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Perception-Participation Dynamics and Mangrove Degradation: A Multi-Group SEM in Northern Central Java, Indonesia

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ABSTRACT

Mangrove ecosystems along northern Central Java are experiencing rapid decline due to ecological pressures, land-use changes, and limited institutional support. This study explores how community perceptions and participation influence mangrove degradation across Brebes, Pemalang, and Demak. A mixed-methods approach was employed, combining a structured household survey (n = 150) with focus group discussions to contextualize quantitative results. Confirmatory Factor Analysis validated measurement accuracy, and Structural Equation Modeling (SEM) with multi-group analysis (MG-SEM) was used to assess causal relationships and spatial variation. In the combined model, perception had a strong positive impact on participation ($\beta = 0.58$, $p < 0.001$) and a direct negative effect on degradation ($\beta = -0.21$, $p = 0.010$). Participation further reduced degradation ($\beta = -0.32$, $p < 0.001$) and partially mediated the perception–degradation link ($\beta_{indirect} = -0.19$, $p < 0.001$). The model accounted for 34% of the variance in participation and 26% in degradation ($R^2 = 0.34$, 0.26) and demonstrated good fit indices ($\chi^2/df = 1.87$, CFI = 0.93, TLI = 0.91, RMSEA = 0.056, SRMR = 0.045). MG-SEM revealed context-specific dynamics: an effective perception–participation–degradation pathway in Brebes, a "Pemalang Paradox," where high participation coexists with significant degradation under intense anthropogenic pressure, and diminished behavioral effects in Demak under extreme ecological stress. These insights emphasize perception and participation as crucial yet bounded factors in mangrove resilience, highlighting the importance of spatially tailored management strategies.

1. INTRODUCTION

Mangrove ecosystems play a vital role in maintaining the stability of tropical coastal areas. Their complex root systems protect shorelines from erosion and seawater intrusion, trap sediments, boost fisheries productivity, and serve as critical habitats for a wide range of aquatic species (Isworo & Oetari 2020). In addition to these ecological advantages, mangroves are recognized as some of the most effective blue-carbon sinks, significantly aiding climate change mitigation through substantial carbon sequestration (Choudhary et al. 2024). By providing these ecological and socio-economic benefits, mangroves underpin the resilience of coastal communities, fostering environmental sustainability, livelihood security, and long-term adaptability (Lovelock et al. 2024).

Despite their significance, Indonesia continues to face substantial mangrove loss. Over the last thirty years, approximately 48 km² of mangroves have vanished-averaging about 3.25 km² annually-due to changes in rainfall patterns, land conversion, and expansion of aquaculture (Wiarta et al. 2025). These declines have broader implications: a 1% reduction in mangrove cover is estimated to cause a 5.3–9.8% decrease in household fishery income. Limited institutional support and ongoing land-use conflicts further complicate management efforts, highlighting the complexity of maintaining coastal ecosystems (Utami et al. 2024).

Within this context, community perception and participation have emerged as critical determinants of restoration success. Favorable perceptions are often linked to stronger engagement in replanting, stewardship programs, and mangrove-based ecotourism, while limited awareness tends to hinder involvement. Empirical evidence shows that these social dimensions influence both ecological outcomes and household livelihoods (Jadloc et al. 2025, Sarujan & Sakurai 2023). Indonesian case studies similarly demonstrate strong associations between mangrove condition and community engagement (Syahputra & Fernando 2024). Nevertheless, existing research remains largely biophysical in orientation, leaving the socio-ecological linkages-particularly the causal interplay among perception, participation, and degradation-underexplored. Comparative studies across locations with varying ecological pressures and institutional arrangements are also limited (Arifanti et al. 2025).

This study makes a significant contribution by employing Structural Equation Modeling (SEM) and Multi-Group SEM (MG-SEM) to examine the causal pathways connecting perception, participation, and mangrove degradation. It systematically compares socio-ecological determinants across Brebes, Pemalang, and Demak to identify site-specific factors influencing rehabilitation outcomes. The findings aim to support the development of adaptive, community-based strategies to enhance mangrove management in coastal regions of Indonesia.

2. MATERIALS AND METHODS

2.1. Research Design and Respondent Characteristics

This study surveyed 150 respondents, selected proportionally from Brebes, Pemalang, and Demak (50 respondents from each site) using purposive, criterion-based sampling. Participants were required to have resided in the study area for at least ten years, be aged 20 or older, and be directly involved in mangrove-related coastal livelihoods. Individuals not meeting these criteria were excluded to minimize sampling bias and ensure respondents had long-term socio-ecological experience relevant to the research context. Purposive sampling is widely recognized as effective for capturing respondents with specific place-based knowledge and direct interactions with coastal ecosystems (Nagel & Partelow 2022), while well-defined inclusion criteria improve internal validity (Dyson et al. 2023). The quantitative analysis included validity and reliability testing, ANOVA, correlation and regression analyses, and Structural Equation Modeling (SEM) to explore the proposed causal relationships among perception, participation, and mangrove degradation. To contextualize and enrich these statistical findings, focus group discussions (FGDs) were held at each site with policymakers, community leaders, and mangrove farmers (about five participants per site). These qualitative insights offered a deeper understanding of local socio-institutional dynamics and rehabilitation practices. Combining survey data with FGD results through methodological triangulation strengthened interpretive depth and increased the robustness of the study's conclusions.

