ROI-Based Substrate Cover Quantification from Underwater Photo Transects Using ImageJ: A Case Study at the Paiton Coal-Fired Power Plant, Indonesia

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ABSTRACT

This paper presents the integrated Underwater Photo Transect (UPT)–ImageJ workflow for quantifying reef substrate cover in an industrial coastal setting near the Paiton coal-fired power plant (PLTU Paiton), East Java, Indonesia. A 70 m transect was surveyed at approximately 5 m depth using 70 photoquadrats (1×1 m). Quadrat images were analyzed in ImageJ through scale calibration and Region-of-Interest (RoI) delineation for standardized substrate classes, yielding class areas that were converted into benthic percent cover. The substrate composition was dominated by rubble (57.62%), followed by rock (17.83%), hard coral (15.44%), sponge (5.97%), and dead coral with algae (3.14%). Based on hard-coral cover (15.44%), the site was classified as Poor/Damaged under the live-coral cover thresholds. The proposed workflow provides a transparent and auditable approach for repeatable substrate-cover monitoring from UPT imagery in high-activity industrial and maritime coastal zones.

Keywords-benthic monitoring; coral reef condition assessment; coral rubble dynamics; environmental baseline; industrial coastal zone; maritime disturbance; reef resilience; spatial heterogeneity

I. INTRODUCTION

Coral reefs are critical marine ecosystems that support biodiversity, coastal protection, and important ecosystem services for coastal communities [1]. However, monitoring reef condition, particularly substrate composition, remains challenging in coastal zones affected by industrial infrastructure and intense maritime activity [2]. Underwater Photo Transect (UPT) is widely used because it is an efficient and non-invasive method [3], but interpretation of underwater photographs may still be affected by image quality limitations, including low illumination, reduced contrast, and color distortion [4]. As image-based reef assessment continues to develop, more consistent and traceable quantification methods are needed. In this context, recent studies have highlighted the growing use of automated image analysis and deep learning to improve scalability and consistency in reef monitoring [5]. In the present study, however, these approaches are referred to only as contextual background and were not applied. Instead, this work uses ImageJ as a practical RoI-based workflow to quantify substrate cover from UPT images through scale calibration, area delineation, and conversion of measured areas into benthic percent cover [6].

This study contributes a transparent RoI-based area-quantification workflow as an alternative to point-intercept interpretation, demonstrates its application in an industrial coastal setting near the PLTU Paiton lighthouse, and provides an auditable monitoring output through saved RoI sets and exported measurement tables. Based on this workflow, the study assesses reef substrate composition and coral condition to provide a site-specific baseline for monitoring and management in a high-activity industrial coastal environment.

II. MATERIALS AND METHODS

A. Study Site

This study was conducted at the PLTU Paiton Lighthouse, Paiton District, Probolinggo, East Java, Indonesia (113.5734° E; 7.70055° S) from 17 to 21 August 2025. The site is adjacent to the PLTU industrial complex in a high-activity coastal zone and was selected to document reef substrate conditions in an industrial coastal setting. The industrial complex and UPT sampling locations are shown in Figure 1. To represent near-field coastal conditions, the study area was restricted to a zone within approximately 1 km from the shoreline.

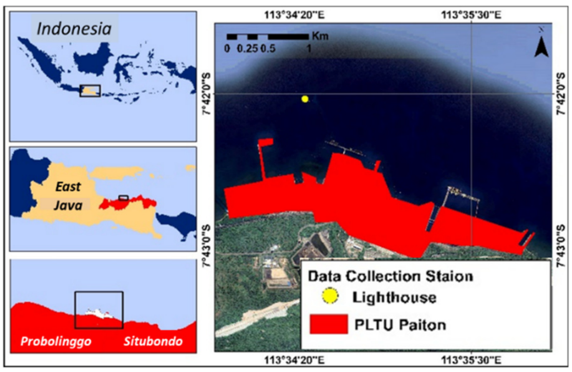

Fig. 1. Study site near the PLTU Paiton lighthouse, East Java, Indonesia, showing the UPT survey area and sampling location.

