Calculation of coral reef volume using 3D underwater photos on Gili Labak Island, Indonesia

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Abstract. Tourism without proper management will bring in tourists who can have a large impact on the environment and coastal ecosystems. Therefore, this study aims to evaluate the condition of coral reefs using the 3D underwater photo method instead of the widely used 2D. The non-invasive method was used to determine the accurate geometrical measurements of corals using a cost and time-effective approach. This new model was built by comparing the calculation of the volume of coral reefs using Archimedes' principle with 3D photos obtained from multiple stereo images both on land and in water. The result showed that the coral reef volume estimation model has the lowest error with a linear regression equation of $y = 0.4835x + 103.34$, with coefficients of determination (R^2) of 0.9039, root-mean-square error (RMSE) of 269 cm^3, and the percentage of RMSE is 21.5%. The application of estimated coral reefs on Gili Labak Island using a model plot of 50 x 50 cm obtained an average volume of 6,780.7 cm^3 $plot^{-1}$ and 27,122.87 cm3 m^{-1}. In conclusion, the accuracy of the 3D model is highly dependent on the complexity of the coral reef.

Key Words: Agisoft Metashape, regression models, RMSE.

Introduction. The tourism industry pressures the environment and coastal ecosystems, especially in the absence of proper management. This is because the large inflow of tourists can make the environment vulnerable to improper activities, which adversely affects the ecosystem (Kurniawan & Darus 2017). Conservation principles in ecotourism management on Gili Labak Island are presently being ignored because they are concentrated on efforts to attract a large number of tourists (Rahardjanto et al 2019). The condition of coral lifeform closure (Insafitri et al 2020a) abiotic elements, *Acropora* branching, and coral foliose (Insafitri et al 2021) are 74%, 22%, 19.88%, and 10.25%. Therefore, the problem of white band disease and syndrome in coral *Acropora* sp. needs to be considered while evaluating the impact of tourism (Huda et al 2018; Insafitri et al 2020b; Nugraha et al 2019). According to preliminary studies, the widely developed underwater photo method is a 2D model (Sari et al 2021; Satyawan & Artiningrum 2021; Schaduw et al 2020; Sirait et al 2021). Unfortunately, there are numerous shortcomings associated with this method, such as the inadequate volume of coral reefs. Therefore, this study developed a 3D model capable of taking more detailed coral reef photos underwater to map its volume correctly.

Sumenep Regency in East Java Province, consisting of approximately 115 islands, is a significant coral reefs and mangroves region. Sapudi and Gili Labak are two of the most common islands in this regency developed as tourist areas (Muhsoni 2017; Muhsoni & Efendy 2017). The development of Gili Labak Island into a tourist attraction has an economic impact on the community. However, tourism stakeholders, especially the local community, have not been able to manage and utilize its natural resources properly (Supriono 2019). The district government has a role as a motivator and facilitator in developing the Maritime Area (Handayani et al 2021).

Coral reefs are usually found in tropical shallow seas, with rock as its main constituent, and are associated with various other biotas. Underwater Photo Transect (UPT) is a method for mapping coral reef conditions using a digital camera with underwater casing (Nurrahman et al 2020; Sagai et al 2017). However, this method only produces 2D data with its results in percentages (Benjamin et al 2019; Harahap et al 2019; Riskiani & Bahar 2019; Utami et al 2018). Several preliminary studies have evaluated the possible use of 3D underwater photos to analyze archaeological artifacts (Jaklič et al 2015). Calders et al (2020), Fukunaga and Burns (2020), and Price et al (2019) used 3D photographs for coral reef ecosystems, and the results provided structural, quantitative, and detailed information, which adds insight into new information about individual organisms and their relationship to their environment. De Oliveira et al (2021) also carried out 3D reconstruction of coral reefs using the Multiscale Geometrical Classification (MGC), Color and Geometrical Classification (CGC), and Object-Based Image Classification (OBIA) methods.

Kurniawan et al (2019) identified corals using the Reef Identification Knowhow Application-Reconstructed by 3D Imagery (RIKA-R3DI) and modified them using the Underwater Photo Transect (UPT) method. Mizuno et al (2018) developed an interesting array of underwater cameras using ships for ocean monitoring, which excludes the diving process. The underwater vehicles used are AUV, ROV (Remotely Operated Vehicle), and ASV (Autonomous Surface Vehicle). The resulting optical map is an abundance of biological factors, such as the distribution of corals and seagrass beds. Dagum et al (2021) carried out coral mapping using structure-from-motion (SFM) and 3D models of underwater reef images.