2.2. Research Location

The study was carried out in three coastal regencies along the northern coast of Central Java—Brebes, Pemalang, and Demak—each characterized by different levels of mangrove degradation. These sites were deliberately selected to reflect diverse socio-ecological conditions and varying degrees of rehabilitation success. (1) Kaliwlingi Village, Brebes (±06°48′19.68″ S, 109°02′26.01″ E), represents a relatively successful rehabilitation effort supported by active community involvement and institutional support. (2) Mojo Village, Pemalang (±06°49′43″ S, 109°32′45″ E), depicts a transitional zone facing moderate challenges due to extensive aquaculture conversion. (3) Bedono Village, Demak (±06°44′28″ S, 110°29′58″ E), exemplifies a critically degraded system where coastal erosion and tidal flooding hinder restoration attempts. Collectively, these sites create a socio-ecological gradient, from successful restoration to contested land use to system collapse, forming a solid empirical basis for cross-site comparison and understanding the specific factors influencing mangrove resilience.

The geographical layout of these three coastal villages, along with their differing rehabilitation conditions, is depicted in Fig. 1.

Research location maps of Kaliwlingi (Brebes), Mojo (Pemalang), and Bedono (Demak), representing distinct socio-ecological conditions: successful rehabilitation in Brebes, transitional aquaculture-dominated conditions in Pemalang, and severe abrasion with rehabilitation failure in Demak.

2.3. Variables and Indicators

This study explored three key constructs—Perception (PERC), Participation (PART), and Mangrove Degradation (DEG)—to understand the socio-ecological factors affecting rehabilitation outcomes. Perception included ecological knowledge, awareness of socio-economic benefits, conservation attitudes, and policy assessments, illustrating how community understanding influences environmental behavior (Jones et al. 2023). Participation assessed involvement in rehabilitation efforts, resource contributions, and engagement in local institutional networks, aligning with evidence that participatory approaches support sustainable restoration (Sarujan & Sakurai 2023). Degradation was evaluated through perceptions of mangrove loss, coastal erosion or tidal flooding, and declines in ecological functions, corroborated with local government data to enhance reliability (Elwin et al. 2024).

2.4. Research Hypotheses

This study indicates that community perception (PERC) positively affects participation (PART), which in turn contributes to reducing mangrove degradation (DEG). It is expected that perception influences degradation both directly and indirectly through participation, with these effects varying across different locations (Cui 2024). Consequently, the hypotheses posit that PERC increases PART (H1) and decreases DEG (H2), that PART reduces DEG (H3) and mediates the relationship between PERC and DEG (H4), that these relationships differ among sites (H5), that institutional support (INST) aids in mitigating degradation (H6), and that anthropogenic pressure (ANTH), combined with ecological stress (ECO), exacerbates degradation (H7). This framework aligns with recent research showing that perception and environmental awareness are crucial drivers of community involvement in mangrove conservation (Cruz Portorreal et al. 2024, Hagger et al. 2022). It also highlights how gaps in knowledge, attitudes, and perception, along with institutional and ecological issues, can affect the success of community-based rehabilitation efforts. Methodologically, analyzing mediation pathways and spatial heterogeneity through SEM and multi-group analysis reflects current best practices in environmental and socio-ecological research (Hair Jr et al. 2021). The conceptual framework (Fig. 2) consolidates these hypotheses into seven directional relationships linking perception, participation, and degradation, influenced by institutional, anthropogenic, and ecological factors. Together, the framework incorporates behavioral and contextual aspects to explain community resilience of mangroves across diverse socio-ecological settings.

2.5. Measurement Model (Confirmatory Factor Analysis/CFA)

The validity and reliability of all constructs were assaessed through Confirmatory Factor Analysis (CFA). Indicators with standardized factor loadings of 0.50 or higher were retained (Hair Jr. et al. 2021), leading to the preservation of PERC3–PERC4, PART1–PART3, and DEG1, DEG2,

Fig. 1: Study area and sampling sites in Brebes, Pemalang, and Demak, showing a gradient of mangrove conditions from successful rehabilitation to severe degradation.

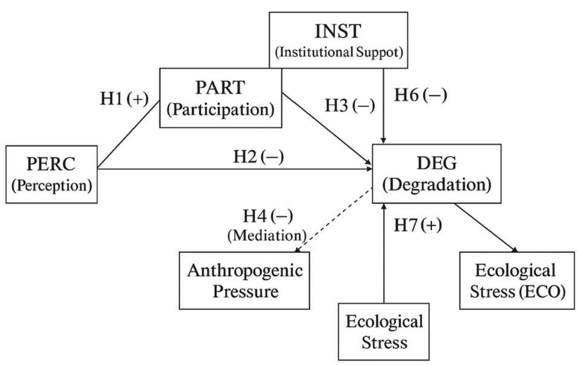

Fig. 2: Conceptual framework of the research hypotheses.

and DEG4. Error covariances were introduced solely when theoretically justified and confined within the same construct, thereby preventing model overfitting and ensuring simplicity (Kline 2023). All constructs demonstrated satisfactory convergent validity and internal consistency, with Composite Reliability (CR) ≥ 0.70 and Average Variance Extracted (AVE) ≥ 0.50 meeting established standards. The final CFA model showed acceptable goodness-of-fit indices, supporting its suitability for further structural analysis: χ^2/df = […], CFI = […], TLI = […], RMSEA = […] (90% CI: […], […]), and SRMR = […].

2.6. Structural Model

The structural model demonstrated that perception had a strong positive impact on participation ($\beta = 0.58$, $p < 0.001$). Subsequently, participation significantly decreased degradation ($\beta = -0.32$, $p < 0.001$), confirming its mediating role in the perception–degradation relationship. Additionally, perception showed a direct negative effect on degradation ($\beta = -0.21$, $p = 0.010$), along with a significant indirect effect via participation ($\beta = -0.19$, $p < 0.001$). The model accounted for 34% of the variance in participation and 26% in degradation. Fit indices suggested that the structural model provided an acceptable fit for hypothesis testing (χ^2/df = 1.87, CFI = 0.93, TLI = 0.91, RMSEA = 0.056, SRMR = 0.045).

