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Beyond taxonomy: A functional approach reveals patterns of reef fish response to wastewater pollution

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ABSTRACT

Coral reefs face severe threats from climate change and local stressors like wastewater pollution, which significantly impact reef ecosystems but remain underexplored. Reef fish are essential for supporting human livelihoods through fisheries and maintaining ecosystem functions such as nutrient cycling and algae control. While most research focuses on wastewater's effects on benthic communities, its impact on reef fish physiology, behavior, and community structure is poorly understood. Few studies apply trait-based approaches to evaluate wastewater's influence on fish's ecological roles. This study systematically reviews 52 papers and conducts a meta-analysis of eight control-impact studies to assess wastewater effects on reef fish taxonomic and functional structure. Taxonomy-based metrics revealed mixed responses, with studies reporting declines, increases, or no changes in abundance, richness, and biomass in polluted sites. Functional analysis provided clearer patterns: polluted sites were dominated by smaller, high-resilience species at mid-trophic levels, while control sites supported larger, low-resilience species at diverse depths and trophic levels. Functional richness was generally higher in control sites. Pollutant-specific effects varied: sediments impaired feeding efficiency and growth, while nutrient enrichment shifted species composition by favoring lower trophic levels. These findings demonstrate the limitations of taxonomy-based metrics and highlight the value of functional approaches for detecting early ecosystem degradation. Integrating functional ecology with wastewater characterization enhances predictions of ecological responses and supports targeted management strategies. This research emphasizes the urgency of addressing wastewater pollution to safeguard reef biodiversity and ecosystem services critical to human well-being.

1. Introduction

Coral reefs are rapidly approaching dangerous tipping points, with current projections indicating that an increase of 1.5 °C in temperature could lead to their near-total collapse (Armstrong McKay et al., 2022). Although climate change is the predominant driver of reef decline, local-scale stressors such as pollution and eutrophication can exacerbate the vulnerability of reefs to increasing temperatures (Ma et al., 2023). Among the various forms of pollution, wastewater—typically composed of a combination of nutrients, sediments, organic matter, and chemicals used in detergents, skin care products, or pharmaceuticals—stands out as one of the most pervasive (Tuholske et al., 2021). Wastewater often originates from urban sources, including domestic sewage and industrial discharges, and while its effects on coral and rocky reefs are profound, they are less understood compared to those of other pollutants like agricultural runoff or oil spills (Fabricius, 2005; Turner and Renegar, 2017). While significant research has focused on the impact of wastewater on benthic communities, particularly corals, the effects on associated biota such as coral and rocky reef fish—which play crucial roles in maintaining ecosystem health and providing vital services to human communities—remain poorly understood (Wear and Thurber, 2015; Wenger et al., 2015). Understanding these effects is essential, given the significant ecological functions reef fish perform, from controlling algal growth to sustaining small-scale fisheries that support local economies.

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Wastewater, particularly from urban sources, can profoundly impact reef fish at both the individual and community levels. Physiology, behavior, and ecological function are all vulnerable to the various components of urban wastewater (hereafter referred to as wastewater). For instance, elevated sediment levels can impair respiration and reduce the foraging success of reef fish by diminishing visibility, which is critical for feeding and avoiding predators (Wenger et al., 2012). Moreover, through nutrient enrichment, wastewater can lead to hypoxic conditions, severely affecting fish behavior and survival, particularly in larvae and juvenile stages that are less capable of escaping low-oxygen environments (Wenger et al., 2015). These impacts can lead to reduced fish growth, altered species distribution, and changes in fish assemblages, with certain species becoming more dominant due to their physiological or behavioral adaptability to degraded conditions (Beger and Possingham, 2008; McKinley and Johnston, 2010).

The effects of wastewater on reef fish assemblages are complex and multifaceted. While increased nutrient loads might temporarily boost food availability, leading in some cases to higher fish abundance, the long-term effects often include declines in species richness and shifts in community structure (Reopanichkul et al., 2009, 2010). These shifts can be particularly pronounced in fish with close benthic associations, such as herbivores and some carnivores, and weaker on planktivores (Reopanichkul et al., 2009). Importantly, although some fish families exhibit dietary flexibility and thus may cope with changing nutrient loads and food availability, this flexibility may not mitigate the negative impacts of wastewater pollution on their habitat (Clever et al., 2024). A comprehensive overview of the effects of wastewater (and its different components) on reef fish assemblages is, however, currently lacking. A compilation and meta-analysis of published studies on the topic could shed light on whether such effects are consistent across sites.

Taxonomy-based indices, which encompass species richness and abundance, have traditionally been used to evaluate these impacts. However, these indices often fall short in detecting ecosystem degradation from disturbances like wastewater pollution, as they focus solely on species presence or abundance. This can overlook the unique contributions of species and the functional roles they play within their habitats, thereby masking early shifts in ecosystem dynamics (Mouillot et al., 2013). In contrast, a trait-based functional approach examines species traits, such as body size, trophic level, depth preference, and resilience, which are directly linked to ecological processes like nutrient cycling, energy transfer, and habitat use (Costello et al., 2015).

Functional traits —defined as morphological, physiological, or behavioral attributes that influence individual performance (Mouillot et al., 2013)— provide a powerful framework for assessing how communities respond to environmental pressures. Ecosystems with higher functional trait diversity tend to support greater biomass, higher biodiversity, and enhanced resilience to disturbances such as fishing and climate change (Duffy et al., 2016; Quimbayo et al., 2019). For example, large-bodied fish and apex predators play crucial roles in maintaining trophic regulation and preventing phase shifts, while communities spanning diverse trophic levels support more efficient energy flow and nutrient cycling (Allgeier et al., 2014; Graham et al., 2011; Schiettekatte et al., 2023).

Because trait-based metrics often respondto environmental change before species disappear, they offer a more sensitive means of detecting ecological degradation (Mouillot et al., 2013). This makes them particularly valuable for assessing the impacts of wastewater pollution, which may lead to functional homogenization even when richness remains unchanged (Mouillot et al., 2014).With most case studies evaluating the effects of wastewater on taxonomic aspects of reef fish communities, fundamental knowledge gaps remain regarding the effects of wastewater pollution on the functional structure of reef fish assemblages. Furthermore, there is scope to test weather emergent trait-based patterns—such as the dominance of mid-trophic levels over higher trophic level species— are consistent across different geographic regions and pollution contexts.

Here, we investigate the effects of domestic wastewater on reef fish assemblages and their functional structure by addressing three key research questions: 1) What are the reported effects of wastewater on the abundance, biomass, and taxonomy-based indices of reef fish assemblages?, 2) How do different wastewater components influence reef fish assemblages' behavioral, physiological, and functional traits?, 3) Based on a meta-analysis using a trait-based functional ecology approach, what is the impact of wastewater on the functional structure of fish assemblages? The two first questions are explored through a systematic review of 52 papers, while the third is addressed through a meta-analysis of a subgroup of 8 studies (25 reef sites) focused on four fish traits. These eight studies were selected as they provided enough data on fish abundance in control-impacted scenarios. The findings from this analysis identify knowledge gaps and underscore the urgent need to tackle wastewater pollution amid increasing threats to coral reefs globally.

2. Methods

2.1. Systematic literature review

We followed the PRISMA protocol (Liberati et al., 2009) to conduct a literature search on the effects of wastewater and pollutants (e.g., nutrients, sediments, organic matter) on reef fish assemblages. Only original research manuscripts in English from 1980 to October 2023 were included. The selected studies fulfilled one or more of these three criteria: (1) they examined wastewater effects on reef fish assemblages, (2) assessed pollutants' effects on fish traits (e.g., behavioral, morphological, physiological), or (3) provided species-level fish abundances for polluted vs. control sites. We focused on domestic wastewater from urban centers, excluding toxicity experiments targeting lethal pollutant concentrations or studies of PAHs, heavy metals, and pesticides. While tropical reef fish were the primary focus, subtropical and temperate reef studies (32° S–40° N) were included for comparison.

We searched Scopus and Science Direct using 10 search strings identified in a pilot review (Sup Table 1), screening 1135 abstracts, 154 full texts, and ultimately selecting 52 papers based on predefined criteria. Two researchers independently assessed selection bias (bias in the criteria used when selecting or rejecting papers relevant to address the research questions), by re-evaluating and selecting 40 manuscripts. We used discrepancies to refine the criteria. The information used in this review was extracted from main texts, supplementary materials, and figures in the selected papers.

2.2. Summary of reef fish responses to wastewater pollution

We analyzed 25 out of the 52 studies which focus on the differences of reef fish assemblages between wastewater polluted and unpolluted scenarios (wastewater studies, Sup table 2). We grouped them based on the study area, sampling methods, water quality parameters, site selection criteria, type of reef, depth of reef, and the additional anthropogenic stressors (stressors different from wastewater affecting reef fish assemblages). Reported effects of wastewater on abundance, biomass, richness, evenness, and Shannon diversity were summarized, quantifying significant increases, decreases, or no change of these variables in polluted sites compared to control sites (unpolluted). Finally, we synthetized the different reported effects of wastewater on reef-fish trophic guilds, size, position in water column and functional indices.

2.3. Effects of the different wastewater components on fish traits

We reviewed 27 out of the 52 papers focusing on the effects of common wastewater pollutants such as sediments, nutrients, organic matter, sunscreen compounds (benzophenone-3), detergent surfactants (LAS: Sodium linear alkylbenzene sulfonate), estrogens (EE2: 17α-Ethinylestradiol), and plasticizers (BPA: Bisphenol-A), on reef-fish traits

Table 1
Methodological approaches used to assess the impact of wastewater on reef-fish. The site selection criteria column lists the variables used to locate the sampling sites. Reef type shows whether the study was carried out in coral or rocky reefs. Anthropogenic stressors are factors other than wastewater pollution that may have influenced the reef-fish assemblages as reported in the reviewed studies.

Site Selection Criteria	Reef type	Anthropogenic stressors	Source
Anthropogenic activity + water quality	Coral reef	Fishing and industrial activities	(Patterson et al., 2021)
Distance to sewage outfall + Water quality	Coral reef	Overfishing	(Ford et al., 2017)
	Coral reef	Land runoff	(Reopanichkul et al., 2009)
	Coral reef	Land runoff	(Reopanichkul et al., 2010)
	Coral reef	None reported	(Russo, 1982)
	Coral reef	Fishing	(Grigg, 1994)
	Coral reef	Industrial activities	(Sasal et al., 2007)
Distance to urban center + Water quality	Coral reef	Agricultural runoff, coastal development, Land runoff	(Baum et al., 2015)
	Coral reef	Fishing and dredging	(Polónia et al., 2019)
	Coral reef	Overfishing, coral mining, and land runoff	(Cleary, 2017)
	Coral reef	Diving activities	(Naumann et al., 2015)
Water quality	Coral reef	None reported	(Chabanet et al., 1995)
	Coral reef	Fishing, golf courses runoff	(Foo et al., 2021)
	Coral reef	Agricultural runoff	(Adam et al., 2021)
Distance to sewage outfall	Rocky reef	None reported	(Azzurro et al., 2010)
	Rocky reef	Fisheries and ports' runoff	(Henriques et al., 2013)
	Rocky reef	Date-mussel fisheries	(Guidetti et al., 2002)
	Rocky reef	Industrial activities	(Nowak, 1996)
	Rocky reef	None reported	(A. K. Smith and Suthers, 1999)
	Rocky reef	None reported	(A. Smith et al., 1999)
Distance to urban center	Coral reef	Land runoff, industrial discharges, Destructive fishing	(Plass-Johnson et al., 2016)
	Coral reef	Agrochemical, Port, and industrial runoff	(Pizarro et al., 2017)
	Coral reef	Fishing	(Durán and Claro, 2009)
	Coral reef	Fishing, agricultural runoff	(Aguilar et al., 2008)
	Coral reef	Anti-fouling paints, Beach litter	(Evans et al., 1995)

(pollutant studies, Supplementary table 3). We grouped the response traits into four categories: feeding behavior and predations success; sensory and behavior; physiology and metabolism; and size and growth. The results were aggregated by trait category, contrasting the papers that were comparable in methodology, species, response traits, and pollutants.