B. UPT Survey and Image Acquisition

UPT surveys were conducted by SCUBA divers using an Olympus TG-6 underwater camera (Olympus Corporation, Tokyo, Japan). A preliminary reconnaissance dive was carried out to confirm site suitability and underwater visibility [7]. A 70 m line transect was then deployed at approximately 5 m depth. Along the transect, 70 photoquadrats (1×1 m) were collected using an alternating-side design to improve spatial representativeness. At each quadrat position, one overview image and four sub-frame images were recorded, yielding a total of 350 images. The sampling procedure and an example of the quadrat image used for analysis are shown in Figures 2 and 3.

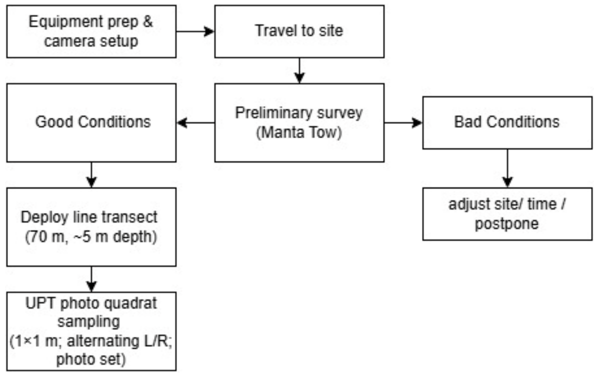

Fig. 2. UPT sampling workflow from transect deployment to systematic photo acquisition.

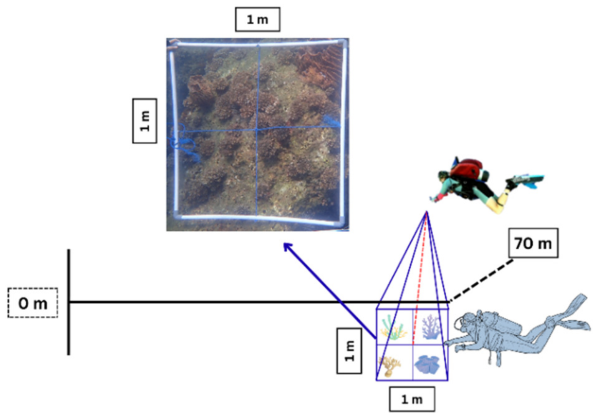

Fig. 3. A representative UPT photoquadrat used as input for substrate classification and area measurement.

C. RoI-Based Substrate Area Measurement in ImageJ

ImageJ was used to quantify substrate cover through scale calibration, RoI delineation, and area extraction [6]. Each quadrat image was calibrated using the known 1×1 m frame dimension and then classified into five substrate classes: Hard Coral (HC), Sponge (SP), Dead Coral with Algae (DCA), Rock, and Rubble. RoIs were traced and measured to obtain class areas. The overall workflow is shown in Figure 4, and the main RoI-analysis steps are illustrated in Figure 5.

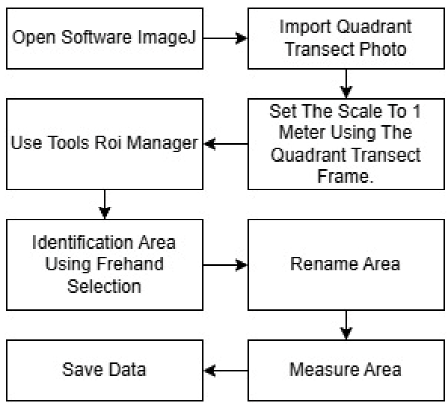

Fig. 4. ImageJ ROI workflow for measuring substrate area and converting it to percent cover.