2.7. Data Analysis

Data analysis was carried out in two phases: initially, descriptive statistics and Pearson correlations were employed to characterize respondents, followed by Structural Equation Modeling (SEM) with robust maximum likelihood estimation (MLE) to examine proposed causal relationships. Construct validity was evaluated via Confirmatory Factor Analysis (CFA), using thresholds of factor loadings ≥ 0.50, CR ≥ 0.70, and AVE ≥ 0.50. Model fit was assessed through CFI, TLI, RMSEA, and SRMR (Hair Jr. et al. 2021). The significance of path coefficients and mediation effects were tested with bootstrapping (2,000 resamples), and control variables including institutional support (INST), anthropogenic pressure (ANTH), and ecological stress (ECO) were integrated into the model.

2.8. Structural Model Results and Multi-Group SEM Analysis

2.8.1. Multi-Group SEM (MG-SEM) Analysis

The MG-SEM findings revealed clear spatial variations among the three districts. In Brebes, perception emerged as the most influential predictor of participation ($\beta = 0.67$, $p < 0.001$), highlighting the critical role of ecological literacy in encouraging community engagement. In Pemalang, participation was most effective in mitigating environmental degradation ($\beta = -0.46$, $p < 0.001$), demonstrating that participatory management approaches are particularly potent in this region. Conversely, in Demak, both pathways appeared to weaken under severe ecological stress: the impact of perception on participation diminished ($\beta = 0.41$, $p < 0.05$), and the relationship between participation and degradation was not significant ($\beta = -0.15$, ns). These results underscore that the influence of perception and participation varies greatly depending on the context, with ecological pressures constraining their effectiveness in heavily degraded areas.

2.8.2. Common Method Bias (CMB) Assessment and Control

Potential common method bias was assessed through Harman's single-factor test and collinearity diagnostics. The initial unrotated factor accounted for less than 40% of the total variance, and VIF values across the latent constructs remained below 2.0, indicating no dominance by a single factor. A comprehensive collinearity VIF evaluation further confirmed that all values were under 3.3, suggesting that CMB was not a significant issue. Procedural measures during data collection-such as ensuring respondent anonymity, using varied scale formats, and separating construct sections-also contributed to minimizing potential bias. Together, these statistical and procedural measures strongly suggest that common method bias is unlikely to threaten the validity of the results.

2.8.3. Structural Equation Modeling Framework

The relationships between the constructs were analyzed using Structural Equation Modeling (SEM), which consists of two parts: the measurement model and the structural model. The measurement model specifies how latent constructs are indicated by their observed variables (Hair Jr. et al. 2021, Harlow 2023).

$$x = \Lambda_x \xi + \delta \,, \quad y = \Lambda_y \eta + \varepsilon$$

Where x and y are vectors of exogenous and endogenous indicators, respectively. ξ and η denote latent variables, while Λx and Λy are the factor loading matrices. The symbols δ and ε represent measurement errors. Factor loadings (λi) indicate the strength of the association between indicators and their respective constructs, whereas residuals (δi) capture unexplained variance. The results of Confirmatory Factor Analysis (CFA) in Table 1 demonstrate that the retained indicators for Perception (PERC), Participation (PART), and Degradation (DEG) exhibit satisfactory loadings, thereby validating their use in subsequent analyses. The structural model outlines the hypothesized causal relationships among the constructs.

$$\eta = B\eta + \Gamma\xi + \zeta$$

In this study, the equations are expressed as:

$$PART = \gamma1 \cdot PERC + \zeta1$$

$$DEG = \beta1 \cdot PART + \gamma2 \cdot PERC + \zeta2$$

This framework includes the perception construct denoted by PERC, participation represented by PART, and mangrove degradation indicated by DEG. The coefficients γ_1 and γ_2 illustrate the directional effects of perception on participation and degradation, respectively, while β_1 captures the mediating effect of participation on degradation. The error terms (ζ_1, ζ_2) account for the unexplained variance within the endogenous constructs. Collectively, these specifications establish a coherent analytical model that enables rigorous testing of measurement validity and the proposed socio-ecological pathways.

3. RESULTS AND DISCUSSION

This section presents the empirical findings of the study, beginning with descriptive characteristics of respondents and key constructs, then covering measurement validation, structural equation modeling, and multi-group analysis. The results are subsequently integrated and discussed in the context of existing socio-ecological theories and policy implications for mangrove governance.

3.1. Description of Main Variable

The demographic profile of respondents offers valuable insights into community dynamics related to mangrove governance. Most participants were within the productive age group (30–55 years) and engaged in activities such as fishing, aquaculture, or small-scale trading, which highlights a strong dependence on mangrove ecosystem services—an aspect known to enhance conservation efforts (Mallick et al. 2021). Educational levels were generally modest, implying that ecological knowledge is mainly acquired through hands-on experience. This underscores the importance of implementing targeted awareness and capacity-building initiatives. Similar socio-economic trends have been observed in other communities reliant on mangroves, where education level and livelihood dependence influence perceptions and conservation attitudes (Hendraswari et al. 2021). Respondents typically resided in the area for over 15 years, reflecting a strong sense of place attachment and long-term exposure to environmental changes. This aligns with findings suggesting that duration of residence affects mangrove usage and management behaviors (Dulyakasem et al. 2025). Descriptive statistics for key constructs—perception (PERC), participation (PART), and degradation (DEG)-are presented in Table 1.

Brebes registered the highest perception score with a mean of 21.16, followed by Pemalang at 20.04 and Demak at 19.18. Participation was most prominent in Pemalang (mean = 16.68), whereas Brebes (mean = 15.22) and Demak (mean = 14.98) showed comparatively lower involvement. Conversely, mangrove degradation was most severe in Pemalang (mean = 14.40), while Brebes (mean = 13.82) and Demak (mean = 12.12) exhibited relatively healthier ecological conditions.