Fukunaga et al (2020) explained that measuring the 3D habitat structure of coral reefs is a vital monitoring aspect because it affects the abundance and diversity of the organisms. This photogrammetric technique is used to examine the relationship between benthic cover and various habitat metrics. Urbina-Barreto et al (2021) conducted research on 3D modeling of coral reefs using data obtained from colony level, diameter, planar area, surface, and cross-sectional volume of coral reefs. Burns et al (2019) investigated the 2D estimation of live coral cover associated with the 3D structural complexity of its reef habitats. Meanwhile, Figueira et al (2015) studied the application of remote sensing and photogrammetry for structural mapping from software to make 3D models of coral reefs with complex biophysical properties and structures. Casella et al (2017) used a small drone comprising a camera and GPS to measure the small-scale three-dimensional features of shallow-water coral reefs, which was analyzed using a structure from motion (SfM) algorithm. Hatcher et al (2020) used the SfM Quantitative Underwater Imaging Device with Five Cameras (SQUID-5), a towed surface vehicle comprising a survey-grade Global Navigation Satellite System (GNSS) and five downward-facing cameras with overlapping images.

Material and Method. Underwater photos were taken continuously from both planar and oblique angles to obtain images of the entire colony surface (Figure 1) with an overlap of 70-80% (Burns et al 2015; Bythell & Pan 2001). All images are uploaded to the software, calibrating the camera with focus information derived from its metadata. Once the software aligns the photos using an algorithm capable of detecting overlapping invariant features between successive images, invariant features are developed to determine the geometric position using a camera (Westoby et al 2012). 3D geometry is built on a 2D drawing plan using extrinsic parameters calculated during the photo-alignment process with intrinsic and focal values obtained from the metadata (Stal et al 2012). All GCPs and the location of each marker are manually looked marked, and reviewed to determine the GCP. The x, y, and z values for each GCP are input into the software to optimize image alignment and ensure the resulting model's accurate interior and exterior orientation (Burns et al 2015).

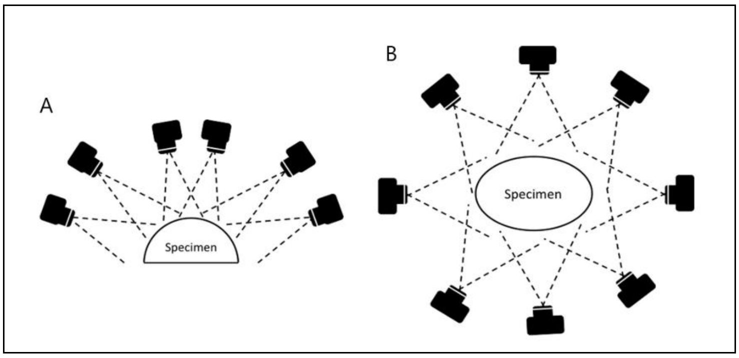

Figure 1. Camera settings to capture all directions and angles of the model (Ahmad et al 2020; House et al 2018; Westoby et al 2012).

Furthermore, the coral photos are analyzed using Agrisoft Metashape Professional software. The analysis steps include (i) estimating the image quality of underwater photos as a function of sharpness, exposure, focus, resolution, and field depth of the image, and (ii) syncing the camera and Building Dense Cloud with the software. Others include (iii) using a scale, (iv) constructing a dense point cloud with depth information for each camera and a densification algorithm, and (v) constructing 3D nets. The Build Texture (optional) step is not required to perform 3D measurement and analysis. All models are oriented by planar projections using orthographic views, then isolated and edited with Agisoft Metashape. The model is, furthermore, exported for quantitative analysis and volume calculation (de Oliveira et al 2021; Kabiri et al 2020). Land and sea pictures of each coral reef object are carried out twice for comparison and calculated using the Archimedes principle to obtain the volume of irregular objects (Abdullah et al 2014; Carter & Gregorich 2006; Siswantoro et al 2013), using the following formula:

$$V_{sample} = V_{water} = \frac{M_{sample\,(air)} - M_{sample(water)}}{\rho_{water}} = \frac{M_{water}}{\rho_{water}}$$

where: V_{water} is the water volume displaced by the sample, M_{water} is the water mass displaced by the sample, $M_{sample(water)}$ is the mass of the sample measured in air, $M_{sample(water)}$ is the mass of the sample measured in water, and water is the water density at ambient temperature (freshwater 1 g cm^{-3}) (Carter & Gregorich 2006).

