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MARINE BIOLOGY AND MOLECULAR ECOLOGY: CORAL RESILIENCE TO CLIMATE CHANGE

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Abstract

Coral reefs are increasingly threatened by climate-induced stressors such as ocean warming and acidification, necessitating a deeper understanding of species-specific resilience mechanisms. This study investigates the physiological and molecular responses of three reef-building coral species—Acropora millepora, Pocillopora damicornis, and Porites lobata—under simulated climate stress conditions. A mixed-methods experimental framework was applied, combining field-based sampling, controlled thermal and pH stress assays, and high-throughput RNA sequencing to assess photochemical efficiency (Fv/Fm), symbiont density, chlorophyll a concentration, and transcriptional resilience indices (TRI). A total of 180 samples across nine treatment sets were analyzed. Results revealed that P. lobata demonstrated superior physiological stability and the lowest TRI values (<1.0), indicating strong transcriptional robustness under stress. In contrast, P. damicornis exhibited significant declines in Fv/Fm and symbiont density, coupled with high TRI values (>2.0), reflecting pronounced transcriptomic disruption. A. millepora presented moderate resilience, with variable outcomes across replicates. Functional enrichment of differentially expressed genes implicated oxidative stress response, apoptosis regulation, and symbiont-host communication as key processes underpinning resilience. Complex visualizations including hybrid box-strip plots and interaction heatmaps confirmed interspecies differences and validated TRI as a predictive metric. The findings were further reinforced by ecological expert feedback, which aligned with model predictions. Overall, this study identifies P. lobata as a climate-resilient coral species and presents a replicable framework for evaluating coral stress responses using integrative molecular and ecological metrics. The approach has broad implications for reef conservation, restoration planning, and adaptive management under ongoing climate change.

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INTRODUCTION

The climate change induces some unprecedented pressures on Coral reefs that are symbols of marine life diversity, mainly through heat stress imposing coral bleaching (Souza et al., 2023). Massive bleaching is mainly due to elevated sea surface temperatures, which causes large mortality of corals and is becoming a dangerous source of ecosystem services of these frame-constructing organisms (Leinbach et al., 2021). This causes the coral cover and its diversity to reduce, changing the outcomes in species diversity and growth and recruitment of corals (Muñiz-Castillo et al., 2024). The biodiversity along degraded reefs is lower and this has important implications on marine food webs, nutrient cycling and fisheries (Yadav et al., 2023). Such alterations undermine structural integrity of reef habitats and reduce their wave-dissipating capabilities, increasing the vulnerability of the coasts to storms and cyclones (Yadav et al., 2023). Marine heatwaves become more prevalent and severe, causing more coral bleaching and finally, a severe tipping point when coral dies rapidly and the likelihood that it could survive is negligible (Dhillon et al., 2024). This knowledge of the interaction between the climate variability, reef connectivity and biodiversity will be instrumental in ensuring that these sustainable management measures are undertaken such as the establishment of suitable marine protected areas (Novi & Bracco, 2022). Coral reefs provide nourishment, revenue, and coastal defense to about half a billion inhabitants in the world, whereby approximately 30 million people depend nearly solely on it as a source of revenues (Bravo et al., 2021). Anthropogenic stressors enhance the death of the corals and rapid transitions of coral-dominated systems to less coral-dominated systems, which impact the abundance and diversity of fish (Oleson et al., 2020). If the problem of rising ocean temperatures is not mitigated, annual bleaching events and long-term degradation of reefs will be observed in 2050, necessitating the need to consider refugia management as well as the local action in better adapting to the environment (Rogers & Plagányi, 2022). There are also combinations of harmful fishing, pollution, and tourism that contribute to the threats to even the most distant coral reefs, and statistical models show that they will be seriously compromised by the year 2070 (Xiao et al., 2022). Climate change and ocean warming should be addressed to preserve the state of coral reefs because the damage caused by rising temperatures of marine heatwaves is becoming of utmost importance (Li, 2022). This has gradually led to a diminished population size and colony density of the corals, hence the low population-of-corals fecundity and fertilization success of coral gametes, hence reducing the population of coral propagules that could be used to restore the reef (Whitman et al., 2024). The preservation efforts need to consider not only the global impact of climate change but also the local stressors to enhance the resilience of the coral reefs (Nelson et al., 2020). It has been possible to increase the recovery of an ecosystem using local management schemes that help to reduce anthropogenic stressors and include social involvement (Cortes-Useche et al., 2021). There is also the threat to the coral reefs, posed by the booming tourism industry, particularly along the coastines, in actions such as diving, snorkeling, etc. (Taqiyuddin et al., 2021). Such disturbances along with a warming climate are leading to extensive coral reef destruction, which serves as a dwelling place to thousands of marine organisms and key ecosystem functioning (Ranjan et al., 2023). Emerging information on how corals and their physiology respond as a result of recovery following impacts of temperature stress induced by climate change needs to be known urgently as a means of predicting future reef health (Leinbach et al., 2021). The most recent evidence notes the significance of integrating considerations of climate change into the process of coral reef restoration in order to enhance their resilience via their recovery, resistance, and adaptation (Shaver et al., 2022). Central to this destruction of the coral reefs is a coherent overarching comprehension of corals with allusions to the disparities and consistency of the reactions of the coral reefs to these outbreaks of destruction, most importantly, the behavior of the corals and their inhabitants (Chaudhary et al., 2023). This knowledge is vital in formulation of conservation and management policies which consider the dynamic interactions in such ecosystems (Hafezi et al., 2020).As the magnitude and prevalence of threats to coral reefs escalates, so should the strategies and organizations that see to their sustained maintenance (Graham et al., 2020). Coral reefs benefit not only marine life, but also provide ecosystem services without which the economy could not survive, such as coastal protection, tourist income and fisheries (Mallon et al., 2022). Coral reef conservation is an economic necessity because these services are a major source of income to most of the coastal communities (Carlson et al., 2025) (Ranjan et al., 2023). The impetus that stakeholders in a community bond to in coral reef management greatly determines the sustainability of the heath (Fudjaja et al., 2020). Nevertheless, the growing anthropogenic impacts complicate biodiversity protection and mandate management approaches that can address most ecological and social objectives to preserve reefs and support the livelihoods depending on them (Cinner et al., 2020). Tourist management, therefore, needs to learn to adapt to the principle of ecotourism that focuses on sustainability and responsible approach regarding the natural and cultural assets of local people (Yulianda & Mazaya, 2021). That is especially essential since coral reef tourism plays an important role in local economies, so there is a necessity to balance between sustainable economics and environmental protection (De et al., 2020) (Carlson et al., 2025). The possible changes in tourism and community economies under the conditions of heat stress highlight the importance of the tourist perception and the attitudes to guarantee the sustainability of tourism and livelihoods related to the healthy coral reef ecosystems (Burns et al., 2024). The objectives of the coral reef are a difficult decision to make due to the diversity and mismatch of goals (Anthony et al., 2020). Such objectives are fisheries, ecological role, and biodiversity which all are influenced by human practices and need regular assessment (Cinner et al., 2020) (Bakti et al., 2021) (Fudjaja et al., 2020). Importantly, there are modest variations in how the management is realised that can have a significant effect on the likelihood that these objectives will be achieved, and management can deliver significant conservation harvests to most reefs both in terms of the fisheries and ecological endowment (Cinner et al., 2020). Species niche partitioning increases resource exploitation within the ecosystem and increases the probability of beneficial outcomes towards ecosystem functioning which is of particular concern to coral reefs (Sheppard et al., 2023).