These findings indicate that higher perception and greater community participation are associated with reduced degradation levels. This suggests that ecological awareness and active engagement contribute to better mangrove outcomes, aligning with recent research showing that enhanced perception boosts participation and governance effectiveness (Rosellón-Druker et al. 2023), while gaps in knowledge and perception correlate with increased degradation (Sathiyamoorthy & Sakurai 2024). However, it is important to note that these descriptive statistics do not establish causality. To explore the relationships more thoroughly and verify the hypothesized associations, inferential analyses—including ANOVA, SEM, and multi-group SEM (MG-SEM)—were conducted to examine the structural links among perception, participation, and degradation.

3.2. Validity and Reliability Tests

3.2.1. Measurement Model Evaluation

The results of the Confirmatory Factor Analysis (CFA) indicate that all indicators satisfied the necessary validity and reliability standards. Standardized factor loadings exceeded 0.50 with t-values greater than 5.0, and both Composite Reliability (ranging from 0.71 to 0.83) and Average Variance Extracted (AVE, between 0.55 and 0.67) demonstrated

Table 1: Descriptive Statistics of Main Variables by Location.

Variable	Brebes (n=50)	Pemalang (n=50)	Demak (n=50)	Total (n=150)
Mean age [years]	43.2 ± 9.6	41.8 ± 10.2	42.5 ± 9.8	42.5 ± 9.9
Education [Junior–Senior HS, %]	68%	72%	74%	71%
Main occupation [Fishing/Aquaculture, %]	64%	66%	70%	67%
Length of residence [years]	15.3 ± 5.8	14.7 ± 6.2	16.1 ± 5.4	15.4 ± 5.8

Table 2: Validity and reliability results.

Construct	Indicator	Loading range	t-value	CR	AVE	Remarks
Perception (PERC)	X1–X5	0.55–0.76	> 5.0	0.83	0.67	Valid and reliable
Participation (PART)	X6–X9	0.46–0.79	> 5.0	0.71	0.55	Valid and reliable
Degradation (DEG)	X10–X13	0.68–1.12	> 5.0	0.76	0.58	Valid and reliable (λ > 1.0 indicates the Heywood case)

adequate internal consistency and convergent validity. One indicator within the Degradation construct exhibited a loading above 1.0 ($\lambda = 1.12$), suggesting a potential Heywood case; however, this likely reflects high correlations among indicators rather than model misspecification. Overall, the measurement model was deemed acceptable and appropriate for subsequent analyses, including ANOVA, SEM, and MG-SEM. Detailed validity and reliability statistics are provided in Table 2.

3.2.2. Discriminant Validity and Heywood Case Handling

The results of the Confirmatory Factor Analysis (CFA) indicated that all indicators satisfied the necessary validity and reliability criteria. Standardized loadings were significant ($\lambda \geq 0.50$, t-values > 5.0), and both Composite Reliability (ranging from 0.71 to 0.83) and Average Variance Extracted (AVE, 0.55 to 0.67) supported convergent validity. One indicator within the Degradation construct (DEG3) showed a loading above 1.0 ($\lambda = 1.12$), indicating a Heywood case (Cooperman & Waller 2022). Several remedial measures were considered, and DEG3 was excluded based on both theoretical rationale and diagnostic analysis. The updated model demonstrated no further issues, with all remaining indicators loading adequately. Discriminant validity was confirmed through the Fornell–Larcker criterion and HTMT analysis, as presented in Table 3. The square roots of AVE surpassed the inter-construct correlations, and all HTMT values remained below 0.85, verifying that perception, participation, and degradation are distinct constructs (Hair & Alamer 2022, Afthanorhan et al. 2021).

Discriminant validity was confirmed using the Fornell–Larcker criterion and the HTMT ratio. As shown in Table 3, the square roots of the AVE values consistently surpassed inter-construct correlations, and all HTMT estimates stayed below the recommended threshold of 0.85. Overall, these results strongly support the notion that the latent constructs represent separate theoretical domains and are free from construct overlap.

3.2.3. Multicollinearity Test

A multicollinearity assessment was performed to verify that the latent constructs were independent and free from redundancy. As indicated in Table 4, all variables exhibited Tolerance values exceeding 0.50 and VIF values below 2.0, which are comfortably within the recommended thresholds (Tolerance > 0.10, VIF < 10). These findings confirm the absence of multicollinearity, suggesting that each construct provides distinct explanatory power to the structural model (Bayman & Dexter 2021).

3.3. Structural Results and Integrated Discussion

3.3.1. Differences Across Locations (ANOVA)

Descriptive statistics for the three primary constructs-perception (PERC), participation (PART), and mangrove degradation (DEG)—are detailed in Table 5. The initial analysis indicates that Brebes has the highest perception scores (Mean = 21.16), whereas Pemalang exhibits the strongest community participation (Mean = 16.68). Conversely, mangrove degradation appears most severe in Pemalang (Mean = 14.40) and least in Demak (Mean = 12.12). These patterns highlight spatial differences among the sites and underpin subsequent inferential analysis through one-way ANOVA.

Table 3: Discriminant validity results (Fornell–Larcker Criterion and HTMT).

Construct	AVE	√AVE	PERC	PART	DEG	HTMT range
Perception (PERC)	0.58	0.76	0.76	0.62	0.55	0.58–0.69
Participation (PART)	0.67	0.82	0.62	0.82	0.60	0.61–0.72
Degradation (DEG)	0.55	0.74	0.55	0.60	0.74	0.57–0.66

Table 4: Multicollinearity test results.

Construct	Tolerance	VIF	Remarks
Perception (PERC)	0.64	1.56	No multicollinearity
Participation (PART)	0.59	1.70	No multicollinearity
Degradation (DEG)	0.61	1.63	No multicollinearity

Note: Tolerance > 0.10 and VIF < 10 indicate the absence of multicollinearity.

