

Sediment-driven pressures and reef resilience in dynamic coastal systems: A systematic review using the CIMO framework

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Abstract. Coral reefs are among the most productive and ecologically valuable marine ecosystems, yet their resilience is increasingly threatened by rising total suspended solids (TSS) in coastal waters. This study examines the relationship between TSS and coral reef resilience using the context-intervention-mechanism-outcome (CIMO) framework, which integrates ecological, hydrodynamic, and socioeconomic perspectives. A systematic literature review was conducted following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines by reviewing 49 Scopus-indexed scientific articles published between 2010 and 2025. Data extraction included study context, intervention type, underlying mechanisms, and ecological outcomes, which were analyzed thematically. The results show that increased TSS consistently weakens coral health through reduced light penetration, sedimentation stress, microbiome alteration, and increased vulnerability to thermal bleaching. Fringing and coastal reefs located in areas with high anthropogenic pressure were identified as the most vulnerable ecosystems. Effective management requires a layered, context-based approach that includes upstream sediment source control, adaptive marine protected area (MPA) implementation, gradual restoration after water quality improvement, and long-term monitoring integrated with hydrodynamic-ecological modeling. The findings offer a transferable blueprint for adaptive reef management in sediment-impacted marine ecosystems, while highlighting future research priorities, including species-specific tolerance thresholds, standardized multi-scale monitoring protocols, and expanded investigations in underrepresented tropical regions.

Keywords: coastal governance, ecological thresholds, reef recovery, sediment runoff, water clarity.

Introduction. Coral reefs are among the most productive and valuable types of marine ecosystem. These ecosystems are not only home to thousands of species, but also serve as a natural barrier that protects coastlines from erosion and storms, supporting the livelihoods of coastal communities through fisheries and tourism (D'Agata & Maina 2022; Harvey et al 2018; Hughes et al 2023; Woesik & Kratochwill 2022). The economic value is significant, as reported in a study in Nha Trang Bay, Vietnam, which estimated the potential economic losses due to coral reef degradation to reach millions of dollars annually (Anthony et al 2020; Harvey et al 2018; Ngoc 2019). However, coral reef now faces increasingly complex threats from climate change, human activities, and declining water quality (Devlin et al 2023; Hughes et al 2023; Li et al 2021; Ouédraogo et al 2021). Additional regional evidence from Indonesia shows tourism growth can coincide with declining coral cover and highlights the need for explicit carrying-capacity limits (Dewi et al 2018; Puryono & Suryanti 2019), while coastal land-use change and plastic pollution exacerbate nearshore water-quality stressors (Kakisina et al 2015; Khoironi et al 2020). A further dimension of coral reef importance lies in their close linkages with fisheries and aquaculture. Coral reef ecosystems provide essential habitat, feeding

grounds, and nursery areas for a large proportion of marine fish species, thereby sustaining artisanal and commercial fisheries. Healthy reef structures support biodiversity and fish biomass, which are critical both for ecological balance and for coastal community livelihoods. Conversely, sustainable fisheries and coral aquaculture initiatives can reinforce reef resilience, creating a reciprocal relationship that underpins food security and conservation goals (Karnan 2022; Isdianto et al 2024; Zhang et al 2023b; Lokrantz et al 2009; Fidler et al 2018; Emslie et al 2015; Barton et al 2020; Leal et al 2014; Osinga et al 2011; Grol et al 2010).

One of the primary factors contributing to degradation is the increase in total suspended solids (TSS), which causes water turbidity and sedimentation. These conditions reduce the penetration of light required for zooxanthellae photosynthesis, inhibiting coral growth and reproduction, and can even lead to mass mortality under extreme conditions (Fabricius et al 2013; Zvifler et al 2021). Excessive sedimentation also has the potential to worsen the effects of thermal stress caused by climate change, thereby increasing the frequency and intensity of coral bleaching (Drury 2020; Romero-Torres et al 2020). Furthermore, changes in the microbiome due to sedimentation potentially reduce the diversity of beneficial symbionts and lower coral resilience to pathogens (Maher et al 2020). Indonesian case studies further corroborate TSS-biota linkages and river-coast coupling, with remote-sensing estimates and estuarine water-quality indices evidencing high TSS, nitrate, and phosphate loads (Suryanti & Hartoko 2017).

In the past decade, studies on TSS and coral reef resilience have advanced significantly through the integration of cutting-edge technologies such as remote sensing (Amani et al 2022; Arifin et al 2020; Junker et al 2020), molecular analysis (Maher et al 2020), and ecological modeling (Chen et al 2022; Pasetto et al 2018). Studies on water quality and TSS dynamics in various aquatic environments (Herawati et al 2023; Lokollo et al 2025) have further emphasized the importance of addressing sediment-related impacts on marine ecosystems. An interdisciplinary approach that combines ecological, oceanographic, and socio-economic data is essential for comprehensively understanding TSS dynamics and the implications for coral reef (Doropoulos et al 2022; Nichols et al 2019). Evidence from studies in Australia, the Caribbean, and Southeast Asia shows that integrating field data, modeling, and active stakeholder engagement can significantly enhance the effectiveness of coral reef conservation strategies (Chan et al 2023; Devlin et al 2023). Comparable integrative approaches have been applied in Indonesia, for example through line intercept transect (LIT)-based reef condition surveys, fisheries-extension governance, marine protected area (MPA) staffing assessments, and sustainable ecotourism evaluations, to operationalize biophysical and socio-institutional evidence (Aspiany et al 2019; Capriati et al 2026; Efendi et al 2023).

Current literature underscores significant knowledge gaps, particularly the lack of long-term studies in developing countries due to resource constraints (Chan et al 2023; Gintert et al 2018; Zhang et al 2023a). The integration of physical, biological, and socio-economic data is also rare, even though this synergy is crucial for designing adaptive and effective interventions (Doropoulos et al 2022; Nichols et al 2019). Comparative studies across tropical regions remain limited (Bang et al 2021; Gibbs & West 2019), hence, global understanding of ecosystem response variations to TSS has not been optimally mapped. These gaps often co-occur with local constraints documented in Indonesia, including limited institutional capacity in MPAs, the need for site-level tourism limits, and catchment-to-coast stressors from land-use change and pollution (Capriati et al 2026; Dewi et al 2018; Kakisina et al 2015).

In this context, this study aimed to fill the existing knowledge gap through a systematic literature review using the context, intervention, mechanism, outcome (CIMO) framework to explore in depth the relationship between TSS and coral reef resilience in dynamic coastal environments. The primary focus includes (1) identifying the geographical and ecological context where TSS mitigation strategies are implemented, (2) analyzing the biological, ecological, and physico-chemical mechanisms, (3) evaluating the impact of interventions on coral health and resilience, and (4) proposing study directions and evidence-based conservation policy recommendations. This approach is

expected to foster a comprehensive synthesis, strengthening the scientific foundation for coral reef management and conservation, particularly in the face of global environmental challenges.

Material and Method

Study design. The study used a systematic literature review approach following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al 2021). PRISMA 2020 was applied to improve the transparency, completeness, and replicability of the review process, including article identification, screening, eligibility assessment, and final inclusion. The review process included planning, literature searching, study selection, data extraction, and analysis, all of which were carried out systematically and in a structured manner to ensure valid, transparent, and replicable results.

