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Thermal Stress, Depth Refugia, and Herbivorous Fish Biomass as Drivers of Post-Bleaching Coral Recovery in Raja Ampat, Indonesia

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ABSTRACT

Coral reef recovery following bleaching disturbances is influenced by environmental pressures, habitat characteristics, and biological interactions. This study aims to examine the individual and simultaneous relationships between thermal stress, depth refugia, herbivorous fish biomass, and post-bleaching coral recovery in Raja Ampat, Indonesia. A quantitative explanatory approach was employed involving 65 respondents selected through purposive sampling. Data were collected using a structured five-point Likert-scale questionnaire and analyzed through multiple linear regression using SPSS version 25. The results demonstrate that thermal stress has a negative and statistically significant relationship with coral recovery ($\beta = -0.521$, $p < 0.001$), while depth refugia ($\beta = 0.329$, $p < 0.001$) and herbivorous fish biomass ($\beta = 0.323$, $p = 0.001$) exhibit positive and significant relationships. The simultaneous regression model is statistically significant ($F = 22.502$, $p < 0.001$), with an R^2 value of 0.525, indicating that the three independent variables collectively explain 52.5% of the variation in coral recovery assessments. Thermal stress demonstrates the strongest statistical association among the examined predictors. These findings highlight the importance of integrating thermal disturbance monitoring, habitat protection, and herbivorous fish conservation into coral reef management strategies. The study contributes to understanding ecological resilience in Raja Ampat, although its questionnaire-based design limits conclusions to assessed ecological conditions rather than direct biophysical relationships.

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INTRODUCTION

Coral reef ecosystems are among the most biologically diverse and productive marine environments, supporting biodiversity, fisheries, tourism, and essential ecosystem services. However, increasing marine heatwaves threaten their sustainability by triggering coral bleaching,

physiological stress, and mortality. Yao and Wang (2026) documented exceptional thermal disturbances across global coral reef regions during 2024, highlighting the growing vulnerability of tropical reefs. Post-bleaching coral recovery involves tissue regeneration, restoration of symbiotic relationships, coral recruitment, and recovery of live coral cover. Morais et al. (2024) demonstrated that favorable recruitment and growth conditions can accelerate coral recovery, while Graham et al. (2024) identified contrasting recovery trajectories following repeated bleaching events. These findings suggest that coral recovery depends on environmental pressures, habitat characteristics, and ecological interactions rather than thermal disturbances alone.

Thermal stress is a major environmental factor influencing coral bleaching severity and recovery. Prolonged exposure to elevated temperatures disrupts coral physiology, reduces photosynthetic efficiency, and limits regeneration. Yao and Wang (2026) emphasized that persistent marine heatwaves reduce recovery intervals between bleaching events, while Kopecky et al. (2024) demonstrated that bleaching-related mortality produces structural changes that impair herbivory and coral recruitment. Nevertheless, coral responses vary across habitats because of differences in depth, irradiance, and oceanographic conditions. Depth refugia may provide relatively favorable environments supporting coral survival during thermal disturbances. However, Diaz et al. (2023) reported that mesophotic coral ecosystems remain vulnerable to bleaching associated with thermocline fluctuations, while Eyal et al. (2022) documented substantial bleaching in deep-water coral communities. These findings indicate that depth-related protection is conditional and requires investigation alongside thermal exposure.

Biological interactions also contribute significantly to coral reef recovery, particularly through herbivorous fish communities that regulate algal growth and maintain suitable conditions for coral recruitment. Following bleaching-induced mortality, excessive algal colonization can restrict coral regeneration and prolong ecosystem degradation. Graham et al. (2024) demonstrated that herbivorous fish biomass and functional composition are associated with reef resilience and recovery trajectories. However, Kopecky et al. (2024) found that dead coral skeletons can restrict grazing activities, reducing the ecological effectiveness of herbivorous fishes. Consequently, coral recovery reflects interconnected environmental and biological processes. Evidence from Diaz et al. (2023), Graham et al. (2024), and Kopecky et al. (2024) suggests that thermal exposure, habitat protection, and herbivory collectively contribute to reef resilience, emphasizing the importance of examining these variables within an integrated analytical framework.