2.4. *Impact of wastewater on the functional structure of fish assemblages*

Although our systematic review identified 52 studies examining reef fish responses to wastewater, only 8 studies met the criteria for inclusion in the trait-based meta-analysis. Specifically, we retained only those studies that compared impacted and control assemblages and provided sufficient species-level information to match abundance and trait data. (Sup Table 4). From these studies, we compiled a list of all reported fish species and retrieved their trait values from FishBase (Froese and Pauly, 2023). Based on previous literature, we focused on four traits that may influence species fitness under wastewater disturbances (Hadj-Hammou et al., 2021; McKinley and Johnston, 2010; Plass-Johnson et al., 2016; Reopanichkul et al., 2010): maximum total length (the maximum size a species can reach in cm), trophic level, maximum depth (the deepest point in a species' distribution range in m), and resilience to fishing pressure (hereafter resilience, calculated from population increase rates, growth coefficient, fecundity, and age at first maturity). Besides their ecological relevance, these traits were selected because of their availability across all reviewed species. According to (Costello et al., 2015), using traits with complete data across all species minimizes bias and ensures more robust and reliable analyses of potential changes in the functional structure of fish assemblages.

Using these trait values, we computed a multidimensional trait space (i.e., functional space) via principal coordinate analysis (PCoA), positioning species according to their traits. Trait-based dissimilarities were calculated using Gower distance, a flexible metric suitable for combining categorical and numerical data (Petchey and Gaston, 2007). To ensure comparability, we applied a scale-center transformation and assigned equal weights to all traits (Hair et al., 2010).

To evaluate the quality of the functional space, we used the *mad* index, which measures the mean absolute deviation between species pairwise trait distances and their corresponding distances in the functional space. We then assessed correlations between traits and principal component axes using linear regression for quantitative traits (reporting R^2 and *p*-values) and a Kruskal-Wallis test for qualitative traits (reporting eta squared (η^2) and p-values) (Magneville et al., 2022).

Based on the topology of this ordination, we computed functional richness (FRic) and functional identity (Fide) on the polluted (impacted) and unpolluted (control) sites in each study. FRic is defined by (Mouillot et al., 2013) as "the volume of multidimensional space occupied by all the species in a community within functional space" and Fide as "the mean value of functional traits, weighted by abundance, across all species in the community". We standardized fish abundances to individuals per m^2 and created a site-by-species abundance matrix. For studies with multiple control or impacted areas, we averaged the abundances to represent a single control and impacted site. When studies provided multiple sampling sites along a gradient of wastewater influence, we selected the sites with the lowest and highest influence of wastewater as control and impacted sites, respectively. Functional indices were computed in the statistical programming environment R (http://cran.r-project.org) using the "mFD" R package (version 1.0.6., R version 4.2.2) (Magneville et al., 2022).

3. Results

We reviewed a total of 52 papers of which 25 focused on the impact of wastewater on reef fish assemblages (wastewater studies) and 27 on the effects of common wastewater pollutants on reef fish traits (pollutants studies). From the wastewater studies only eight provided raw fish abundance data to be used in the meta-analysis.

The wastewater studies spanned across 14 countries. These studies employed various criteria for selecting sampling sites. For instance, 12 % of the studies established a water quality gradient by measuring parameters such as nutrient levels, organic matter, Chlorophyll-a, and/or sediment concentrations ($n = 3$). Others (44 %) based their site selection on a combination of water quality measurements and proximity to a sewage outfall ($n = 6$), distance from an urban center ($n = 4$), or the number of tourists in the area at a certain point in time ($n = 1$). The remaining studies (44 %) assumed a wastewater gradient based solely on the distance to a sewage outfall (n = 6) or an urban center ($n = 5$).

Sampling methods were consistent across most studies: 80 %

employed underwater visual censuses (UVC) using belt transects (n = 20), while few used alternative methods such as stationary point counts (n = 1), video recordings (n = 1), or manual collections (n = 3). Most of the studies were conducted on coral reefs (76 %, n = 19), while six studies (24 %) focused on rocky reefs (Table 1).

3.1. Effects of wastewater on the abundance, biomass, and taxonomy-based indices of reef fish assemblages

Research reveals inconsistent patterns in fish abundance between polluted and unpolluted sites. However, trends appear to be influenced by trophic guilds, more than other traits like habitat associations. Compared to abundance, biomass and taxonomy-based indices were less frequently reported, limiting our ability to identify consistent response patterns (Fig. 1).

3.1.1. Context-dependent changes in fish abundance

Fish abundance was lower in polluted sites in 52 % of studies (n = 13), higher in 20 % (n = 5), and unchanged in 8 % (n = 2), with one study reporting variable results over time. These patterns did not correlate clearly with site selection criteria, reef type, or additional anthropogenic stressors (Table 1). For example, both higher and lower fish abundances were reported at impacted sites, regardless of survey method, reef type, or other stressors (Sup Table 2).

Trophic guild appears to mediate how reef fish respond to wastewater pollution. Of the reviewed studies, 60.9 % (n = 14) reported significant differences in the abundance of specific trophic guilds between polluted (impacted) and unpolluted sites (control). The effects of wastewater on carnivorous fish were inconsistent. Two studies observed a negative effect (Henriques et al., 2013; Patterson et al., 2021), while one found a positive effect (Russo, 1982). suggesting species-specific or context-dependent responses.

Planktivores and particulate organic matter feeders responded more consistently. Four studies reported increased abundance in polluted areas, likely due to enhanced food availability from nutrient loading (Grigg, 1994; Guidetti et al., 2002; A. Smith et al., 1999; A. K. Smith and Suthers, 1999). Moreover, omnivores and invertebrate feeders generally declined in abundance under polluted conditions, except for *Coris julis* in one study (Henriques et al., 2013). This suggests that responses are influenced by factors other than diet.

The responses among herbivorous fish were variable. While some studies reported declines, particularly among browsers and larger herbivores affected by nitrogen pollution (Durán and Claro, 2009; Foo et al., 2021), others found positive or no effects (Ford et al., 2017; Russo, 1982). Additionally, a study revealed how this parameter may vary across time, for example, herbivore abundance was significantly higher at polluted sites during the first year of sampling but significantly lower by the fourth year (Naumann et al., 2015), suggesting that fish responses may exhibit a non-linear response to wastewater.

Habitat association did not show a consistent influence on fish responses to wastewater pollution. In Thailand, the abundance of benthic-associated fish was lower in polluted sites, while water-column species were more abundant (Reopanichkul et al., 2009). In contrast, in Hawaii, benthic-associated species such as surgeonfish and goatfish colonized the sewage outfall area, with no significant changes reported in overall community structure (Russo, 1982).

These contrasting findings may reflect differences in wastewater treatment and reef conditions. In Thailand, untreated sewage was

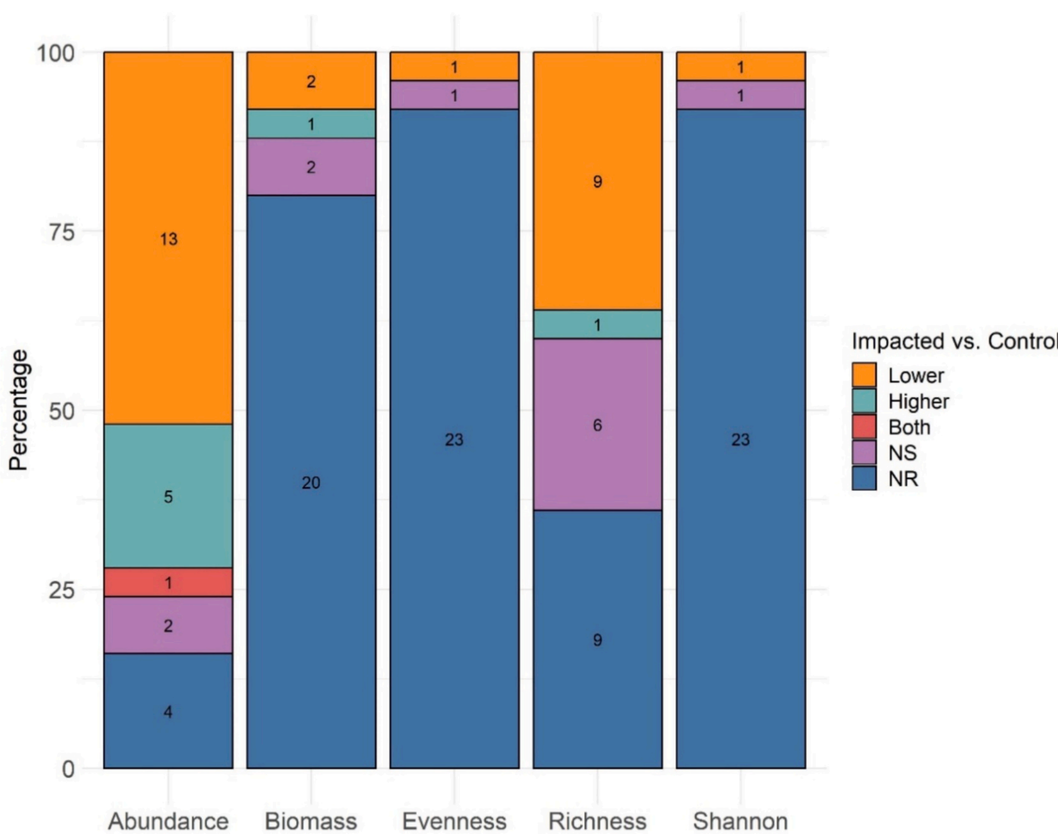

Fig. 1. Percentage of wastewater studies reporting different values of abundance, biomass, evenness, richness, and Shannon diversity of reef fish assemblages between wastewater polluted (impacted) and unpolluted (control) sites. Stacked bars indicate the percentage of studies reporting significantly lower values in the impacted sites (orange), significantly higher values in the impacted sites (green), both significantly higher and lower values at the impacted sites (red), and not significant (NS) differences between sites. NR: not reported values. Numbers in each box represent the number of studies (n = 25). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

discharged directly into the reef system, whereas Hawaii used advanced primary treatment. Additionally, surveys in Hawaii were conducted at the outfall structure, which may have provided a solid substrate for benthic communities, unlike the more diffuse impacts observed in Thailand.