Literature search strategy. The literature search was conducted online through the Scopus database, which was selected because of its broad international coverage of peer-reviewed journals, strict indexing standards, and suitability for systematic literature reviews. Scopus was used as a deliberate methodological boundary rather than as a dismissal of the relevance of Web of Science. Using a single database helped maintain metadata consistency during article identification, screening, extraction, classification, and visualization, particularly because the review process was supported by the Watase UAKE System (Wahyudi 2024). This choice also reduced duplication and inconsistencies that may arise when combining databases with different metadata formats and journal coverage. Nevertheless, this database restriction is acknowledged as a limitation, and future reviews may integrate Scopus and Web of Science to broaden literature coverage. The search was carried out during July–August 2025. The systematic literature review was conducted using the Watase UAKE System web-based application (Wahyudi 2024), which supports article screening, classification, extraction, and visualization in a structured review workflow. The stages included: (1) identifying keywords, criteria, and search limitations; (2) screening relevant articles; (3) conducting further searches and excluding articles that did not meet the criteria; (4) reading the titles, abstracts, and keywords of selected articles; and (5) extracting information into a standardized worksheet. The keywords used were “particulate matter coral reef”, “sedimentation coral reef”, “turbidity coral reef”, and “coral reef water quality”. Logical operators “AND” and “OR” were used to expand or narrow the search results. Search limitations included the publication period from 2010 to 2025, peer-reviewed journal articles indexed in Scopus quartiles Q1–Q4, and English-language publications.

Eligibility criteria. The inclusion and exclusion criteria were carefully designed to ensure that only relevant, up-to-date, and high-quality studies were included in the review. Key considerations include the relevance of the topic to the objectives, the credibility of the publication, as well as the completeness and availability of sufficient data for comprehensive analysis (Table 1).

Table 1
Inclusion and exclusion criteria (eligibility criteria)

<i>Inclusion</i>	<i>Exclusion criteria</i>
Empirical studies related to TSS, sedimentation, turbidity, or water quality in coral reef ecosystems	Duplicate articles
Studies conducted in coastal/marine ecosystems with coral reef	Articles before 2010
Published in Q1–Q4 journals indexed by Scopus	Articles without abstracts or full texts

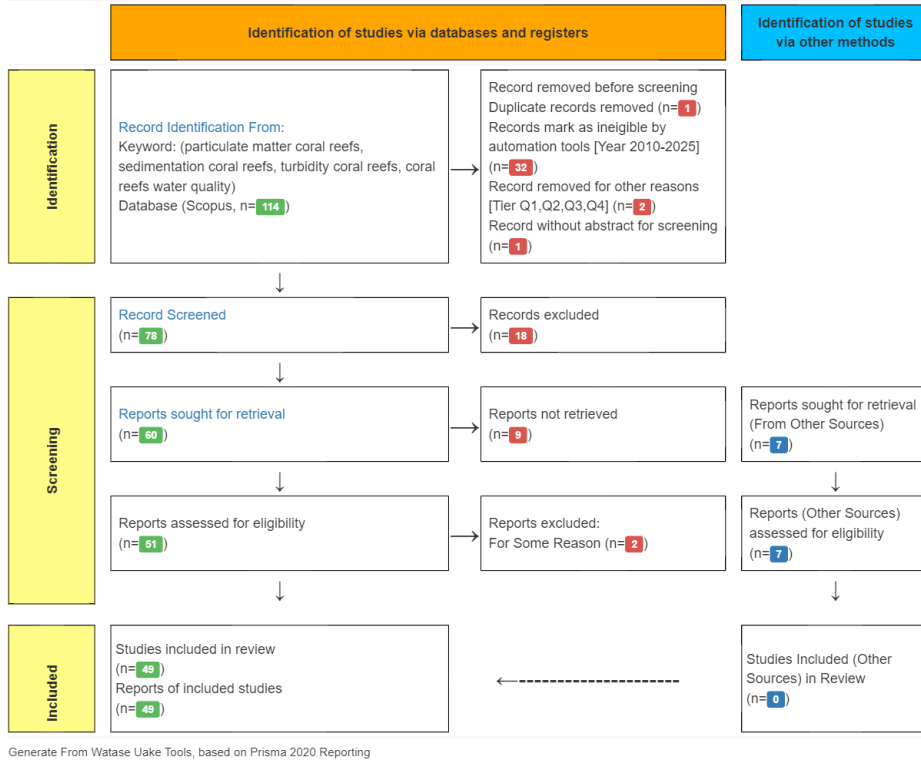


Figure 1. Identification, screening, and inclusion steps.

Study selection process. Following the PRISMA flow in Figure 1, the selection process was conducted in four stages as follows Identification: 114 articles found, 1 duplicate removed → 113 articles; screening: 32 outside the publication period, 2 outside Q1–Q4, 1 without abstract removed → 78 articles; eligibility: 18 irrelevant articles were removed → 60 articles; final inclusion: 9 articles without full text and 2 that did not meet the criteria were removed → 49 articles for analysis.

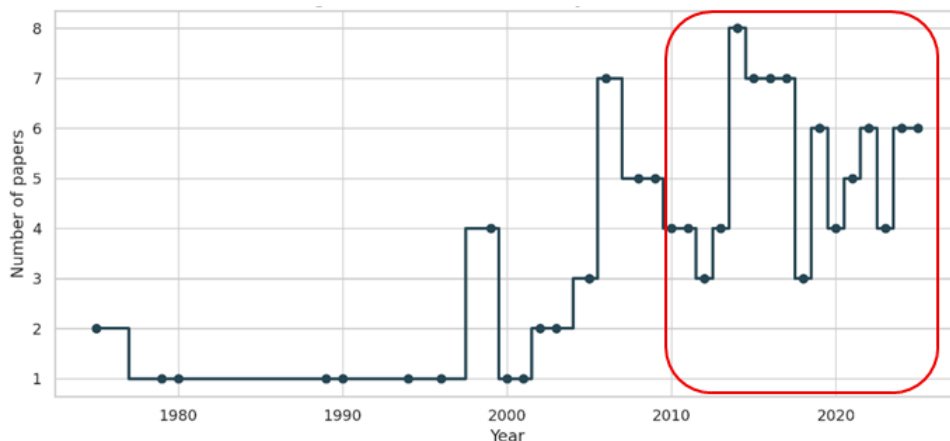


Figure 2. Results from keyword search.

Figure 2 shows the number of articles published throughout the year related to the keywords “particulate matter coral reefs,” “sedimentation coral reefs,” “turbidity coral reefs,” and “coral reefs water quality.” This graph shows a significant increase in the number of articles around the 2000s, with fluctuations in the following decades. A systematic literature review only examined articles published between 2010 and 2025 (1.5 decades or 15 years).

Data extraction and analysis. The extracted data included bibliographic information, study context, objectives and questions, design and methodology, variables and indicators, types of intervention, identified mechanisms, and key results. The analysis was conducted using thematic analysis (Braun & Clarke 2006) combined with the CIMO framework.

CIMO framework. The CIMO framework was used as follows: Context - environmental, geographical, and socioeconomic conditions of the study location; Intervention - strategies or actions to reduce TSS or enhance coral resilience; Mechanism - biological, physical, and social processes linking interventions to outcomes; Outcome - measured impacts, such as changes in coral cover, biodiversity, or resilience indicators.