(a)

(b)

(c)

(d)

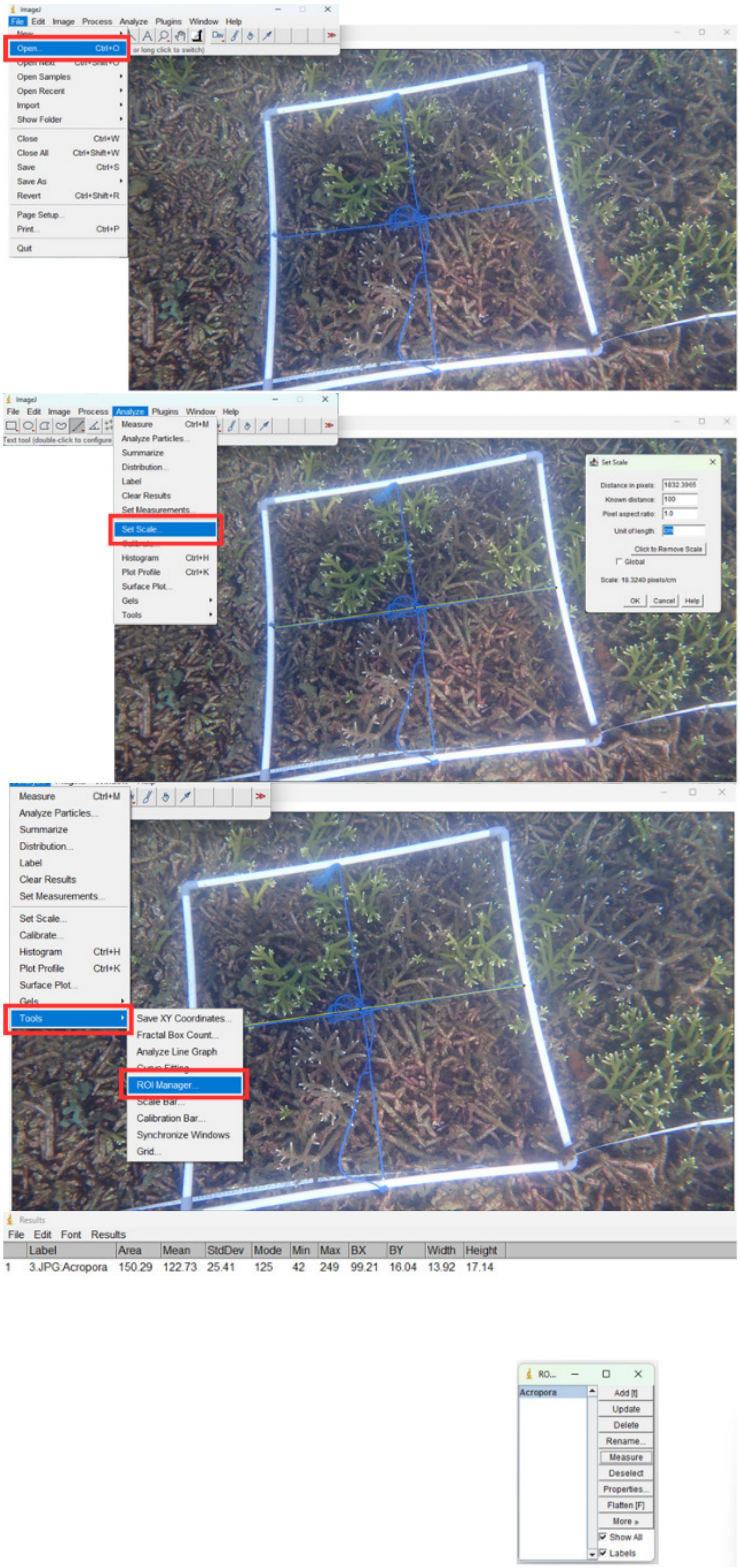

Fig. 5. Step-by-step RoI creation and area extraction in ImageJ: (a) Raw UPT photo opened in ImageJ, (b) set scale / calibration dialogue, (c) opening RoI manager, (d) result table (area per RoI/class).

