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Variations in Hard Coral and Macroalgal Cover on Pareiwella Reef, (Tangalle, Sri Lanka) in response to the 2023 El Niño and Post-Event Recovery

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Abstract: Coral reefs, essential for marine biodiversity and ecosystem services, are increasingly threatened by climate anomalies such as El Niño. Sri Lanka has also been affected by El Niño events over the past few decades. This study provides the first documented assessment of coral bleaching impacts and short-term recovery dynamics on a Sri Lankan reef system. We evaluated variation in Hard Coral Cover (HCC), Macroalgal Cover (MaC), and Other Benthic Cover (OBC) in the back reef zone of the Pareiwella Coral Reef, Tangalle, Sri Lanka, during the El Niño event (August–October 2023) and the post-El Niño period (January–March 2025). Bleaching assessments for HCC were conducted in August 2023 and January 2025, classifying colonies as totally bleached (TBC), partially bleached (PBC), pale-colored (PCC), recently dead (RDC), dead (DC), or healthy (HC). Data were collected along six permanent transects with 0.5×0.5 m² quadrats deployed at regular intervals. During the El Niño period, mean percentage cover± SD of HCC, MaC, and OBC was 35.77 ± 1.97%, 47.39 13 ± 2.80%, and 16.84 ± 2.36%, respectively. HCC and OBC of post-El Niño values increased to 56.61 ± 5.63%, 18.23 ± 3.95%, while MaC decreased to 40.87 ± 4.89%. Bleaching severity during El Niño showed high TBC (11.31%) and PCC (16.93%), and only 42.39% healthy colonies, whereas post-El Niño assessments indicated an increase in healthy colonies to 53.26 ± 8.92%. Repeated measures ANOVA revealed significant variation in HCC among coral genera ($p < 0.05$), with notable genus time interactions. Monthly variation in HCC was only significant in the post-El Niño period. MaC showed no significant temporal or taxon-level differences, although *Caulerpa* spp. remained consistently dominant. The decline in HCC during El Niño was linked to repeated bleaching impacts, especially in non-dominant genera. In contrast, partial recovery in resilient genera following the event corresponded with improved environmental conditions. These findings highlight taxon-specific benthic responses to the 2023 El Niño event and provide insight into post-event coral recovery, with direct implications for reef monitoring and management.

Keywords: Hard coral cover, Macroalgal cover, 2023 El Niño event, Thermal stress, Pareiwella Reef

INTRODUCTION

Coral reef ecosystems are predominantly restricted to tropical latitudes within 30° of the equator and, compared to other ecosystems, are subject to relatively stable environmental conditions and benign seasonal variations. This long-term thermal consistency may promote the evolution of highly specialised organisms and communities; however, such specialisation can also result in reduced resilience to rapid and compound environmental fluctuations, including rainfall- and runoff-driven stressors, as highlighted by Byrne *et al*., 2025. Coral reef ecosystems are highly vulnerable to environmental disturbances and are regarded as sensitive indicators of changes in their surroundings, including those driven by global climate change (McClanahan *et al*., 2002; Hughes *et al*., 2017).

According to the Status of Coral Reefs of the World: 2025 report, global coral reef systems have exhibited a significant decline in coral cover from 1980 to 2020, with an especially rapid decline observed over the last decade (2010–2020) (Souter *et al*., 2021). Both anthropogenic and natural factors have contributed to this trend. Key stressors include climate change, which affects water quality parameters such as temperature, salinity, pH, light availability, and nutrient levels (LAv, NC). Hard corals, which form the structural foundation of reef ecosystems, generally persist under relatively stable conditions: water temperatures of 23–29°C, salinity levels of 32–42 ppt, light availability above 50 $\mu Em^{-2}s^{-1}$, low nutrient concentrations typical of oligotrophic waters, and pH values between 8.0 and 8.4 (Vine *et al*., 1986). Between 2009 and 2018, global hard coral cover declined by approximately 13.5%, from 33.3% to 28.8%, highlighting the accelerating vulnerability of coral reefs worldwide (Souter *et al*., 2021).

