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# Thermal Stress, Microplastic Pollution, and Coral Reef Resilience: A Comparative Environmental Analysis of the Great Barrier Reef and the Coral Triangle

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**ABSTRACT**

Coral reef ecosystems are increasingly exposed to interacting climate and pollution stressors that alter physiological tolerance, microbial stability, carbonate accretion, and long-term ecological resilience. This study examines how thermal stress and microplastic contamination influence coral reef vulnerability through a comparative environmental analysis of the Great Barrier Reef and the Coral Triangle. The article argues that reef degradation cannot be adequately explained by ocean warming alone because local pollution, hydrodynamic retention, reef governance, and biological community structure mediate the ecological consequences of marine heatwaves. Using interdisciplinary environmental analysis, satellite-derived thermal stress evidence, peer-reviewed ecological studies, coral bleaching records, microplastic pollution literature, and international scientific reports, the study compares two reef systems with high ecological significance but different oceanographic, institutional, and anthropogenic pressures. The findings indicate that thermal anomalies drive bleaching risk through disruption of coral–Symbiodiniaceae photosymbiosis, oxidative stress, and metabolic imbalance, whereas microplastics intensify ecological vulnerability by altering coral feeding, microbial assemblages, disease susceptibility, and contaminant exposure. The comparative evidence suggests that the Great Barrier Reef exhibits stronger monitoring and governance capacity but high recurrent thermal exposure, while the Coral Triangle exhibits exceptional biodiversity and adaptive potential but higher coastal pollution pressure and governance fragmentation. This article contributes to natural sciences scholarship by integrating climate physiology, pollution ecology, marine biogeochemistry, and reef resilience

theory into a comparative framework for understanding coral ecosystem sustainability.

**Keywords:** coral bleaching; microplastics; marine heatwaves; reef resilience; climate change; Coral Triangle; Great Barrier Reef; environmental stress; marine ecology; sustainability science

## INTRODUCTION

Coral reefs are among the most biologically diverse and socio-ecologically valuable ecosystems on Earth, yet they are increasingly threatened by interacting global and local environmental stressors. Rising sea surface temperatures, marine heatwaves, ocean acidification, eutrophication, sedimentation, overfishing, and plastic pollution are transforming reef structure, coral physiology, microbial ecology, and ecosystem services at unprecedented rates (Hughes et al., 2018; IPCC, 2023). The global significance of reef decline extends beyond biodiversity loss because coral reefs support fisheries, coastal protection, tourism economies, carbon and calcium carbonate cycling, and cultural livelihoods for hundreds of millions of people (Hoegh-Guldberg et al., 2019; UNEP, 2024).

The global climate context is particularly severe. The IPCC (2023) concludes that climate change has already caused widespread impacts on marine and coastal ecosystems, including increased heat stress and reduced ecological resilience. NASA reports that the ocean has absorbed approximately 90% of excess heat from planetary warming since the mid-twentieth century, making ocean heat content a central indicator of climate change (NASA, 2025). NOAA confirmed the fourth global coral bleaching event in April 2024, and subsequent Coral Reef Watch updates reported that bleaching-level heat stress affected a very large proportion of the world's reef area during 2023–2025 (NOAA, 2025). These observations indicate that coral reefs are no longer facing isolated stress events but recurrent and spatially extensive disturbances.

Thermal stress affects corals primarily by destabilizing the symbiosis between the cnidarian host and photosynthetic Symbiodiniaceae. Under elevated temperature, photosynthetic electron transport becomes impaired, reactive oxygen species accumulate, cellular damage increases, and corals expel or lose symbiotic algae, producing bleaching (Lesser, 2011; Suggett & Smith, 2020). If thermal stress persists, energetic depletion reduces growth, reproduction, immune competence, calcification, and survival (Hughes et al., 2018). However, bleaching outcomes vary substantially across species, habitats, thermal histories, nutrient regimes, hydrodynamic conditions, and local disturbance profiles (Sully et al., 2019; McClanahan, 2022).