Table 5: Descriptive statistics of key variables (perception, participation, and mangrove degradation) by study site.

Variable	Brebes (Mean ± SD)	Pemalang (Mean ± SD)	Demak (Mean ± SD)
Perception (PERC)	21.16 ± 2.85	20.04 ± 2.72	19.18 ± 2.64
Participation (PART)	15.22 ± 2.48	16.68 ± 2.31	14.98 ± 2.27
Degradation (DEG)	13.82 ± 2.14	14.40 ± 2.36	12.12 ± 2.05

Table 6: Results of one-way ANOVA across locations.

Variable	F-value	p-value	Significance	Main Differences (Tukey HSD)
Perception (PERC)	8.42	<0.001	***	Brebes ≠ Demak (significant)
Participation (PART)	6.35	0.002	**	Pemalang ≠ Demak (significant)
Degradation (DEG)	9.87	<0.001	***	Pemalang ≠ Demak (significant)

The one-way ANOVA (Table 6) reveals significant differences across sites for all key constructs. Perception varied notably among locations ($F = 8.42$, $p < 0.001$), with Brebes showing the highest ecological awareness, followed by Pemalang, while Demak recorded the lowest scores. Participation also differed significantly ($F = 6.35$, $p = 0.002$), with Pemalang demonstrating the greatest engagement and Demak consistently the lowest. Similarly, mangrove degradation levels varied significantly across sites ($F = 9.87$, $p < 0.001$), highest in Pemalang and least severe in Demak. Post hoc Tukey's HSD confirmed that the most significant contrasts were between Brebes and Demak, with Pemalang occupying an intermediate position—characterized by relatively high perception and participation but also the highest degradation. This pattern indicates that strong community participation alone may not suffice to reduce degradation if external pressures—such as coastal erosion, land conversion, or infrastructure development—are predominant. These findings underscore that community-based conservation efforts must be complemented by institutional and ecological interventions to effectively mitigate ecosystem degradation (Polas et al. 2024).

Table 7 summarizes the ANOVA and Tukey HSD results for clarity. Brebes exhibited strong perception but only moderate levels of participation and degradation. Pemalang showed the highest participation alongside the greatest degradation, indicating a persistent socio-ecological trade-off between livelihood activities and environmental stress. Demak consistently had the lowest perception and participation, yet also experienced the least degradation, suggesting limited community engagement in an environment under relatively lower pressure.

Brebes exhibited the highest level of perception, alongside moderate participation and degradation levels. Pemalang showed the strongest community participation but also the highest degradation, revealing a socio-ecological trade-off where active involvement occurs amidst significant environmental pressure. In contrast, Demak consistently recorded the lowest perception and participation but experienced the least degradation, indicating minimal community engagement in a relatively less degraded ecosystem. These spatial differences suggest that variations in awareness and participation are closely influenced by site-specific ecological conditions, institutional support, and adaptive management across the three coastal districts.

Fig. 3 presents a comparison of mean scores and the structural relationships among perception (PERC), participation (PART), and mangrove degradation (DEG) across the study sites. Brebes showed the highest perception levels, while Pemalang exhibited the strongest participation along with the greatest degradation. Demak had the lowest perception and participation but experienced the least degradation. SEM analysis indicates that perception positively influences participation ($\beta = 0.58$, $p < 0.001$) and directly reduces degradation ($\beta = -0.21$, $p = 0.010$), with participation further diminishing degradation ($\beta = -0.32$, $p < 0.001$). A significant indirect effect ($\beta = -0.19$, $p < 0.001$) confirms partial mediation, implying that ecological awareness enhances resilience mainly through community engagement. The model demonstrated a good fit to the data

Table 7: Summary of ANOVA and Tukey HSD across locations.

Variable	F-value	p-value	Main Differences (Tukey HSD)	Key Interpretation
Perception	8.42	<0.001***	Brebes ≠ Demak, Pemalang moderate	Highest in Brebes, lowest in Demak
Participation	6.35	0.002**	Pemalang ≠ Demak, Brebes moderate	Highest in Pemalang, lowest in Demak
Degradation	9.87	<0.001***	Pemalang ≠ Demak, Brebes moderate	Highest in Pemalang, lowest in Demak

***p < 0.001, **p < 0.01

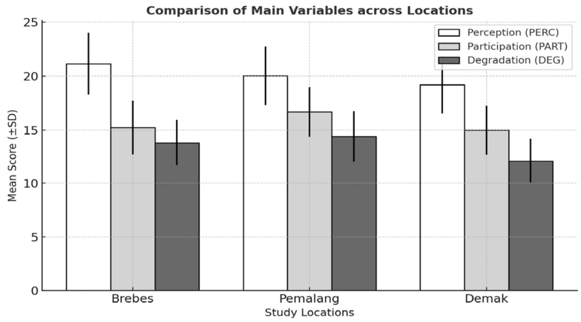

Fig. 3: Comparison of the mean scores for PERC, PART, and DEG.

Table 8: Path estimates of Structural Equation Modeling (SEM) and Multi-Group SEM (MG-SEM) results across study site.

Hypothesized Path	Coefficient (β)	t-value	p-value	Sign	Interpretation
PERC → PART	0.58	9.84	<0.001	***	Positive, strong
PERC → DEG	–0.21	–2.61	0.010	**	Negative, moderate
PART → DEG	–0.32	–3.87	<0.001	***	Negative, significant
PERC → DEG (via PART)	–0.19	Bootstrapping	<0.001	**	Partial mediation

Model fit: $\chi^2/df = 1.87$, CFI = 0.93, TLI = 0.91, RMSEA = 0.056, SRMR = 0.045 (Kang & Ahn 2021)

($\chi^2/df = 1.87$, CFI = 0.93, TLI = 0.91, RMSEA = 0.056, SRMR = 0.045).