Limitations. This study was limited to English-language articles indexed in Scopus, suggesting a potential for publication bias. Differences in study design, methods, and indicators also limited direct quantitative comparisons. However, the strict application of the systematic literature review protocol helped maintain consistency, minimize bias, and strengthen the validity of the results.

Results

General characteristics of the studies analyzed. A total of 49 scientific articles that met the inclusion criteria were analyzed in depth. These articles were published between 2010 and 2025, with a significant increase in the mid-2010s. The publication trend indicates that studies on the relationship between TSS and coral reef resilience fluctuated over time, with peaks in 2014 (6 articles) and 2019 (5 articles). These results show that the topic started to receive significant attention in the middle of the decade. Based on Figure 3 and previous literature reviews, studies related to TSS and coral reef have been conducted in various countries, including Australia, the United States, and Indonesia. The methods used include field monitoring, satellite data analysis, and modeling (Browne et al 2015; Fabricius et al 2013). The results show that TSS has a negative impact on coral reef, such as reducing light availability for photosynthesis and increasing sedimentation. For example, Fabricius et al (2013) in Australia reported a decline in coral reef health due to high TSS levels. Browne et al (2015) in Singapore found a significant impact of TSS on coral conditions, while Thompson et al (2014) emphasized the role of river discharge and pollutants in affecting coral communities.

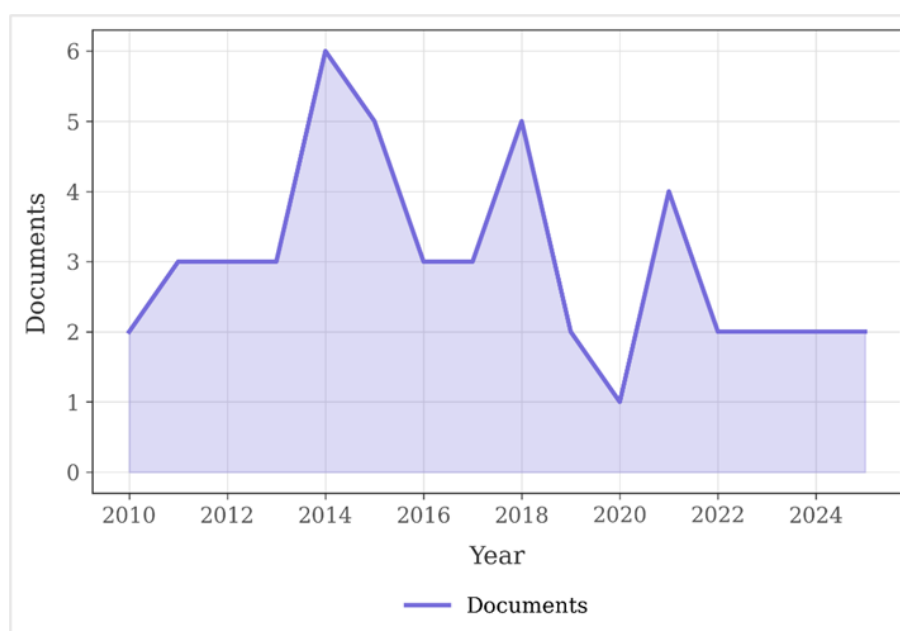


Figure 3. Year of publication trends.

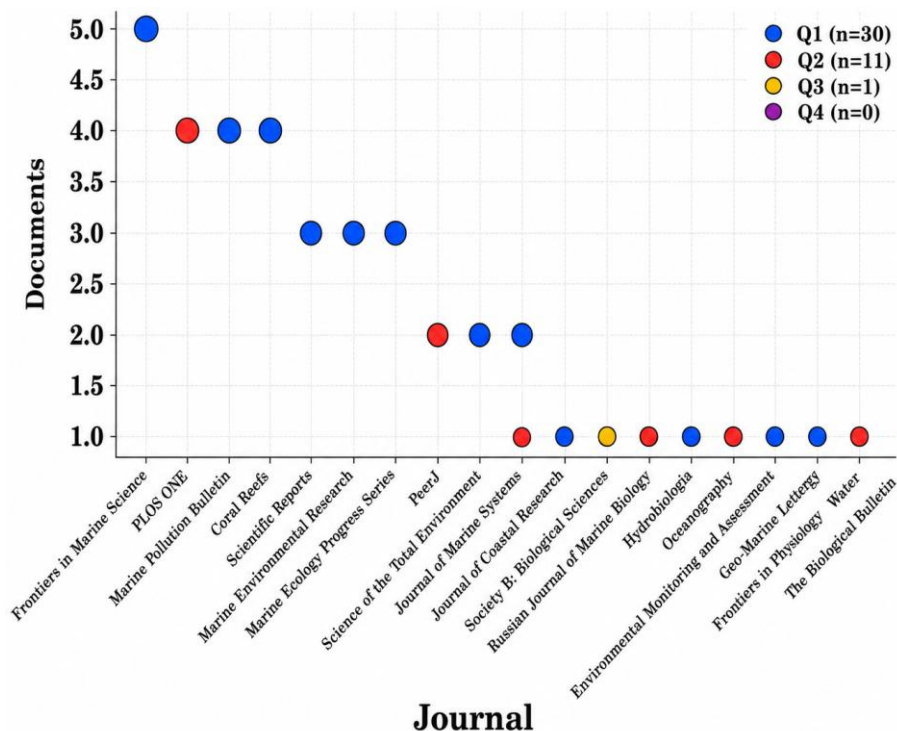


Figure 4. Journal quartile distribution and top 20 journal sources.

Figure 4 shows that the majority of articles (34 out of 49) were published in Q1 journals, such as Coral Reef, Marine Pollution Bulletin, Marine Environmental Research, and Frontiers in Marine Science (Fabricius et al 2013; Loiola et al 2019; Otaño-Cruz et al 2017; Thompson et al 2014). Studies in these high-impact journals underscore the quality and significant influence of investigations in this field. Articles in Q1 journals tend to have high citation counts, for example, Maina et al (2013) in Nature Communications and Samperiz et al (2025) in Scientific Reports. Other important articles, such as Pollock et al (2014), Wakwella et al (2020), and Lock et al (2024), discussed sedimentation thresholds and coral transcriptomic responses. This trend shows the ongoing relevance of the topic and the urgency of further studies to develop mitigation and adaptation strategies for TSS impacts in the context of global environmental change (Brown et al 2017; Van Maren et al 2014). In general, studies focus on coral reef ecology, the influence of environmental factors, the effectiveness of conservation strategies, as well as developing remote sensing-based monitoring technologies and ecological modeling (Amani et al 2022; Chen et al 2022; Li et al 2021; Pasetto et al 2018).

Geographic distribution and ecosystems studied. Figure 5 shows that studies on the relationship between TSS and coral reef resilience have been conducted in various geographic regions around the world. Among the 49 articles analyzed, Australia ranked first as the dominant location with 10 articles (Browne et al 2015; Cartwright et al 2023; Collins et al 2015; Drake et al 2025; Fabricius et al 2013; Luter et al 2012; Pollock et al 2014; Rucker et al 2019; Thompson et al 2014). The explored topics in this region include the impact of water quality changes on coral communities, the effects of sedimentation on coral health, and historical analyses of ecosystem development. The United States ranked second with 8 articles, followed by Puerto Rico (5 articles), Brazil and Singapore (3 articles each), and Fiji, Vietnam, and the United Kingdom (2 articles each). Other countries, such as Indonesia, Kenya, Madagascar, Palau, New Caledonia, and Guam, each contributed 1 article.