Plastic pollution has emerged as an additional global stressor with increasing relevance for reef systems. UNEP estimates that 19–23 million tonnes of plastic waste leak into aquatic ecosystems annually, contaminating rivers, lakes, seas, and coastal environments (UNEP, 2025). Microplastics, typically defined as plastic particles smaller than 5 mm, can be ingested by corals, adsorb persistent organic pollutants, alter microbial communities, and influence disease dynamics (Hall et al., 2015; Lamb et al., 2018; Reichert et al., 2019). While thermal bleaching has received extensive attention, the interaction between microplastic contamination and climate-induced physiological stress remains insufficiently integrated in reef resilience

 

research.

The Great Barrier Reef and the Coral Triangle provide scientifically important comparative contexts. The Great Barrier Reef is one of the world's largest reef systems and has experienced repeated mass bleaching events since 1998, with severe events in 2016, 2017, 2020, 2022, and 2024 (Hughes et al., 2018; NOAA, 2024). It also benefits from extensive monitoring infrastructure, marine park governance, and long-term ecological datasets. The Coral Triangle, spanning parts of Indonesia, Malaysia, the Philippines, Papua New Guinea, Timor-Leste, and Solomon Islands, contains the highest coral biodiversity globally and supports major fisheries and coastal livelihoods (Veron et al., 2015; Hoegh-Guldberg et al., 2019). However, it faces intense coastal development, plastic leakage, land-based pollution, and governance complexity.

Existing literature has substantially advanced understanding of coral bleaching and climate vulnerability. Hughes et al. (2018) demonstrated that recurrent mass bleaching events reduce recovery windows and transform reef assemblages. Sully et al. (2019) showed that bleaching risk varies with thermal history and depth, indicating that ecological responses depend on environmental context rather than temperature alone. Hoegh-Guldberg et al. (2019) emphasized that coral reefs are among the ecosystems most vulnerable to warming beyond 1.5°C. Other researchers argue that local management remains important because reducing pollution, overfishing, and sedimentation can increase ecological resistance and recovery capacity (Graham et al., 2015; McClanahan, 2022).

Pollution ecology studies provide complementary evidence. Hall et al. (2015) found that corals can ingest microplastics, raising concerns regarding feeding interference and physiological stress. Lamb et al. (2018) reported that plastic contact was associated with elevated disease likelihood in reef-building corals across the Asia-Pacific region. Reichert et al. (2019) demonstrated that microplastic exposure can affect coral performance depending on particle type and concentration. However, current natural sciences literature fails to fully explain how microplastic exposure interacts mechanistically with thermal stress across reef systems with different biodiversity, oceanography, and governance contexts.

A further limitation concerns scale integration. Climate studies often rely on satellite-derived thermal stress indicators, while microplastic studies frequently use laboratory exposure experiments or localized field sampling. These approaches are individually valuable but insufficiently integrated. Existing scientific scholarship remains limited in connecting satellite-scale thermal anomalies, organismal stress physiology, reef microbiome alteration, and local pollution pathways within a comparative systems framework.

This article addresses these gaps by integrating environmental science, marine ecology, climate physiology, pollution chemistry, and sustainability science. The study does not claim to generate new laboratory measurements; rather, it synthesizes empirically verifiable evidence from peer-reviewed studies, international scientific reports, satellite monitoring, and comparative ecological datasets. The novelty lies in the comparative analytical framework that links thermal stress and microplastic pollution through shared physiological and ecological mechanisms affecting coral resilience.

The central analytical framework is: environmental stressors → physicochemical and biological response → coral physiological disruption → reef community transformation → ecosystem resilience outcomes. Thermal stress operates through elevated sea surface temperature, oxidative stress, symbiosis breakdown, and bleaching. Microplastic pollution operates through ingestion, surface-associated microbial transport, contaminant exposure, physical abrasion, and disease facilitation. Their combined effects may reduce ecological resilience by weakening coral energy balance, immune response, recruitment capacity, and microbial stability.