In Sri Lanka, a diverse range of coral reef ecosystems exists predominantly in the form of fringing and patch reefs, distributed along the northwestern, eastern, and southern coasts. Significant coral reef sites include the Jaffna Peninsula, Trincomalee, Batticaloa, Kalpitiya, Hikkaduwa, and Polhena (Environmental Foundation Limited, 2022). These ecosystems are not only ecologically important but also crucial for the livelihoods of coastal communities, providing essential ecosystem services such as supporting artisanal fisheries, promoting tourism, and protecting shorelines from erosion (Pendleton *et al*., 2016). Sri Lanka's coral reefs have similarly experienced degradation and decline; however, comprehensive and recent scientific publications quantifying this trend remain limited. Nevertheless, it is evident that both natural (e.g., El Niño and La Niña events, microbial stress, and coral diseases) and anthropogenic (e.g., ocean pollution, overharvesting of organisms, unsustainable fishing practices such as blast fishing, and unregulated coastal development) factors have contributed significantly to the deterioration of coral reef health around the island (Rajasuriya *et al*., 2000; Rajasuriya & Karunarathna, 2013).

The present study primarily focuses on El Niño, a naturally occurring climatic phenomenon characterised by the anomalous warming of sea surface temperatures (SSTs) in the central and eastern tropical Pacific Ocean. El Niño forms part of the broader El Niño–Southern Oscillation (ENSO) system, which also includes La Niña, the cooling phase. El Niño events are of particular physiological importance to corals because they are associated with anomalously elevated SSTs that frequently exceed coral thermal tolerance thresholds. Such thermal stress disrupts the coral Symbiodiniaceae symbiosis by impairing photosynthetic performance, increasing oxidative stress, and ultimately triggering coral bleaching, disease susceptibility, and mortality.

In the context of global climate variability, the influence of the El Niño–Southern Oscillation (ENSO), particularly El Niño events, on coral reef ecosystems has been extensively documented worldwide. The very strong 1982–1983 El Niño event was historically regarded as the most severe of the 20th century and marked the first instance in which widespread adverse impacts on coral reef ecosystems were systematically documented (Glynn, 1984, 1988, 1990a). Significant levels of coral bleaching and mortality were reported throughout the eastern Pacific during this period (Glynn, 1983, 1990b; von Prahl, 1983, 1985, 1986a; Cortés *et al*., 1984; Robinson, 1985; Guzmán *et al*., 1987). Additionally, localised bleaching events were recorded in regions of the Indo-Pacific and Caribbean basins (Brown, 1987; Coffroth *et al*., 1990; Williams & Bunkley-Williams, 1990). On the Great Barrier Reef, extensive coral bleaching was first observed in early 1982. Although these bleaching episodes coincided with elevated SST anomalies and increased solar irradiance, they were not directly linked to the 1982–1983 El Niño event in the eastern Pacific.

More recently, several significant El Niño events have impacted coral reefs globally. The 2015–2016 El Niño was classified as a very strong event and led to unprecedented mass coral bleaching across major reef systems worldwide, including the Great Barrier Reef, parts of the Pacific Ocean, and the Indian Ocean. This event was notable for its extensive spatial coverage and severe ecological consequences (Hughes *et al*., 2017). Subsequently, a weaker and shorter lived El Niño event occurred between 2018 and 2019, categorised as weak to moderate in strength, with limited but notable environmental impacts. The latest El Niño event (2023–2024) has been categorised as moderate to strong in intensity. According to the National Oceanic and Atmospheric Administration (NOAA), this event is expected to generate widespread global environmental effects, including impacts on coral reef ecosystems, as well as droughts and floods in different parts of the world. These recurrent El Niño events underscore the susceptibility of coral reefs to climatic fluctuations and emphasise the critical need for continuous monitoring and adaptive management strategies to mitigate long-term ecosystem degradation.

The present study focuses on the Pareiwella coral reef ecosystem (PWCR), located near the Tangalle harbour in southern Sri Lanka, a region that also serves as a popular tourist destination. This coral reef is particularly susceptible to anthropogenic stressors, including unregulated waste disposal, nutrient enrichment (e.g., elevated nitrate and phosphate), and sedimentation associated with river runoffs, harbour activities and coastal tourism (Kumara *et al*., 2015; Athukorala & Kumara, 2015). Although coral reefs are considered to possess partial regenerative capacity (De Silva *et al*., 1995), increasing human-induced pressures and localised pollution sources have significantly compromised the health and stability of the PWCR (Geeganage *et al*., 2024).