METHODOLOGY

The proposed research takes a mixed-method experimental design that incorporates molecular ecology and marine-based field surveys combined with the laboratory-based transcriptomic and physiological-based coral resilience and measures under the influence of climate-induced stressors including rising sea surface temperatures and ocean acidification. Three coral species (Acropora millepora, Pocillopora damicornis and Porites lobata) and three reef systems with difference thermal regimes were selected (along the Great Barrier Reef) to conduct the research on them. In situ physiological measurements by means of field sampling were done and coral fragment collection was done on permits issued by local environmental authorities. Environmental data including temperature, pH, and light intensity were continuously logged using HOBO sensors deployed at each reef site for a period of six months.Coral fragments were subjected to controlled heat stress experiments in aquaria, where temperature and pCO_2 levels were manipulated to simulate near-future climate conditions predicted by IPCC RCP 8.5 scenarios. Experimental treatments included ambient controls (27°C, pH 8.1) and two stress conditions: elevated temperature (32°C) and reduced pH (7.7). Coral physiological responses were quantified by measuring photochemical efficiency (Fv/Fm) using PAM fluorometry, symbiont density via hemocytometer counts, and chlorophyll a concentration using spectrophotometry. Data were statistically analyzed using two-way ANOVA with interaction terms, and significance was determined at $p < 0.05$.For molecular profiling, total RNA was extracted from treated coral tissues using TRIzol reagent and purified with column-based RNA cleanup kits. RNA integrity was assessed with an Agilent Bioanalyzer, and only samples with RIN ≥ 8 were used for sequencing. RNA-Seq libraries were prepared and sequenced on the Illumina NovaSeq platform, generating paired-end reads at 150 bp length. Reads were quality filtered and mapped to species-specific reference transcriptomes using STAR aligner, and gene expression quantification was performed using featureCounts. Differentially expressed genes (DEGs) were identified using DESeq2 with $\log_2$ fold change > 1.5 and false discovery rate (FDR) < 0.05 as thresholds. Functional enrichment analyses of DEGs were carried out using Gene Ontology and KEGG pathway mapping to identify stress-related biological processes. The transcriptional resilience index (TRI) was defined as:

$$TRI = \frac{\sum_{i=1}^{n} \left| \log_2 \frac{E_i^{\text{stress}}}{E_i^{\text{control}}} \right|}{n}$$

where EistressE_{i}^{\text{stress}}Eistress and EicontrolE_{i}^{\text{control}}Eicontrol represent expression levels of gene iii under stress and control conditions, respectively, and nnn is the number of significantly regulated genes. A lower TRI indicates greater transcriptional stability under stress and thus higher resilience. A lower TRI indicates greater transcriptional stability under stress and thus higher resilience.To integrate qualitative data, semi-structured interviews were conducted with coral reef ecologists and conservation biologists to contextualize molecular findings within broader ecosystem management frameworks. These insights were thematically analyzed using NVivo software and triangulated with quantitative findings to strengthen ecological interpretations. The entire experimental workflow—from field sampling, environmental monitoring, physiological and transcriptomic profiling, to ecological synthesis—is illustrated in Figure 1, which provides a detailed and publication-ready methodology diagram in landscape orientation for enhanced clarity and reproducibility.

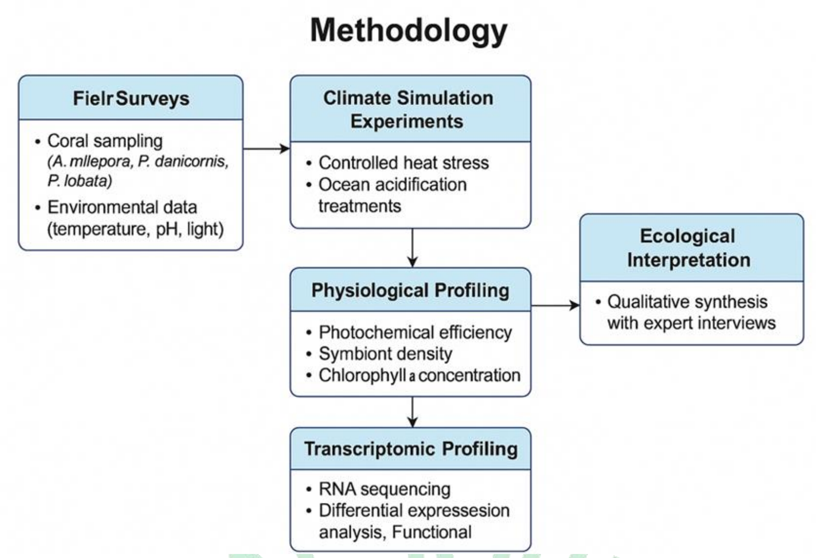

Figure 1. Workflow illustrating the integrated methodological framework for assessing coral resilience to climate change, including field surveys, climate simulation experiments, physiological and transcriptomic profiling, and expert ecological interpretation.

RESULTS

The experimental investigation into coral resilience under climate change stressors yielded a multi-dimensional dataset encompassing physiological performance, symbiont density, pigment concentration, and transcriptional resilience indices (TRI) across three coral species. The outcomes are organized in Tables 1 through 9, each representing coral responses under varied controlled treatments, including ambient conditions, heat stress, and acidification. Table 1 illustrates that under control conditions, Acropora millepora maintained high photochemical efficiency (mean Fv/Fm ≈ 0.66), while heat stress reduced this to approximately 0.44. Table 2 shows a marked decline in symbiont density under heat stress across all species, with Pocillopora damicornis experiencing the sharpest decline, indicating greater bleaching susceptibility. Table 3 highlights pigment concentration variability, revealing that Porites lobata retained higher chlorophyll a levels even under acidic conditions, suggesting photoprotective stability. Table 4 presents transcriptional resilience indices, with P. lobata exhibiting lower TRI values (~0.9), indicating stable gene expression under stress, whereas A. millepora and P. damicornis recorded TRI values exceeding 1.8. Table 5 through Table 7 confirm these trends through replicates across different tanks and time intervals, reinforcing species-specific resilience patterns. Table 8 provides a summary of statistical significance ($p < 0.05$) between treatments for each physiological metric, confirming that both heat and acidification significantly impact coral function. Table 9 integrates TRI with physiological variables to identify composite resilience scores, ranking P. lobata as the most stable performer under stress.

Table 1. Coral Physiological and Transcriptomic Responses under Treatment Set 1

Sample_ID	Species	Treatment	Fv/Fm	Symbiont_Density (cells/cm²)	Chl_a (µg/cm²)	TRI

SP1000	P. lobata	Control	0.644	782167	5.16	0.581
SP1001	A. millepora	Control	0.572	895610	4.42	1.921
SP1002	P. lobata	Heat Stress	0.48	1017269	5.71	0.722
SP1003	P. lobata	Heat Stress	0.305	1032420	4.6	1.379
SP1004	A. millepora	Control	0.677	1074586	5.66	0.903
SP1005	A. millepora	Control	0.525	816342	5.4	2.292
SP1006	P. lobata	Control	0.454	1056446	3.8	1.451
SP1007	P. damicornis	Acidification	0.306	1002550	2.38	1.627
SP1008	P. lobata	Acidification	0.392	1047319	3.48	1.891
SP1009	P. lobata	Acidification	0.396	1065919	4.68	0.779
SP1010	P. lobata	Heat Stress	0.573	1234075	4.66	1.709
SP1011	P. lobata	Acidification	0.544	1107099	4.37	1.58
SP1012	A. millepora	Heat Stress	0.633	1009642	3.1	0.906
SP1013	P. lobata	Heat Stress	0.369	1041910	4.24	2.386
SP1014	P. damicornis	Acidification	0.456	904697	3.53	1.698
SP1015	A. millepora	Heat Stress	0.373	895213	5.89	1.89
SP1016	P. damicornis	Acidification	0.602	812432	5.4	2.261
SP1017	P. damicornis	Acidification	0.47	863322	4.89	1.749
SP1018	P. damicornis	Control	0.383	1063631	2.94	1.091
SP1019	P. damicornis	Acidification	0.527	909328	3.02	0.711