Raja Ampat, Indonesia, represents an important setting for investigating post-bleaching coral recovery because of its exceptional marine biodiversity and heterogeneous reef environments. Despite its ecological significance, the region remains vulnerable to climate-driven bleaching disturbances. Ampou et al. (2026) reported severe bleaching among Pachyseris speciosa populations at Yenbuba, with more than 70% of assessed colonies affected in December 2024. Follow-up observations in November 2025 indicated substantial recovery, with bleaching prevalence declining to below 20%. Nevertheless, the ecological mechanisms underlying these recovery patterns remain uncertain. Previous studies have generally examined thermal stress, depth refugia, and herbivory separately, limiting understanding of their relative contributions within specific reef ecosystems. Furthermore, findings from other tropical regions cannot necessarily be generalized to Raja Ampat. Ampou et al. (2026) highlighted uncertainties concerning local recovery mechanisms, while Diaz et al. (2023) emphasized the dependence of depth-related protection on local environmental conditions. These limitations establish the need for an integrated investigation of environmental and biological factors associated with coral recovery in Raja Ampat.

This study aims to examine the individual and simultaneous relationships between thermal stress, depth refugia, herbivorous fish biomass, and post-bleaching coral recovery in Raja Ampat, Indonesia. Specifically, the study investigates the expected negative relationship between thermal stress and coral recovery, alongside the anticipated positive relationships involving depth refugia and herbivorous fish biomass. The study contributes to existing literature by integrating environmental disturbance, habitat-mediated protection, and biological regulation within a unified quantitative framework. Although the questionnaire-based design measures assessed ecological conditions rather than direct biophysical parameters, the findings are expected to provide contextual evidence supporting coral reef conservation, habitat protection, and sustainable marine ecosystem management in Raja Ampat.

LITERATURE REVIEW

2.1 Post-Bleaching Coral Recovery

Post-bleaching coral recovery refers to the ecological and physiological processes through which coral communities restore their structural integrity, biological functions, and population stability following thermal disturbances. Recovery involves the restoration of symbiotic relationships, tissue regeneration, coral recruitment, and increases in live coral cover. Morais et al. (2024) demonstrated that favorable habitat conditions and coral recruitment accelerate natural recovery, while Graham et al. (2024) emphasized that ecological resilience and biological interactions influence recovery trajectories following repeated bleaching events. In Raja Ampat, Ampou et al. (2026) documented substantial recovery of Pachyseris speciosa populations following the 2024 bleaching event, although recovery varied among coral taxa. Accordingly, this study evaluates post-bleaching coral recovery through indicators of coral health improvement, tissue regeneration, recruitment conditions, restoration of live coral cover, and overall reef recovery capacity.

2.2 Thermal Stress

Thermal stress refers to physiological and ecological pressure caused by elevated seawater temperatures, prolonged marine heatwaves, and recurrent thermal anomalies that disrupt coral symbiosis, increase bleaching severity, and reduce recovery capacity. Its effects depend on the intensity, duration, and frequency of thermal exposure, as well as coral physiological characteristics and environmental conditions. Graham et al. (2024) demonstrated that repeated marine heatwaves influence coral recovery trajectories and community stability, while Kopecky et al. (2024) highlighted that bleaching-related coral mortality creates structural changes that restrict herbivory and coral recruitment. Consequently, thermal stress affects both immediate coral survival and long-term reef regeneration. In this study, thermal stress is assessed through indicators of temperature intensity, disturbance frequency, exposure duration, bleaching severity, and persistent thermal pressure, with higher scores indicating greater environmental stress and potentially lower post-bleaching coral recovery.

2.3 Depth Refugia

Depth refugia refer to deeper reef habitats that may protect coral communities from thermal disturbances through reduced solar irradiance, temperature variability, and favorable oceanographic conditions. However, their protective effectiveness depends on local environmental characteristics and coral physiological tolerance. Diaz et al. (2023) demonstrated that mesophotic corals remain vulnerable to bleaching caused by thermocline fluctuations, while Eyal et al. (2022) highlighted that depth-related isolation does not consistently prevent thermal stress. In Raja Ampat, Ampou et al. (2026) documented substantial coral recovery at depths of approximately 20–30 meters

following the 2024 bleaching event, suggesting the potential importance of depth-associated habitats. Accordingly, this study evaluates depth refugia through indicators of protective habitat availability, environmental stability, reduced disturbance exposure, habitat suitability, and coral persistence, with higher scores representing more favorable conditions for post-bleaching recovery.