The 3D photos and Archimedes principle are linked to obtaining the most suitable model for coral volume estimation using a regression model approach. The volume is then tested for accuracy using root-mean-square error (RMSE) (Hatcher et al 2020). Furthermore, the model is tested on Gili Labak Island with the 3D Coral Photogrammetry (CP) photo method carried out by SCUBA diving using an underwater camera (Ahmad et al 2020).

Results. 3D photos on the entire surface of 11 coral samples are taken underwater and on land for comparison (Fukunaga et al 2020). The average number of photos in each coral sample is 75-82 images. Furthermore, the photos are analyzed using the Agisoft Metashape software (de Oliveira et al 2021; Kabiri et al 2020), and the results are shown in Figure 2.

The photos are analyzed in 3D with Agisoft Metashape 1.7.4 software, which is used to obtain the RMSE control point value. The results showed that the average RMSE for underwater is 75 photos, with average X, Y, Z, XY and total errors of 0.3741 mm, 0.3464 mm, 0.2281 mm, 0.5234 mm, and 0.5873 mm. Meanwhile, for photos on land with an average photo of 82, the average X, Y, Z, XY, and total errors are 0.1737 mm, 0.4399 mm, 0.1499 mm, 0.4782 mm, and 0.5109. mm. The error value for 3D photos is less than 1 mm, but the error for 3D photos taken on land is smaller than for underwater photos. This difference is due to the influence of water which can distort the camera.

Table 1 shows the results of calculating coral volume using the Archimedes principle and coral volume from 3D photos for photos in the water and photos on land.