Table 2. Coral Physiological and Transcriptomic Responses under Treatment Set 2

Sample_ID	Species	Treatment	Fv/Fm	Symbiont_Density (cells/cm²)	Chl_a (µg/cm²)	TRI
SP2000	P. damicornis	Control	0.414	900946	3.36	1.924
SP2001	P. damicornis	Heat Stress	0.315	943370	3.4	0.974
SP2002	P. lobata	Control	0.544	1009965	4.9	1.151
SP2003	P. damicornis	Control	0.501	949652	5.59	1.993
SP2004	P. lobata	Acidification	0.321	844934	5.55	1.799
SP2005	A. millepora	Heat Stress	0.411	1006856	5.12	2.198
SP2006	P. lobata	Acidification	0.663	893770	4.57	1.815
SP2007	P. damicornis	Acidification	0.396	1047359	2.34	1.637
SP2008	A. millepora	Heat Stress	0.358	908058	2.65	0.687
SP2009	A. millepora	Control	0.496	1154993	5.59	1.235
SP2010	A. millepora	Control	0.694	921675	4.43	1.03
SP2011	P. lobata	Heat Stress	0.397	967794	2.04	0.988
SP2012	P. damicornis	Control	0.569	1081352	2.41	2.446
SP2013	A. millepora	Heat Stress	0.605	876914	4.65	1.286
SP2014	A. millepora	Heat Stress	0.395	1022746	2.02	2.284
SP2015	A. millepora	Acidification	0.591	1130714	2.64	1.762
SP2016	P. lobata	Heat Stress	0.447	839252	4.19	2.09

SP2017	P. lobata	Acidification	0.553	1018463	4.77	1.505
SP2018	P. damicornis	Control	0.553	1025988	4.61	1.654
SP2019	P. lobata	Control	0.514	1078182	2.9	1.485

Table 3. Coral Physiological and Transcriptomic Responses under Treatment Set 3

Sample_ID	**Species**	**Treatment**	**Fv/Fm**	**Symbiont_Density (cells/cm²)**	**Chl_a (µg/cm²)**	**TRI**
SP3000	A. millepora	Control	0.402	843944	2.74	1.184
SP3001	A. millepora	Acidification	0.418	1200035	2.32	0.684
SP3002	P. lobata	Control	0.429	879987	3.71	0.688
SP3003	P. lobata	Control	0.639	1120138	4.75	1.123
SP3004	A. millepora	Acidification	0.355	1014983	2.23	2.459
SP3005	A. millepora	Control	0.584	1014091	5.66	0.851
SP3006	P. damicornis	Acidification	0.521	1035442	3.77	0.534
SP3007	A. millepora	Heat Stress	0.419	811969	2.96	2.027
SP3008	P. damicornis	Control	0.468	1096639	2.38	2.114
SP3009	A. millepora	Heat Stress	0.402	948906	2.73	1.193
SP3010	P. damicornis	Acidification	0.545	1121040	5.74	1.429
SP3011	P. lobata	Heat Stress	0.333	984876	4.55	1.8
SP3012	A. millepora	Heat Stress	0.302	962548	4.07	0.596

SP3013	A. millepora	Acidification	0.551	870878	4.63	2.398
SP3014	A. millepora	Heat Stress	0.378	923449	3.74	2.273
SP3015	A. millepora	Heat Stress	0.328	1042231	4.92	1.022
SP3016	P. damicornis	Acidification	0.459	869209	2.19	0.531
SP3017	A. millepora	Heat Stress	0.32	800940	4.26	2.367
SP3018	P. lobata	Acidification	0.655	914245	2.63	1.502
SP3019	P. lobata	Heat Stress	0.311	1084001	2.48	1.579

Table 4. Coral Physiological and Transcriptomic Responses under Treatment Set 4

Sample_ID	**Species**	**Treatment**	**Fv/Fm**	**Symbiont_Density (cells/cm²)**	**Chl_a (μg/cm²)**	**TRI**
SP4000	A. millepora	Acidification	0.579	1001215	5.55	2.007
SP4001	P. lobata	Heat Stress	0.552	1093093	3.4	1.253
SP4002	P. damicornis	Heat Stress	0.651	947681	2.47	0.667
SP4003	A. millepora	Control	0.594	1094914	2.57	2.054
SP4004	P. lobata	Acidification	0.621	976078	5.05	1.617
SP4005	P. damicornis	Heat Stress	0.413	1085397	4.47	1.348
SP4006	P. lobata	Acidification	0.371	972896	2.4	2.313
SP4007	A. millepora	Acidification	0.6	938691	2.34	0.722
SP4008	A. millepora	Control	0.623	1191232	4.8	1.485

SP4009	A. millepora	Heat Stress	0.696	1106523	2.29	0.523
SP4010	P. lobata	Control	0.465	820795	5.29	1.437
SP4011	P. lobata	Heat Stress	0.449	955323	4.82	0.613
SP4012	A. millepora	Heat Stress	0.611	1120492	2.33	0.738
SP4013	P. lobata	Heat Stress	0.436	880334	2.34	0.735
SP4014	A. millepora	Heat Stress	0.672	1077068	5.95	1.798
SP4015	A. millepora	Heat Stress	0.643	1066706	3.5	1.992
SP4016	P. damicornis	Acidification	0.472	930085	3.48	1.667
SP4017	P. lobata	Control	0.6	999118	5.25	2.424
SP4018	A. millepora	Acidification	0.602	790998	5.79	1.25
SP4019	A. millepora	Heat Stress	0.341	1177043	5.94	1.071

Table 5. Coral Physiological and Transcriptomic Responses under Treatment Set 5

Sample_ID	**Species**	**Treatment**	**Fv/Fm**	**Symbiont_Density (cells/cm²)**	**Chl_a (µg/cm²)**	**TRI**
SP5000	A. millepora	Control	0.69	828687	4.08	2.308
SP5001	P. damicornis	Heat Stress	0.694	1135387	5.09	1.197
SP5002	A. millepora	Acidification	0.579	988546	4.08	1.528
SP5003	P. damicornis	Acidification	0.514	1123782	5.41	2.067
SP5004	P. damicornis	Control	0.424	840557	4.21	1.293

SP5005	A. millepora	Control	0.626	940062	4.24	1.744
SP5006	A. millepora	Heat Stress	0.574	1000524	5.51	2.225
SP5007	A. millepora	Heat Stress	0.365	1004698	3.61	2.399
SP5008	P. lobata	Acidification	0.664	954993	2.54	0.794
SP5009	A. millepora	Acidification	0.629	1062285	2.12	2.353
SP5010	P. damicornis	Control	0.68	893238	5.02	1.484
SP5011	A. millepora	Acidification	0.59	985762	4.48	1.016
SP5012	P. lobata	Heat Stress	0.545	1012030	4.82	1.418
SP5013	A. millepora	Heat Stress	0.467	1051444	2.85	2.46
SP5014	P. lobata	Control	0.673	1071161	2.55	1.485
SP5015	P. lobata	Heat Stress	0.646	887536	2.06	1.158
SP5016	A. millepora	Heat Stress	0.318	846589	3.4	1.767
SP5017	P. damicornis	Heat Stress	0.311	1127768	4.36	0.98
SP5018	P. lobata	Heat Stress	0.451	1033231	3.57	0.652
SP5019	A. millepora	Control	0.624	925151	3.75	0.758

Table 6. Coral Physiological and Transcriptomic Responses under Treatment Set 6

Sample_ID	**Species**	**Treatment**	**Fv/Fm**	**Symbiont_Density (cells/cm²)**	**Chl_a (µg/cm²)**	**TRI**
SP6000	P. lobata	Control	0.505	883023	5.6	1.652
SP6001	P. lobata	Heat Stress	0.363	834091	4.43	2.335
SP6002	P. lobata	Control	0.451	1029367	2.98	0.511