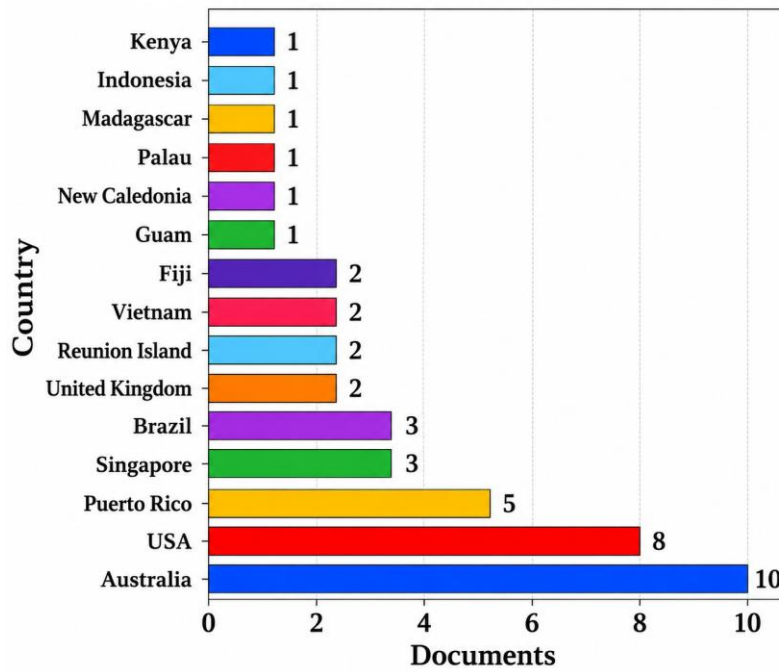


Figure 5. Geographic distribution of studies.

These studies not only examined environmental aspects, but also the biological and ecological dimensions of coral reef (Luter et al 2012; Pollock et al 2014), providing practical implications for the development of conservation strategies. The trends show that studies related to TSS and coral reef resilience will continue to be an important field in the future, with significant contributions to the development of mitigation strategies to address environmental pressures and climate change (Maina et al 2013; Samperiz et al 2025). These studies also offer insight into the impacts of human activities on marine ecosystems and the formulation of effective coastal management solutions (Morgan et al 2020; Torres-Pérez et al 2021).

Figure 6 shows that fringing coral reef dominated, accounting for 54.17% of the entire study, followed by coastal coral reef at 35.42%, inshore coastal coral reef at 4.17%, as well as deep sea and offshore coral reef at 2.08% each.

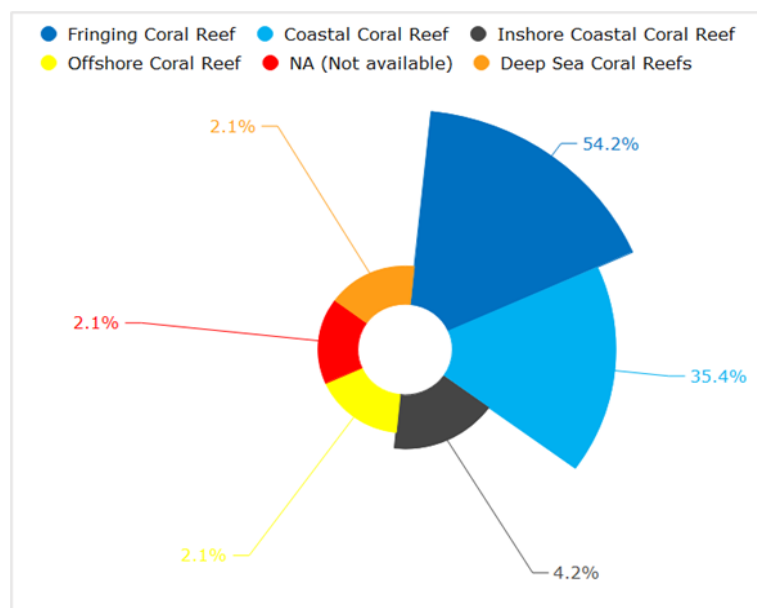


Figure 6. Types of coral reef ecosystems.

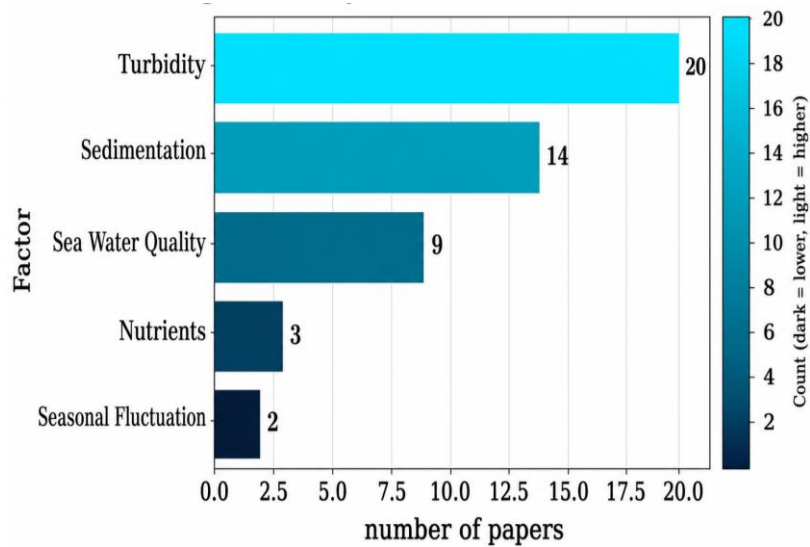


Figure 8. Key environmental factors.

The results emphasize the need for effective management strategies to minimize the impact of turbidity and other environmental factors on coral reef. Future studies are needed to develop more advanced technologies and methods for monitoring seawater quality. This is essential to support the conservation of coral reef ecosystems that are important for marine biodiversity and coastal economic sustainability.

Impact of TSS on coral health and resilience. A synthesis of 49 articles shows that an increase in TSS has a significant negative impact on coral reef health and resilience. Increased TSS directly raises water turbidity, reduces light penetration, and inhibits zooxanthellae photosynthesis. These conditions reduce growth rates, disrupt reproductive processes, and in extreme conditions can cause mass coral colony mortality (Fabricius et al 2013; Zvifler et al 2021). As shown in Figure 9, the most discussed topic was the impact of water quality on ecosystem communities (18 articles) and coral resilience and adaptation (13 articles). These studies emphasize the influence of changes in water quality, including increased sedimentation and turbidity, on coral reef ecosystems (Browne et al 2015; Fabricius et al 2013; Maina et al 2013) as well as how coral can survive and adapt to environmental changes (Loiola et al 2019; Samperiz et al 2025). Other categories include the identification of bioindicators (5 articles), the decline in coral condition (5 articles), the impact of heavy metal pollution (4 articles), and the effects of sedimentation on coral spawning (3 articles).