3.1.2. Limited reports on biomass and taxonomy-based indices

Only 20 % of the studies (n = 5) quantified fish biomass: two observed significantly lower biomass in polluted sites (8 %), one (4 %) found higher values, and two (8 %) found no significant differences. Regarding species richness, 36 % of the studies (n = 9) observed significantly lower richness in impacted areas, while only 4 % (n = 1) reported higher values, and 24 % (n = 6) found no significant differences between sites. In terms of species' evenness, one study documented a significant decrease in polluted areas, while another found no significant difference. Similarly, Shannon diversity was reported to be significantly lower in one study but showed no significant differences in another.

3.2. Influence of wastewater components on reef fish traits

Pollutant studies (n = 27) showed that fish responses to wastewater pollutants are trait-specific and dependent on the type of pollutant and its concentration. Significant effects of common wastewater pollutants were reported on feeding behavior and predation success, sensory and behavioral traits, physiology and metabolism, and size and growth of 19 fish species and four fish groups (Fig. 2). The most tested pollutant affecting these traits was sediment (sedimentation, suspended sediments, and turbidity), which was discussed in 70.4 % of the studies (n = 19), followed by chemical agents such as linear alkylbenzene sulfonate (LAS), 17α-Ethinylestradiol (EE2), benzophenone-3 (BP-3), and Bisphenol A (BPA), reported in 18.5 % of the studies (n = 5), and nutrients and organic matter in 11.1 % (n = 3). Most of the studies (n = 24) reported significant effects on at least one fish trait.

3.2.1. Feeding behavior and predation success

Fish abundance in polluted waters may be reduced due to various mechanisms that impair feeding behavior. Several studies (n = 7) investigated the effects of sedimentation and suspended sediments on the feeding behavior of reef fish (Fig. 2). Herbivores were particularly affected by settled sediment, with species from the Acanthuridae, Scaridae, and Siganidae families showing feeding rate reductions of 57 % to 99 % in response to increased sediment loads on the epilithic algae matrix (85 % more sediment than the control). This reduction is primarily due to the fish avoiding sediments, which negatively affect food palatability, digestion, and overall fish health (Bellwood and Fulton, 2008; Goatley and Bellwood, 2012). The grain size and origin of the sediments also play a role, with species such as *Ctenochaetus striatus* showing lower feeding rates on fine riverine silicates compared to coarser reefal carbonates (Tebbett et al., 2017). Nutrient enrichment had no significant effect on fish grazing rates (Hoop et al., 2001), although it did increase the gut microbial diversity of the damselfish *Stegastes nigricans*, which may negatively affect feeding efficiency and digestive health (Degregori et al., 2021).

Carnivores and zooplanktivores were more affected by suspended than settled sediments. For example, the feeding rate of the spiny chromis (*Acanthochromis polyacanthus*) was reduced by 31 % at a sediment concentration of 45 mg/L, highlighting how turbidity impairs the ability of planktivores to visually hunt for food (Wenger et al., 2012). Similarly, the triggerfish (*Rhinecanthus aculeatus*) showed a marked decrease in foraging efficiency, taking nearly four times longer to find food in turbid waters compared to clear waters, although the turbidity level tested in this study (154 mg/L) was considerably higher than in others (Newport et al., 2021). Moreover, the predation success of *Chromis atripectoralis* was significantly reduced by suspended sediments at concentrations of 24 mg/L and 42 mg/L, while *Neopomacentrus azysron* and *N. bankieri* were only affected at the highest concentration, possibly due to their inshore reef habitats, which experience higher sedimentation compared to the outer-shelf reefs where *C. atripectoralis* is

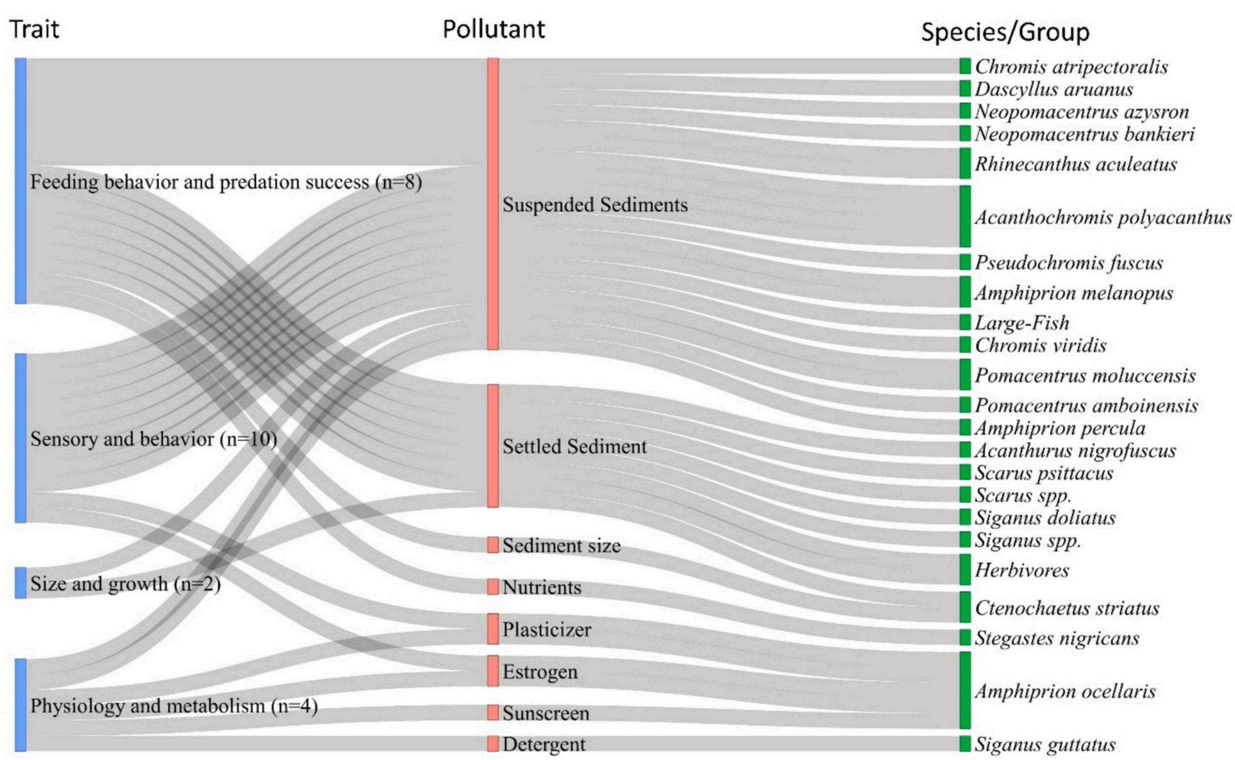

Fig. 2. Sankey diagram illustrating the traits significantly affected by different pollutants and the species or fish groups studied in the reviewed literature. Each link represents a study examining the impact of a specific pollutant on a particular fish trait. Abbreviations: Detergent (LAS: Linear Alkylbenzene Sulfonate), Estrogen (EE2: 17α-Ethinylestradiol), Sunscreen (BP-3: Benzophenone-3), Plasticizer (BPA: Bisphenol A), and Nutrients (Inorganic nitrogen and phosphorus).

more abundant (Johansen and Jones, 2013). Conversely, the prey consumption rate of the Brown dottyback (*Pseudochromis fuscus*) did not change significantly under low and high turbidity (30 and 60 mg/L) and even increased by 25 % at a medium turbidity level (45 mg/L), illustrating the predator's advantage over its prey on these conditions (Wenger et al., 2013).

3.2.2. Sensory and behavior

Suspended sediments also impair the sensory and behavioral traits of reef fish. When exposed to high concentrations of suspended sediments, *Amphiprion melanopus* (180 mg/L) and *Acanthochromis polyacanthus* (41 mg/L) exhibited faster reaction times and higher escape speeds from predators than when exposed to clear waters. They also reduced movement and avoided open areas, likely to minimize predation risk (Hess et al., 2019; Leahy et al., 2011). Increased sheltering behavior in turbid environments was also observed in 22 large fish species, particularly from the Acanthuridae, Lutjanidae, and Serranidae families, possibly for protection from predators (Kerry and Bellwood, 2017).

Behavioral impairment can also affect feeding and predation. Reduced activity in predators and increased vigilance in prey may limit foraging success, potentially lowering fish growth and abundance in the long term (Hess et al., 2019). Furthermore, sediments disrupt fish recruitment by impairing their ability to settle in favorable habitats, such as live corals. Studies showed that low to medium sediment concentrations (15–50 mg/L) significantly reduced the number of juveniles settling on live coral across multiple species, including *Amphiprion percula*, *Chromis viridis*, *Pomacentrus amboinensis*, and *P. moluccensis* (O'Connor et al., 2016; Wenger et al., 2011, 2014; Wenger and McCormick, 2013). Disruption of sensory mechanisms, such as chemosensory detection and visual acuity, contributes to lower recruitment rates, which can lead to shifts in community composition and reduced biodiversity (O'Connor et al., 2016; Wenger and McCormick, 2013).

Estrogens (EE2) have also been shown to affect fish behavior. High concentrations (100 ng/g) significantly increased the aggressive behavior of *Amphiprion ocellaris* over a 4-week period (Chen and Hsieh, 2017). However, environmentally relevant concentrations (0.02 ng/g) did not affect behavior, even after six months of exposure (Gonzalez et al., 2021). Moreover, chemical compounds such as bisphenol A (BPA) at 100 ng/g reduced the aggressive behavior of clownfish towards male intruders after three months of exposure (Gonzalez et al., 2021). Sunscreen compounds like BP-3 showed no significant effect on aggressive behavior (Gonzalez et al., 2021).

3.2.3. Physiology and metabolism

Wastewater pollutants such as sediments also affect the physiology and metabolism of fish. The gills, being one of the most exposed organs, are particularly vulnerable. In *Acanthochromis polyacanthus* and *Amphiprion melanopus*, medium concentrations of suspended sediments (45 mg/L) reduced the functional lamellar length by approximately 20 %, affecting oxygen diffusion and uptake. However, in *Amphiprion percula*, even high concentrations (180 mg/L) did not significantly affect the gill lamellae, indicating a potential physiological adaptation that may allow this species to outcompete others in turbid environments (Hess et al., 2017).

Chemical agents like LAS used in detergents also increased the metabolic rate of *Siganus guttatus* by 28 %, driven by an increase in oxygen consumption due to gill damage (Baum et al., 2016). Sunscreen chemicals like BP-3 at 10 μg/L for 7 days significantly increased triglycerides, total cholesterol, and non-esterified fatty acids in the liver of *Amphiprion ocellaris*, indicating metabolic disorders that could lead to long-term health issues (Zhang et al., 2023). Additionally, chemicals like EE2 and BPA at concentrations of 0.02 ng/g and 100 ng/g of food, respectively, reduced 11-ketotestosterone levels in clownfish (*A. ocellaris*), leading to gonadal feminization and impaired reproductive capacity in males (Gonzalez et al., 2021).

3.2.4. Size and growth

Increased suspended sediment negatively impacted the growth rate of *Acanthochromis polyacanthus*. Due to reduced food consumption, fish exposed to sediments had a proportional growth of 17 % and 13 % at concentrations of 45 mg/L and 180 mg/L, respectively, compared to a 27 % proportional growth in clear waters (0 mg/L) (Wenger et al., 2012). This could explain why fish assemblages in sediment-exposed environments tend to be composed of smaller fish compared to those in clearer waters (Mallela et al., 2007). Conversely, pollutants like EE2 and BPA did not significantly affect fish size or growth (Gonzalez et al., 2021).