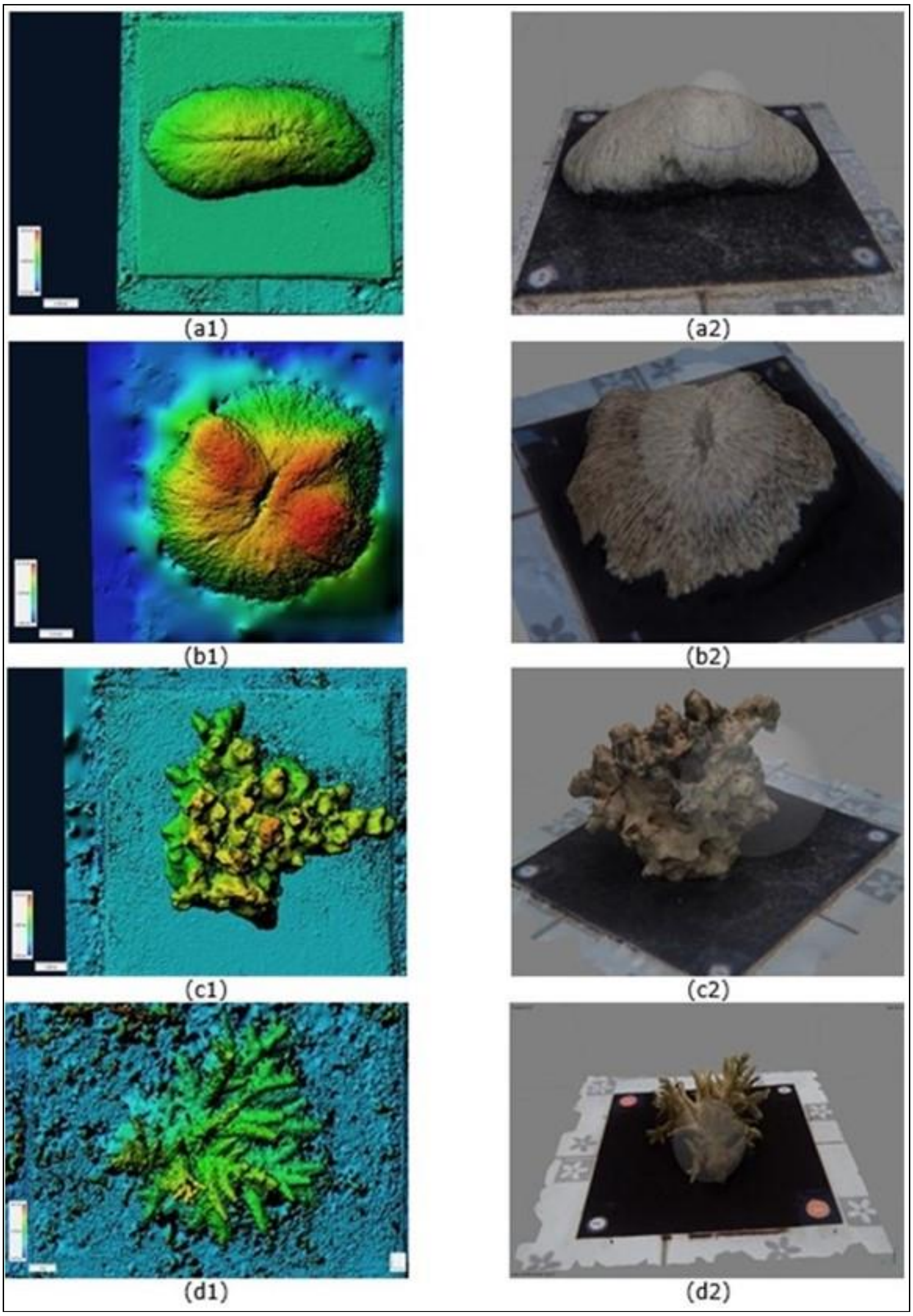

Figure 2. Analysis results of 3D coral reef photos using Agisoft Metashape software; (a1), (b1), (c1), (d1) DEM image analysis results; (a2), (b2), (c2), (d2) 3D image analysis result.

The coral colony orientation used to calculate volume is based on its orthographic projections. In contrast, growth orientation depends on environmental characteristics, such as habitat complexity, slope, light, and plane, thereby encouraging possible bias in estimation (Urbina-Barreto et al 2021). The 3D photo analysis using Agisoft Metashape software cannot be directly considered using the coral reefs volume. This is due to the complex shape, concave bottom with small cavities in their structure. It is usually invisible and legible to calculate the volume of the 3D photo model. Therefore, a conversion is needed to minimize errors conducted using a regression approach. Urbina-Barreto et al (2021) regression models have high accuracy for predicting the volume of 3D from 2D metrics. The results of linear and non-linear regression are shown in Table 2.

Table 1

Coral volume using Archimedes principle and 3D photo analysis volume

Coral number	*Volume measurement using Archimedes principle (cm^3) average*	*3D photo volume in water (cm^3)**	*3D photo volume on land (cm^3)**
1	512.7	1041.0	1271.0
2	923.3	1157.0	1873.0
3	633.3	944	1222.0
4	693.3	1443.0	2370.0
5	1583.3	3369.0	3358.0
6	955.2	1423.0	1317.0
7	1234.8	2117.0	2498.0
8	105.8	313.0	297.0
9	493.9	694.0	770.0
10	158.8	355.0	375.0
11	352.8	609.0	525.0

Note: * 3D volume analysis results using Agisoft Metashape software.

Table 2

Coral volume modeling using linear and non-linear regression, for coral volume using the Archimedes principle (y) with coral volume calculated using 3D photos (x) (3D photos in water and 3D photos on land)

Description	*3D photo in water*	*3D photo on land*
Linear	$y = 0.4835x + 103.34$ $R^2 = 0.9039$, RMSE =269 cm^3, N=20, %RMSE=21.5%	$y = 0.4023x + 78.067$ $R^2 = 0.8035$, RMSE =172.8 cm^3 N=11, %RMSE=24.9%
Logarithmic	$y = 603.19\ln(x) - 3458$ $R^2 = 0.9176$, RMSE =324.3 cm^3, N=20, %RMSE=25.9%	$y = 474.1\ln(x) - 2670.4$ $R^2 = 0.7455$, RMSE =200.5 cm^3, N=11, %RMSE=28.8%
Polynomial	$y = -0.0001x^2 + 0.8487x - 117.25$ $R^2 = 0.9446$, RMSE =361.9 cm^3, N=20, %RMSE=28.9%	$y = 2E\text{-}05x^2 + 0.3246x + 123.38$ $R^2 = 0.8057$, RMSE =277.4 cm^3, N=11, %RMSE=39.9%
Power/ geometric	$y = 0.2556x^{1.1119}$ $R^2 = 0.9186$, RMSE =324.3 cm^3, N=20, %RMSE=25.9%	$y = 0.7002x^{0.9398}$ $R^2 = 0.8703$, RMSE =173.8 cm^3, N=11, %RMSE=25.0%