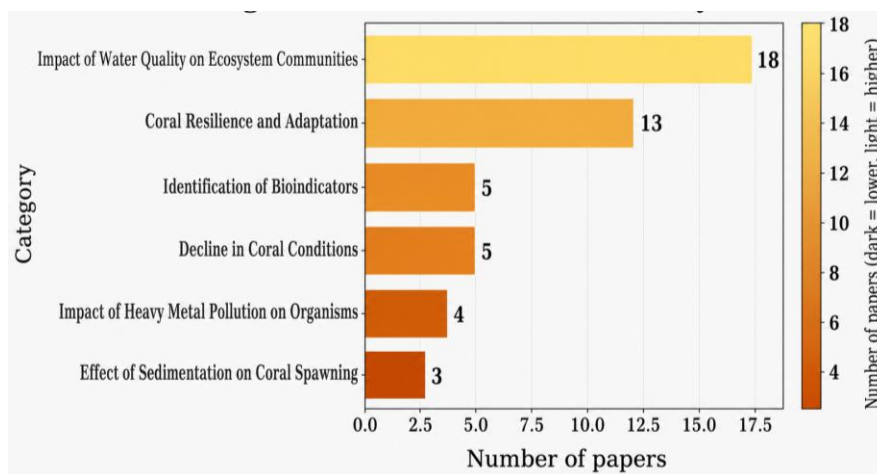


Figure 9. Main results of the study.

Figure 10 shows that the largest category is “The effect of turbidity on coral recruitment and reproduction” (35%) with 13 articles (Butler et al 2015; Drake et al 2025; Edmunds & Gray 2014; Ennis et al 2016; Jordan et al 2010; Maina et al 2013; Marques et al 2019; Miller et al 2016; Oliver et al 2018; Otaño-Cruz et al 2017; Padilla-Gamiño et al 2014; Pollock et al 2016; Stender et al 2014; Thompson et al 2014; Wakwella et al 2020). The next category is Coral reef adaptation to turbid environments (21%) with 11 articles (Brown et al 2017; Browne et al 2015; Fabricius et al 2013; Linton-Izquierdo et al 2024; Loiola et al 2019; Morgan et al 2020; Ogston & Field 2010; Rocker et al 2019; Van Maren et al 2014; Wattelez et al 2017). This distribution emphasizes the significant focus regarding the impacts of turbidity on coral biological processes, physiological adaptation mechanisms, community resilience, and tolerance to sedimentation.

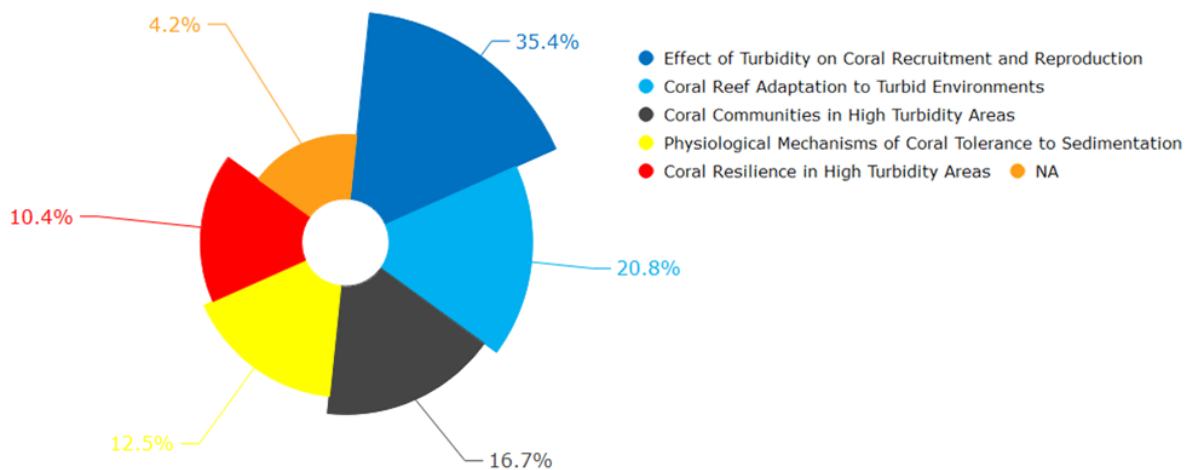


Figure 10. Coral reef adaptation to turbid environments.

High sedimentation also worsens thermal stress caused by climate change, increasing the incidence of coral bleaching (Drury 2020; Romero-Torres et al 2020). Changes in the composition of the microbiome in highly turbid waters reduce beneficial symbionts and increase pathogenic microbes, thereby reducing coral resistance to disease (Maher et al 2020). TSS effects also interact with nutrient pollution, overfishing, and coastal habitat degradation (Browne et al 2015; Morgan et al 2020), ultimately slowing ecosystem recovery (Loiola et al 2019; Maina et al 2013). These results underscore the importance of water quality management and control of TSS sources as part of effective conservation strategies to maintain coral reef resilience amid global environmental changes.

Synthesis of results based on the CIMO framework. Based on the analysis of 49 included articles, the results can be synthesized using the CIMO framework as follows:

Context: The studies were conducted in various tropical and subtropical regions with diverse environmental, geographical, and socioeconomic conditions. Most locations were in coastal areas affected by human activities, including coastal development, tourism, and agriculture, as well as global pressures, namely climate change (Fabricius et al 2013; Maina et al 2013). Variations in environmental conditions, including differences in ocean currents, tides, and natural sedimentation rates, influence the response of coral ecosystems to TSS.

Intervention: Intervention strategies include the establishment of marine protected areas (MPAs), ecosystem-based management, the use of remote sensing technology to monitor water quality, and active restoration programs such as coral transplantation (Cartwright et al 2023; Loiola et al 2019). Coastal spatial planning is also focused on reducing TSS sources from land. Based on Figure 11, the dominant category is long-term monitoring (17 articles), followed by model development and simulation, emphasizing the importance of both approaches.

Mechanism: TSS affects coral reef through biological, ecological, and physico-chemical mechanisms. Turbidity and sedimentation reduce light penetration, inhibit zooxanthellae photosynthesis, slow growth, and disrupt reproduction (Zvifler et al 2021). Sedimentation can also alter the microbiome, increase disease susceptibility (Maher et al 2020), and worsen bleaching when synergizing with thermal stress (Romero-Torres et al 2020). Outcome: The results show a decrease in live coral cover, reduced biodiversity, and weakened ecosystem resilience to environmental disturbances. Conversely, locations with effective interventions experienced improved water quality, increased coral cover, and ecosystem function recovery (Morgan et al 2020; Samperiz et al 2025). Based on Figure 12, the topic of coral reef management and conservation was predominant (17 articles), followed by the impacts of human activities such as agriculture, construction, and tourism (12 articles), the role of long-term monitoring (9), sedimentation mitigation strategies (8), and policies and regulations (2).