3.3. Impact of wastewater on the functional structure of fish assemblages (meta-analysis)

We assessed the functional structure of fish assemblages from eight studies, of which half were tropical coral reefs and half were temperate reefs. These studies reported abundances from 24 sites across eight countries, encompassing a global pool of 314 species (Sup table 4). Analyses were conducted in the three-dimensional functional space with the best quality, i.e. with the lowest mean absolute deviation (mad = 0.017).

Species dispersion was significantly influenced by all selected fish traits on the first two functional axes (PC1 and PC2; $p < 0.05$) and, except for Trophic Level, on the third axis (PC3; $p > 0.05$; Sup Fig. 1). Resilience ($\eta^2 = 0.666$) increased along the positive values of PC1, while Max Total Length (TLmax, $R^2 = 0.491$), Trophic Level ($R^2 = 0.455$), and Max Depth (dmax, $R^2 = 0.180$) increased towards its negative values (Fig. 3). On PC2, Trophic Level, Resilience, and dmax ($R^2 = 0.488$, $\eta^2 = 0.331$, and $R^2 = 0.013$, respectively) increased along positive values, while TLmax ($R^2 = 0.042$) increased towards negative scores. Finally, on PC3, Resilience ($\eta^2 = 0.667$) and dmax ($R^2 = 0.426$) increased along negative values, while TLmax ($R^2 = 0.027$) increased along positive values (Sup Fig. 2).

Building upon the above ordination, we observed that FRic was generally higher at control sites across most reviewed locations (Fig. 4). Differences in FRic between assemblages were primarily driven by species located at the most negative scores of PC1 (large size, low resilience), the most positive and negative scores of PC2 (higher and lower trophic levels, respectively), and the most negative scores of PC3 (greater maximum depth). These species were present in control sites but often absent in impacted ones. For instance, clear differences along PC1 were observed in Colombia, Indonesia, and Italy (Fig. 4A, D, F). In contrast, differences along PC2 were more pronounced in Hawaii and Australia (Fig. 4B, E). Finally, differences along the PC3 axis were primarily evident in studies conducted in Colombia, Hawaii, Indonesia, and Italy (Sup Fig. 3A, B, D, F).

The differences observed across sites did not conclusively align with reef type; similar patterns were observed in both tropical coral reefs (Fig. 4A–D) and subtropical/temperate reefs (Fig. 4E–H). For example, most locations showed the presence of low trophic levels (herbivores) in both control and impacted sites. However, in Hawaii and Indonesia, large fish with low trophic levels were either absent or less abundant in impacted sites (Fig. 4B, D).

Moreover, few locations showed similar FRic between control and impacted sites. In Portugal, fish assemblages were primarily composed of species with mid trophic levels, small to medium sizes, and medium to high resilience. This composition resulted in relatively low FRic values for both assemblages compared to other locations. Although FRic was slightly higher in the control than the impacted site, these differences were relatively small and driven by species with medium trait values rather than extreme values, as observed in other locations (Fig. 4H).

In India, FRic was similar between sites; however, mean abundances of larger fish (TLmax >50 cm) were significantly higher at the control site (0.376 ± 0.014 ind/m^2) compared to the impacted site (0.208 ± 0.006 ind/m^2, $p = 0.021$). This abundance difference resulted in a lower

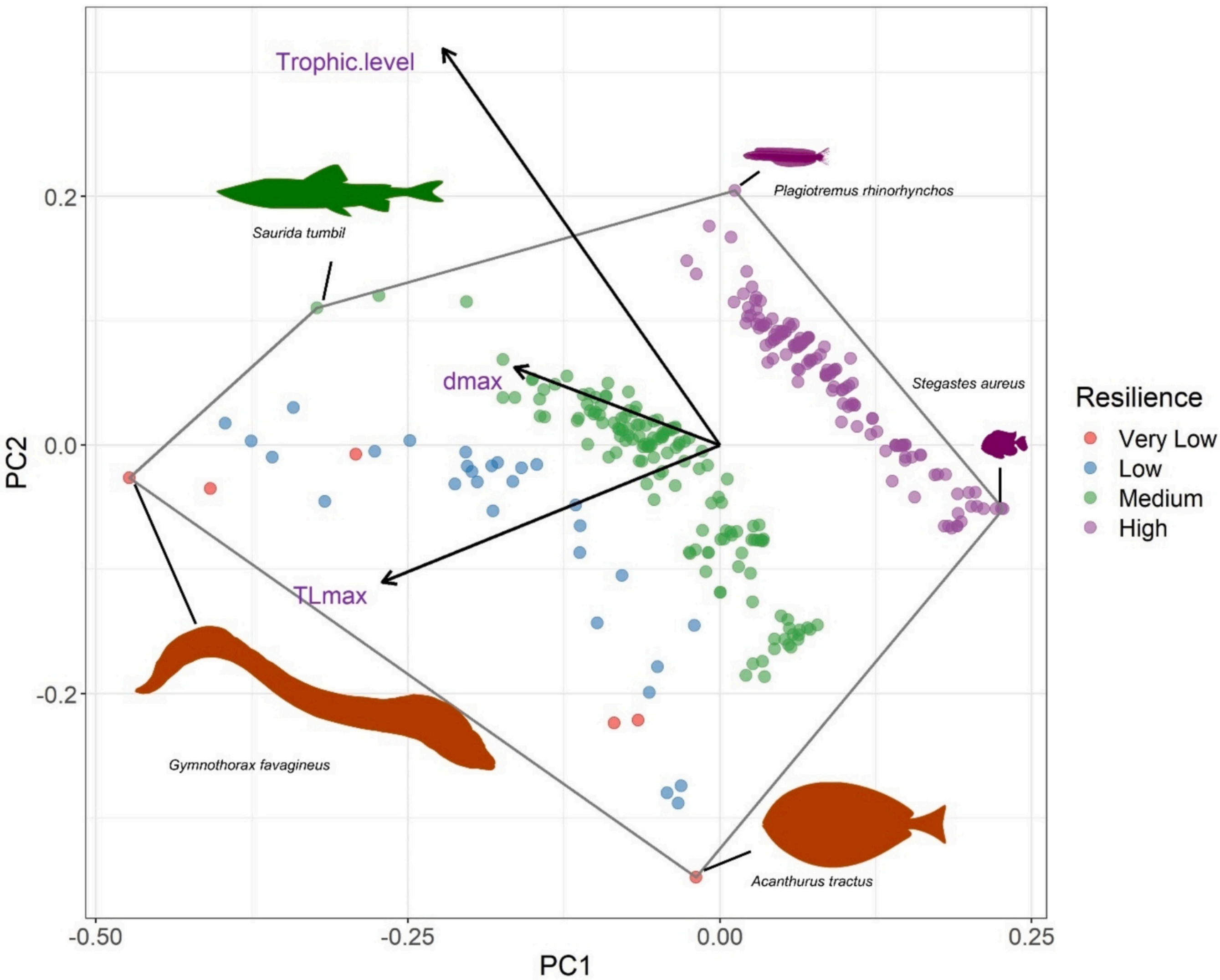

Fig. 3. Principal Coordinate Analysis (PCoA) of fish species (dots) based on their trait values within the first two dimensions (PC1 and PC2). Numerical traits include Maximum Total Length (TLmax), Trophic Level, and Maximum Depth (dmax), represented as vectors, whereas resilience to fishing pressure, a categorical trait, is depicted using colour codes. The distances between points represent functional dissimilarity, and the length and direction of vectors indicate the strength and direction of each numerical trait's influence on species dispersion within the functional space. The arrows were scaled down to 40 % for better visualization. Silhouettes representing vector species in the functional space along PC1 and PC2 were sourced from macrovector on Freepik.com.

Functional Identity (FIde) for the control site along PC1 (Fig. 4C).

In Malta, FRic was also similar between sites but higher in the impacted site (Fig. 4G). This was driven by a greater number of small-sized species with high resilience and medium trophic levels at the impacted site (6 species) compared to the control (4 species). Their abundance was significantly higher at the impacted site (0.968 ± 0.164 ind/m^2) than at the control site (0.005 ± 0.001 ind/m^2, $p = 0.046$), leading to a higher FIde value along PC1 for the impacted site (Fig. 4G).

There was no consistent pattern in FIde values across locations on any axes. While these values were similar between assemblages in most cases, clear differences were observed in others. For instance, in Hawaii (Fig. 4B) FIde values were lower on PC1, PC2, and PC3 in the control site compared to the impacted site. This suggests distinct trait compositions and/or species abundances between sites. For example, larger species were more abundant at the control site, pulling the mean trait values closer to zero on PC1, while smaller species dominated the impacted site, raising the FIde value along the same axis. Additionally, the lower FIde values on PC3 at the control site indicate a higher abundance of fish with greater maximum depth compared to the impacted site. A similar pattern was observed in Malta along PC1 and PC3, although the differences were smaller (Sup Fig. 3B, G).

Overall, our analysis revealed diverse responses of fish assemblages to wastewater pollution across locations, yet a general pattern emerged. Wastewater-impacted sites had lower FRic values and were typically composed of a higher proportion of species with greater resilience to fishing, smaller body sizes, medium trophic levels, and shallower depth ranges. In contrast, most control sites supported higher richness or abundance of larger-bodied species with lower resilience, spanning a broader range of trophic levels and depths. While specific responses varied by location, this general pattern provides a valuable framework for understanding the broad impacts of wastewater on reef fish assemblages.