This study aims to analyze comparatively how thermal stress and microplastic pollution influence coral reef resilience in the Great Barrier Reef and the Coral Triangle, and to identify the physical, chemical, biological, and ecological mechanisms through which these interacting stressors shape measurable environmental outcomes and sustainability implications.

## METHODOLOGY

This study employs a comparative interdisciplinary environmental research design integrating satellite-based climate stress interpretation, peer-reviewed ecological synthesis, pollution-mechanism analysis, and systems-oriented reef resilience assessment. The Great Barrier Reef and the Coral Triangle were selected because they represent two globally significant reef systems with contrasting but analytically complementary characteristics: the Great Barrier Reef has extensive monitoring capacity, repeated documented bleaching exposure, and comparatively strong marine governance, whereas the Coral Triangle has exceptional coral biodiversity, high socio-ecological dependence, intense coastal pollution pressure, and complex transboundary management conditions. The unit of analysis consists of reef-system response to interacting environmental stressors, specifically thermal anomaly exposure and microplastic contamination. The analytical variables include sea surface temperature anomalies, bleaching-level heat stress, coral–Symbiodiniaceae stability, oxidative stress response, coral disease susceptibility, microplastic exposure pathways, biodiversity-mediated resilience, governance-relevant monitoring capacity, and ecosystem service vulnerability. The theoretical-methodological alignment follows reef resilience theory and stress physiology by linking environmental forcing to organismal mechanisms and ecosystem-scale outcomes.

The empirical foundation is derived from satellite and monitoring products, including NOAA Coral Reef Watch thermal stress assessments and NASA ocean warming indicators, combined with IPCC climate synthesis evidence, UNEP plastic pollution assessments, peer-reviewed coral physiology literature, microplastic exposure studies, reef biodiversity datasets, and ecological resilience research. Analytical interpretation was conducted through comparative systems analysis rather than fabricated primary measurement, with evidence triangulated across satellite observations, field-based ecological studies, laboratory exposure experiments, and international scientific reports. Mechanistic comparison focused on causal pathways connecting heat stress, oxidative damage, symbiosis disruption, plastic ingestion, microbial dysbiosis, disease risk, and reef recovery potential. Validation was strengthened by prioritizing convergent findings across independent data sources and by distinguishing between directly observed patterns, experimentally supported mechanisms, and plausible but still uncertain interactive effects. Ethical and environmental considerations were addressed by relying exclusively on published, publicly available data without

disturbing reef organisms or protected habitats. The principal limitation is that cross-system inference remains constrained by uneven monitoring intensity and heterogeneous microplastic sampling methods; nevertheless, the design provides robust analytical transferability for evaluating interacting climate and pollution stressors in coral reef ecosystems.

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## Findings and Discussion

### 1. Thermal Stress, Bleaching Dynamics, and Physiological Vulnerability

The comparative evidence demonstrates that thermal stress is the dominant large-scale driver of acute coral bleaching in both the Great Barrier Reef and the Coral Triangle. Elevated sea surface temperatures and prolonged marine heatwaves create physiological instability within coral holobionts by disrupting photosynthesis in Symbiodiniaceae, increasing reactive oxygen species, damaging cellular structures, and reducing host–symbiont metabolic coordination (Lesser, 2011; Suggett & Smith, 2020). Bleaching is therefore not merely a visual ecological symptom but a measurable physiological breakdown of symbiotic energy exchange.

The Great Barrier Reef provides strong empirical evidence of repeated thermal disturbance. Mass bleaching events in 2016 and 2017 affected large spatial areas and demonstrated that short recovery intervals can reduce reef-scale resilience (Hughes et al., 2018). Later bleaching events further indicated that recurrent thermal anomalies are becoming a chronic ecological pressure rather than exceptional disturbances. NOAA's confirmation of the fourth global coral bleaching event in 2024 reinforces that coral reefs are increasingly exposed to heat stress at planetary scale (NOAA, 2024).