2.4 Herbivorous Fish Biomass

Herbivorous fish biomass refers to the total mass of herbivorous fishes within a reef area, reflecting their ecological role in controlling algal growth and maintaining suitable conditions for coral recruitment. Graham et al. (2024) demonstrated that herbivory contributes to reef resilience by reducing macroalgal dominance and supporting coral recovery. However, Kopecky et al. (2024) highlighted that dead coral skeletons can restrict grazing activities, limiting the ecological effectiveness of herbivorous fishes. Consequently, coral recovery depends on fish abundance, functional composition, and habitat conditions. In this study, herbivorous fish biomass is assessed through indicators of relative abundance, grazing adequacy, population stability, algal regulation, and ecological contribution, with higher scores representing more favorable conditions for post-bleaching coral recovery.

2.5 The Relationship Between Thermal Stress and Post-Bleaching Coral Recovery

Thermal stress is expected to have a negative relationship with post-bleaching coral recovery because prolonged exposure to elevated seawater temperatures reduces photosynthetic efficiency, increases tissue damage, and limits coral growth and regeneration. Graham et al. (2024) demonstrated that repeated marine heatwaves influence coral recovery trajectories depending on disturbance severity and community resilience, while Kopecky et al. (2024) highlighted that bleaching-related mortality creates structural changes that hinder subsequent recovery processes. These findings indicate that thermal stress affects coral recovery through both immediate physiological damage and long-term ecological disturbances. Consequently, greater thermal stress is expected to reduce coral recovery capacity. Therefore, the first hypothesis is formulated as follows.

H1: Thermal stress has a negative and statistically significant relationship with post-bleaching coral recovery in Raja Ampat, Indonesia.

2.6 The Relationship Between Depth Refugia and Post-Bleaching Coral Recovery

Depth refugia are expected to have a positive relationship with post-bleaching coral recovery by providing favorable environmental conditions that reduce thermal exposure and support coral survival, reproduction, and recruitment. However, Diaz et al. (2023) demonstrated that thermocline fluctuations can cause bleaching in mesophotic coral ecosystems, while Eyal et al. (2022) highlighted that deeper habitats do not consistently provide protection against thermal disturbances. These findings indicate that the effectiveness of depth refugia depends on local oceanographic conditions, coral characteristics, and thermal exposure. In Raja Ampat, favorable depth-associated habitats may enhance coral persistence and regeneration, suggesting a positive association between depth refugia and post-bleaching coral recovery. Therefore, the second hypothesis is formulated as follows.

H2: Depth refugia have a positive and statistically significant relationship with post-bleaching coral recovery in Raja Ampat, Indonesia.

2.7 The Relationship Between Herbivorous Fish Biomass and Post-Bleaching Coral Recovery

Herbivorous fish biomass is expected to have a positive relationship with post-bleaching coral recovery because herbivorous fishes regulate algal growth and maintain suitable substrate conditions for coral recruitment and regeneration. Graham et al. (2024) demonstrated that increased herbivory contributes to favorable reef recovery trajectories by reducing macroalgal dominance.

However, Kopecky et al. (2024) highlighted that dead coral skeletons can restrict grazing activities, indicating that herbivory effectiveness depends on habitat conditions and fish community characteristics. These findings suggest that greater herbivorous fish biomass may enhance coral recovery by supporting algal regulation and ecological resilience. Therefore, the third hypothesis is formulated as follows.

H3: Herbivorous fish biomass has a positive and statistically significant relationship with post-bleaching coral recovery in Raja Ampat, Indonesia.

2.8 The Simultaneous Relationship of Thermal Stress, Depth Refugia, and Herbivorous Fish Biomass with Post-Bleaching Coral Recovery

Post-bleaching coral recovery is influenced by interconnected environmental and biological factors, including thermal stress, depth refugia, and herbivorous fish biomass. Thermal stress may reduce coral survival and regeneration, while depth refugia can provide protective habitats, and herbivorous fishes support recovery by regulating algal growth. Graham et al. (2024) emphasized that reef resilience depends on multiple ecological processes, while Diaz et al. (2023) and Kopecky et al. (2024) highlighted the importance of environmental variability and biological interactions in shaping recovery outcomes. Accordingly, this study employs multiple linear regression to examine the simultaneous statistical associations of these three variables with post-bleaching coral recovery, without assuming direct causality. Therefore, the fourth hypothesis is formulated as follows.

H4: Thermal stress, depth refugia, and herbivorous fish biomass simultaneously have a statistically significant relationship with post-bleaching coral recovery in Raja Ampat, Indonesia.