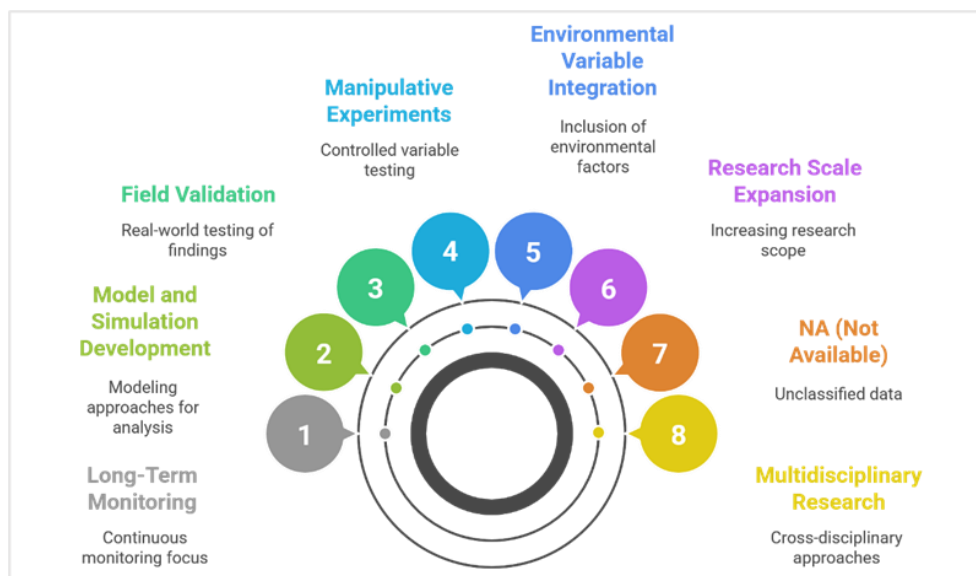


Figure 11. Recommendations based on highest order.

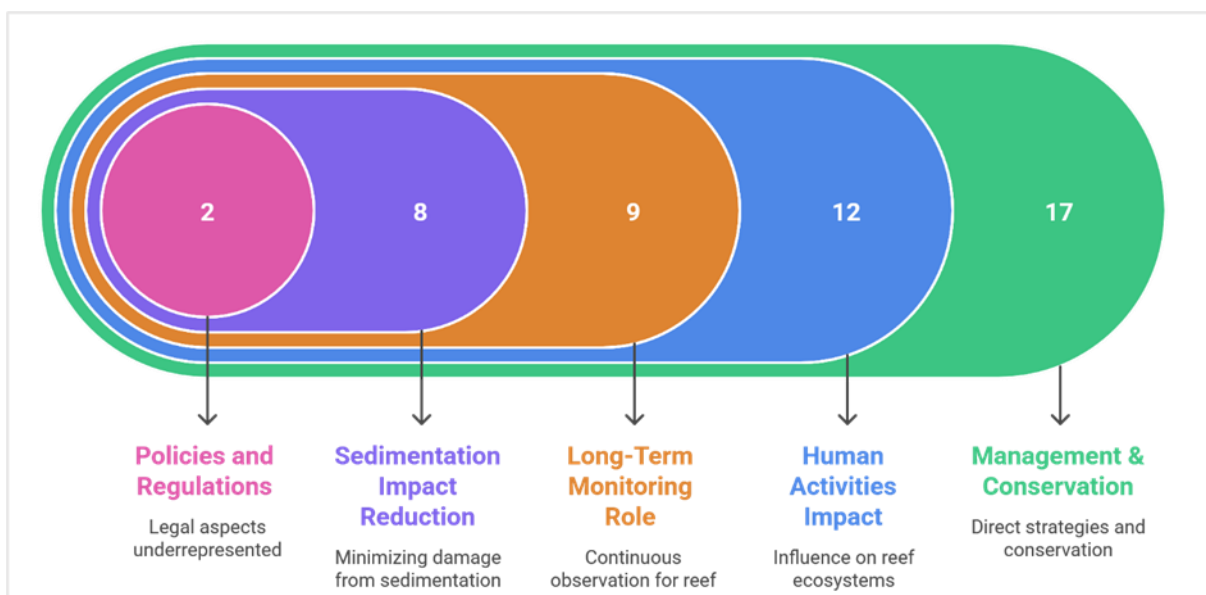


Figure 12. Coral reef management and conservation based on the number of articles.

These studies emphasize the need for comprehensive management strategies to reduce pressures from human activities and environmental changes (Fabricius et al 2013; Loiola

et al 2019; Miller et al 2016; Morgan et al 2020; Pollock et al 2016). A combination of context-specific interventions and an understanding of biological mechanisms is crucial for enhancing coral reef resilience to TSS pressures and other stressors.

Discussion

Interpretation of key results. The results show a strong correlation between an increase in TSS and a decline in coral reef ecosystem health. Article trend data (Figure 3) show an increase in attention to this topic since the mid-2010s, in line with growing scientific evidence on the impact of TSS on marine ecosystem quality (Browne et al 2015; Fabricius et al 2013; Thompson et al 2014). Geographical distribution analysis (Figure 5) shows a concentration of studies in Australia, the United States, and Puerto Rico, each with varying TSS intensities and distinct ecosystem responses (Drake et al 2025; Pollock et al 2014; Rocker et al 2019). The most commonly studied ecosystem types were fringing reef and coastal coral reef (Figure 6), which are ecologically more vulnerable to land runoff and sedimentation (Browne et al 2015; Maina et al 2013). The main theme analysis (Figure 7) and important environmental factors (Figure 8) reinforce the result, showing that turbidity and sedimentation are the dominant factors influencing coral resilience. These two factors reduce light penetration, disrupt zooxanthellae photosynthesis, as well as decrease coral growth and reproduction rates (Fabricius et al 2013; Jordan et al 2010; Zvifler et al 2021). The impacts are reflected in the results (Figures 9 and 10), showing that water quality degradation and declining coral conditions are central issues, followed by a focus on coral adaptation to turbid environments (Loiola et al 2019; Samperiz et al 2025). The CIMO framework synthesis (Section 4.5) showed that interventions such as long-term monitoring, model development, sedimentation mitigation strategies, and integrated conservation management were effective in strengthening ecosystem resilience (Loiola et al 2019; Morgan et al 2020; Pollock et al 2016). The implementation of these strategies in areas with low TSS levels has been shown to correlate with coral cover recovery and improved ecosystem function (Maina et al 2013; Samperiz et al 2025). In general, the results confirm that effective TSS management through sediment source control, watershed management, and protection of critical habitats are crucial steps for maintaining and restoring coral reef health facing global environmental pressures.

Variability of ecosystem response to TSS. The analysis results show that the response of coral reef ecosystems to TSS varies greatly, influenced by a combination of geographical factors, hydrodynamics, ecosystem type, and anthropogenic pressures. Areas with strong ocean currents, significant tidal ranges, and good water circulation (some locations in the Great Barrier Reef) tend to be more resistant to TSS accumulation. These conditions facilitate sediment dispersion and reduce direct deposition on coral colonies, thereby lowering turbidity levels and the risk of chronic sedimentation (Browne et al 2015; Cuttler et al 2018; Fabricius et al 2013; Justic et al 2021; Maina et al 2013; Morgan et al 2020; Thompson et al 2014). Ecosystem type plays an important role in determining sensitivity to TSS. Coastal reefs close to land (fringing) receive direct runoff from human activities such as agriculture, construction, and tourism, thereby increasing vulnerability to the impacts of TSS. In contrast, barrier reef and atolls located further from the coastline generally experience lower TSS exposure (Cartwright et al 2023; Fabricius et al 2013; Hayes et al 2021; Le et al 2023; Loiola et al 2019; Nguyen et al 2022; Torres-Pérez et al 2021). Geographical distribution data (Figure 5) and ecosystem type classification (Figure 6) reinforce these results, showing consistent exposure patterns. Response variability is also closely related to the level of anthropogenic pressure. Areas with high intensity of coastal development, port activities, mass tourism, and resource exploitation tend to have higher sediment loads. Conversely, areas with strict environmental regulations and good coastal management practices can maintain more stable water quality (Chan et al 2023; Doropoulos et al 2022; Mejias-Rivera et al 2023; Nichols et al 2019; Otaño-Cruz et al 2017; Rogers & Ramos-Scharrón 2022; Tuholske et al 2021). Analysis of key environmental factors (Figure 8) shows that

turbidity, sedimentation, and water quality are the main indicators in determining the level of risk to ecosystems. Effective TSS management strategies must be based on a thorough understanding of local ecosystem characteristics, hydrodynamic dynamics, and specific pressure sources. This location-based approach enables the design of more targeted interventions through sediment source control, strengthened coastal regulations, or the implementation of long-term monitoring technologies (Browne et al 2015; Cartwright et al 2023; Chan et al 2023; Fabricius et al 2013; Hayes et al 2021; Maina et al 2013; Rogers & Ramos-Scharrón 2022).