In Sri Lanka, while previous studies have investigated the impacts of El Niño on coral reef ecosystems in areas such as Bar Reef, Hikkaduwa, and Pigeon Island (Rajasuriya *et al*., 1995; Athukorala *et al*., 2012), to the best of the authors' knowledge, no comprehensive scientific assessment has previously examined El Niño-related impacts on the PWCR. A preliminary observational study by Geeganage *et al*. 2024 represented the first effort to document El Niño driven stress on the PWCR; however, spatiotemporal changes in hard coral and macroalgal cover and post-event recovery dynamics have not yet been quantitatively evaluated. The current study builds upon that foundation by examining reef responses during and after the 2023–2024 El Niño event, with post-event recovery assessment being essential for evaluating reef resilience, potential shifts in benthic community structure, and long-term ecosystem trajectories. The primary aim of this study was to assess the status of hard coral and macroalgae cover in the PWCR during and post El Niño period. The study was guided by the following specific objectives: 1) To quantify the percentage cover of hard corals (HCC), macroalgae (MaC), and other benthic categories (OBC) during the El Niño (August–October 2023) and post-El Niño (January–March 2025) periods, including the identification of dominant genera. 2) To assess hard coral health by categorising corals as totally bleached (TBC), partially bleached (PBC), pale-colored (PCC), recently dead (RDC), dead (DC), or healthy (HC) during the same periods. 3) To investigate the spatiotemporal dynamics of hard coral cover and macroalgae cover across selected reef locations during the El Niño (August–October 2023) and post-El Niño (January–March 2025) months. This research integrates ecological baseline assessments, coral health evaluations, and the temporal dynamics of benthic cover and dominant genera to provide valuable insights into the reef's condition during and post El Niño events. The findings are expected to contribute significantly to future coral reef conservation planning and the development of climate resilience strategies in the southern coastal region of Sri Lanka.

MATERIALS AND METHODS

The study was carried out at the PWCR, which is a fringing reef, located near Tangalle in southern Sri Lanka (Figure 01), during two distinct periods: from August to October 2023, corresponding to the El Niño phase, and from January to March 2025, representing the post-El Niño phase. Six permanent transects were established perpendicular to the shoreline within the back reef zone (depth 1.0 m-high tide), each starting 10 m from the shoreline and extending 15 m in length, and 4 m distant between each transect. Benthic surveys were conducted via snorkelling, and data were collected using 0.5 m × 0.5 m grid quadrats systematically placed along each transect Sixty quadrats per permanent transect were assessed during each three-month survey interval, with benthic surveys conducted monthly. The primary benthic categories recorded included Hard Coral Cover (HCC), Macroalgae Cover (MaC), and Other Benthic Cover (OBC). Additionally, to assess coral health dynamics concerning the El Niño event, HCC was further categorised in August 2023 and January 2025 into six conditions: Detailed definitions of these categories are presented in Table 01 (Wickrama-Arachchige A.U.K., personal communication; Kumara & Wijesekara, 2013). Sea Surface Temperature (SST) was measured in situ using a mercury thermometer, and pH was determined with a portable multipara meter (LEV015.53.2200A). All collected data were organised in Microsoft Excel 2013 for initial Processing. Statistical analyses were performed using Minitab version 19 and IBM SPSS Statistics version 25.

Table 1: Classification of Hard Coral Health

Abbreviation	Coral Category	Picture	Description
TBC	Totally Bleached		Complete loss of color; white skeleton with transparent tissue due to loss of zooxanthellae
PBC	Partially Bleached		Partial loss of pigmentation; portions of colony appear white while other areas remain healthy
PCC	Pale-Colored		Noticeably lighter coloration than healthy colonies due to reduced zooxanthellae abundance
RDC	Recently Dead		Recently dead coral with white skeleton and no tissue
DC	Dead		Coral skeleton with no living tissue; skeleton no longer white. Some other epilithic communities can be overgrown on the dead coral skeleton
PD	Partially Dead		Part of the coral colony is healthy with usual color while the rest of the colony is dead
HC	Healthy		Normal coloration; no signs of bleaching or tissue loss