3.3.2. Structural Equation Modeling (SEM)

The SEM analysis revealed significant and theoretically consistent pathways (Table 8). Perception substantially enhanced participation ($\beta = 0.58$, $t = 9.84$, $p < 0.001$) and directly diminished degradation ($\beta = -0.21$, $t = -2.61$, $p = 0.010$), while increased participation further reduced degradation ($\beta = -0.32$, $t = -3.87$, $p < 0.001$). Mediation testing verified a notable partial mediation effect ($\beta\_indirect = -0.19$, $p < 0.001$), suggesting that ecological awareness primarily promotes mangrove resilience through community engagement. These findings are consistent with socio-ecological models that highlight behavioral engagement as a mediator translating environmental cognition into conservation outcomes. The refined model demonstrated a good fit ($\chi^2/df = 1.87$, CFI = 0.93, TLI = 0.91, RMSEA = 0.056, SRMR = 0.045) after theory-driven re-specification. It accounted for 34% of the variance in participation ($R^2 = 0.34$) and 26% of the variance in degradation ($R^2 = 0.26$), underscoring the importance of the perception → participation → degradation pathway in fostering socio-ecological resilience (Hair & Alamer 2022).

The SEM analysis demonstrates that community perception significantly increases participation, while both perception and participation directly reduce degradation. The indirect pathway confirms that ecological awareness contributes to ecosystem resilience primarily when translated into active engagement.

3.3.3. Multi-Group SEM (MG-SEM)

The MG-SEM results demonstrate significant spatial variation in the relationships among perception (PERC), participation (PART), and mangrove degradation (DEG). In Brebes, perception showed a strong positive influence on participation ($\beta = 0.84$, $p < 0.001$), while both participation ($\beta = -0.28$, $p < 0.05$) and perception ($\beta = -0.35$, $p < 0.01$) significantly contributed to reducing degradation. This indicates a functional socio-ecological feedback loop maintained by relatively stable institutional frameworks.

In Pemalang, participation emerged as the primary factor in mitigating degradation ($\beta = -0.41$, $p < 0.01$), along with a notable direct effect of perception on degradation ($\beta = -0.32$, $p < 0.05$). However, Pemalang also faced the highest levels of degradation, suggesting that vigorous participation often occurs under intense human pressures, such as shrimp pond conversion, aquaculture expansion, and unmanaged coastal land use.

In Demak, both primary pathways diminished in strength and became statistically non-significant (PERC → DEG: $\beta = -0.21$, n.s., PART → DEG: $\beta = -0.25$, n.s.), suggesting that intense biophysical pressures—such as coastal erosion, land subsidence, and seawater intrusion—surpass community-based mitigation measures. These findings (Table 9, Fig. 5) illustrate that while perception consistently predicts increased participation across all sites, its effectiveness in reducing mangrove degradation depends on the context, influenced by ecological stressors, external disturbances, and institutional support mechanisms (Durak & Bulut 2024).

Table 9: SEM and Multi-Group SEM (MG-SEM).

Path	Pooled SEM β (t, p)	Brebes β	Pemalang β	Demak β
PERC → PART	0.79 (t=10.55, p<0.001)	0.84***	0.76**	0.71*
PERC → DEG	–0.38 (t=–4.09, p<0.001)	–0.35**	–0.32*	–0.21 n.s.
PART → DEG	–0.32 (t=–3.47, p=0.001)	–0.28*	–0.41**	–0.25 n.s.
PERC → DEG (via PART)	–0.25 (Bootstrapping, p<0.01)	—	—	—

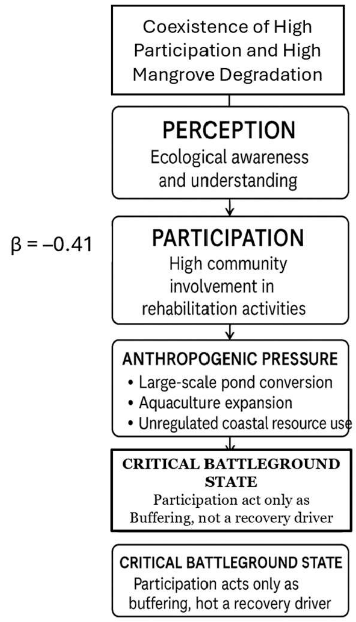

Fig. 4: Pemalang paradox framework.

3.3.4. The Pemalang Paradox

The Pemalang case highlights a unique socio-ecological paradox where high community involvement coexists with consistently high levels of mangrove degradation. This can be explained by the strong connections between community efforts and external anthropogenic pressures (ANTH). Although the MG-SEM results indicate that participation significantly mitigates degradation (β = –0.41), this protective influence exists within a landscape under intense external pressures, including large-scale pond conversions, expansion of aquaculture, and unregulated coastal resource use.

Under such conditions, participation primarily functions as a buffering mechanism, slowing ecological decline rather than enabling full recovery. Pemalang thus emerges as a key socio-ecological battleground, where community engagement provides a defensive layer against pressures that exceed the natural regenerative capacity of the mangrove system. The continued degradation despite active community involvement suggests that participation alone is insufficient to reverse ecological decline when structural drivers remain unaddressed.

These findings emphasize the importance of comprehensive policy interventions that go beyond community initiatives, including more stringent regulation of land conversion, enhanced coastal zoning enforcement, and improved environmental governance. Implementing these structural measures is essential to reduce the prominent human pressures and support community efforts in achieving meaningful ecological results. The conceptual dynamics of this paradox are depicted in Fig. 4 (Pemalang Paradox Framework).