The Coral Triangle is also highly vulnerable to thermal stress, but its response is mediated by exceptional biodiversity, heterogeneous reef habitats, and variable local conditions. High coral diversity may increase portfolio effects, where different species exhibit different tolerances and recovery strategies (Veron et al., 2015). However, biodiversity alone does not guarantee resilience when heat stress is recurrent and compounded by pollution, overfishing, and coastal development. In some Coral Triangle sites, shallow reefs, restricted circulation, and land-based pollution may amplify thermal stress impacts by reducing water quality and increasing metabolic stress.

Cross-system comparison indicates that the Great Barrier Reef has stronger monitoring resolution and a clearer long-term bleaching record, while the Coral Triangle has greater biological heterogeneity but less evenly distributed monitoring. This difference matters scientifically because observed vulnerability may partly reflect measurement intensity. The Great Barrier Reef is often interpreted as highly climate-exposed because thermal events are well documented, whereas Coral Triangle degradation may be underestimated where monitoring is less systematic.

The findings support previous scholarship showing that bleaching risk is governed by both thermal intensity and ecological context (Sully et al., 2019; McClanahan, 2022). They also extend reef resilience theory by emphasizing that monitoring capacity itself shapes scientific interpretation. A reef system with better observation

infrastructure may appear more severely affected simply because impacts are better detected.

Scientifically, thermal stress mitigation requires global greenhouse gas reduction because local management cannot prevent ocean warming. Environmentally, however, local management remains relevant because reduced pollution and herbivore protection can improve recovery potential after bleaching. The implication is that reef conservation requires multiscalar intervention linking climate policy, water quality control, biodiversity protection, and long-term monitoring.

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**2. Microplastic Pollution, Coral Health, and Biogeochemical Stress Pathways**

Microplastic contamination represents a mechanistically distinct but ecologically interacting stressor. Unlike thermal anomalies, which operate primarily through energy imbalance and oxidative stress, microplastics affect corals through ingestion, surface contact, physical abrasion, contaminant transport, microbial colonization, and disease facilitation (Hall et al., 2015; Lamb et al., 2018; Reichert et al., 2019). These pathways are especially important because coral health depends on stable tissue surfaces, efficient feeding, microbial regulation, and immune function.

In the Great Barrier Reef, microplastic exposure is influenced by coastal runoff, tourism, fishing activity, urban discharge, and oceanographic transport. Although Australia's regulatory and monitoring systems are comparatively strong, plastics can persist and fragment in marine environments, making local control difficult. Microplastics may be ingested by coral polyps or trapped in mucus layers, potentially increasing energetic costs associated with particle rejection and tissue cleaning.

In the Coral Triangle, microplastic pollution pressure is generally intensified by dense coastal populations, riverine inputs, inadequate waste management infrastructure in some areas, and high dependence on coastal economies. UNEP reports that millions of tonnes of plastic waste enter aquatic ecosystems annually, with coastal and marine environments receiving substantial leakage (UNEP, 2025). This creates significant exposure risk for reef organisms in semi-enclosed bays, near urban centers, and around heavily populated islands.

The comparative evidence suggests that microplastic impacts may be more spatially heterogeneous than thermal stress. Thermal stress can affect entire reef provinces during marine heatwaves, while microplastic exposure often varies with proximity to rivers, urban centers, currents, tourism zones, and waste pathways. Consequently, pollution vulnerability is strongly linked to local governance, waste infrastructure, hydrodynamics, and coastal land use.

Experimental studies indicate that corals can ingest microplastics and that exposure outcomes vary by particle type, concentration, and coral species (Hall et al., 2015; Reichert et al., 2019). Lamb et al. (2018) reported associations between plastic debris and coral disease, suggesting that plastic surfaces may facilitate microbial colonization or tissue damage. These mechanisms are highly relevant under warming conditions because heat-stressed corals often exhibit reduced immune competence and altered microbiomes.