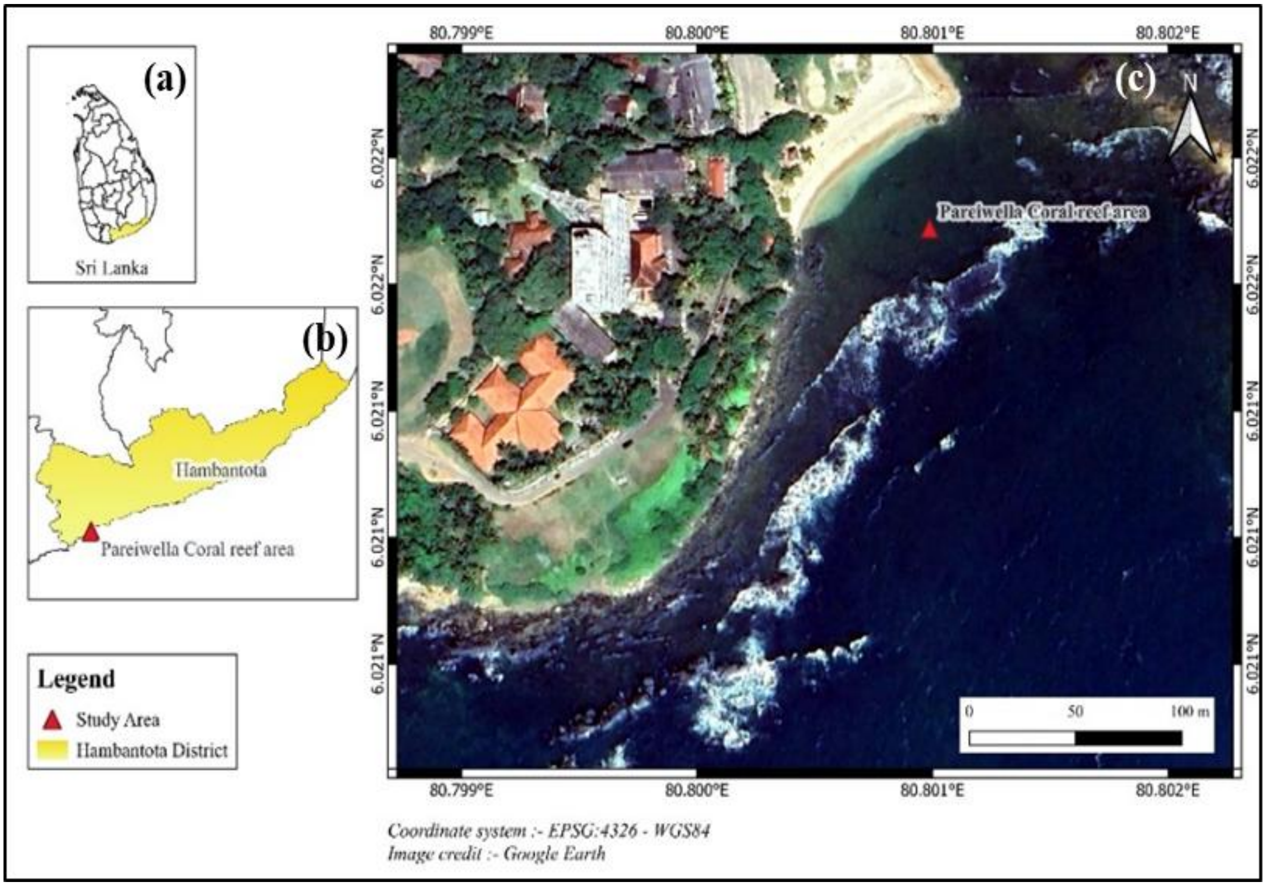

Fig 1. Geographic location of the study area: (a) map of Sri Lanka in the northern Indian Ocean, (b) map of Hambantota District, and (c) the study site at Pareiwella Coral Reef.

RESULTS

Dynamics of benthic categories during El Nino and post-El Nino periods

The mean percentage cover (± SD) of the major benthic categories during the El Niño period (August to October 2025) was as follows: HCC at 35.77 ± 3.97%, MaC at 47.39 ± 4.80%, and OBC at 16.84 ± 4.36%. During the post–El Niño period (January–March 2025), field observations recorded a marked proliferation of macroalgae and opportunistic benthic organisms, including Zoanthids and sponges, classified under OBC (Figure 03c, d). Hard Coral Cover (HCC) increased to 56.61 ± 5.63%, while MaC decreased to 40.87 ± 4.89%, and OBC slightly increased to 18.23 ± 3.95% (Figure 02.a). A marked decline in HCC (7.92±0.85%) was observed between August and October 2023, coinciding with peak El Niño conditions (Figure 02.b). In contrast, temporal patterns from January to March 2025 indicated a progressive increase in HCC, reaching its highest value in March (17.77 ± 2.65%; Figure 02c). Meanwhile, MaC and OBC exhibited a gradual decline over the same period. These trends reflect the temporal variation in benthic composition at the PWCR associated with the transition from El Niño to post–El Niño conditions (Figure 02a–c).