4. Discussion

Fish responses to wastewater disturbances are varied and nuanced. Traditional metrics like abundance and richness fail to capture species-specific responses influenced by traits, pollutant types, and concentrations. By combining taxonomy-based metrics with a functional approach (trait-based analysis), we gain a more comprehensive view of the

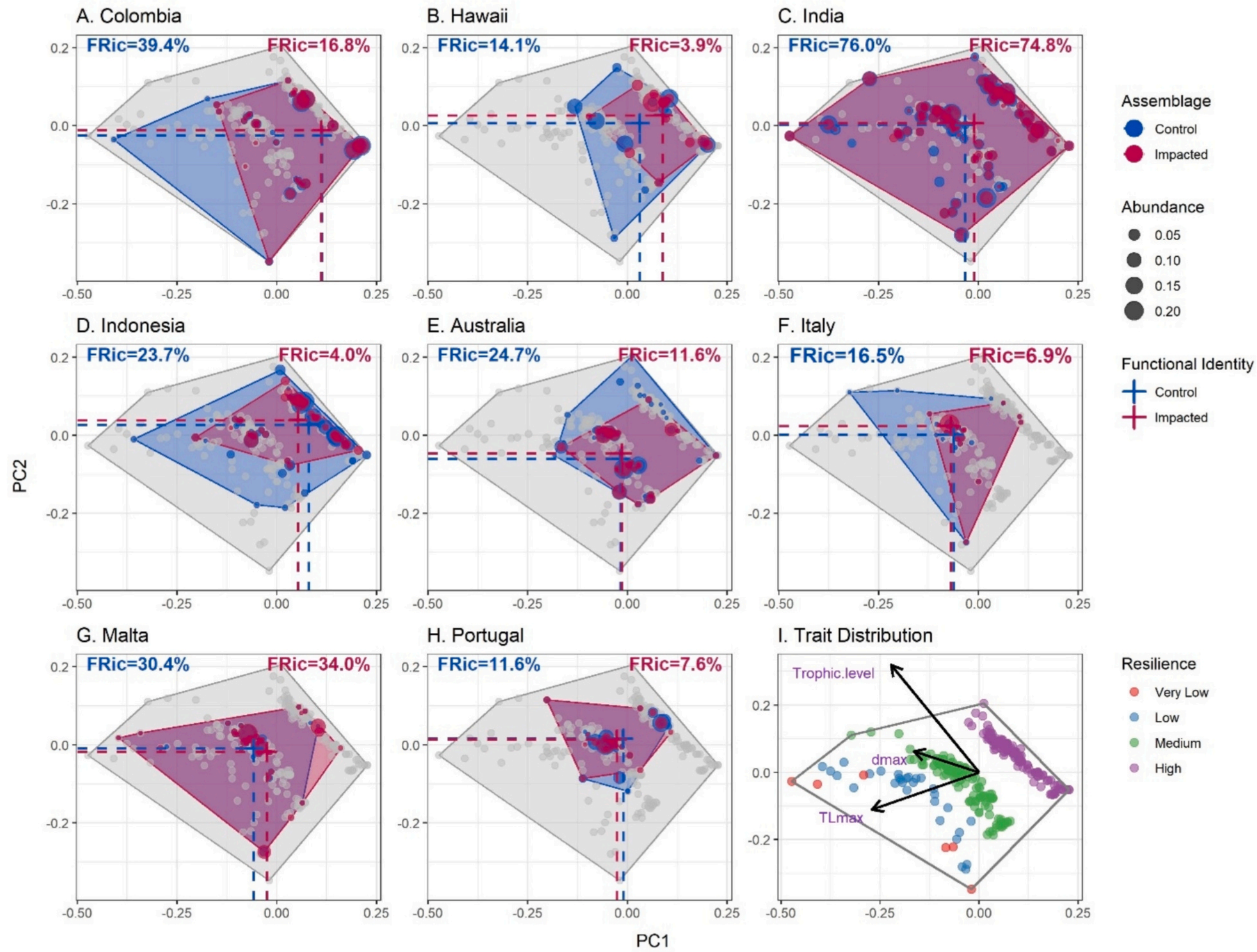

Fig. 4. Functional richness (FRic) and functional identity (FIde) in PC1 and PC2 of reef fish assemblages in control and impacted sites across eight locations: A) Colombia, B) Hawaii, C) India, D) Indonesia, E) Australia, F) Italy, G) Malta, and H) Portugal. I) Global trait distribution in the functional space (detailed description in Fig. 3). Gray dots represent species within a "global" pool comprised of species from all locations. Colored dots represent species present at control (blue) or impacted (red) sites. Dot size indicates species abundance (individuals m^{-2}). Colored convex hulls represent the percent volume of functional space occupied (FRic) by fish assemblages recorded at control (blue) and impacted sites (red), relative to the global species pool (gray). Crosses and dashed lines show the Fide values at the control (blue) and impacted (red) sites in both axes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

complex dynamics shaping reef fish assemblages in wastewater-polluted reefs. We observed contrasting scenarios in which abundance and richness were higher, lower, or unaffected in impacted sites compared to controls. Additionally, our results showed that fish responses to wastewater pollution were trait-specific and shaped by pollutant type and concentration. A general pattern emerged in our meta-analysis: impacted assemblages were characterized by a higher proportion of smaller fish with low to mid trophic levels, greater resilience to fishing pressures, and shallower depth ranges compared to those in unpolluted sites. This underscores the value of a functional approach, revealing that fish responses are more nuanced than abundance and richness metrics alone suggest. This trait-specific perspective provides a clearer framework for interpreting the ecological consequences of wastewater pollution, particularly regarding species resilience and functional roles within reef ecosystems.

4.1. Mixed responses of reef fish assemblages

Our review underscores the mixed findings regarding the effects of wastewater on reef fish abundance, richness, and other taxonomy-based metrics. This variability aligns with McKinley and Johnston's (2010) review, which found inconclusive trends across ecosystems and wastewater sources. While they observed that industrial effluents and sewage often reduced fish abundance with minimal impact on richness, our findings showed that 36 % of studies reported lower richness in impacted sites. These inconsistencies suggest that abundance and richness metrics may fluctuate irregularly with wastewater pollution. For instance, some studies describe a "rise and fall" effect in fish abundance following nutrient inputs, where spikes of initial productivity decline as eutrophication induces hypoxia or degrades benthic habitats (Naumann et al., 2015; Oczkowski and Nixon, 2008). Similarly, other studies observed that reducing organic matter through wastewater treatment initially decreased fish populations reliant on nutrient-rich environments; however, these populations later declined further due to oxygen depletion and habitat degradation (Baer et al., 2017; Ribeiro et al., 2008).

Wastewater pollution can degrade coral structures, indirectly impacting fish populations that depend on coral habitats to thrive (Pratchett et al., 2014; Reopanichkul et al., 2010). Still, nutrient input may boost fish abundance, especially for planktivores and particulate feeders, via food subsidies. This effect is seen on the Great Barrier Reef, where pelagic nutrient inputs accounted for 41 % of fish productivity, underscoring the potential for nutrient subsidies to sustain fish productivity even in degraded reefs (Morais and Bellwood, 2019). The apparent stability in abundance and richness may thus be partly attributed to the dietary flexibility that enables some reef fish to adapt to altered food resources in degraded environments (Clever et al., 2024).

Habitat connectivity with productive areas such as seagrass beds and mangroves may also buffer the adverse effects of wastewater on reef fish, as these areas can provide alternative resources and shelter, stabilizing fish communities (Gilby et al., 2016). Together, nutrient subsidies, dietary adaptability, and habitat connectivity help sustain fish populations under degraded conditions, explaining the contrasting results observed here and in (McKinley and Johnston, 2010) review. These subsidies may, however, mask long-term ecological stress within these communities, emphasizing the need for a trait-based approach to detect nuanced impacts beyond taxonomy-based metrics such as abundance and richness.

A potential source of variability in the observed fish assemblage responses is the methodological heterogeneity across studies. Differences in underwater visual census (UVC), diver-operated video, Remote Operated Video (RUV), and manual collection methods may influence results. For instance, manual collection has been shown to yield consistently different outcomes compared to UVC and video techniques (Lopez-Gonzalez et al., 2022). UVC and diver-operated video surveys may produce comparable results, particularly when targeting the same groups of species (Grane-Feliu et al., 2019). In contrast, RUV tend to report higher fish abundance and diversity than UVC or snorkeling-based methods (Dearden et al., 2010; Zarco-Perello and Enríquez, 2019). Further research, with greater representation of alternative survey approaches, is needed to assess how methodological differences may influence the detection of wastewater impacts on reef fish assemblages.

4.2. A functional approach reveals directional patterns

Our results indicate that fish responses to wastewater pollution are mediated by the four traits used in our functional analysis—maximum total length, trophic level, max depth, and resilience to fishing—revealing a more directional pattern across regions and reef types than taxonomy-based metrics alone. This suggests that the combination of specific trait values may enhance or hinder a fish's fitness in polluted environments. Hadj-Hammou et al. (2021) emphasized that traits like fish size and diet are often used to assess responses to disturbances (response traits) and ecosystem processes (effect traits). Although less studied in the context of pollution than in climate change or fishing, their review notes that some studies observe reductions in size and trophic level due to habitat degradation from pollution.

In our meta-analysis, large fish were less abundant or absent in impacted sites compared control sites. Size may be a disadvantage in oxygen-poor environments resulting from high organic matter, as larger fish typically have greater oxygen requirements and are less tolerant to hypoxia than smaller fish (Verberk et al., 2022; Xiao, 2015). Smaller species like gobies and blennies can tolerate oxygen levels below 3 % of air saturation, whereas larger fish, like damselfish, are intolerant of levels below 10 % (Nilsson and Östlund-Nilsson, 2004). Conversely, size may provide an advantage for some herbivorous fish in environments with high sediment loads from wastewater. For example, larger surgeonfish (*Acanthurus tractus*) exhibit greater tolerance for sediment-covered algae than their smaller counterparts, aided by more developed digestive systems that mechanically process sediment. This provides larger fish with a functional advantage in consuming a broader range of algae, enhancing their dietary resilience in degraded habitats (Duran et al., 2019). This adaptability may help explain why large herbivores were present only in control sites in some studies but persisted in impacted sites in others, as they may be influenced by wastewater composition and how it affects water quality through factors like oxygen availability and sediment load.

Our results were more consistent for large fish with high trophic levels, which were either absent or exhibited lower abundances in impacted sites. Unlike herbivores, predator fish lack the adaptations needed to cope with high sediment levels in polluted environments. For example, large predators like the coral grouper (*Plectropomus maculatus*) may shift prey on degraded reefs, yet declines in preferred prey biomass can ultimately lead to population decreases (Hempson et al., 2017). Furthermore, turbidity in polluted waters can impair visibility, reducing prey capture success (Newport et al., 2021; Ortega et al., 2020; Wenger et al., 2013), while also affecting prey escape responses, increasing movement speed, and reducing reaction times to predators (Hess et al., 2019). These combined effects make wastewater pollution particularly detrimental for large predators in reef ecosystems.

Our findings also show that species with a higher maximum depth were less abundant in impacted sites. Visual acuity adaptations may partially explain this trend. Species inhabiting horizon-dominated areas, such as deeper, less complex reefs or sandy bottoms, often have significantly lower visual acuity compared to those in shallow, complex habitats like coral reefs (Caves et al., 2017). This may present a particular disadvantage in polluted environments where visibility is compromised, as reduced visual capacity can hinder feeding behavior and predation of fish (Wenger et al., 2013; Wenger and McCormick, 2013), compounding the effects of wastewater pollution.

We observed that fish with high and medium resilience were present in both impacted and control sites, while species with low or very low resilience were scarce or absent in impacted areas. The early age at first maturity, higher fecundity, and rapid growth rates of highly resilient fish may help them cope with the adverse effects of wastewater, particularly in early developmental stages. Wastewater pollution can significantly affect embryo viability, delaying hatching and increasing mortality during these critical stages (Costello and Gamble, 1992). Additionally, sewage pollution can impair photomotor and visual motor responses in embryos and larvae, resulting in behavioral impairments that jeopardize survival, as responsive movements are essential for avoiding predators and foraging effectively (Gauthier and Vijayan, 2020). Finally, pollutants can block larvae from detecting settlement cues, impairing the connectivity and meta-population dynamics, vital for replenishing populations after disturbances (Mora et al., 2016).

The response of reef fish to wastewater pollution is thus shaped by the interplay of the four traits used in our analysis, where each offers a distinct advantage or vulnerability in impacted environments. Large, low-resilience species at high trophic levels are particularly disadvantaged in polluted sites, where limited visibility, reduced prey availability, and hypoxic conditions compromise their fitness and survival. Conversely, small, high-resilience species with flexible diets and low trophic levels are more likely to persist and even thrive in impacted sites, benefiting from nutrient subsidies and their ability to adapt to changing food resources.