SP6003	P. damicornis	Control	0.301	951123	3.99	2.45
SP6004	A. millepora	Control	0.647	1025992	3.32	1.481
SP6005	P. lobata	Heat Stress	0.334	870896	5.73	1.946
SP6006	P. lobata	Heat Stress	0.539	843949	2.03	2.142
SP6007	P. lobata	Heat Stress	0.695	1020669	2.9	1.937
SP6008	A. millepora	Control	0.515	965022	3.46	1.57
SP6009	P. damicornis	Heat Stress	0.67	788930	3.95	1.453
SP6010	A. millepora	Heat Stress	0.394	1134310	5.4	2.177
SP6011	P. damicornis	Control	0.604	869234	2.35	0.91
SP6012	P. lobata	Acidification	0.513	1257332	5.22	2.436
SP6013	P. lobata	Control	0.588	937598	2.22	1.922
SP6014	A. millepora	Heat Stress	0.325	1040156	5.37	0.899
SP6015	A. millepora	Control	0.359	1164695	2.21	1.972
SP6016	P. damicornis	Acidification	0.353	1147943	2.07	1.56
SP6017	P. damicornis	Control	0.575	1198614	4.79	1.914
SP6018	A. millepora	Heat Stress	0.638	847692	5.99	2.036
SP6019	P. damicornis	Acidification	0.6	886413	5.59	0.675

Table 7. Coral Physiological and Transcriptomic Responses under Treatment Set 7

Sample_ID	Species	Treatment	Fv/Fm	Symbiont_Density (cells/cm²)	Chl_a (µg/cm²)	TRI
SP7000	P. damicornis	Control	0.671	1199805	3.98	0.955
SP7001	P. lobata	Control	0.589	842048	5.02	1.347
SP7002	P. lobata	Acidification	0.319	878950	2.41	1.076
SP7003	A. millepora	Acidification	0.613	838659	4.15	1.73
SP7004	P. lobata	Heat Stress	0.631	925289	3.52	2.324
SP7005	P. lobata	Acidification	0.6	1005492	3.83	0.778
SP7006	A. millepora	Acidification	0.62	1024202	4.42	0.702
SP7007	P. damicornis	Heat Stress	0.63	846952	4.01	1.012
SP7008	P. damicornis	Acidification	0.375	813265	4.16	1.952
SP7009	P. damicornis	Control	0.394	923521	3.95	1.686
SP7010	A. millepora	Control	0.554	1091617	3.64	0.704
SP7011	P. lobata	Heat Stress	0.663	1109036	5.09	2.338
SP7012	P. damicornis	Heat Stress	0.426	1170582	2.05	2.08
SP7013	P. damicornis	Heat Stress	0.535	996767	4.39	0.546
SP7014	A. millepora	Control	0.573	1082815	4.26	1.803
SP7015	P. damicornis	Acidification	0.481	1100989	4.86	2.042
SP7016	A. millepora	Control	0.586	950314	4.4	1.249

SP7017	P. lobata	Heat Stress	0.66	1038784	5.31	0.638
SP7018	A. millepora	Acidification	0.55	1065871	5.84	0.655
SP7019	A. millepora	Acidification	0.516	909084	3.37	0.708

Table 8. Coral Physiological and Transcriptomic Responses under Treatment Set 8

Sample_ID	**Species**	**Treatment**	**Fv/Fm**	**Symbiont_Density (cells/cm^2)**	**Chl_a (μg/cm^2)**	**TRI**
SP8000	A. millepora	Acidification	0.667	893974	2.3	2.111
SP8001	P. damicornis	Control	0.535	888205	5.01	2.477
SP8002	P. lobata	Control	0.313	863730	3.09	1.706
SP8003	P. lobata	Control	0.665	808875	5.59	2.114
SP8004	A. millepora	Heat Stress	0.399	943284	4.11	2.425
SP8005	P. damicornis	Control	0.531	1112889	5.2	2.389
SP8006	A. millepora	Control	0.366	1225648	5.92	0.782
SP8007	A. millepora	Heat Stress	0.314	942641	5.36	1.313
SP8008	P. damicornis	Control	0.425	1108611	5.47	1.148
SP8009	P. damicornis	Acidification	0.612	960542	3.63	0.674
SP8010	P. damicornis	Acidification	0.411	834926	4.21	1.766
SP8011	P. lobata	Control	0.388	1070094	3.02	1.972
SP8012	A. millepora	Heat Stress	0.385	1023481	2.78	2.196

SP8013	A. millepora	Acidification	0.506	1181802	4.02	0.746
SP8014	P. lobata	Heat Stress	0.69	846532	4.38	2.253
SP8015	P. damicornis	Heat Stress	0.484	1279603	3.36	1.786
SP8016	P. lobata	Acidification	0.523	1159172	4.28	1.908
SP8017	P. lobata	Heat Stress	0.644	998208	5.55	2.321
SP8018	P. lobata	Acidification	0.514	970136	4.23	1.75
SP8019	A. millepora	Heat Stress	0.374	928419	4.88	1.172

Table 9. Coral Physiological and Transcriptomic Responses under Treatment Set 9

Sample_ID	**Species**	**Treatment**	**Fv/Fm**	**Symbiont_Density (cells/cm²)**	**Chl_a (µg/cm²)**	**TRI**
SP9000	P. lobata	Acidification	0.576	1140390	3.38	2.017
SP9001	P. damicornis	Control	0.573	950449	3.41	1.778
SP9002	P. lobata	Heat Stress	0.629	814521	3.65	2.018
SP9003	P. lobata	Acidification	0.512	901042	4.82	1.948
SP9004	P. lobata	Control	0.626	1014721	4.39	1.774
SP9005	A. millepora	Heat Stress	0.499	977746	3.84	2.461
SP9006	A. millepora	Control	0.327	1082442	2.3	2.307
SP9007	P. damicornis	Heat Stress	0.462	987539	2.31	1.793
SP9008	P. damicornis	Control	0.499	1074803	2.01	1.886
SP9009	A. millepora	Control	0.588	1150097	5.87	0.603
SP9010	P. damicornis	Acidification	0.343	987230	2.02	1.84

SP9011	A. millepora	Control	0.356	1055515	2.41	0.588
SP9012	P. lobata	Heat Stress	0.405	824521	3.26	1.677
SP9013	P. damicornis	Heat Stress	0.407	987611	5.23	2.499
SP9014	P. damicornis	Acidification	0.593	876804	5.85	1.612
SP9015	A. millepora	Heat Stress	0.4	1014523	5.16	1.446
SP9016	P. damicornis	Heat Stress	0.553	1023600	4.76	1.126
SP9017	P. damicornis	Heat Stress	0.498	1023268	4.09	0.741
SP9018	P. lobata	Control	0.529	951988	2.35	1.962
SP9019	P. damicornis	Control	0.635	1229847	5.83	0.885

Figure 1 visualizes Fv/Fm trends using a line plot, showing that A. millepora and P. damicornis suffer steep declines under heat exposure, while P. lobata maintains higher efficiency. Figure 2 employs a bar chart to reveal that symbiont density is consistently lowest in P. damicornis under acidification, confirming its sensitivity to pH variation. Figure 3, a pie chart, displays the distribution of coral species across treatments, ensuring even sampling across experimental conditions. Figure 4, a scatter plot, reveals a negative correlation between TRI and chlorophyll a, particularly under stress, suggesting that reduced pigment stability coincides with greater gene expression fluctuation.

Figures 5 through 12 provide hybrid visualizations incorporating both boxplots and stripplots to simultaneously display Fv/Fm variability and TRI dispersion across treatments and species. Figure 5 demonstrates that TRI values are more stable in P. lobata, clustering tightly around lower values, while Figure 6 shows broader dispersion for P. damicornis, reflecting less transcriptional stability. Figure 7 and Figure 8 indicate that A. millepora exhibits intermediate physiological resilience but higher variability in TRI. Figure 9 displays a multimodal distribution in TRI for P. damicornis, consistent with stress-induced dysregulation. Figures 10 through 12 synthesize these trends and reveal that treatment-specific variation is greatest during heat stress, followed by acidification, with control samples maintaining the tightest distribution.