SST, pH, and Hard Coral Response during El Niño 2023 and Post–El Niño Periods

During the El Niño phase, the mean SST was 29.8 ± 1.26 °C, and the mean pH was recorded at 8.4 ± 0.76 (Figure 03.a). In contrast, the post-El Niño phase showed a decrease in SST to 27.1 ± 1.06 °C and a slight reduction in mean pH to

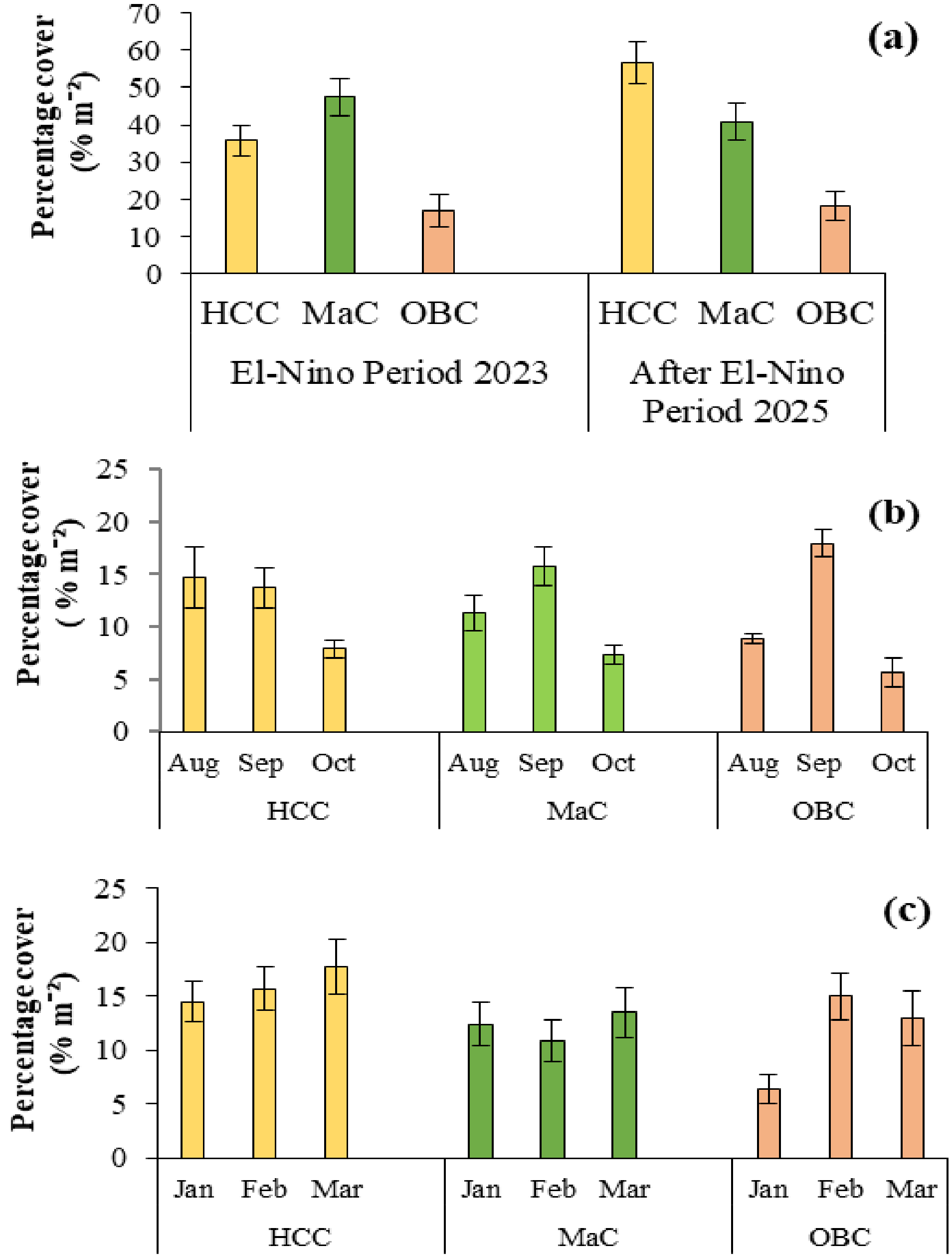

Fig 2. Mean percentage cover (± SD) of hard coral cover (HCC), macroalgal cover (MaC), and other benthic cover (OBC) in Pareiwella coral reef across El Niño and post-El Niño periods. (a) Comparison of mean HCC, MaC, and OBC during the 2023 El Niño period and the 2025 post-El Niño period. (b) Monthly variation in mean HCC, MaC, and OBC during the El Niño period (August–September 2023). (c) Monthly variation in mean HCC, MaC, and OBC during the post-El Niño period (January–March 2025).