 

This reflects an important theoretical linkage: microplastics may not always produce immediate mortality under isolated conditions, but they can lower physiological margins of safety when combined with heat stress, eutrophication, or disease exposure. The stressor interaction is therefore likely nonlinear rather than additive. Small increases in pollution pressure may produce disproportionate ecological effects when corals are already thermally compromised.

The environmental implication is clear: microplastic management constitutes a reef resilience intervention. While plastic reduction cannot stop bleaching caused by marine heatwaves, it may reduce secondary stress pathways that impair recovery. Policies improving waste management, wastewater treatment, riverine plastic interception, and coastal pollution control may therefore contribute meaningfully to reef sustainability.

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### 3. Comparative Matrix of Mechanisms and Outcomes

**Table 1. Comparative Matrix of Experimental Variables, Scientific Mechanisms, and Measurable Outcomes**

| Variable | Case/System 1: Great Barrier Reef | Case/System 2: Coral Triangle | Empirical Evidence | Analytical Interpretation |
|---|---|---|---|---|
| **Thermal stress exposure** | Recurrent documented marine heatwaves and mass bleaching | High thermal vulnerability with spatially heterogeneous exposure | NOAA bleaching records; IPCC climate synthesis; peer-reviewed bleaching studies | Heat stress disrupts coral–algal symbiosis and reduces recovery windows |
| **Biodiversity structure** | High diversity but lower than Coral Triangle | Global center of coral biodiversity | Biogeographic reef diversity studies | Biodiversity may enhance response diversity but cannot fully offset recurrent heat stress |
| **Microplastic exposure** | Coastal runoff, tourism, fishing, and ocean transport | Stronger pressure from dense coastal populations and waste leakage pathways | UNEP plastic pollution assessments; reef pollution studies | Pollution risk is more locally governed than thermal exposure |
| **Physiological mechanism** | Oxidative stress, bleaching, reduced calcification | Similar heat mechanisms, compounded by local pollution in many sites | Coral physiology and bleaching literature | Shared cellular mechanisms produce system-specific |

| | | | | |
|---|---|---|---|---|
| | | | | ecological outcomes |
| **Disease and microbiome risk** | Increased after bleaching and local stress | Potentially amplified by plastic contact, eutrophication, and coastal disturbance | Plastic–disease association studies | Microplastics may intensify microbial instability and disease susceptibility |
| **Monitoring and validation** | Strong long-term monitoring and satellite integration | Uneven monitoring across countries and reef provinces | Reef monitoring programs and published datasets | Evidence certainty differs by monitoring capacity |
| **Governance relevance** | Strong marine park structure but climate exposure remains high | Transboundary governance complexity and variable waste infrastructure | Conservation and sustainability literature | Governance capacity mediates local stress reduction but not global warming |
| **Sustainability implications** | Requires climate mitigation plus local water-quality management | Requires integrated waste, fisheries, climate, and livelihood strategies | IPCC, UNEP, and ecological resilience evidence | Reef resilience depends on multiscalar environmental management |

The comparative matrix demonstrates that the Great Barrier Reef and the Coral Triangle share fundamental biological vulnerability to warming, but differ in biodiversity structure, pollution exposure, monitoring capacity, and governance context. The Great Barrier Reef illustrates how even well-managed reef systems remain highly vulnerable when global thermal forcing exceeds physiological thresholds. The Coral Triangle illustrates how biodiversity-rich systems may possess substantial adaptive potential but face intensified local pressures from pollution, coastal development, and fragmented governance.

Analytically, the table suggests that reef resilience cannot be inferred from one variable alone. Thermal exposure, microplastic contamination, biodiversity, hydrodynamics, and governance interact across scales. A reef with high biodiversity may still degrade rapidly if exposed to repeated marine heatwaves and chronic pollution. Conversely, strong governance may reduce local stress but cannot eliminate climate-driven bleaching without global mitigation.

This interpretation aligns with the broader resilience literature, which conceptualizes ecosystems as dynamic systems shaped by disturbance regimes, response diversity, feedback mechanisms, and recovery processes (Graham et al., 2015; McClanahan, 2022). The comparative evidence also supports pollution ecology studies showing that local contaminants may amplify biological vulnerability under climate stress (Lamb et al., 2018; Reichert et al., 2019).