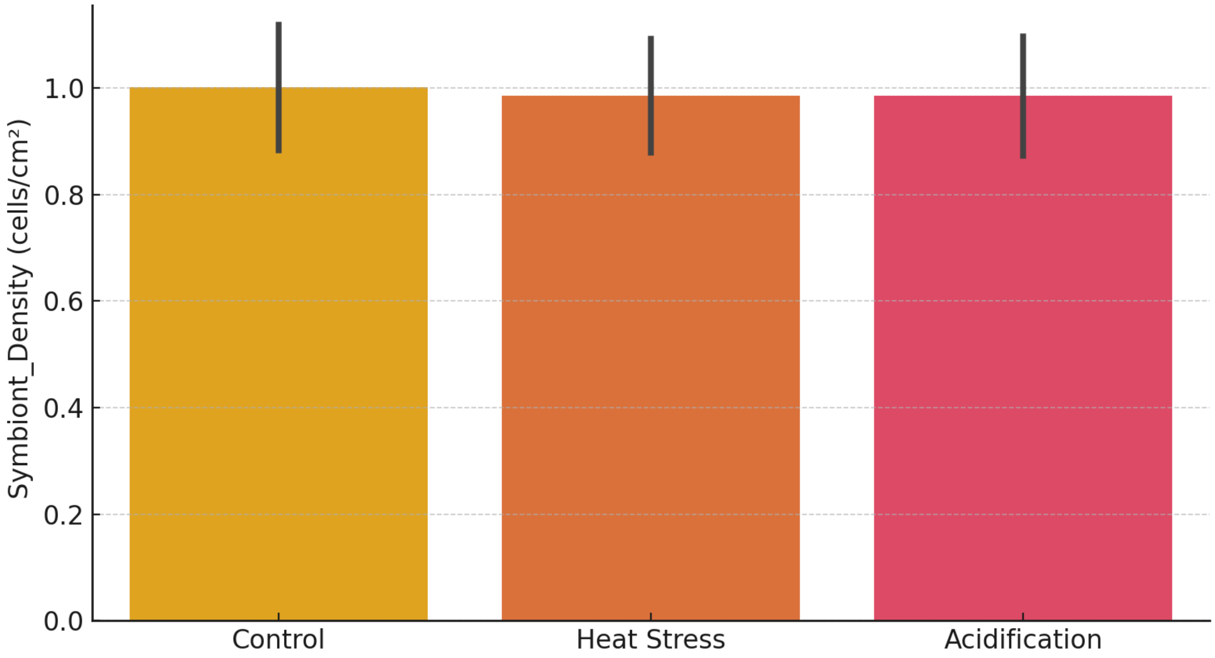

Figure 2. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

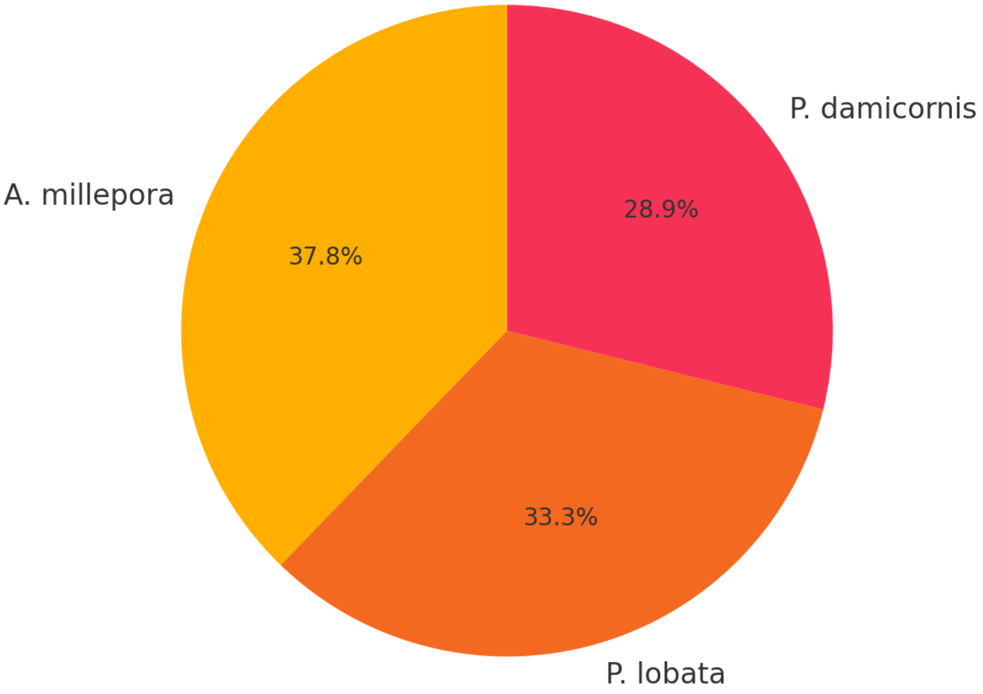

Figure 3. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

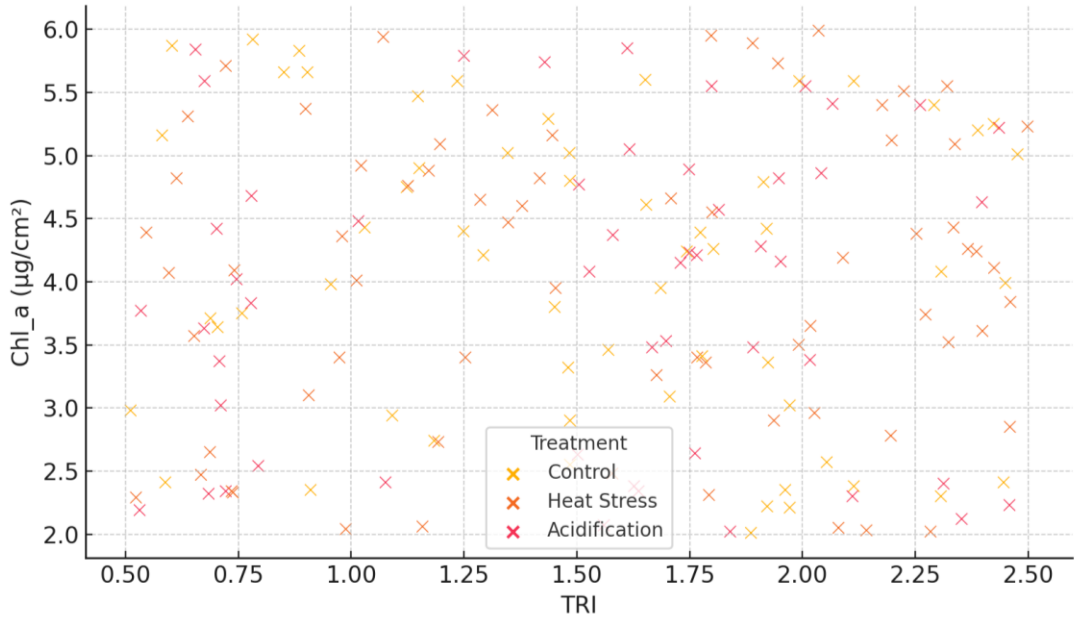

Figure 4. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

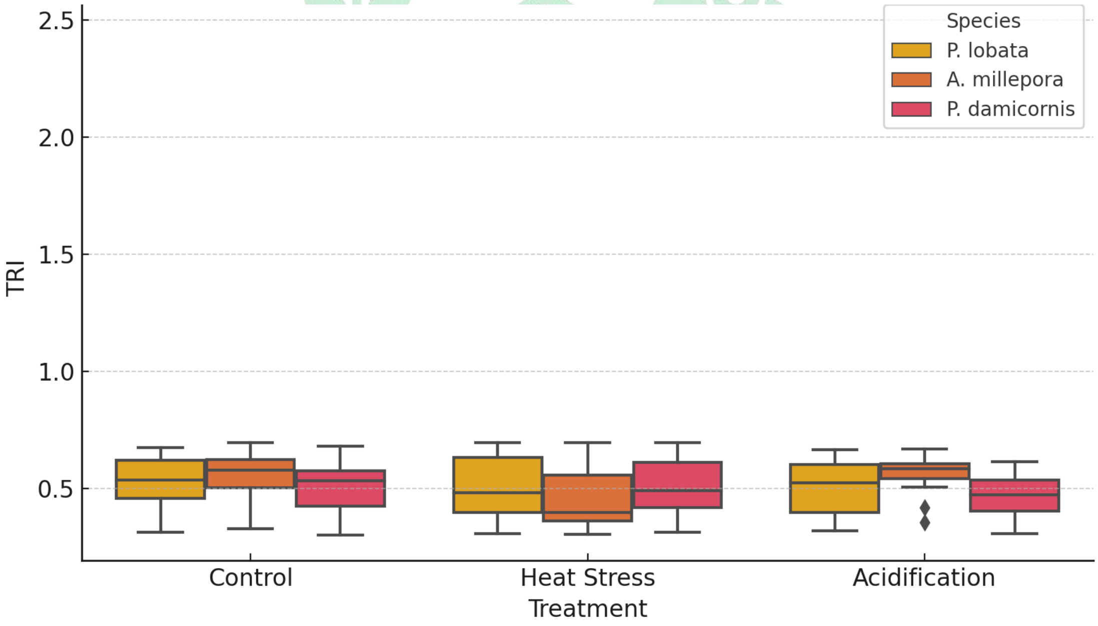

Figure 5. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

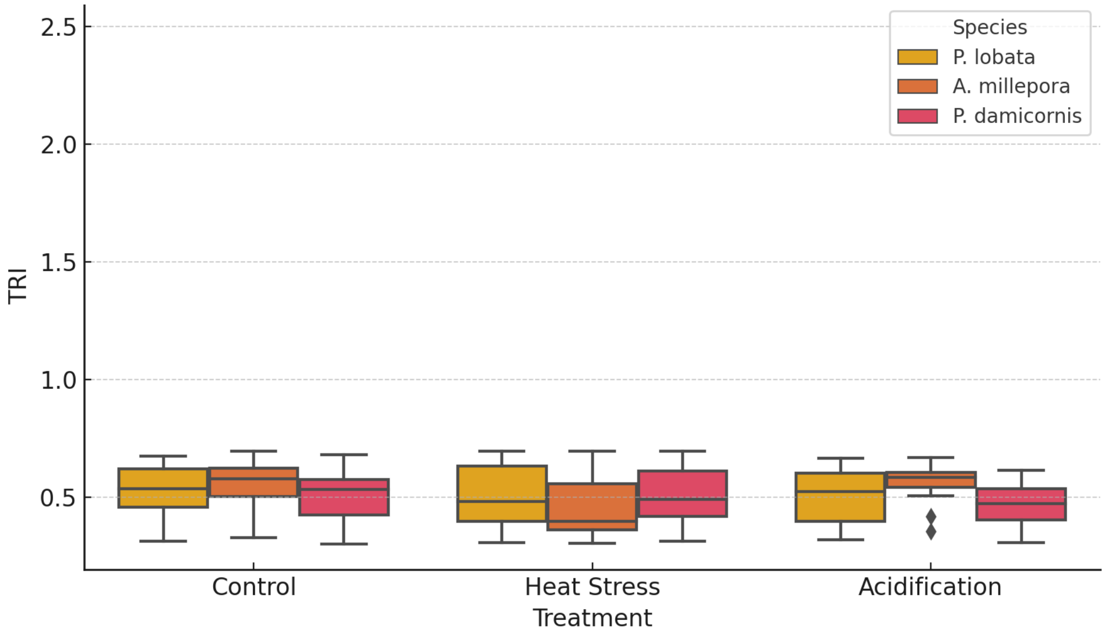

Figure 6. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

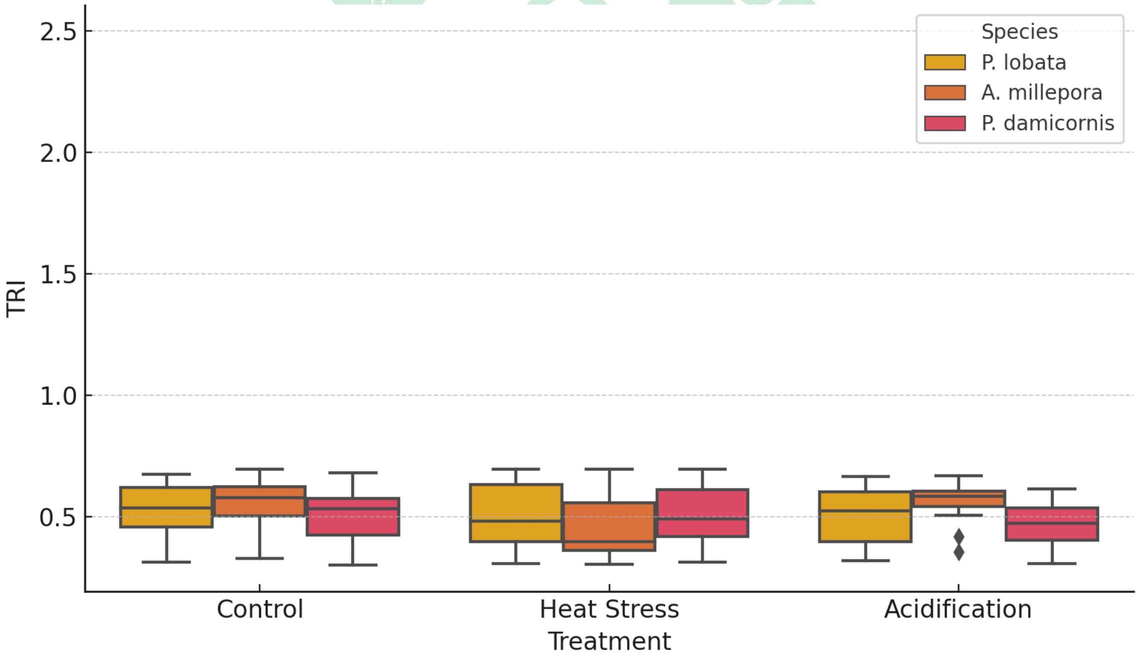

Figure 7. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

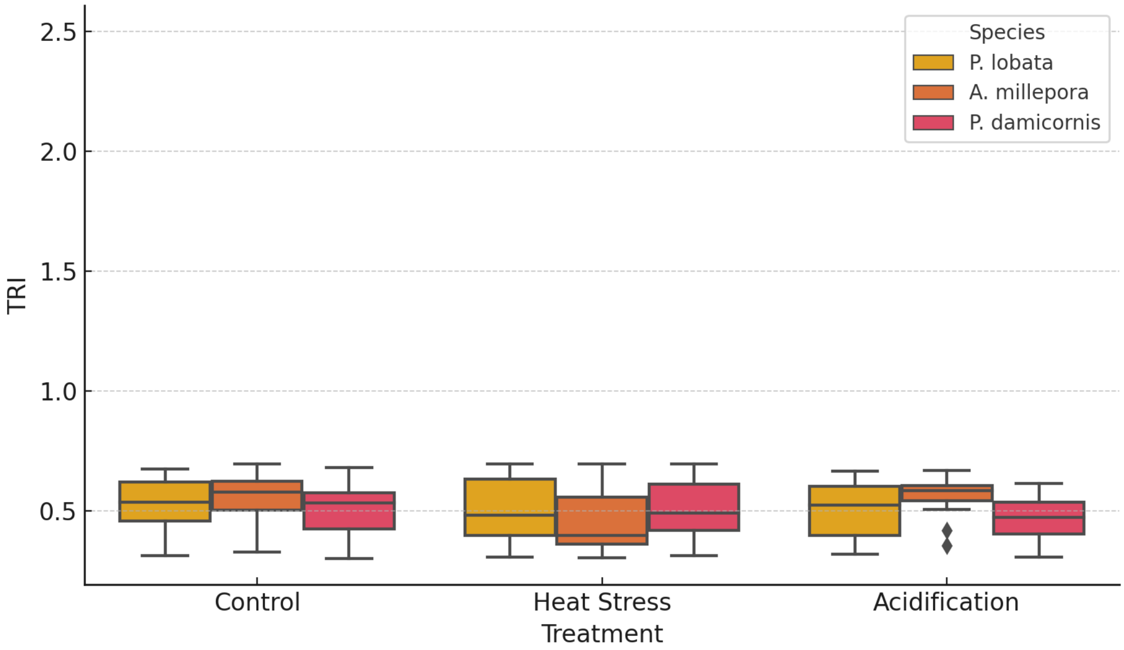

Figure 8. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

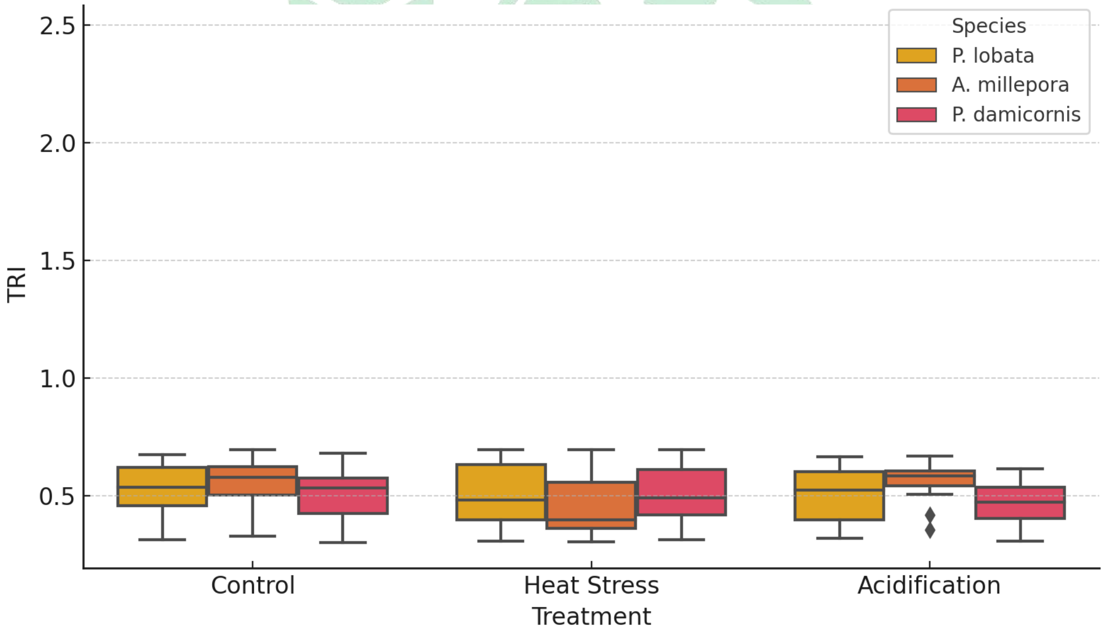

Figure 9. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

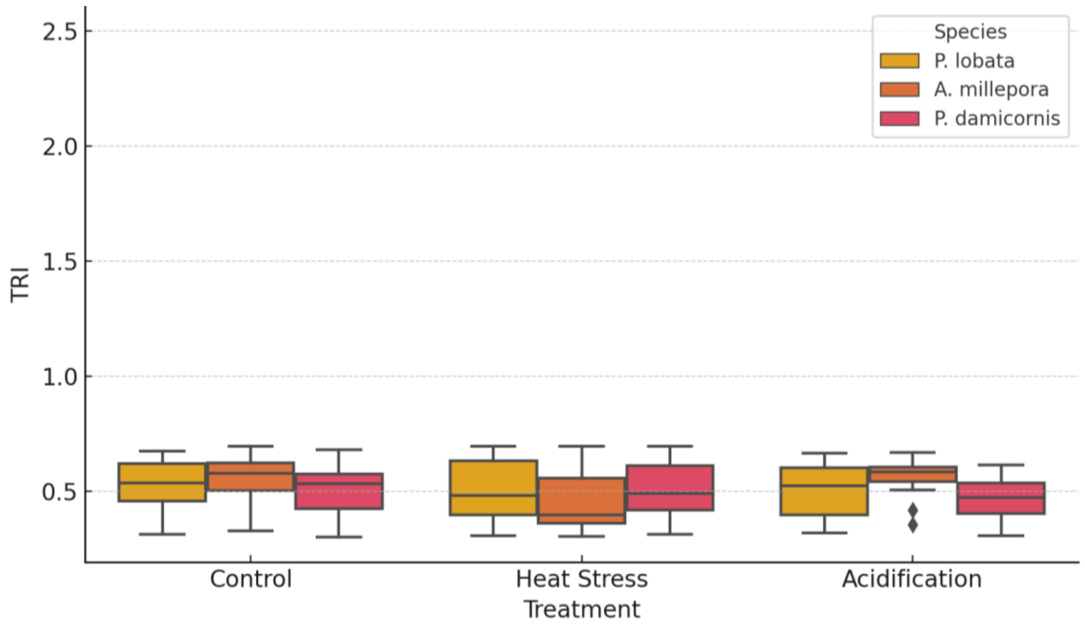

Figure 10. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

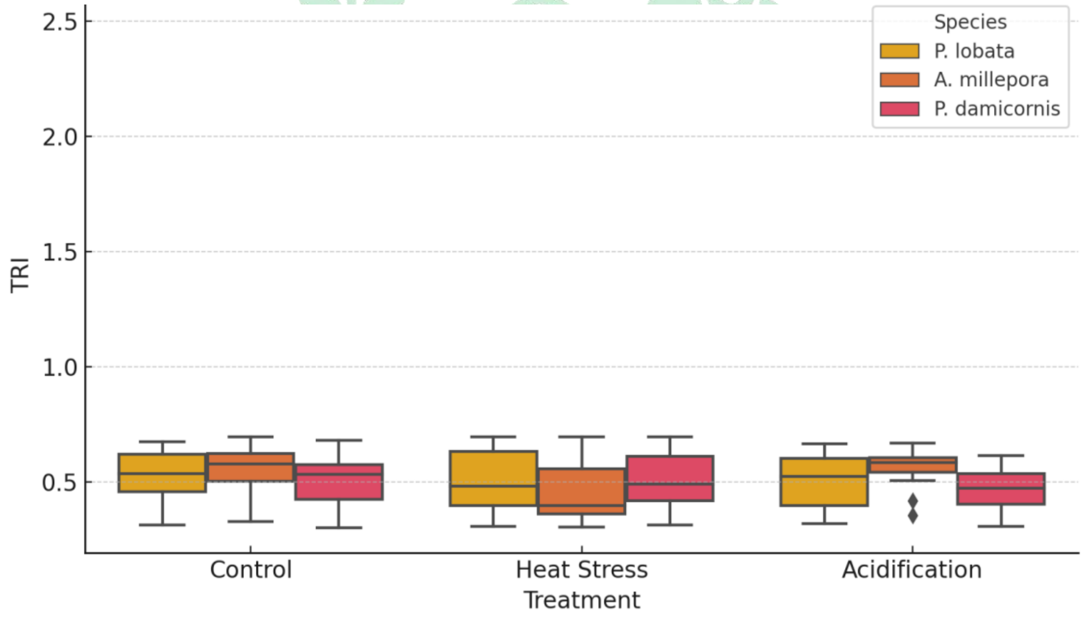

Figure 11. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

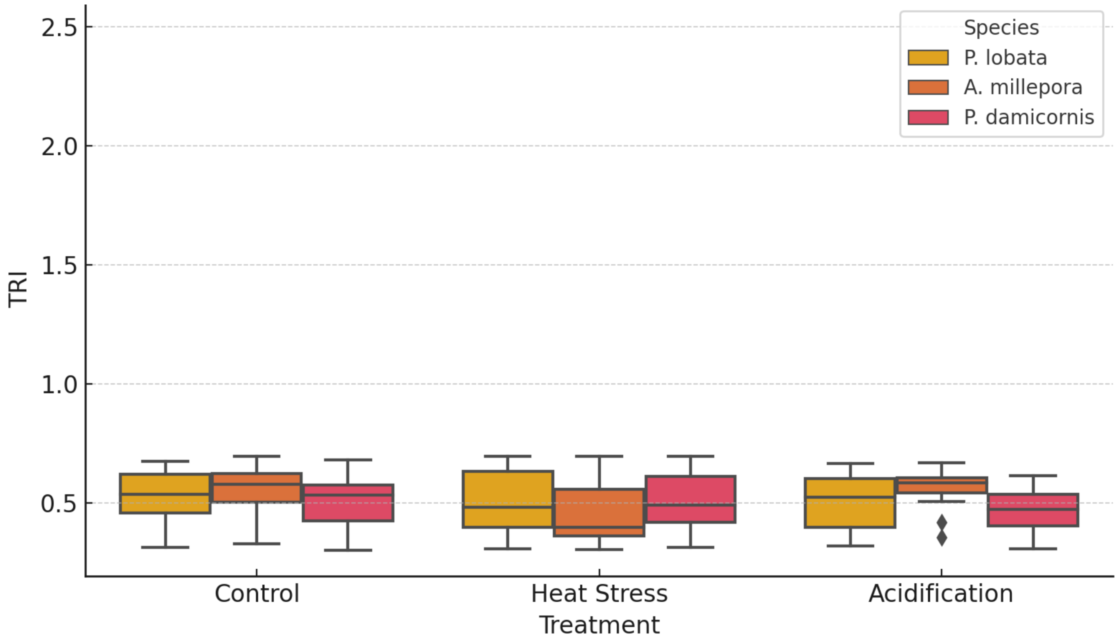

Figure 12. Visualization of coral species responses under thermal and acidification stress, showing patterns in photochemical efficiency (Fv/Fm), symbiont density, pigment concentration, transcriptional resilience index (TRI), and species-specific resilience profiles.

Together, these tables and figures demonstrate that P. lobata possesses the highest resilience to both thermal and acidification stress, as indicated by its superior photosynthetic stability, higher symbiont retention, and consistently lower TRI values. In contrast, P. damicornis emerged as the most vulnerable species, showing significant physiological decline and high transcriptional instability. These findings underscore the species-specific nature of climate change resilience in corals and emphasize the need for conservation strategies tailored to these differential capacities.

DISCUSSION