Table 2 shows that the 3D volume with the highest accuracy for photos in the water is a linear regression model, with the equation $y = 0.4835x + 103.34$, with R^2, RMSE, and % RMSE values of 0.9039, 269 cm^3, and 21.5%. Meanwhile, the 3D photos on land is a linear regression model, with the equation $y = 0.4023x + 78.067$, with R^2, RMSE and % RMSE values of 0.8035, 172.8 cm^3, and 24.9%. Urbina-Barreto et al (2021) used a linear model with high accuracy to predict 3D volume metrics from 2D to obtain an R^2 of 0.96. This result is still compared to the study of Figueira et al (2015), who obtained a metric of 10% in surface rugosity.

3D coral reef data collection on Gili Labak Island. The photo shot on Gili Labak Island was taken by diving using a 50x50 cm or 2500 cm^2 plot. The results were analyzed to obtain coral volume data using Agisft Metashape 1.7.4 software, as shown in Figure 3.

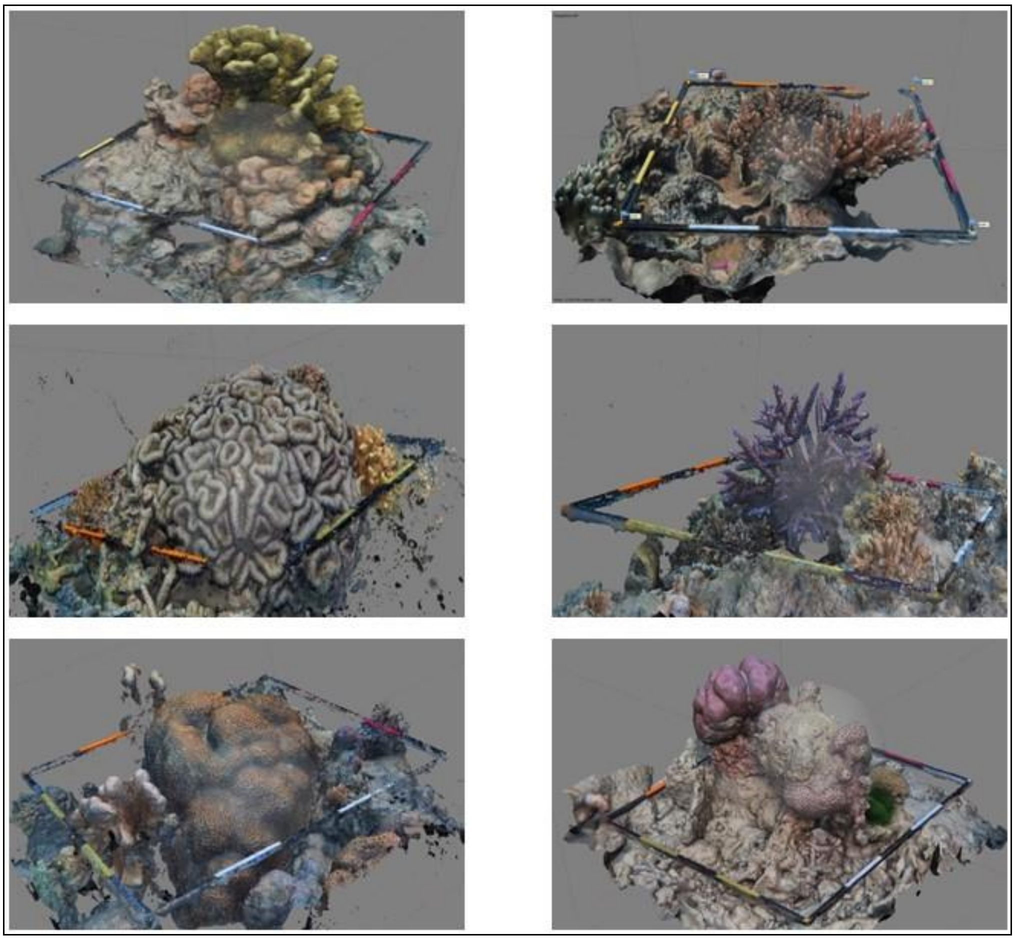

Figure 3. Results of 3D photo analysis of coral reefs on Gili Labak Island.