Scientifically, the table highlights the need for integrated monitoring combining satellite thermal stress, in situ coral health surveys, microplastic quantification, microbial analysis, and recovery metrics. Environmental policy should therefore move beyond single-stressor management toward cumulative risk assessment.

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## 4. Biological Adaptation, Community Reorganization, and Reef Resilience

Coral reefs can respond to environmental stress through acclimatization, adaptation, species sorting, symbiont community shifts, and ecological reorganization. Some corals can increase thermal tolerance through association with more heat-tolerant Symbiodiniaceae, prior exposure to variable temperatures, or physiological acclimatization (Suggett & Smith, 2020). However, these mechanisms have limits when warming is rapid, recurrent, and combined with other stressors.

In the Great Barrier Reef, repeated bleaching has altered coral community composition by disproportionately affecting thermally sensitive taxa. Fast-growing branching corals may suffer high mortality during severe events, while more stress-tolerant massive corals may persist but support different habitat structures and biodiversity assemblages (Hughes et al., 2018). This produces ecological reorganization rather than simple recovery.

In the Coral Triangle, exceptional species richness may provide greater functional redundancy and adaptive diversity. However, local stressors can erode this advantage by reducing recruitment, increasing disease, degrading water quality, and damaging juvenile coral survival. Biodiversity provides resilience potential only when environmental conditions allow recovery mechanisms to operate.

The comparative evidence reveals a critical distinction between resistance and recovery. Resistance refers to the ability to withstand stress without major degradation, whereas recovery refers to the capacity to regain structure and function after disturbance. The Great Barrier Reef may benefit from strong monitoring and protected areas, but repeated heatwaves reduce recovery intervals. The Coral Triangle may benefit from high biodiversity, but local pollution and governance fragmentation may reduce recruitment success and recovery quality.

These findings support ecological theory emphasizing response diversity and functional redundancy, while also demonstrating that resilience is constrained by cumulative stress load. Existing scholarship remains limited when it treats adaptation as an inherent property of biodiversity rather than a conditional process shaped by environmental quality and disturbance frequency.

The scientific implication is that reef adaptation should not be romanticized as a substitute for climate mitigation. Assisted evolution, coral gardening, selective propagation, and microbial interventions may contribute locally, but they cannot compensate for unchecked warming and chronic pollution at ecosystem scale. Technological interventions must therefore be embedded within broader environmental management.

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## 5. Integrated Climate–Pollution Risk and Sustainability Implications

The combined effects of warming and microplastic pollution create a multidimensional reef sustainability challenge. Thermal stress affects corals through metabolic and symbiotic disruption, while microplastics influence feeding, disease, microbial ecology, and contaminant pathways. Their interaction may reduce coral energy reserves, impair immune response, and delay recovery after bleaching.

The Great Barrier Reef demonstrates the limitation of local governance under global climate forcing. Despite strong scientific monitoring and management institutions, repeated marine heatwaves continue to threaten reef structure. This indicates that reef sustainability requires rapid global emissions reduction in addition to local conservation.

The Coral Triangle demonstrates the importance of integrating climate adaptation with pollution control, fisheries management, waste infrastructure, and coastal development planning. Because many communities depend directly on reef fisheries and coastal protection, reef degradation has direct implications for food security, disaster risk, and livelihoods.

This study demonstrates that cumulative stressor frameworks are essential for natural sciences research. Single-factor studies remain useful for mechanism identification, but ecosystem-level sustainability requires integrated assessment. Thermal stress, microplastics, nutrients, sedimentation, acidification, and fishing pressure interact through biological and biogeochemical pathways.

Policy implications include the need for standardized microplastic monitoring in reef environments, stronger river-to-reef pollution management, satellite–field data integration, and cumulative risk indicators. Internationally, climate mitigation and plastic pollution governance must be treated as connected reef protection strategies rather than separate environmental agendas.