3.3.5. Ecological Threshold in the Demak Case (Ecological "Ambang")

In contrast to the Pemalang pattern, the Demak results indicate that the key pathways-perception leading to degradation and participation leading to degradation—become statistically non-significant. This finding offers an important theoretical insight: under conditions of extreme ecological stress (ECO), the capacity of social interventions to influence ecological outcomes is greatly limited. Demak, a coastal system facing compounded biophysical disturbances such as severe shoreline erosion, land subsidence, and seawater intrusion, demonstrates that the mangrove ecosystem has surpassed an ecological threshold. Once this threshold is crossed, incremental social or behavioral interventions are insufficient to produce measurable ecological improvements. Ecological outcomes are then driven primarily by biophysical forces rather than by variations in perception or participation. This threshold-dynamics perspective aligns with resilience theory, which suggests that the success of social actions depends on whether the ecological system maintains its capacity to respond effectively.

This conceptualization enhances our theoretical understanding by illustrating that the success of social interventions depends not only on their intensity but also on the ecological condition of the system, particularly whether biophysical factors still allow social actions to effect measurable ecological change.

3.3.6. Role of Control Variables INST, ANTH, and ECO

The extended SEM and MG-SEM models incorporated Institutional Support (INST), Anthropogenic Pressure (ANTH), and Ecological Stress (ECO) as key control variables to capture the structural and biophysical context in which social processes operate. These variables play a crucial role in shaping the magnitude and direction of degradation dynamics. Institutional support (INST) acts as an enabling factor that amplifies the perception → participation → degradation pathway. This influence is particularly evident in Brebes, where coherent governance, ongoing facilitation, and formalized community programs foster conditions that convert awareness into sustained participation. These findings support H6 and align with governance literature emphasizing that community-based initiatives require institutional scaffolding to be effective. Conversely, anthropogenic pressure (ANTH)-driven by land conversion, aquaculture expansion, and intensive coastal exploitation-exerts a direct and significant effect on degradation. High levels of ANTH accelerate ecological decline while simultaneously limiting the impact of participation, confirming H7. The Pemalang case exemplifies this dynamic clearly: despite high community engagement, strong external pressures reduce the capacity for participation to promote ecological recovery. Ecological stress (ECO) further defines the boundary conditions under which social mechanisms can influence ecological outcomes. In Demak, extreme biophysical disturbances-such as abrasion, subsidence, and saline intrusion-completely suppress the effects of perception and participation, consistent with ecological threshold theory. Under such threshold-exceeding conditions, social interventions lose their predictive power because physical forces predominantly drive ecological processes. When these control variables are integrated into the model, they enable it to explain 26% of the variance in degradation ($R^2 = 0.26$). This indicates that mangrove degradation results not only from community behavior but also from a constellation of structural and biophysical constraints that define the limits of social efficacy. These findings highlight the importance of situating community-based interventions within broader governance, land-use, and ecological contexts to fully understand and address coastal degradation processes.

3.3.7. Joint Insights (ANOVA + SEM + MG-SEM) and Policy Implications

The initial pooled SEM model demonstrated poor fit indices (CFI = 0.82, GFI = 0.77, TLI = 0.78, SRMR = 0.10, RMSEA = 0.16). However, re-specification guided by modification indices significantly improved the model's performance (χ^2/df = 1.87, CFI = 0.93, TLI = 0.91, RMSEA = 0.056, SRMR = 0.045), confirming its appropriateness for hypothesis testing. The refined structural pathways reveal

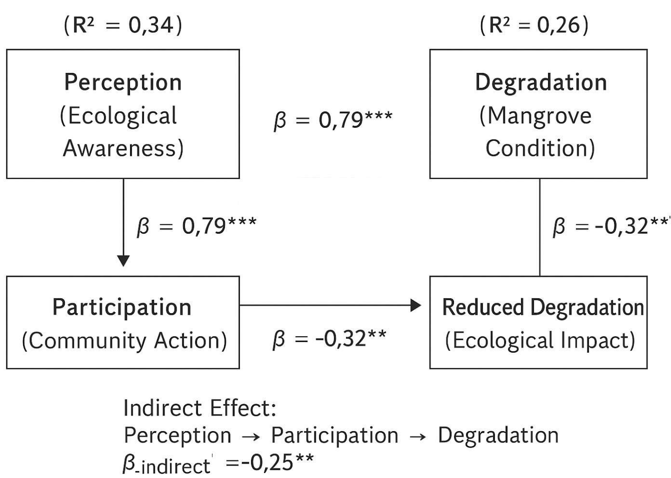

Fig. 5: Conceptual and empirical SEM model linking perception (PERC), participation (PART), and mangrove degradation (DEG).

that perception strongly enhances participation ($\beta = 0.79$, $p < 0.001$), while both perception ($\beta = –0.38$, $p < 0.001$) and participation ($\beta = –0.32$, $p = 0.001$) considerably decrease mangrove degradation. Mediation analysis indicates partial mediation by participation ($\beta_{indirect} = –0.25$, $p < 0.01$), highlighting that ecological awareness yields tangible benefits primarily when converted into active engagement. The model accounts for 34% of the variance in participation ($R^2 = 0.34$) and 26% in degradation ($R^2 = 0.26$), emphasizing the importance of the perception → participation → degradation pathway. The MG-SEM analysis incorporates a vital spatial aspect: while the pathway holds in Brebes and Pemalang, it loses significance in Demak, where intense ecological stress suppresses social influences. Cross-group comparisons using ANOVA reveal that the effectiveness of social mechanisms depends on ecological conditions. Fig. 5 illustrates the conceptual and empirical structure of these relationships, detailing the direct and indirect effects connecting perception, participation, and degradation within the SEM framework.