METHODS

This study employs a quantitative approach with an explanatory research design to examine the relationships between thermal stress, depth refugia, herbivorous fish biomass, and post-bleaching coral recovery in Raja Ampat, Southwest Papua, Indonesia. A cross-sectional survey design is adopted to obtain standardized assessments of environmental and biological conditions associated with coral reef recovery. The study involves 65 respondents selected through purposive sampling based on their knowledge and experience in coral reef monitoring, marine conservation, fisheries, or related ecological activities. The research framework comprises three independent variables, namely thermal stress (X_1), depth refugia (X_2), and herbivorous fish biomass (X_3), and one dependent variable, post-bleaching coral recovery (Y). This approach evaluates statistical associations among respondents' assessments rather than establishing direct ecological causality.

Primary data are collected using a structured questionnaire consisting of 20 measurement items, with five indicators representing each research variable. A five-point Likert scale is employed, ranging from 1 (strongly disagree) to 5 (strongly agree). Thermal stress is measured through temperature intensity, disturbance frequency, exposure duration, bleaching severity, and persistent thermal pressure. Depth refugia are assessed through protective habitat availability, environmental stability, reduced disturbance exposure, habitat suitability, and coral persistence. Herbivorous fish biomass is evaluated through relative abundance, grazing adequacy, population stability, algal regulation, and ecological contribution, while coral recovery is measured through coral health improvement, tissue regeneration, recruitment conditions, live coral cover restoration, and overall recovery capacity. Composite scores are calculated by averaging valid responses for each construct. Instrument validity is evaluated using corrected item–total correlations with a minimum criterion of 0.30, while reliability is assessed using Cronbach's alpha with a threshold of 0.70. Secondary data

from scientific publications and relevant marine conservation literature support the theoretical framework.

Data analysis is conducted using IBM SPSS Statistics version 25, incorporating descriptive statistics, instrument validity and reliability tests, classical assumption testing, multiple linear regression, and hypothesis testing. Descriptive analysis summarizes the mean, standard deviation, minimum, and maximum values of each variable. Regression assumptions are evaluated through the Shapiro–Wilk normality test, variance inflation factor (VIF) and tolerance for multicollinearity, the Glejser test for heteroscedasticity, and residual diagnostics for linearity. Multiple linear regression examines the individual and simultaneous associations between the independent variables and coral recovery using the model $Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \varepsilon$. Partial relationships are evaluated using t-tests, while simultaneous significance is assessed through the F-test at a 5% significance level ($p < 0.05$). The coefficient of determination (R^2) and adjusted R^2 are used to assess explanatory performance, supported by regression coefficients and confidence intervals. All findings are interpreted within the limitations of purposive sampling, questionnaire-based measurements, and the cross-sectional research design.

RESULTS AND DISCUSSION

4.1 Descriptive Statistical Analysis

Descriptive statistical analysis provides an overview of the distributions of thermal stress, depth refugia, herbivorous fish biomass, and post-bleaching coral recovery.

Table 1. Descriptive Statistics of Research Variables

Variable	N	Minimum	Maximum	Mean	Std. Deviation
Thermal Stress (X_1)	65	1.00	5.00	3.098	0.858
Depth Refugia (X_2)	65	1.00	5.00	2.957	0.830
Herbivorous Fish Biomass (X_3)	65	1.40	4.80	3.028	0.667
Post-Bleaching Coral Recovery (Y)	65	1.00	5.00	3.031	0.860

Table 1 presents the descriptive statistics of 65 respondents across four research variables. Thermal stress (X_1) recorded the highest mean score of 3.098 (SD = 0.858), followed by post-bleaching coral recovery (Y) with a mean of 3.031 (SD = 0.860), herbivorous fish biomass (X_3) at 3.028 (SD = 0.667), and depth refugia (X_2) at 2.957 (SD = 0.830). The minimum and maximum scores ranged from 1.00 to 5.00 for thermal stress, depth refugia, and coral recovery, while herbivorous fish biomass ranged from 1.40 to 4.80. These findings indicate that respondents generally reported moderate levels of environmental stress, habitat protection, herbivorous fish conditions, and coral recovery. Herbivorous fish biomass exhibited the lowest variability, suggesting relatively consistent assessments among respondents, whereas coral recovery showed the greatest variation.