D. ROI Annotation Rules and Class Labeling

To improve reproducibility, ROI delineation followed predefined annotation rules for the five substrate classes used in this study. HC denoted living hard coral tissue, SP a porous sessile invertebrate attached to stable substrate, DCA dead coral framework covered by algal film or turf, Rock consolidated hard substrate, and Rubble loose coral fragments. Boundaries followed the clearest visible transitions between adjacent classes. Mixed patches were separated when possible and were assigned to the dominant visible class otherwise. Areas with severe blur, shadow, or backscatter obscuring boundaries were excluded from annotation. Because RoI delineation and substrate labeling involve visual interpretation, they are operator-dependent, therefore, consistent class definitions and annotation rules were applied throughout the analysis. Each RoI represented one substrate class only and was traced as a non-overlapping polygon in ImageJ [6].

E. QA/QC for ROI Labeling and Area Calculation

Quality control was applied to annotation consistency and area-calculation integrity. After RoI tracing, each image was reviewed to confirm that the RoIs were non-overlapping and that class boundaries followed visible substrate transitions. All measurements were extracted using the same ImageJ settings and exported directly to reduce transcription errors. For each image, the sum of class areas and derived percent covers was checked against the total analyzable area so that values summed to approximately 100% within rounding. A subset of images was re-opened to verify the RoI-to-class assignment and the consistency of the exported measurement table.

F. Percentage Substrate Cover

Percent cover for each substrate class was calculated from ImageJ-derived areas as:

$$PC_i = \frac{A_i}{A_T} \times 100\% \quad (1)$$

where PC_i is the percent cover of substrate class *i* (%), A_i is the measured area of class *i* (m^2), and A_T the total analyzed quadrat area (m^2). Coral-reef condition was classified from live hard-coral cover using the thresholds presented in Table I [8]. Percent-cover outputs were subsequently used to summarize substrate composition and classify reef condition.

TABLE I. CORAL REEF CONDITION

Live coral cover (%)	Condition category
0–24.9	Poor/Damaged
25–49.9	Fair
50–74.9	Good
75–100	Very Good

III. RESULTS AND DISCUSSION

A. General Condition of the Study Area

During the survey period, water clarity near the lighthouse was visually higher than in nearshore waters closer to Desa Binor, particularly toward the eastern discharge-outlet vicinity. The site also exhibited relatively strong currents and wave-driven motion, which affected underwater visibility and diver stability during UPT photography.

The surrounding area is characterized by intense coastal use, including small-scale fishing and frequent vessel movement associated with port operations and coal transport serving the power plant. Vessel operations close to shallow reefs can generate propeller-jet or wash hydrodynamic forcing that mobilizes and resuspends seabed sediments [9]. Elevated suspended sediments reduce light availability and increase sediment exposure for corals [10]. In addition to these chronic pressures, acute disturbances such as ship grounding can directly damage reef substrates [11], whereas built structures may impose additional ecological and physical effects on shallow tropical coral reefs [12]. Field observations indicated that coral colonies, including *Acropora*, remain present near the lighthouse; however, the reef is exposed to persistent physical stress associated with chronic maritime activity.

Fig. 6. Coastal setting of the study area around the lighthouse sector.

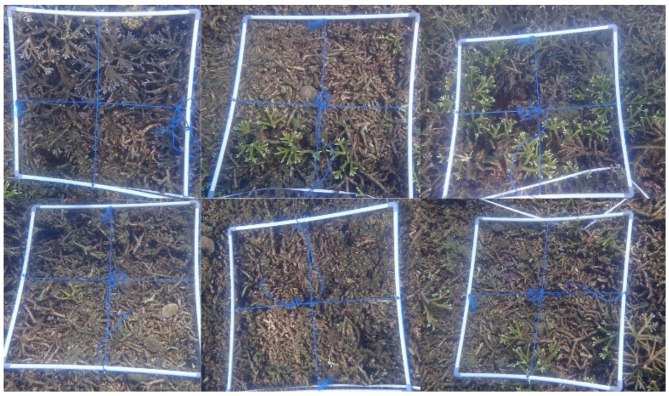

Fig. 7. Representative field photo showing typical benthic/substrate condition in the lighthouse sector.