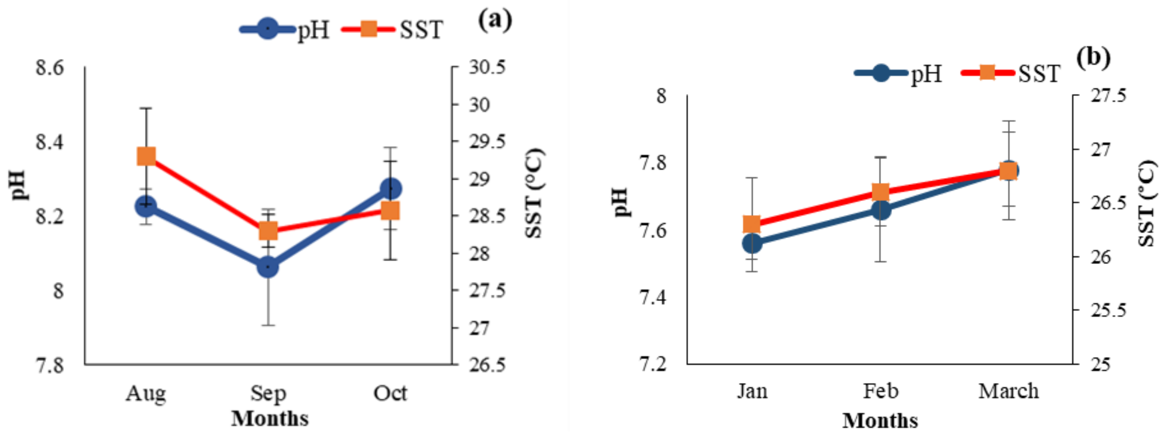

Fig 3. Mean sea surface temperature (SST; °C) and Mean pH (± SD) in PWCR during (a) the El Niño phase (August–October 2023) and (b) the post–El Niño phase (January–March 2025)

SST, pH, and Hard Coral Response during El Niño 2023 and Post–El Niño Periods

During the El Niño phase, the mean SST was 29.8 ± 1.26 °C, and the mean pH was recorded at 8.4 ± 0.76 (Figure 03.a). In contrast, the post-El Niño phase showed a decrease in SST to 27.1 ± 1.06 °C and a slight reduction in mean pH to 7.9 ± 0.65 (Figure 03.b). A marked decline in HCC was observed between August and October 2023, coinciding with the peak El Niño conditions.

Coral Genera Composition in El Nino 2023 and post-El Nino periods

During the El Niño period (August–October 2023), the dominant coral genera included *Pocillopora* spp. (5.01%), *Montipora* spp. (4.11%), *Acropora* spp. (2.07%), and *Leptoseris* spp. (0.49%). The low coral cover observed during this period is primarily attributed to elevated thermal stress associated with El Niño event. In the post- El Niño period, a noticeable increase in coral cover was observed, with dominant genera recorded as *Pocillopora* spp. (8.01%), *Montipora* spp. (7.61%), *Acropora* spp. (4.17%), and *Goniastrea* spp. (1.49%). (Figure 03.a, 03.b, 03.c and 03.d).

Hard coral status in PWCR during El Niño and post–El Niño periods

The analysis revealed a marked improvement in overall coral coverage during the post-El Niño phase. As shown in Figure 04.a, the mean percentage cover of healthy corals significantly increased from 42.39 ± 7.85% during the El Niño period to 53.26 ± 8.92% in the post-El Niño phase. A two-sample t-test confirmed that this increase was statistically significant ($p < 0.05$) in healthy coral cover between the El Niño and post-El Niño period Indicating clear signs of ecologically enhanced reef resilience. Conversely, stress-related categories TBC (1.93 ± 0.72%), PBC (1.63 ± 0.82%), and PCC (2.36 ± 1.32%) showed a clear decline following the El Niño event, indicating an overall reduction in bleaching-related stress conditions. Figures 04.c to 04.f illustrate the impacts on various hard corals observed across the two time periods.