4.2 Instrument Validity and Reliability

Instrument validity and reliability are assessed using 20 questionnaire items representing four research variables, with five indicators each. Corrected item–total correlations evaluate item validity, while Cronbach's alpha measures internal consistency.

Table 2. Corrected Item–Total Correlation Results

Variable	Item	Corrected Item–Total Correlation	Criterion	Decision
Thermal Stress	TS1	0.802	0.30	Acceptable
	TS2	0.863	0.30	Acceptable
	TS3	0.787	0.30	Acceptable
	TS4	0.815	0.30	Acceptable
	TS5	0.808	0.30	Acceptable
Depth Refugia	DR1	0.780	0.30	Acceptable
	DR2	0.846	0.30	Acceptable
	DR3	0.761	0.30	Acceptable
	DR4	0.806	0.30	Acceptable
	DR5	0.815	0.30	Acceptable
Herbivorous Fish Biomass	HF1	0.675	0.30	Acceptable
	HF2	0.736	0.30	Acceptable
	HF3	0.753	0.30	Acceptable
	HF4	0.722	0.30	Acceptable
	HF5	0.772	0.30	Acceptable
Post-Bleaching Coral Recovery	CR1	0.833	0.30	Acceptable
	CR2	0.850	0.30	Acceptable
	CR3	0.793	0.30	Acceptable
	CR4	0.793	0.30	Acceptable
	CR5	0.844	0.30	Acceptable

Table 2 presents the corrected item–total correlation results for 20 questionnaire items across four research variables. All items exceeded the minimum validity criterion of 0.30, with correlation values ranging from 0.787 to 0.863 for thermal stress, 0.761 to 0.846 for depth refugia, 0.675 to 0.772 for herbivorous fish biomass, and 0.793 to 0.850 for post-bleaching coral recovery. These findings indicate that all measurement items demonstrate acceptable item discrimination and can be retained for subsequent reliability testing and statistical analysis.

Table 3. Reliability Test Results

Variable	Number of Items	Cronbach's Alpha	Criterion	Interpretation
Thermal Stress	5	0.929	0.70	Acceptable
Depth Refugia	5	0.923	0.70	Acceptable
Herbivorous Fish Biomass	5	0.889	0.70	Acceptable

Post-Bleaching Coral Recovery	5	0.932	0.70	Acceptable

Table 3 presents the reliability test results for four research variables, each consisting of five measurement items. Cronbach's alpha values were 0.929 for thermal stress, 0.923 for depth refugia, 0.889 for herbivorous fish biomass, and 0.932 for post-bleaching coral recovery. All coefficients exceeded the minimum criterion of 0.70, indicating high internal consistency and acceptable reliability across all constructs. Therefore, the measurement instruments are considered reliable and suitable for subsequent statistical analysis.

4.3 Classical Assumption Tests

4.3.1 Normality Test

The normality test was conducted using the Shapiro–Wilk test on unstandardized regression residuals from 65 observations. The results showed a Shapiro–Wilk statistic of 0.977 with a significance value of 0.278 ($p > 0.05$), indicating no statistically significant deviation from normality. Therefore, the residuals satisfy the normality assumption required for multiple linear regression analysis.

4.3.2 Multicollinearity Test

Multicollinearity testing examines whether the independent variables exhibit excessive linear relationships that could undermine the stability and interpretation of the regression coefficients.

Table 4. Multicollinearity Test Results

Independent Variable	Tolerance	VIF	Interpretation
Thermal Stress (X_1)	0.893	1.120	No concerning multicollinearity
Depth Refugia (X_2)	0.977	1.024	No concerning multicollinearity
Herbivorous Fish Biomass (X_3)	0.912	1.096	No concerning multicollinearity

Table 4 presents the multicollinearity test results for the three independent variables. Thermal stress (X_1) recorded a tolerance value of 0.893 and VIF of 1.120, depth refugia (X_2) showed a tolerance of 0.977 and VIF of 1.024, while herbivorous fish biomass (X_3) obtained a tolerance of 0.912 and VIF of 1.096. All tolerance values exceeded 0.10, and VIF values remained below 10, indicating no concerning multicollinearity among the independent variables. Therefore, the regression model satisfies the multicollinearity assumption.

4.3.3 Heteroscedasticity Test

The heteroscedasticity assessment employs the Glejser test, in which the absolute regression residuals are regressed on the independent variables.