B. Substrate Cover Results (2025 UPT–ImageJ)

The substrate assemblage around the lighthouse was dominated by rubble (57.62%), followed by rock (17.83%), hard coral (15.44%), sponge (5.97%), and dead coral with algae (3.14%) (Figure 8). Based on hard-coral cover, the site falls within the Poor/Damaged category according to Table I [8].

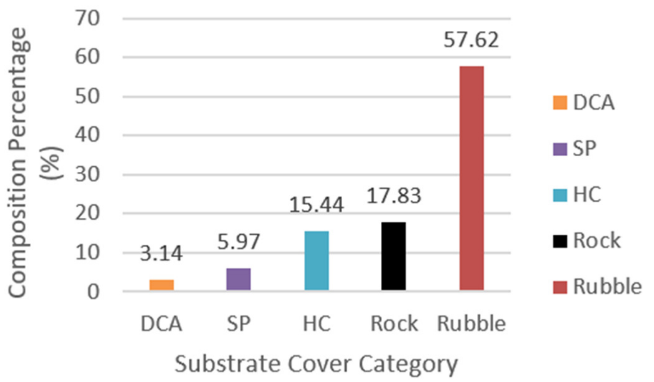

Fig. 8. ROI-derived percent cover for each substrate class from the lighthouse-sector image set.

Hard coral cover showed strong spatial variability across photoquadrats, as indicated by the descriptive statistics in Table II (mean ± SD = 15.45 ± 20.59%; range = 0.00–89.00) and the distribution pattern shown in Figure 9. This pattern suggests a patchy occurrence of live coral within the lighthouse sector. Rubble also varied widely among quadrats (Table II, mean ± SD = 57.61 ± 35.26%; range = 0.00–100.00), indicating heterogeneous substrate conditions with localized rubble fields interspersed with consolidated substrate patches. Because this study was designed as a single-site, single-period baseline assessment, descriptive statistics and boxplot-based visualization were considered sufficient to summarize within-transect variability rather than to test inferential hypotheses across multiple spatial or temporal groups.

TABLE II. DESCRIPTIVE STATISTICS OF SUBSTRATE COVER (%) ACROSS PHOTOQUADRATS (n=70).

Substrate class	Mean ± SD (%)	Median (%)	Min–Max (%)
HC	15.45 ± 20.59	6.81	0.00–89.00
SP	5.98 ± 10.80	0.14	0.00–49.00
DCA	3.13 ± 7.78	0.00	0.00–40.00
Rock	17.83 ± 27.66	0.00	0.00–92.00
Rubble	57.61 ± 35.26	66.73	0.00–100.00

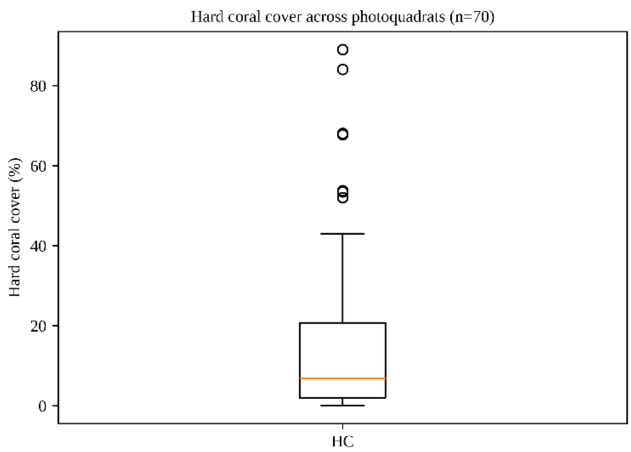

Fig. 9. Boxplot of HC cover (%) across photoquadrats (n = 70).