Role of other environmental factors. Based on the results, the response of coral reef ecosystems to TSS was modulated by various other environmental factors that worked additively and synergistically. The mapping of themes and factors (Figures 7–8) identified turbidity, sedimentation, and water quality as the main drivers. The results (Figures 9–10) imply that the impact of TSS is often worsened by thermal stress, nutrient pollution, local hydrodynamic dynamics, and extreme weather events. Spatial and temporal variations showed in the geographical distribution and ecosystem types (Figures 5–6) help explain differences in coral sensitivity and recovery patterns between areas (Browne et al 2015; Fabricius et al 2013; Maina et al 2013; Morgan et al 2020; Thompson et al 2014). The following subsections summarize the major interacting factors that shape coral reef responses to TSS across different environmental contexts:

(a) TSS–Thermal Stress Interaction. Rising sea surface temperatures worsen TSS effects by suppressing zooxanthellae photosynthetic capacity and lowering the bleaching threshold. These conditions imply that even small sediment accumulations can trigger widespread damage (Drury 2020; Romero-Torres et al 2020; Woesik & Kratochwill 2022). Recurrent marine heatwaves prolong the duration of disturbances, thereby reducing recruitment success in high-turbidity locations (Skirving et al 2019; Sully & Woesik 2020; Zvifler et al 2021).

(b) Nutrients and Water Quality. Increased nitrogen and phosphorus from agriculture, domestic waste, and industry trigger the growth of macroalgae that compete with coral for space and light, while trapping sediment on colony surfaces (Browne et al 2015; Fabricius et al 2013; Otaño-Cruz et al 2017). Excess nutrients reduce water clarity, increase light scattering, and worsen the effects of turbidity on photosynthetic efficiency (Polónia et al 2015; Wagner et al 2011). These indirect impacts are associated with reduced spawning success and recruitment (Adam et al 2021; Donovan et al 2020; Marangoni et al 2020; Mejias-Rivera et al 2023; Morgan et al 2020; Torres-Pérez et al 2021).

(c) Hydrodynamics and Habitat Morphology. Strong currents, large tidal ranges, and short water residence times aid in sediment flushing, reducing deposition on coral colonies. Conversely, semi-enclosed bays with weak currents tend to accumulate TSS (Cuttler et al 2018; Justic et al 2021; Maina et al 2013; Thompson et al 2014). Regarding ecosystem types in Figure 6, fringing reef are more vulnerable to land-based runoff than barrier reef or atolls (Cartwright et al 2023; Hayes et al 2021; Le et al 2023; Loiola et al 2019; Nguyen et al 2022; Rogers & Ramos-Scharrón 2022).

(d) Land Use and Extreme Events. Land reclamation, port construction, and coastal land use change increase erosion and sediment load (Nichols et al 2019; Rogers & Ramos-Scharrón 2022; Tuholske et al 2021). Heavy rainfall and tropical storms trigger spikes in TSS, causing abrasion of the network, colony accumulation, and recruitment failure during critical spawning periods (Becker & Silbiger 2020; Fisher et al 2019; Jordan et al 2010; Miller et al 2016; Pollock et al 2016). This pattern is consistent with the focus in Figure 9 on declining coral conditions and the need for risk-based management.

(e) Multi-Stressor Management Implications. Given the multi-factor nature of the problem, effective strategies must not only reduce TSS but also integrate nutrient control, habitat protection, and preparedness for heatwaves and storms (Anthony et al 2020; Hughes et al 2023; Loiola et al 2019). The recommendations in Figure 11, including long-term monitoring, modeling, and field validation, provide an operational basis for evaluating local thresholds and designing adaptive interventions. The policies in Figure 12 emphasize the priority of land-based mitigation, watershed management, and

MPAs to maintain ecosystem functions in high-risk locations (Cartwright et al 2023; Samperiz et al 2025).

In general, the role of other environmental factors implies that responses to TSS are context-specific. Management approaches must be tailored to the combination of local pressures, including thermal, nutrient, hydrodynamic, and extreme events, to optimize coral reef recovery and resilience (Browne et al 2015; Chan et al 2023; Fabricius et al 2013; Maina et al 2013; Morgan et al 2020).

Effectiveness of intervention strategies. Based on the results and priority mapping (Figures 11–12), the effectiveness of intervention strategies to reduce the impact of TSS is highly dependent on the location context (geography, ecosystem type) and a combination of other stressors such as turbidity, nutrients, and thermal stress. Geographical distribution and ecosystem type data (Figures 5–6) show that fringing/coastal reef near land, the most frequently studied field, require control of sediment sources from land as a first step. Meanwhile, offshore locations often flushed by currents tend to respond more quickly to habitat protection and marine conservation area interventions (Browne et al 2015; Fabricius et al 2013; Maina et al 2013; Morgan et al 2020; Thompson et al 2014). The following subsections outline the main intervention pathways identified in the reviewed studies and explain why their effectiveness varies across environmental and governance contexts.

(a) Land-based Source Control and Watershed Management. Upstream–downstream interventions such as land rehabilitation, conservation agriculture practices, drainage management, and installation of silt traps have proven to be the most cost-effective for reducing TSS in coastal areas with high runoff. The results in Figure 12 (sedimentation mitigation and human activity impact priorities) support literature connecting reduced sediment and nutrient inputs to improved water clarity and ecosystem function recovery (Browne et al 2015; Miller et al 2016; Pollock et al 2016; Rogers & Ramos-Scharrón 2022; Tuholske et al 2021). Effectiveness increases when combined with coastal spatial planning policies that restrict high-risk construction expansion (Chan et al 2023; Nichols et al 2019).

(b) MPAs and Habitat Protection. MPAs are effective in maintaining habitat integrity and ecological processes, specifically when designed adaptively, reducing local pressures (overfishing, anchoring, mining), and combined with TSS control from land. The success of MPAs increases with local stakeholder participation, adequate funding, and strong monitoring systems (Anthony et al 2020; Cartwright et al 2023; Grorud-Colvert et al 2021; Hughes et al 2023; Loiola et al 2019; Samperiz et al 2025). Evidence in Figure 12 shows the importance of integrating MPAs with long-term monitoring strategies.