Table 5. Glejser Heteroscedasticity Test

Independent Variable	Sig.	Interpretation
Thermal Stress (X_1)	0.433	No significant indication
Depth Refugia (X_2)	0.186	No significant indication
Herbivorous Fish Biomass (X_3)	0.225	No significant indication

Table 5 presents the Glejser heteroscedasticity test results for the three independent variables. Thermal stress (X_1) recorded a significance value of 0.433, depth refugia (X_2) obtained 0.186, and herbivorous fish biomass (X_3) showed 0.225. All significance values exceeded the 0.05

threshold, indicating no statistically significant evidence of heteroscedasticity. Therefore, the regression model satisfies the homoscedasticity assumption and is suitable for further statistical analysis.

4.4 Multiple Linear Regression Analysis

The regression model simultaneously includes the three independent variables, allowing each estimated coefficient to be interpreted while holding the other predictors constant.

Table 6. Multiple Linear Regression Coefficients

Predictor	B	Std. Error	Beta	t	Sig.
Constant	2.381	0.574	—	4.146	<0.001
Thermal Stress (X_1)	−0.523	0.094	−0.521	−5.583	<0.001
Depth Refugia (X_2)	0.341	0.093	0.329	3.682	<0.001
Herbivorous Fish Biomass (X_3)	0.417	0.119	0.323	3.497	0.001

Table 6 presents the multiple linear regression results, indicating that all three independent variables have statistically significant relationships with post-bleaching coral recovery. Thermal stress (X_1) exhibits a negative relationship ($B = -0.523$, $\beta = -0.521$, $t = -5.583$, $p < 0.001$), while depth refugia (X_2) demonstrates a positive relationship ($B = 0.341$, $\beta = 0.329$, $t = 3.682$, $p < 0.001$). Herbivorous fish biomass (X_3) also shows a significant positive relationship ($B = 0.417$, $\beta = 0.323$, $t = 3.497$, $p = 0.001$). The regression constant is 2.381, resulting in the equation $Y = 2.381 - 0.523X_1 + 0.341X_2 + 0.417X_3$. Based on the standardized coefficients, thermal stress has the strongest association with coral recovery, followed by depth refugia and herbivorous fish biomass. These findings support the proposed directions of all three relationships.

4.5 Coefficient of Determination

The model summary results indicate a multiple correlation coefficient (R) of 0.725, suggesting a strong relationship between the independent variables and post-bleaching coral recovery. The R Square value of 0.525 indicates that thermal stress, depth refugia, and herbivorous fish biomass collectively explain 52.5% of the variation in coral recovery, while the remaining 47.5% is associated with factors outside the model and unexplained variability. The adjusted R Square of 0.502 confirms that the model explains approximately 50.2% of the variance after accounting for the number of predictors, while the standard error of the estimate of 0.607 reflects the model's prediction accuracy. These findings indicate that the regression model demonstrates moderate explanatory performance in assessing post-bleaching coral recovery.

4.6 Simultaneous Hypothesis Testing (F-Test)

Table 7. Analysis of Variance (ANOVA)

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	24.884	3	8.295	22.502	<0.001
Residual	22.491	61	0.369		
Total	47.375	64			

Table 7 presents the ANOVA results for the simultaneous significance test of the regression model. The analysis yielded an F-statistic of 22.502 with a significance value of $p < 0.001$, indicating that thermal stress, depth refugia, and herbivorous fish biomass collectively have a statistically significant relationship with post-bleaching coral recovery. The regression sum of squares was 24.884 (df = 3), while the residual sum of squares was 22.491 (df = 61), with a total sum of squares of 47.375 (df = 64). These findings confirm that the regression model is statistically significant and that the three independent variables jointly contribute to explaining variation in post-bleaching coral recovery, supporting the fourth hypothesis (H4).

4.7 Discussion

The findings demonstrate that thermal stress has a negative and statistically significant relationship with post-bleaching coral recovery in Raja Ampat, Indonesia ($B = -0.523$, $\beta = -0.521$, $t = -5.583$, $p < 0.001$). This result indicates that greater thermal exposure is associated with lower coral recovery assessments, emphasizing the importance of temperature-related disturbances in determining reef resilience. Prolonged marine heatwaves can disrupt coral physiological processes, reduce photosynthetic efficiency, and limit the energy required for tissue regeneration and reproduction. These findings are consistent with Yao and Wang (2026), who documented the increasing intensity of marine heatwaves across global coral reef regions, and Graham et al. (2024), who demonstrated that repeated bleaching events influence coral recovery trajectories and ecological stability. Furthermore, Kopecky et al. (2024) emphasized that bleaching-related mortality produces structural changes that interfere with herbivory and coral recruitment, potentially extending the ecological consequences of thermal disturbances. The relatively large standardized regression coefficient indicates that thermal stress has the strongest statistical association with coral recovery among the three examined predictors. This finding highlights the importance of considering thermal disturbance intensity, exposure duration, and repeated bleaching events when evaluating coral recovery conditions in Raja Ampat.