3.3.8. Integrated SEM and MG-SEM Findings

The combined ANOVA, SEM, and MG-SEM analyses reveal that the relationships among perception (PERC), participation (PART), and mangrove degradation (DEG) are statistically significant but highly dependent on context. At the pooled level, perception significantly boosts participation ($\beta = 0.58$, $p < 0.001$), and both perception ($\beta = –0.21$, $p = 0.010$) and participation ($\beta = –0.32$, $p < 0.001$) notably decrease degradation. Mediation analysis confirmed a partial effect ($\beta_{indirect} = –0.19$, $p < 0.001$), suggesting that perception mainly promotes ecological improvement when translated into behavioral engagement. The final SEM indicated a good model fit ($\chi^2/df = 1.87$, CFI = 0.93, TLI = 0.91, RMSEA = 0.056, SRMR = 0.045), accounting for 34% of the variance in participation and 26% in degradation.

The MG-SEM results highlight the spatial variability of these processes (Fig. 6). In Brebes, perception had the most significant influence on participation, reflecting favorable institutional and social conditions that promote awareness-driven actions. In Pemalang, participation was the primary factor in reducing degradation, although its effectiveness was limited by intense anthropogenic pressure. In Demak, both pathways diminished considerably under extreme ecological stress, aligning with threshold-based ecological dynamics where biophysical degradation diminishes the predictive capacity of social variables. These findings demonstrate that perception, participation, and degradation function within a dynamic socio-ecological feedback loop, whose strength varies depending on local environmental conditions.

Therefore, adaptive management should focus on ecological education and perception enhancement in Brebes, implement participatory livelihood and co-management strategies in Pemalang, and apply engineering-based resilience measures—such as sediment nourishment and hybrid coastal protection—before community-driven actions can be successful in Demak (Yuliantina et al. 2024, Dash & Paul 2021).

4. DEMAK CONTEXT AND SYNTHESIS OF MG-SEM FINDINGS

The analysis of Demak reveals that both primary pathways, perception leading to participation and participation leading to degradation, are significantly weakened and become statistically non-significant (Fig. 7). This pattern reflects the dominant influence of extreme biophysical pressures, including intense coastal abrasion, land subsidence, and seawater intrusion, which collectively surpass the community's adaptive capacity and diminish the effectiveness of social efforts. Under such conditions, community participation alone is insufficient to produce meaningful ecological improvements without large-scale technical or engineering support. Overall, the MG-SEM findings demonstrate that while perception consistently promotes participation across all sites, the ability of participation to

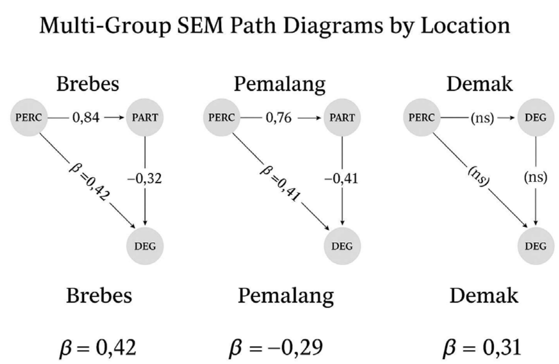

Fig. 6: Multi-group SEM results across locations (Brebes, Pemalang, and Demak).

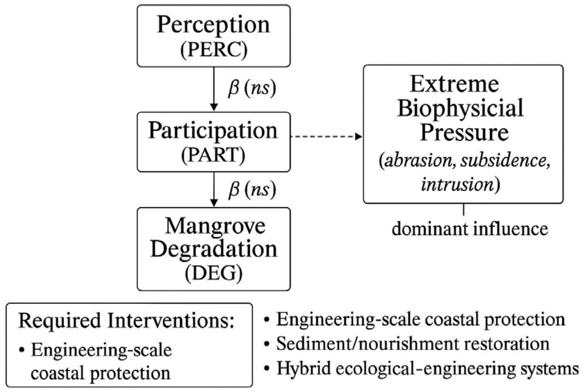

Fig. **7**: Integrated SEM framework of perception, participation, and mangrove degradation (adapted from Listiana 2024).

mitigate degradation is highly context-dependent, influenced by local variations in human activities and biophysical factors. These results highlight the importance of spatially adaptive mangrove management, where interventions are customized to the ecological and social context of each area rather than uniformly implemented across regions.

5. CONCLUSIONS

This study illustrates that community perception and participation are crucial, yet their influence varies depending on the context, in determining mangrove resilience along the northern coast of Central Java. In the combined model, perception consistently boosted participation, and together, these factors reduced mangrove degradation, with participation partially mediating the relationship between perception and degradation. The structural model demonstrated strong explanatory power and a good fit, suggesting that ecological awareness leading to community action is a key behavioral mechanism in supporting mangrove restoration.

However, multi-group SEM analysis revealed significant spatial differences. In Brebes, high ecological literacy and stable institutional support maintained an effective pathway from perception to participation to reduction in degradation. In Pemalang, participation had the most substantial impact on decreasing degradation, but widespread human activities hindered ecological recovery, creating what can be called a ‘Pemalang Paradox’—community engagement helped buffer degradation but was insufficient to overcome broader structural pressures. In Demak, both behavioral pathways were non-significant under extreme ecological stress, indicating that the system had exceeded a biophysical threshold where social mechanisms no longer held predictive power.

The integration of institutional support, anthropogenic pressure, and ecological stress highlights that participation alone is insufficient for successful rehabilitation. Instead, the effectiveness of social pathways is contingent on enabling governance frameworks and ecological conditions that retain recovery potential. These findings advance mangrove governance theory by clarifying the coupled behavioral, institutional, and biophysical drivers shaping rehabilitation outcomes.

Policy implications are therefore site-specific. Brebes requires ongoing ecological education and stable institutional support; Pemalang needs interventions that enhance participation and decrease human pressure; and Demak necessitates engineering-based restoration to restore baseline ecological stability before community-driven approaches can be successful. Although limited by its cross-sectional design and reliance on perceived degradation metrics, this study offers compelling empirical evidence that ecological and institutional factors influence social drivers of rehabilitation. Long-term monitoring and broader governance indicators are recommended to improve understanding of the socio-ecological mechanisms discussed.

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