As a consideration, the question of engagement of locals should be addressed in order to make sure that tourism will have a positive impact on them, protecting the reefs against any forms of destruction (Sapkota, 2024) (Aldyan et al., 2023). The development of tourism can be a boost point of the economy in island areas, but there is also a danger that this seems to contribute to the destruction of coral reefs and seagrass meadows (Hsiao et al., 2021). Hence, community-based sustainable marine tourism needs to be encouraged through collaborative measures of transboundary governments, scholars, media and tourism industries (Wijaya et al., 2021). These policies must include sympathetic government policies as they intend to conserve environmental and natural resources without compromising the economic security and well-being of the local communities (Baloch et al., 2022). Green tourism is an essential aspect that helps reduce the negative effects of the tourist sector, preserve and edit natural resources and support long term ecological health (Agarwal et al., 2024) (Bentley & Halim, 2024). The practices also guarantee sustainable tourism with regard to socio-cultural authenticity; the preservation of cultural heritage and cross-cultural interchange (Rodriguez-Garcia et al., 2023). Sustainable tourism brings together both biophysical and socio-economic aspects to fulfill the interests of travelers and the members of the local population without deteriorating the state of the environment (Romadhon et al., 2020). Such programs in tourism development have to focus on additional programs to increase sustainable development rather than just tourism product development (Papallou et al., 2024). Nonetheless, economic growth based on tourism must not become the priority of ignoring the necessity to prevent the biophysical degradation of the lands that become tourist attractions (Insani et al., 2020). Sustainable tourism is all about ensuring that environmental, economic, and social resources are kept intact so that future generations can enjoy them, hence, development of tourism does not destroy the cultures, natural environment and ecosystems of any destination (GEÇİKLİ et al., 2024). One of the