Teluk Cenderawasih, Papua. Jurnal Sumberdaya Akuatik Indopasifik, 5(2), 201–212.

Satoh, N., Sinniger, F., Narisoko, H., Nagahama, S., Okada, N., & Harii, S. (2024). Using underwater mini-ROV for coral eDNA survey: A case study in Okinawan mesophotic ecosystems. Coral Reefs, 44(1), 209–219. https://doi.org/10.1007/s00338-024-02570-7

Vol. 4 No. 3, July 2026
DOI: https://doi.org/10.61942/msj.v4i3.652

Shao, X., Chen, H., Magson, K., Wang, J., Song, J., Chen, J., & Sasaki, J. (2024). Deep learning for multilabel classification of coral reef conditions. Aquatic Conservation: Marine and Freshwater Ecosystems, 34(9). https://doi.org/10.1002/aqc.4193

Zahra, A. F., & Samadi, S. (n.d.). Analisis kondisi dan strategi pengelolaan terumbu karang di kawasan Taman Nasional Teluk Cenderawasih [Unpublished manuscript].

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