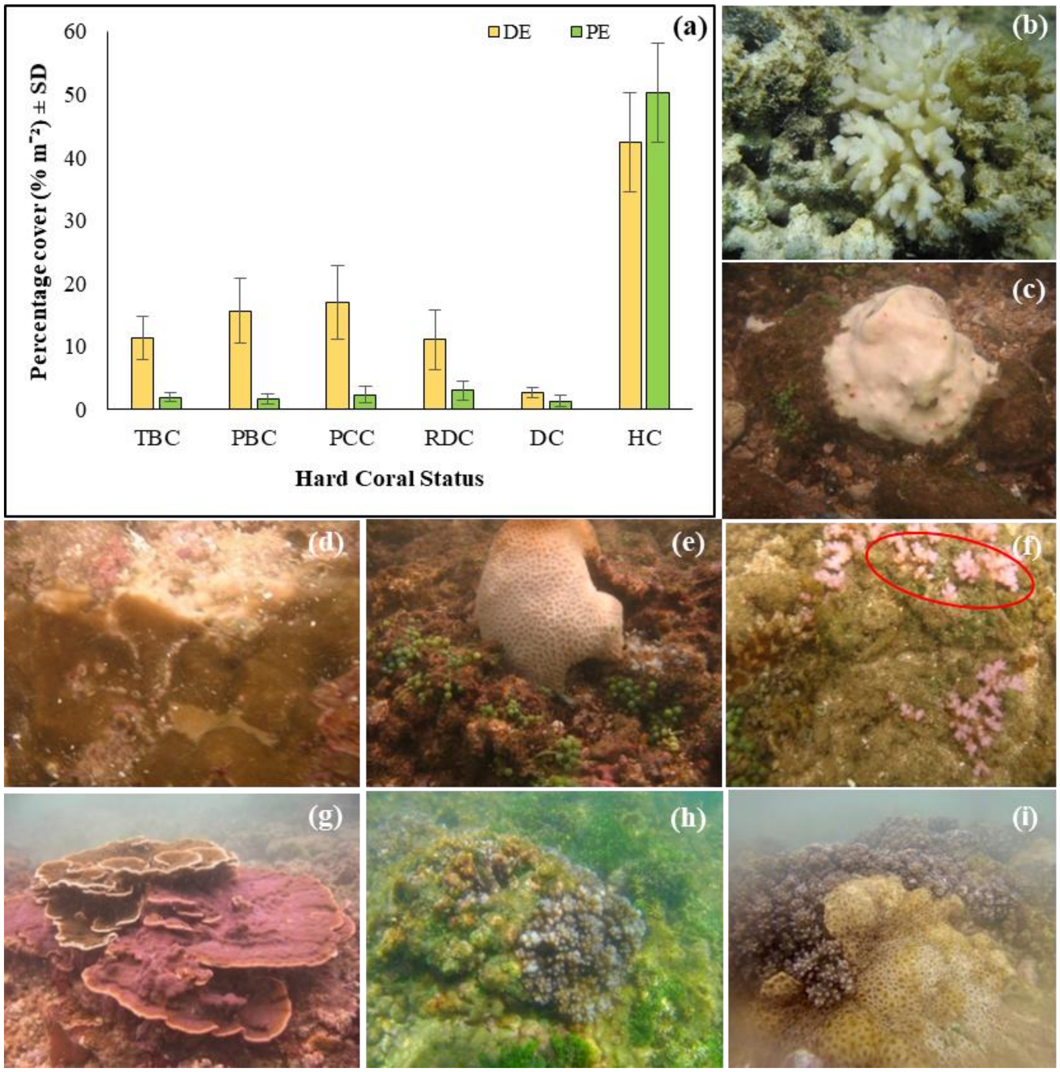

Fig 04. Benthic and coral health observations at Pareiwella reef during the El Niño period (August 2023) and post–El Niño recovery (January 2025).(a) Mean percentage cover (± SD) of coral health categories: healthy coral (HC), pale-colored coral (PCC), partially bleached coral (PBC), totally bleached coral (TBC), recently dead coral (RDC), and dead coral (DC). (b) Totally bleached *Pocillopora* sp. colony observed during the peak of El Niño. (c) Totally bleached *Porites* sp. colony with complete loss of pigmentation. (d) Partially bleached *Porites* sp. colony indicating intermediate stress response. (e) Recently dead *Goniastrea* sp. colony with tissue loss and algal overgrowth. (f) Pale-colored *Pocillopora* sp., representing early bleaching stage. (g) Healthy *Montipora* sp. colony recorded post–El Niño, indicating recovery under improved conditions. (h) Overgrowth of macroalgae (*Caulerpa* spp.) on *Pocillopora* sp.observed during the post El Niño phase.(i) Overgrowth of Zoanthids on *Pocillopora* sp., illustrating benthic competition following coral stress.

Short-term spatiotemporal dynamics of HCC and MaC during the El Niño and post-El Niño periods.