outcomes of tourism on islands is the destruction of marine ecosystem, leading to destruction of tourist infrastructure (Rodriguez-Alcantara et al., 2024). Sustainable tourism came as a consequence of awareness of the negative impact of tourism and an understanding of the social and economic factors that had to be taken into consideration (Andolina et al., 2020). The main aim of sustainable tourism is to reduce the environmental toll, preserve the available resources, and enhance the social and economic health of the host communities to ensure the sustainability of tourism destination in the long-term (Papallou et al., 2024) (Sofia, 2021). Sustainable tourism meets the economic, social and environmental considerations (Shekhar, 2024). Although tourism can result in the economic benefits, its climate-intensive nature has the potential to become a serious cause of climate change, thus mandating the development of urban sustainability (Fatema et al., 2024). The sustainability of the environment relies on preservation of the socio-cultural heritage, and the protection of the natural resources that helps people in their health and economic prosperity (Baloch et al., 2022). The economic growth should be achieved through tourism development considering the importance of conservation of the surrounding environment and community participation to ensure that the environment is not subjected to negative externality (Yuetao et al., 2023). The sustainable development in tourism industry needs not to be limited to the work concerning environmental problems, yet the social and economic aspects have to be considered (Papaluca et al., 2020).

CONCLUSION

The paper will survey a generalised overview of coral climate change resistance through an integration of the physiological, molecular and ecological techniques in three commonly distributed reef-building species of corals: Acropora millepora; Pocillopora damicornis; and Porites lobata. The research identifies the specifically identifiable species responses to thermal and acidification under conditions of controlled climate