Table 3
Volume of 3D photos produced by Agisoft software and volume of coral conversion using a linear regression model

No	*The volume of 3D Photo analysis by Agisoft (cm^3)*	*Coral volume estimation using linear regression model (cm^3)*
1	32,719.0	15,923.0
2	13,727.0	6,740.3
3	5,228.0	2,631.1
4	4,992.0	2,517.0
5	34,433.0	16,751.7
6	3,103.0	1,603.6
7	21,831.0	10,658.6
8	3,060.0	1,582.9
9	25,551.0	12,457.2
10	2,052.0	1,095.5
11	7,389.0	3,675.9
12	11,641.0	5,731.8
	Mean	6,780.7
	Sum	81,368.6

The volume of coral reefs on Gili Labak Island is obtained by converting the 3D photos using a linear regression equation model $y = 0.4835x + 103.34$, $R^2 = 0.9039$. The average volume of the coral is 6,780.7 cm^3 $plot^{-1}$, while a total volume of 81,368.6 cm^3 was obtained for 12 plots (Table 3). The average volume of coral in one square meter is 27122.87 cm^3.

Discussion. One of the fundamental steps in estimating the potential of ecosystems to support biodiversity is measuring coral colonies in reef landscapes (Urbina-Barreto et al 2021). Coral reef monitoring methods mainly rely on 1D or 2D coral cover while ignoring the changing ecological aspects of the reef, as it does not include vertical or volumetric information (House et al 2018). This study looks for relationships between 2D and 3D metrics of coral size with the surface area and volume scales consistent with the plane area. The photogrammetric approach uses software to estimate the ability of photogrammetry to estimate coral measurements in 3D. The development of photogrammetric technology is a valid and practical technique for studying coral reefs (House et al 2018).

It is essential to assess the accuracy and precision of photogrammetric measurements to support their application in mapping, monitoring, and quantifying the shape and structure of coral reefs. Furthermore, this study evaluated the precision and accuracy of the geometry and structural complexity derived from 3D photogrammetric models of marine benthic habitats (Figueira et al 2015). Coral 3D measurement is an accurate quantitative study of the physiology of coral colonies of various sizes in situ. This technique can also be used for morphometric measurements such as branch distance, density, length, and species angle. The 3D approach accurately measures architectural complexity, topography, rugosity, volume, and other structural characteristics that play an essential role in ecosystems (Burns et al 2015).

The field of coral reef ecology has recognized complexity as an essential component of ecosystem diversity and productivity (Dustan et al 2013). According to Burns et al (2016), 3D reconstruction techniques create high-resolution models of coral reef habitats affected by biodiversity and the abundance of associated reef organisms. Complex corals cannot be adequately modeled with this technique due to the difficulty of obtaining complete photographs of all surfaces. This technique is a non-invasive way to obtain accurate geometric measurements of underwater corals and other irregular objects (Bythell & Pan 2001). This result also showed that the RMSE value is 25.9%, which is in the not very good category, with a relative RMSE of 0.013% (Hatcher et al 2020).

Methods for obtaining accurate 3D measurements of coral surfaces are limited to techniques using complex, bulky, and expensive equipment, highlighting the clear need for non-invasive methods (Bythell & Pan 2001). This study showed that the survey method using inexpensive action cameras for 3D coral photogrammetry provides suitable results in coral life formations. Hypothetically, increasing the camera quality will produce higher accuracy. Ahmad et al (2020) research on 3D coral surveys used remotely operated vehicles with less field time and seafloor information. Moreover, this research provided a cost-effective and time-effective approach to reconstructing coral colonies and measuring complex 3D features associated with their morphology (Burns et al 2015).

Conclusions. In conclusion, the coral reef volume estimation model with the lowest error used a linear regression approach and was determined using the equation $y = 0.4835x + 103.34$, with R^2, RMSE, and % RMSE values of 0.9039, 269 cm^3, and 21.5%. The application of this method on the coral reefs of Gili Labak Island used a plot of 50 x 50 cm with an average, minimum, and maximum coral volume of 6,780.7 cm^3/plot, 1,095.5 cm^3/plot, and 16,751.7 cm^3/plot. The total coral volume for the 12 plots is 81,368.6 cm^3, hence it is average. The average volume of coral in one square meter is 27122.87 cm^3. Therefore, this method is a non-invasive way to obtain accurate coral geometric measurements with a cost-effective and time-saving approach. Accuracy is highly dependent on the complexity of the coral reef due to the difficulty of obtaining complete photos of all surfaces.

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Conflict of interest. The authors declare that there is no conflict of interest.

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