This combination of traits allows some species to occupy new ecological roles in polluted reefs, but it may also mask underlying ecological stress. The emergence of new ecological roles does not necessarily imply functional redundancy or resilience at the ecosystem level. Trait homogenization—such as the dominance of small, resilient, mid-trophic level species—can lead to food web simplification and the erosion of key ecological processes. For example, the loss of large predators may weaken top-down control, enabling the proliferation of opportunistic species or algae and potentially triggering trophic cascades (Rizzari et al., 2015). Similarly, the decline of species with specialized habitat use or key functional roles (e.g., bioeroders, browsers, or detritivores) can reduce the capacity of reefs to recover from disturbances, maintain habitat complexity, or regulate nutrient cycling and energy transfer (Mor et al., 2022). Although trait-based compositional shifts may initially appear adaptive, they can conceal long-term ecological stress and declining ecosystem functionality (Ling et al., 2018). Recognizing these shifts is essential for anticipating delayed or nonlinear impacts of wastewater pollution on reef health. In this context, our study reinforces the value of trait-based approaches in uncovering the nuanced, context-dependent responses of fish assemblages to wastewater pollution, ultimately enhancing our understanding of ecosystem resilience and vulnerability.

4.3. Wastewater components as potential predictors of reef fish responses

Our review highlights the critical role of wastewater composition in shaping reef fish responses, as different components may affect specific fish traits. Interestingly, none of the reviewed studies reported the precise composition of wastewater, with nearly half assuming pollution based solely on the distance to sewage outfalls. Though the main components of wastewater allow one to infer effects of eutrophication and turbidity, a more detailed analysis of wastewater could clarify and support the observed patterns in fish assemblages.

For instance, nutrients and organic matter from sewage may lead to lower trophic levels in impacted sites. These pollutants initially mask degradation by providing food subsidies supporting fish richness and abundance. However, lower trophic-level species, such as herbivores and planktivores, often dominate as they adapt their diets to these available resources, while predators shift to feeding on lower trophic-level prey, effectively simplifying and shortening the food web (Bozec et al., 2005; Hempson et al., 2017). In contrast, sediments from wastewater discharge can filter high and low trophic levels. Increased sedimentation and turbidity impair herbivore feeding by covering the epilithic algal matrix with fine particles (Goatley et al., 2016), while visual predators experience decreased feeding rates and capture efficiency due to reduced prey visibility (Ortega et al., 2020). These contrasting outcomes highlight how different traits respond to specific wastewater pollutants, underscoring the importance of understanding wastewater composition to identify which pollutants to target for reducing impacts on reef fish assemblages.

Integrating wastewater composition analysis with a functional approach offers a powerful framework for informed wastewater management and impact mitigation. By linking specific pollutants to trait-based responses, it becomes possible to prioritize actions that target the most detrimental components of wastewater, such as reducing sediment loads or controlling nutrient input. This targeted approach could prevent the dominance of lower trophic-level species and maintain the trait diversity and ecological balance of reef fish assemblages. Moreover, functional metrics, which are sensitive to early ecosystem degradation, provide a valuable tool for monitoring the effectiveness of mitigation strategies. Combining wastewater profiling with a functional perspective could provide more precise and targeted management strategies, ultimately preserving both biodiversity and the essential ecosystem services reef fish provide.

5. Synthesis and implications for reef fish conservation

This study reveals that wastewater pollution shapes reef fish assemblages in trait-specific ways, with impacted sites generally dominated by smaller, high-resilience species with mid-trophic levels and shallower depth ranges, while control sites support larger, low-resilience species spanning broader trophic levels and depths. These patterns emerged despite the geographical diversity of the reviewed studies and potential disparities in wastewater treatment among sites, reinforcing the limitations of taxonomy-based metrics (e.g., abundance and richness) and underscoring the value of functional approaches for detecting ecosystem change.

Despite its clear effects on reef biodiversity and ecosystem services, sewage management remains underprioritized relative to threats like overfishing and climate change (Wear et al., 2021). Our findings provide a clear framework for understanding species responses to both wastewater pollution and its composition. This can support more effective conservation and mitigation strategies, such as prioritizing sediment filtration in coastal infrastructure and mandating tertiary wastewater treatment to reduce nutrient loads—both pollutants linked to functional homogenization and reef degradation.

We strongly recommend that trait-based indices (e.g., functional richness, functional identity) be incorporated into reef monitoring programs, as they do not need additional data collection in the field, and they are sensitive to early ecological changes than taxonomy-based metrics alone (Mouillot et al., 2013). Policymakers should also consider setting discharge thresholds based on pollutant impacts on functional traits, not only total biomass or species richness.

Future research should build on these findings by expanding trait datasets to include reproductive strategies, diet, and home range, and by increasing in situ trait measurements across polluted and unpolluted reefs. Manipulative experiments and mesocosm studies should be prioritized to test dose–response relationships between specific wastewater pollutants and fish traits. This will help clarify trait–pollutant interactions and improve predictive models of reef fish responses to pollution.

CRediT authorship contribution statement

Ramón Alejandro Plazas-Gómez: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sonia Bejarano:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Camille Magneville:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis. **Marie Fujitani:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to improve readability and correct grammar mistakes. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118024.

Data availability

This study is based entirely on previously published data, which are available in the cited sources. Data extracted from figures and tables in these sources are provided in the supplementary materials. No new data was generated.

References

Adam, T.C., Burkepile, D.E., Holbrook, S.J., Carpenter, R.C., Claudet, J., Loiseau, C., Thiault, L., Brooks, A.J., Washburn, L., Schmitt, R.J., 2021. Landscape-scale patterns of nutrient enrichment in a coral reef ecosystem: implications for coral to algae phase shifts. Ecol. Appl. 31 (1). https://doi.org/10.1002/eap.2227.

Aguilar, C., González-Sansón, G., Faloh, I., Curry, R.A., 2008. Spatial variation in stable isotopes (δ13C and δ 15N) in marine fish along the coast of Havana City: evidence of human impacts from harbor and river waters. J. Coast. Res. 24 (5), 1281–1288. https://doi.org/10.2112/07-0832.1.

Allgeier, J.E., Layman, C.A., Mumby, P.J., Rosemond, A.D., 2014. Consistent nutrient storage and supply mediated by diverse fish communities in coral reef ecosystems. Glob. Chang. Biol. 20 (8), 2459–2472. https://doi.org/10.1111/gcb.12566.

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J., Lenton, T.M., 2022. Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science 377 (6611). https://doi.org/10.1126/science.abn7950.

Azzurro, E., Matiddi, M., Fanelli, E., Guidetti, P., Mesa, G. La, Scarpato, A., Axiak, V., 2010. Sewage pollution impact on Mediterranean rocky-reef fish assemblages. Mar. Environ. Res. 69 (5), 390–397. https://doi.org/10.1016/j.marenvres.2010.01.006.

Baer, J., Eckmann, R., Rösch, R., Arlinghaus, R., Brinker, A., 2017. Managing upper Lake Constance fishery in a multi-sector policy landscape: Beneficiary and victim of a century of anthropogenic trophic change. In: Song, A.M., Bower, S.D., Onyango, P., Cooke, S.J., Chuenpagdee, R. (Eds.), *Inter-Sectoral Governance of Inland Fisheries* (TBTI P. Series, pp. 32–47). St John's. https://www.researchgate.net/publication/306034743.

Baum, G., Januar, H.I., Ferse, S.C.A., Kunzmann, A., 2015. Local and regional impacts of pollution on coral reefs along the thousand islands north of the megacity Jakarta, Indonesia. PLoS One 10 (9). https://doi.org/10.1371/journal.pone.0138271.

Baum, G., Kegler, P., Scholz-Böttcher, B.M., Alfiansah, Y.R., Abrar, M., Kunzmann, A., 2016. Metabolic performance of the coral reef fish Siganus guttatus exposed to combinations of water borne diesel, an anionic surfactant and elevated temperature in Indonesia. Mar. Pollut. Bull. 110 (2), 735–746. https://doi.org/10.1016/j.marpolbul.2016.02.078.

Beger, M., Possingham, H., 2008. Environmental factors that influence the distribution of coral reef fishes: modeling occurrence data for broad-scale conservation and management. Mar. Ecol. Prog. Ser. 361, 1–13. https://doi.org/10.3354/meps07481.

Bellwood, D.R., Fulton, C.J., 2008. Sediment-mediated suppression of herbivory on coral reefs: decreasing resilience to rising sea levels and climate change? Am. Soc. Limnol. Oceanogr. 6 (53), 2695–2701.

Bozec, Y.M., Kulbicki, M., Chassot, E., Gascuel, D., 2005. Trophic signature of coral reef fish assemblages: towards a potential indicator of ecosystem disturbance. Aquat. Living Resour. 18 (2), 103–109. https://doi.org/10.1051/alr:2005013.

Caves, E.M., Sutton, T.T., Johnsen, S., 2017. Visual acuity in ray-finned fishes correlates with eye size and habitat. J. Exp. Biol. 220 (9), 1586–1596. https://doi.org/10.1242/jeb.151183.

Chabanet, P., Dufourb, V., Galzin, R., 1995. Disturbance impact on reef fish communities in Reunion Island (Indian Ocean). J. Exp. Mar. Biol. Ecol. 188.

Chen, T.H., Hsieh, C.Y., 2017. Fighting Nemo: effect of 17A-ethinylestradiol (EE2) on aggressive behavior and social hierarchy of the false clown anemonefish Amphiprion ocellaris. Mar. Pollut. Bull. 124 (2), 760–766. https://doi.org/10.1016/j.marpolbul.2016.12.042.

Cleary, D.F.R., 2017. Linking fish species traits to environmental conditions in the Jakarta Bay-Pulau Seribu coral reef system. Mar. Pollut. Bull. 122 (1–2), 259–262. https://doi.org/10.1016/j.marpolbul.2017.06.054.

Clever, F., Preziosi, R.F., Nguyen, B., De Gracia, B., Quintero, H., McMillan, W.O., Altieri, A.H., O'Dea, A., Knowlton, N., Leray, M., 2024. Dietary Resilience of Coral Reef Fishes to Habitat Degradation. https://doi.org/10.1101/2024.05.22.595166.

Costello, M.J., Gamble, J.C., 1992. Effects of sewage sludge on marine fish embryos and larvae. Mar. Environ. Res. 33 (1), 49–74. https://doi.org/10.1016/0141-1136(92)90005-7.

Costello, M.J., Claus, S., Dekeyzer, S., Vandepitte, L., Tuama, É., Lear, D., Tyler-Walters, H., 2015. Biological and ecological traits of marine species. In: PeerJ (Vol. 2015, Issue 8). PeerJ Inc. https://doi.org/10.7717/peerj.1201

Dearden, P., Theberge, M., Yasué, M., 2010. Using underwater cameras to assess the effects of snorkeler and SCUBA diver presence on coral reef fish abundance, family richness, and species composition. Environ. Monit. Assess. 163 (1–4), 531–538. https://doi.org/10.1007/s10661-009-0855-3.

Degregori, S., Casey, J.M., Barber, P.H., 2021. Nutrient pollution alters the gut microbiome of a territorial reef fish. Mar. Pollut. Bull. 169. https://doi.org/10.1016/j.marpolbul.2021.112522.