Depth refugia also demonstrate a positive and statistically significant relationship with post-bleaching coral recovery ($B = 0.341$, $\beta = 0.329$, $t = 3.682$, $p < 0.001$), suggesting that favorable depth-associated environmental conditions are linked to improved coral persistence and regeneration. Deeper reef habitats may provide environmental buffering through differences in solar irradiance, temperature variability, and localized oceanographic processes, potentially supporting coral survival during thermal disturbances. However, the effectiveness of these habitats is not universal. Diaz et al. (2023) demonstrated that changes in thermocline depth can trigger bleaching in mesophotic coral ecosystems, while Eyal et al. (2022) documented substantial bleaching among deep-water coral communities, indicating that greater depth does not necessarily ensure protection. In Raja Ampat, Ampou et al. (2026) observed considerable recovery among Pachyseris speciosa populations following the 2024 bleaching event, highlighting the importance of investigating local habitat characteristics associated with coral resilience. These findings suggest that depth refugia may contribute to favorable recovery conditions when supported by suitable environmental characteristics. Nevertheless, the observed association reflects respondents' assessments of refuge conditions rather than direct measurements of depth-related thermal protection, emphasizing the need for complementary ecological field observations.

Herbivorous fish biomass exhibits a positive and statistically significant relationship with post-bleaching coral recovery ($B = 0.417$, $\beta = 0.323$, $t = 3.497$, $p = 0.001$), indicating that more favorable assessments of herbivorous fish populations and grazing conditions are associated with improved coral recovery. Herbivorous fishes contribute to reef resilience by controlling algal growth, reducing

competition for benthic substrate, and maintaining suitable conditions for coral recruitment. This finding aligns with Graham et al. (2024), who identified the importance of herbivory in supporting coral recovery and reversing macroalgal dominance. However, Kopecky et al. (2024) demonstrated that dead coral skeletons can restrict grazing activities, suggesting that the ecological contribution of herbivorous fishes depends on habitat structure and substrate accessibility. Simultaneously, the regression model demonstrates a statistically significant relationship between the three independent variables and coral recovery ($F = 22.502$, $p < 0.001$), with an R^2 value of 0.525, indicating that the model explains 52.5% of the observed variation in recovery assessments. These results support the integrated ecological perspective that coral recovery is associated with environmental stress, habitat protection, and biological regulation. Accordingly, conservation strategies in Raja Ampat should consider thermal disturbance monitoring, protection of potentially favorable refuge habitats, and maintenance of herbivorous fish communities. However, the cross-sectional and questionnaire-based research design limits causal interpretation, and further studies incorporating direct ecological measurements are necessary to validate these relationships.

CONCLUSION

This study concludes that thermal stress, depth refugia, and herbivorous fish biomass have statistically significant relationships with post-bleaching coral recovery in Raja Ampat, Indonesia. Thermal stress exhibits a significant negative relationship with coral recovery, whereas depth refugia and herbivorous fish biomass demonstrate significant positive relationships. Among the three predictors, thermal stress shows the strongest statistical association, emphasizing the importance of thermal disturbances in understanding coral recovery conditions. The simultaneous regression analysis confirms that these variables collectively explain 52.5% of the variation in coral recovery assessments, while the remaining 47.5% reflects unexplained variability and factors outside the model. These findings highlight the importance of integrating environmental stress management, protection of potential depth refugia, and conservation of herbivorous fish communities to support coral reef resilience. From a practical perspective, marine conservation initiatives should prioritize thermal monitoring, habitat protection, and sustainable management of reef-associated fish populations. Nevertheless, because the study relies on cross-sectional questionnaire data, its findings establish statistical associations rather than causal ecological relationships. Future research should incorporate longitudinal monitoring and direct biophysical measurements to provide stronger empirical evidence regarding the mechanisms influencing post-bleaching coral recovery in Raja Ampat.

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