C. Comparison with Historical/Published Records (2016–2018)

A previous assessment in the lighthouse area reported live coral cover of 57.65% in 2016, with dead coral accounting for 1.45%, whereas the remaining substrate consisted of other biota (23.2%) and abiotic components (17.7%) [13] (Figure 10). In 2018, a barge-grounding incident involving a coal-carrying vessel was reported to have damaged approximately 5,340 m² of reef area near the lighthouse, with extensive coral breakage and rubble accumulation on the seafloor [14]. Taken together, the 2016 record and the reported 2018 grounding provide context for the substantially lower hard-coral cover observed in 2025. However, direct quantitative comparison between the 2016 dataset and the present survey is not appropriate due to differences in survey design, analytical workflow, and substrate classification scheme. Therefore, the earlier information is used here only for contextual and qualitative interpretation.

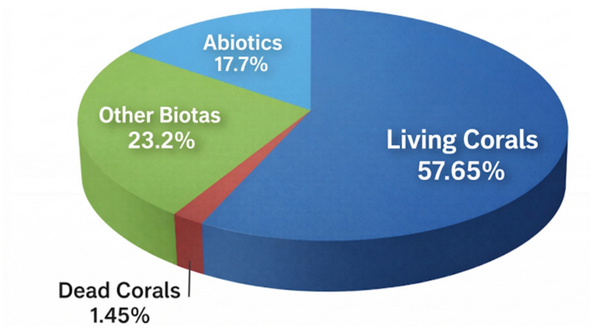

Fig. 10. Coral condition in 2016 at the study area, used for temporal comparison with the present survey.

D. Implications of Disturbance and Recovery Constraints

Ship-grounding impacts have also been documented in other Indonesian reef systems, including the Karimunjawa National Park, where hard coral cover decreased substantially within the impacted area and rubble accumulation was observed [15]. Physical breakage and colony dislodgement can reduce habitat complexity and shift reef surfaces toward unstable rubble fields that constrain coral recruitment and slow recovery [16]. These patterns support the importance of preventive measures, including navigation management, mooring control, and route zoning, for reefs located in industrial and high-traffic coastal zones.

E. Workflow Novelty and Practical Utility

This study demonstrates a practical RoI-based area-quantification workflow in ImageJ for estimating substrate cover from UPT photoquadrats. Compared with point-intercept approaches [3], RoI delineation explicitly captures contiguous substrate patches and mixed-substrate boundaries, thereby improving transparency in classification decisions for heterogeneous reef surfaces. The workflow also produces an auditable record through saved RoI sets and exported measurement tables, supporting re-checking and repeat monitoring. From an applied perspective, this low-cost approach is suitable for industrial and high-activity coastal settings where rubble and disturbance footprints can be spatially patchy.

IV. CONCLUSION

This study demonstrates an integrated UPT–ImageJ workflow for transparent and auditable quantification of reef substrate cover in an industrial coastal setting at the PLTU Paiton Lighthouse. The substrate assemblage was dominated by rubble (57.62%), followed by rock (17.83%), hard coral (15.44%), sponge (5.97%), and dead coral with algae (3.14%). Based on hard-coral cover, the site falls within the Poor/Damaged category under the live-coral cover thresholds applied in this study.

The proposed workflow provides a site-specific baseline for repeat monitoring in high-activity industrial and maritime coastal zones. However, the present assessment is limited by operator-dependent RoI delineation, a single-time survey design, and the absence of concurrent turbidity/TSS measurements. Future work should evaluate inter-analyst repeatability, extend monitoring across time, and integrate supporting environmental measurements to improve comparability and strengthen inference on reef-condition drivers.

DECLARATION OF COMPETING INTERESTS

Not applicable to this work.

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DATA AVAILABILITY

The underwater photo transect image dataset generated and analyzed during the current study is not publicly available due to data management and site-permission considerations, but is available from the corresponding author upon reasonable request.

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