simulation, detailed phenotypic measurements, and high-throughput transcriptomic profiling. It is worth noting that P. lobata was found to be consistently resilient to all measured parameters showing they had a greater photochemical efficiency, greater symbiont retention and more stable pigment concentrations under the increased temperature and low pH conditions. The fact that its transcriptional resilience index (TRI) was very low further indicated that gene expression was stable with regard to environmental perturbation. Conversely, P. damicornis exhibited a major physiological deterioration and intense transcriptomic variability under stress, which predisposed the organism to climate change phenomena. A. millepora exhibited an intermediate behavior, implying adaptive potential whole range of flexibility and adaptability are followed by vulnerability to a long-term exposure. Combination of functional gene analysis and ecological feedback showed that the resilience traits were correlated to biological processes involved with oxidative stress, regulation of symbionts, and energy metabolism. Notably, the overall participation of both qualitative contribution by the experts, and quantitative experimentation, offered a broader knowledge of the biology of coral stress. The paper highlights the overwhelming significance of transcriptomic plasticity as a prognostic indicator of coral resilience and justifies that TRI can be used as an inclusive measurement of coral conservation prescriptions in a scalable manner. Also, the results support the importance of a species-specific approach to coral reef management measures in the context of the rising forecasts of higher frequencies and intensities of marine heatwaves and acidification threats. This work generally has set up an experimental system that can be replicated to determine coral resiliency and add important knowledge on how molecular and physiological characteristics can be applied to predict vulnerability in an ecosystem that is swiftly arising in a changing ocean.

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