Duffy, J.E., Lefcheck, J.S., Stuart-Smith, R.D., Navarrete, S.A., Edgar, G.J., 2016. Biodiversity enhances reef fish biomass and resistance to climate change. Proc. Natl. Acad. Sci. USA 113 (22), 6230–6235. https://doi.org/10.1073/pnas.1524465113.

Durán, A., Claro, R., 2009. Actividad alimentaria de los peces herbívoros y su impacto en arrecifes con diferente nivel de degradación antrópica. In: Rev. Biol. Trop. (Int. J. Trop. Biol. ISSN) (Vol. 57, Issue 3).

Duran, A., Adam, T.C., Palma, L., Moreno, S., Collado-Vides, L., Burkepile, D.E., 2019. Feeding behavior in Caribbean surgeonfishes varies across fish size, algal abundance, and habitat characteristics. Mar. Ecol. 40 (4). https://doi.org/10.1111/maec.12561.

Evans, S.M., Dawson, M., Day, J., Frid, C.L.J., Gill, M.E., Pattisinat, L.A., Porter, J., 1995. Domestic waste and TBT pollution in coastal areas of Ambon Island (eastern Indonesia). Mar. Pollut. Bull. Vol. 30, Issue 94.

Fabricius, K., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50 (2), 125–146. https://doi.org/10.1016/j.marpolbul.2004.11.028.

Foo, S.A., Walsh, W.J., Lecky, J., Marcoux, S., Asner, G.P., 2021. Impacts of pollution, fishing pressure, and reef rugosity on resource fish biomass in West Hawaii. Ecol. Appl. 31 (1). https://doi.org/10.1002/eap.2213.

Ford, A.K., Van Hoytema, N., Moore, B.R., Pandihau, L., Wild, C., Ferse, S.C.A., 2017. High sedimentary oxygen consumption indicates that sewage input from small islands drives benthic community shifts on overfished reefs. Environ. Conserv. 44 (4), 405–411. https://doi.org/10.1017/S0376892917000054.

Froese, R., Pauly, D., 2023. FishBase. FishBase. World Wide Web Electronic Publication. https://www.fishbase.se/search.php.

Gauthier, P.T., Vijayan, M.M., 2020. Municipal wastewater effluent exposure disrupts early development, larval behavior, and stress response in zebrafish. Environ. Pollut. 259. https://doi.org/10.1016/j.envpol.2019.113757.

Gilby, B.L., Tibbetts, I.R., Olds, A.D., Maxwell, P.S., Stevens, T., 2016. Seascape context and predators override water quality effects on inshore coral reef fish communities. Coral Reefs 35 (3), 979–990. https://doi.org/10.1007/s00338-016-1449-5.

Goatley, C.H.R., Bellwood, D.R., 2012. Sediment suppresses herbivory across a coral reef depth gradient. Biol. Lett. 8 (6), 1016–1018. https://doi.org/10.1098/rsbl.2012.0770.

Goatley, C.H.R., Bonaldo, R.M., Fox, R.J., Bellwood, D.R., 2016. Sediments and herbivory as sensitive indicators of coral reef degradation. Ecol. Soc. 21 (1). https://doi.org/10.5751/ES-08334-210129.

Gonzalez, J.A., Histed, A.R., Nowak, E., Lange, D., Craig, S.E., Parker, C.G., Kaur, A., Bhuvanagiri, S., Kroll, K.J., Martyniuk, C.J., Denslow, N.D., Rosenfeld, C.S., Rhodes, J.S., 2021. Impact of bisphenol-A and synthetic estradiol on brain, behavior, gonads and sex hormones in a sexually labile coral reef fish. Horm. Behav. 136. https://doi.org/10.1016/j.yhbeh.2021.105043.

Graham, N.A.J., Chabanet, P., Evans, R.D., Jennings, S., Letourneur, Y., Aaron Macneil, M., Mcclanahan, T.R., Öhman, M.C., Polunin, N.V.C., Wilson, S.K., 2011. Extinction vulnerability of coral reef fishes. Ecol. Lett. 14 (4), 341–348. https://doi.org/10.1111/j.1461-0248.2011.01592.x.

Grigg, R.W., 1994. Effects of sewage discharge, fishing pressure and habitat complexity on coral ecosystems and reef fishes in Hawaii. Mar. Ecol. Prog. Ser. 25–34.

Guidetti, P., Fanelli, G., Fraschetti, S., Terlizzi, A., Boero, F., 2002. Coastal fish indicate human-induced changes in the Mediterranean littoral. Mar. Environ. Res. 53, 77–94. www.elsevier.com/locate/marenvrev.

Hadj-Hammou, J., Mouillot, D., Graham, N.A.J., 2021. Response and effect traits of coral reef fish. In: Frontiers in Marine Science, vol. 8. Frontiers Media S.A. https://doi.org/10.3389/fmars.2021.640619

Hair, J., Black, W., Babin, B., Anderson, R., 2010. Multivariate Data Analysis, Seventh edition. Pearson.

Hempson, T.N., Graham, N.A.J., MacNeil, M.A., Williamson, D.H., Jones, G.P., Almany, G.R., 2017. Coral reef mesopredators switch prey, shortening food chains, in response to habitat degradation. Ecol. Evol. 7 (8), 2626–2635. https://doi.org/10.1002/ece3.2805.

Henriques, S., Pais, M.P., Batista, M.I., Costa, M.J., Cabral, H.N., 2013. Response of fish-based metrics to anthropogenic pressures in temperate rocky reefs. Ecol. Indic. 25, 65–76. https://doi.org/10.1016/j.ecolind.2012.09.003.

Hess, S., Prescott, L.J., Hoey, A.S., McMahon, S.A., Wenger, A.S., Rummer, J.L., 2017. Species-specific impacts of suspended sediments on gill structure and function in coral reef fishes. Proc. R. Soc. B Biol. Sci. 284 (1866). https://doi.org/10.1098/rspb.2017.1279.

Hess, S., Allan, B.J.M., Hoey, A.S., Jarrold, M.D., Wenger, A.S., Rummer, J.L., 2019. Enhanced fast-start performance and anti-predator behaviour in a coral reef fish in response to suspended sediment exposure. Coral Reefs 38 (1), 103–108. https://doi.org/10.1007/s00338-018-01757-6.

Hoop, H., Booth, D., Broadbent, A., Brodie, J., Bucher, D., Capone, D., Coll, J., Dennison, W., Erdmann, M., Harrison, P., Hoegh-Guldberg, O., Hutchings, P., Jones, G.B., Larhum, A.W.D., O'neil, J., Steven, A., Tentori, E., Ward, S., Williamson, J., Yellowlees, D., 2001. ENCORE: the effect of nutrient enrichment on coral reefs. Synthesis of results and conclusions. Mar. Pollut. Bull. 42 (2), 91.

Johansen, J.L., Jones, G.P., 2013. Sediment-induced turbidity impairs foraging performance and prey choice of planktivorous coral reef fishes. Ecol. Appl. 23 (6), 1504–1517. https://doi.org/10.1890/12-0704.1.

Kerry, J.T., Bellwood, D.R., 2017. Environmental drivers of sheltering behaviour in large reef fishes. Mar. Pollut. Bull. 125 (1–2), 254–259. https://doi.org/10.1016/j.marpolbul.2017.08.037.

Leahy, S.M., McCormick, M.I., Mitchell, M.D., Ferrari, M.C.O., 2011. To fear or to feed: the effects of turbidity on perception of risk by a marine fish. Biol. Lett. 7 (6), 811–813. https://doi.org/10.1098/rsbl.2011.0645.

Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gøtzsche, P.C., Ioannidis, J.P.A., Clarke, M., Devereaux, P.J., Kleijnen, J., Moher, D., 2009. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. BMJ (Clin. Res. Ed.) 339. https://doi.org/10.1136/bmj.b2700.

Ling, S.D., Davey, A., Reeves, S.E., Gaylard, S., Davies, P.L., Stuart-Smith, R.D., Edgar, G.J., 2018. Pollution signature for temperate reef biodiversity is short and simple. Mar. Pollut. Bull. 130, 159–169. https://doi.org/10.1016/j.marpolbul.2018.02.053.

Ma, Y., Jiang, C., Li, S., Liu, Y., Wen, X., Long, Y., Yuan, S., Kang, Y., Wang, Y., Wu, R., 2023. Ecological vulnerability assessment of coral islands and reefs in the South China Sea based on remote sensing and reanalysis data. Front. Ecol. Evol. 11. https://doi.org/10.3389/fevo.2023.1066961.

Magneville, C., Loiseau, N., Albouy, C., Casajus, N., Claverie, T., Escalas, A., Leprieur, F., Maire, E., Mouillot, D., Villéger, S., 2022. mFD: an R package to compute and illustrate the multiple facets of functional diversity. Ecography 2022 (1). https://doi.org/10.1111/ecog.05904.

Mallela, J., Roberts, C., Harrod, C., Goldspink, C.R., 2007. Distributional patterns and community structure of Caribbean coral reef fishes within a river-impacted bay. J. Fish Biol. 70 (2), 523–537. https://doi.org/10.1111/j.1095-8649.2007.01323.x.

McKinley, A., Johnston, E.L., 2010. Impacts of contaminant sources on marine fish abundance and species richness: a review and meta-analysis of evidence from the field. Mar. Ecol. Prog. Ser. 420, 175–191. https://doi.org/10.3354/meps08856.