(c) Active Restoration and Success Conditions. Coral transplantation and artificial substrate installation accelerate recovery only when water quality is below the local TSS threshold. In areas with chronic TSS levels, high failure rates result from repeated stressors such as turbidity, sedimentation on polyps, and epifouling (Browne et al 2015; Doropoulos et al 2022; Fabricius et al 2013; Mejias-Rivera et al 2023; Morgan et al 2020; Nguyen et al 2022). The latest guidelines recommend staged restoration, where reducing TSS sources should be prioritized before biological interventions (Boström-Einarsson et al 2020).

(d) Long-Term Monitoring and Modeling. Figure 11 emphasizes long-term monitoring as the primary recommendation because TSS trends are non-linear and seasonal. Remote sensing, in situ sensors, and hydrodynamic–ecological modeling enable early detection of water quality anomalies, source mapping, and evaluation of mitigation scenarios (Amani et al 2022; Chen et al 2022; Hayes et al 2021; Li et al 2021; Pasetto et al 2018; Tuholske et al 2021). Integrating monitoring and modeling strengthens adaptive management and reduces the risk of ineffective policies.

(e) Governance, Policy, and Community Participation. Long-term effectiveness is influenced by the quality of policies (construction permits, discharge standards, economic instruments), cross-sectoral coordination, and community participation through law enforcement, co-management, and education (Anthony et al 2020; Cartwright et al

2023; Hughes et al 2023; Jacquemont et al 2022). Figure 12 shows the central role of policy/regulation in supporting the sustainability of technical interventions.

(f) Contextual Effectiveness. In fringing/coastal reef (Figure 6) with high land-based pressures (Figures 5, 8), the most effective intervention package is source control (watershed and land use management) → policy/regulation → adaptive MPAs → restoration after water quality meets thresholds → monitoring and modeling for feedback (Browne et al 2015; Grorud-Colvert et al 2021; Miller et al 2016; Pollock et al 2016). In offshore locations with strong currents, habitat protection and local pressure reduction tend to provide faster benefits (Anthony et al 2020; Hughes et al 2023; Maina et al 2013; Thompson et al 2014).

The most effective strategy is a combination of upstream TSS source control, habitat protection through adaptive MPAs, restoration after meeting water quality thresholds, alongside monitoring–modeling to manage uncertainty and update policies. This approach is consistent with studies and management priorities in Figures 11–12 and supported by cross-site evidence (Anthony et al 2020; Cartwright et al 2023; Chan et al 2023; Fabricius et al 2013; Hughes et al 2023; Maina et al 2013; Morgan et al 2020).

Implications for conservation and future studies. The results confirm that TSS control is a key prerequisite for maintaining coral reef health and resilience. Previous studies (Figure 3) show an increase in interest since the mid-2010s, in line with strong evidence of TSS impacts on ecosystem quality (Browne et al 2015; Fabricius et al 2013; Thompson et al 2014). Geographical patterns and ecosystem types (Figures 5–6) show the highest vulnerability in fringing/coastal reef near land receiving sediment and nutrient runoff. Meanwhile, theme analysis and key factors (Figures 7–8) identify turbidity, sedimentation, and water quality as the primary drivers of degradation. These impacts are reflected in the main results and adaptation responses (Figures 9–10), while the CIMO framework (Figures 11–12) provides guidance for implementable interventions (Loiola et al 2019; Morgan et al 2020; Samperiz et al 2025). From a conservation perspective, the priority is to reduce sediment sources from land through watershed management, conservation agriculture practices, runoff control infrastructure, and coastal spatial planning that limits high-risk situations (Browne et al 2015; Miller et al 2016; Nichols et al 2019; Pollock et al 2016; Rogers & Ramos-Scharrón 2022; Tuholske et al 2021). In areas with strong currents and high flushing, habitat protection through adaptive MPAs can provide faster benefits when synergized with TSS control (Anthony et al 2020; Grorud-Colvert et al 2021; Hughes et al 2023; Loiola et al 2019). Active restoration measures such as coral transplantation or substrate installation should be carried out after water quality falls below local TSS thresholds, following a phased approach that reduces the risk of failure in areas with chronic turbidity (Doropoulos et al 2022; Fabricius et al 2013; Mejias-Rivera et al 2023; Morgan et al 2020; Nguyen et al 2022). Moreover, effective governance requires quality standards, economic instruments, co-management mechanisms, and public education to ensure the sustainability of implementation (Cartwright et al 2023; Grorud-Colvert et al 2021).

Methodologically, long-term monitoring is the backbone of conservation evaluation, as recommended in Figure 11. Remote sensing (multispectral/hyperspectral), in situ sensor networks, and hydrodynamic–ecological modeling enable mapping of sources, early detection of water quality anomalies, and testing of mitigation scenarios before policy implementation (Amani et al 2022; Chen et al 2022; Hayes et al 2021; Li et al 2021; Pasetto et al 2018). Given that the impacts of TSS are often non-linear and seasonal, management must be adaptive with operational thresholds derived from local data and updated regularly (Drury 2020; Maina et al 2013; Romero-Torres et al 2020). Integrating monitoring and modeling helps reduce the risk of ineffective policies and accelerates management feedback in the field. Future study agendas should expand coverage to underrepresented areas, particularly in developing countries with high coastal pressures (Chan et al 2023; Le et al 2023; Marangoni et al 2020; Mejias-Rivera et al 2023; Nguyen et al 2022; Otaño-Cruz et al 2017; Torres-Pérez et al 2021). Manipulative experiments and threshold studies (e.g., deposition rates, turbidity duration, and interactions with thermal and nutrient stress) are crucial for mapping

species and community tolerance limits (Jordan et al 2010; Miller et al 2016; Pollock et al 2016; Samperiz et al 2025; Wakwella et al 2020). Other priorities include standardizing data protocols, ensuring metadata openness, and developing cross-scale models connecting watershed coastal reef processes, enabling more precise evidence-based policy design (Hayes et al 2021; Rogers & Ramos-Scharrón 2022; Tuholske et al 2021). Therefore, layered conservation strategies combining source control, adaptive MPAs, gradual restoration, and monitoring and modeling have the greatest potential to maintain coral reef ecosystem functions in the long term (Anthony et al 2020; Hughes et al 2023; Morgan et al 2020).

Conclusions. This study presents a comprehensive synthesis of the interaction between TSS and coral reef resilience using the CIMO framework, which integrates ecological, hydrodynamic, and socioeconomic perspectives. The analysis of 49 scientific articles shows that increased TSS consistently weakens coral health through multiple mechanisms, including reduced light penetration, sedimentation stress, changes in microbiome composition, and increased vulnerability to thermal bleaching. The novelty of this study lies in its comparative cross-regional perspective and its integration of biological mechanisms with practical management insights, showing that fringing and coastal reefs in high-pressure areas are the most vulnerable ecosystems. The evidence synthesized in this study supports layered, context-based conservation strategies, including upstream sediment source control, adaptive marine protected area implementation, gradual restoration after water quality improvement, and long-term monitoring integrated with hydrodynamic-ecological modeling. This integrated framework not only supports reef recovery but also offers a transferable blueprint for adaptive management of sediment-impacted marine ecosystems. To strengthen future conservation and research, further studies should focus on underrepresented tropical regions, species-specific tolerance thresholds, and standardized multi-scale monitoring protocols to improve coral reef resilience under accelerating global environmental change.

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