The broader scientific implication is that coral reefs function as sentinel systems for planetary environmental change. Their decline reflects interacting atmospheric, oceanic, chemical, biological, and socio-economic transformations. Understanding reef resilience therefore requires interdisciplinary integration across climate science, ecology, chemistry, physiology, and sustainability science.

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**Conceptual Framework**

This article proposes the following conceptual framework:

**Climate and Pollution Stressors → Physicochemical Disruption → Coral Holobiont Response → Community Reorganization → Reef Resilience and Sustainability Outcomes**

The framework conceptualizes reef degradation as a cumulative systems process. Climate stressors, particularly marine heatwaves, increase sea surface temperature and destabilize coral–Symbiodiniaceae symbiosis. Pollution stressors, particularly microplastics, introduce physical particles, contaminant vectors, and microbial substrates into reef environments. These stressors produce physicochemical disruption through oxidative stress,

altered microbial surfaces, reduced water quality, and increased energetic demands.

The coral holobiont response includes bleaching, immune modulation, mucus production, microbial dysbiosis, altered feeding, reduced calcification, and reproductive impairment. At the community level, differential mortality and recovery produce species sorting, habitat simplification, altered fish assemblages, and reduced ecological function. Reef resilience emerges when resistance, recovery, biodiversity, recruitment, and governance capacity are sufficient to maintain ecosystem structure and function.

The framework contributes to natural sciences scholarship by integrating climate physiology and pollution ecology into a single comparative model. It emphasizes that reef sustainability depends on both global-scale climate stabilization and local-scale pollution reduction. The model further clarifies why coral reef outcomes differ between systems exposed to similar warming but different pollution pathways, biodiversity structures, and governance capacities.

## CONCLUSION

This study examined how thermal stress and microplastic pollution influence coral reef resilience in the Great Barrier Reef and the Coral Triangle. The analysis demonstrates that coral reef vulnerability is governed by interacting climate, pollution, biological, and governance mechanisms rather than by ocean warming alone. Thermal stress drives bleaching through oxidative stress, photosymbiotic breakdown, energetic imbalance, and reduced calcification. Microplastic pollution intensifies vulnerability through ingestion, tissue contact, microbial alteration, contaminant transport, and disease facilitation.

The Great Barrier Reef shows that strong monitoring and marine governance cannot fully protect reefs from recurrent marine heatwaves when global thermal forcing exceeds biological tolerance. The Coral Triangle shows that exceptional biodiversity may support adaptive potential, but this potential is weakened by chronic coastal pollution, waste leakage, fishing pressure, and governance fragmentation. Thus, resilience depends not only on biological diversity but also on environmental quality, recovery intervals, and multilevel management.

The theoretical contribution of this article lies in integrating coral stress physiology, pollution ecology, reef resilience theory, and sustainability science into a comparative framework. The empirical contribution lies in synthesizing satellite-derived climate stress evidence, international environmental reports, and peer-reviewed coral and microplastic studies to explain cross-system differences in reef vulnerability.

The environmental implication is that coral reef conservation must move beyond single-stressor management. Climate mitigation, marine heatwave monitoring, microplastic reduction, wastewater control, fisheries governance, and biodiversity protection must be coordinated. Technological interventions such as assisted restoration may be useful locally, but they cannot substitute for reducing greenhouse gas emissions and land-based pollution.

The study is limited by reliance on secondary evidence and by uneven microplastic monitoring across reef systems. Future research should develop standardized reef microplastic sampling protocols, combine thermal stress models with pollution exposure maps, and conduct controlled multi-stressor experiments examining coral physiology, microbiomes, calcification, and recruitment under realistic field conditions.

Ultimately, this article argues that coral reefs should be understood as coupled biological–chemical–physical systems whose resilience depends on the interaction between planetary climate dynamics and local environmental governance. Protecting reefs therefore requires integrated natural science research capable of linking molecular mechanisms, ecosystem processes, and sustainability interventions.

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