Mor, J.R., Muñoz, I., Sabater, S., Zamora, L., Ruhi, A., 2022. Energy limitation or sensitive predators? Trophic and non-trophic impacts of wastewater pollution on stream food webs. Ecology 103 (2). https://doi.org/10.1002/ecy.3587.
Mora, C., Graham, N.A.J., Nyström, M., 2016. Ecological limitations to the resilience of coral reefs. In: Coral Reefs (Vol. 35, Issue 4, pp. 1271–1280). Springer Verlag. https://doi.org/10.1007/s00338-016-1479-z.
Morais, R.A., Bellwood, D.R., 2019. Pelagic subsidies underpin fish productivity on a degraded coral reef. Curr. Biol. 29 (9), 1521–1527.e6. https://doi.org/10.1016/j.cub.2019.03.044.
Mouillot, D., Graham, N.A.J., Villéger, S., Mason, N.W.H., Bellwood, D.R., 2013. A functional approach reveals community responses to disturbances. In: Trends in Ecology and Evolution (Vol. 28, Issue 3, pp. 167–177). https://doi.org/10.1016/j.tree.2012.10.004.
Mouillot, D., Villéger, S., Parravicini, V., Kulbicki, M., Arias-González, J.E., Bender, M., Chabanet, P., Floeter, S.R., Friedlander, A., Vigliola, L., Bellwood, D.R., 2014. Functional over-redundancy and high functional vulnerability in global fish faunas on tropical reefs. Proc. Natl. Acad. Sci. 111 (38), 13757–13762. https://doi.org/10.1073/pnas.1317625111.
Naumann, M.S., Bednarz, V.N., Ferse, S.C.A., Niggl, W., Wild, C., 2015. Monitoring of coastal coral reefs near Dahab (Gulf of Aqaba, Red Sea) indicates local eutrophication as potential cause for change in benthic communities. Environ. Monit. Assess. 187 (2), 1–14. https://doi.org/10.1007/s10661-014-4257-9.
Newport, C., Padget, O., de Perera, T.B., 2021. High turbidity levels alter coral reef fish movement in a foraging task. Sci. Rep. 11 (1). https://doi.org/10.1038/s41598-021-84814-5.
Nilsson, G.E., Östlund-Nilsson, S., 2004. Hypoxia in paradise: widespread hypoxia tolerance in coral reef fishes. Proc. R. Soc. B Biol. Sci. 271 (Suppl. 3). https://doi.org/10.1098/rsbl.2003.0087.
Nowak, B.F., 1996. Cheilodactylus fuscus, and rock Cale, Crinodus lophodon, from Sydney cliff-face sewage OutfaHs. Mar. Pollut. Bull. 33, 281–292.
O'Connor, J.J., Lecchini, D., Beck, H.J., Cadiou, G., Lecellier, G., Booth, D.J., Nakamura, Y., 2016. Sediment pollution impacts sensory ability and performance of settling coral-reef fish. Oecologia 180 (1), 11–21. https://doi.org/10.1007/s00442-015-3367-6.
Oczkowski, A., Nixon, S., 2008. Increasing nutrient concentrations and the rise and fall of a coastal fishery; a review of data from the Nile Delta, Egypt. Estuar. Coast. Shelf Sci. 77 (3), 309–319. https://doi.org/10.1016/j.ecss.2007.11.028.
Ortega, J.C.G., Figueiredo, B.R.S., da Graça, W.J., Agostinho, A.A., Bini, L.M., 2020. Negative effect of turbidity on prey capture for both visual and non-visual aquatic predators. In: Journal of Animal Ecology (Vol. 89, Issue 11, pp. 2427–2439). Blackwell Publishing Ltd. https://doi.org/10.1111/1365-2656.13329.
Patterson, E.J.K., Jayanthi, M., Malleshappa, H., Immaculate Jeyasanta, K., Laju, R.L., Patterson, J., Diraviya Raj, K., Mathews, G., Marimuthu, A.S., Grimsditch, G., 2021. COVID-19 lockdown improved the health of coastal environment and enhanced the population of reef-fish. Mar. Pollut. Bull. 165. https://doi.org/10.1016/j.marpolbul.2021.112124.
Petchey, O.L., Gaston, K.J., 2007. Dendrograms and measuring functional diversity. Oikos 116 (8), 1422–1426. https://doi.org/10.1111/j.2007.0030-1299.15894.x.
Pizarro, V., Rodríguez, S.C., López-Victoria, M., Zapata, F.A., Zea, S., Galindo-Martínez, C.T., Iglesias-Prieto, R., Pollock, J., Medina, M., 2017. Unraveling the structure and composition of Varadero Reef, an improbable and imperiled coral reef in the Colombian Caribbean. PeerJ 2017 (12). https://doi.org/10.7717/peerj.4119.
Plass-Johnson, J.G., Taylor, M.H., Husain, A.A.A., Teichberg, M.C., Ferse, S.C.A., 2016. Non-random variability in functional composition of coral reef fish communities along an environmental gradient. PLoS One 11 (4). https://doi.org/10.1371/journal.pone.0154014.
Polónia, A.R.M., Cleary, D.F.R., Duine, A.A., Van Dijk, J., De Voogd, N.J., 2019. Assessment of fish community structure along the Jakarta Bay-Pulau Seribu reef complex. J. Mar. Biol. Assoc. U. K. 99 (2), 503–516. https://doi.org/10.1017/S0025315418000152.
Pratchett, M.S., Hoey, A.S., Wilson, S.K., 2014. Reef degradation and the loss of critical ecosystem goods and services provided by coral reef fishes. In: Current Opinion in Environmental Sustainability (Vol. 7, pp. 37–43). https://doi.org/10.1016/j.cosust.2013.11.022.
Quimbayo, J.P., Dias, M.S., Kulbicki, M., Mendes, T.C., Lamb, R.W., Johnson, A.F., Aburto-Oropeza, O., Alvarado, J.J., Bocos, A.A., Ferreira, C.E.L., Garcia, E., Luiz, O. J., Mascareñas-Osorio, I., Pinheiro, H.T., Rodriguez-Zaragoza, F., Salas, E., Zapata, F. A., Floeter, S.R., 2019. Determinants of reef fish assemblages in tropical oceanic islands. Ecography 42 (1), 77–87. https://doi.org/10.1111/ecog.03506.
Reopanichkul, P., Schlacher, T.A., Carter, R.W., Worachananant, S., 2009. Sewage impacts coral reefs at multiple levels of ecological organization. Mar. Pollut. Bull. 58 (9), 1356–1362. https://doi.org/10.1016/j.marpolbul.2009.04.024.
Reopanichkul, P., Carter, R.W., Worachananant, S., Crossland, C.J., 2010. Wastewater discharge degrades coastal waters and reef communities in southern Thailand. Mar. Environ. Res. 69 (5), 287–296. https://doi.org/10.1016/j.marenvres.2009.11.011.
Ribeiro, J., Monteiro, C., Monteiro, P., Bentes, L., Coelho, R., Goncalves, J., Lino, P., Erzini, K., 2008. Long-term changes in fish communities of the Ria Formosa coastal lagoon (southern Portugal) based on two studies made 20 years appart. Estuar. Coast. Shelf Sci. 76, 57–68.
Rizzari, J.R., Bergseth, B.J., Frisch, A.J., 2015. Impact of conservation areas on trophic interactions between apex predators and herbivores on coral reefs. Conserv. Biol. 29 (2), 418–429. https://doi.org/10.1111/cobi.12385.
Russo, A.R., 1982. Temporal changes in fish community structure near a sewage ocean outfall, Mokapu, Oahu, Hawaii. Mar. Environ. Res. 6, 83–98.
Sasal, P., Mouillot, D., Fichez, R., Chifflet, S., Kulbicki, M., 2007. The use of fish parasites as biological indicators of anthropogenic influences in coral-reef lagoons: A case study of Apogonidae parasites in New-Caledonia. Mar. Pollut. Bull. 54 (11), 1697–1706. https://doi.org/10.1016/j.marpolbul.2007.06.014.
Schiettekatte, N.M.D., Casey, J.M., Brandl, S.J., Mercière, A., Degregori, S., Burkepile, D., Van Wert, J.C., Ghilardi, M., Villéger, S., Parravicini, V., 2023. The role of fish feces for nutrient cycling on coral reefs. Oikos 2023 (9). https://doi.org/10.1111/oik.09914.
Smith, A.K., Suthers, I.M., 1999. Effects of sewage effluent discharge on the abundance, condition and mortality of hulafish, Trachinops taeniatus (Plesiopidae). Environ. Pollut. 106, 97–106. www.elsevier.com/locate/envpol.
Smith, A., Ajani, P., Roberts, D., 1999. Spatial and temporal variation in fish assemblages exposed to sewage and implications for management. Mar. Environ. Res. 47, 241–260.
Tebbett, S.B., Goatley, C.H.R., Bellwood, D.R., 2017. Fine sediments suppress detritivory on coral reefs. Mar. Pollut. Bull. 114 (2), 934–940. https://doi.org/10.1016/j.marpolbul.2016.11.016.
Tuholske, C., Halpern, B.S., Blasco, G., Villasenor, J.C., Frazier, M., Caylor, K., 2021. Mapping global inputs and impacts from of human sewage in coastal ecosystems. PLoS One 16 (11), e0258898. https://doi.org/10.1371/journal.pone.0258898.
Turner, N.R., Renegar, D.A., 2017. Petroleum hydrocarbon toxicity to corals: a review. Mar. Pollut. Bull. 119 (2), 1–16. https://doi.org/10.1016/j.marpolbul.2017.04.050.
Verberk, W.C.E.P., Sandker, J.F., van de Pol, I.L.E., Urbina, M.A., Wilson, R.W., McKenzie, D.J., Leiva, F.P., 2022. Body mass and cell size shape the tolerance of fishes to low oxygen in a temperature-dependent manner. Glob. Chang. Biol. 28 (19), 5695–5707. https://doi.org/10.1111/gcb.16319.
Wear, S.L., Thurber, R.V., 2015. Sewage pollution: mitigation is key for coral reef stewardship. Ann. N. Y. Acad. Sci. 1355 (1), 15–30. https://doi.org/10.1111/nyas.12785.
Wear, S.L., Acuña, V., McDonald, R., Font, C., 2021. Sewage pollution, declining ecosystem health, and cross-sector collaboration. In: Biological Conservation, vol. 255. Elsevier Ltd. https://doi.org/10.1016/j.biocon.2021.109010
Wenger, A.S., McCormick, M.I., 2013. Determining trigger values of suspended sediment for behavioral changes in a coral reef fish. Mar. Pollut. Bull. 70 (1–2), 73–80. https://doi.org/10.1016/j.marpolbul.2013.02.014.
Wenger, A.S., Johansen, J.L., Jones, G.P., 2011. Suspended sediment impairs habitat choice and chemosensory discrimination in two coral reef fishes. Coral Reefs 30 (4), 879–887. https://doi.org/10.1007/s00338-011-0773-z.
Wenger, A.S., Johansen, J.L., Jones, G.P., 2012. Increasing suspended sediment reduces foraging, growth and condition of a planktivorous damselfish. J. Exp. Mar. Biol. Ecol. 428, 43–48. https://doi.org/10.1016/j.jembe.2012.06.004.
Wenger, A.S., McCormick, M.I., McLeod, I.M., Jones, G.P., 2013. Suspended sediment alters predator-prey interactions between two coral reef fishes. Coral Reefs 32 (2), 369–374. https://doi.org/10.1007/s00338-012-0991-z.
Wenger, A.S., McCormick, M.I., Endo, G.G.K., McLeod, I.M., Kroon, F.J., Jones, G.P., 2014. Suspended sediment prolongs larval development in a coral reef fish. J. Exp. Biol. 217 (7), 1122–1128. https://doi.org/10.1242/jeb.094409.
Wenger, A.S., Fabricius, K.E., Jones, G.P., Brodie, J.E., 2015. Effects of sedimentation, eutrophication, and chemical pollution on coral reef fishes. In: Mora, C. (Ed.), Ecology of Fishes on Coral Reefs. Cambridge University Press, pp. 145–153. https://doi.org/10.1017/CBO9781316105412.017.
Xiao, W., 2015. The hypoxia signaling pathway and hypoxic adaptation in fishes. In: Science China Life Sciences (Vol. 58, Issue 2, pp. 148–155). Science in China Press. https://doi.org/10.1007/s11427-015-4801-z.
Zarco-Perello, S., Enríquez, S., 2019. Remote underwater video reveals higher fish diversity and abundance in seagrass meadows, and habitat differences in trophic interactions. Sci. Rep. 9 (1). https://doi.org/10.1038/s41598-019-43037-5.
Zhang, Y.K., Ke, H.Y., Qin, Y.Q., Ju, H.Y., Chen, Y.M., Lin, F., Zhang, J.L., Diao, X.P., 2023. Environmental concentrations of benzophenone-3 disturbed lipid metabolism in the liver of clown anemonefish (Amphiprion ocellaris). Environ. Pollut. 317. https://doi.org/10.1016/j.envpol.2022.120792.