A repeated-measures ANOVA revealed a statistically significant difference in the mean percentage cover (± SD) of hard coral genera over time ($F(2, 1) = 7.032$, $p = 0.005$; Figure 05.a), indicating significant genus-specific differences in coral cover responses to El Niño conditions, with some genera showing pronounced declines while others remained comparatively stable. However, no significant temporal variation was detected across the sampling months, F (1, 8) = 2.030, p = 0.095, suggesting a general decline rather than month-specific changes. A significant interaction between coral genera and months was identified, F (1, 4) = 54.664, p = 0.001, $p < 0.05$, confirming that different genera responded differently to El Niño-associated stress. Across the El Niño months, all dominant hard coral genera—including *Pocillopora* spp., *Montipora* spp., and *Acropora* spp.—which are relatively fast-growing, branching, and plate-like compared with slower-growing, boulder-type corals, exhibited a notable decline in cover. This indicates a consistent reduction in genus-level hard coral abundance during this period. For macroalgae, repeated measures ANOVA showed no significant differences in percentage cover among the dominant genera (*Caulerpa* spp., *Halimeda* spp., *Chaetomorpha* sp., and *Padina* sp.; F(2,1) = 0.769, p = 0.477, $p > 0.05$) or across months (F(2,8) = 1.183, p = 0.372, $p > 0.05$; Figure 05b). However, the significant interaction between genera and months, F (1, 4) = 246.04, p = 0.002, $p < 0.05$, indicated genus-specific temporal patterns. Among them, *Caulerpa* sp. maintained dominant coverage throughout the El Niño period, while others showed greater variability. Following the El Niño event, reef assessments conducted from January to March 2025 demonstrated signs of hard coral recovery. Repeated measures ANOVA indicated (Figure 05.c) a significant increase in HCC among coral genera, F (2, 1) = 11.3, p = 0.001, $p < 0.05$, and also a significant difference across months, F (2, 8) = 18.6, p = 0.002, $p < 0.05$, suggesting temporal improvements in coral cover. Additionally, the interaction between coral genera and months remained significant, F (1, 4) = 476.3, p = 0.001, $p < 0.05$, emphasising differential recovery capacities among taxa. In contrast, MaC showed (Figure 05.d) no significant variation among genera, F (2, 1) = 0.769, p = 0.241, $p > 0.05$, and no significant monthly changes, F (2, 8) = 1.174, p = 0.168, $p > 0.05$, during the post-El Niño period. However, a significant interaction between genera and months was observed, F (1, 4) = 32.94, p = 0.001, $p < 0.05$, indicating some temporal shifts in species composition. (Figure 05.a, 05.b, 05.c and 05.d)

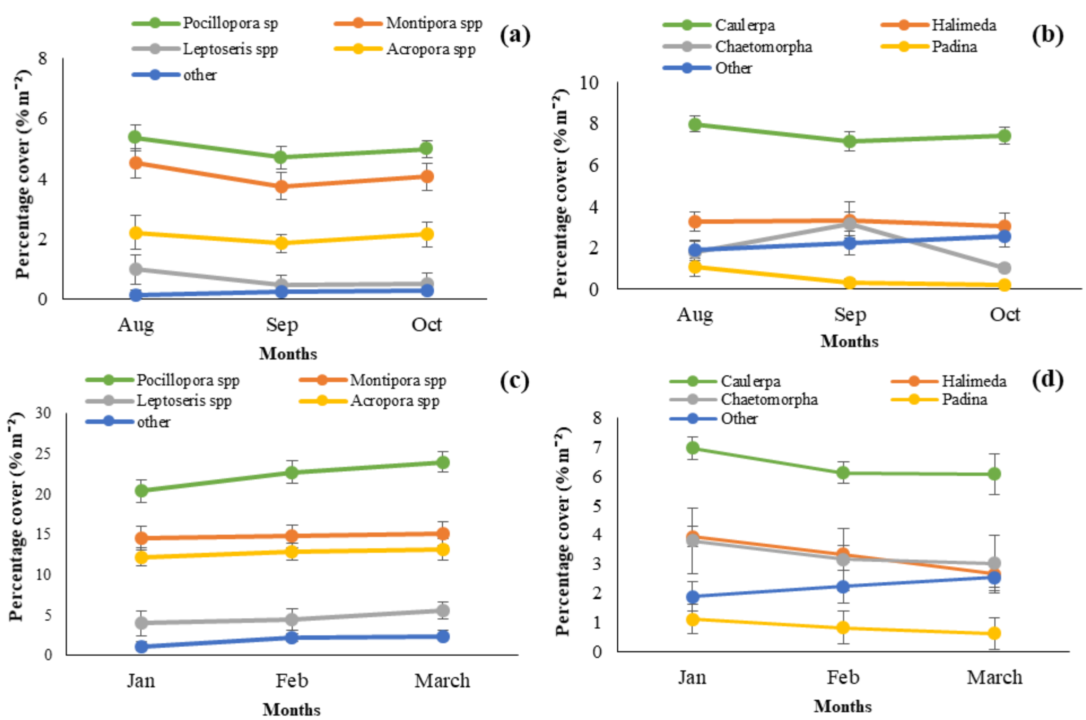

Fig 5: Mean percentage cover (± SD) of benthic categories in Pareiwella coral reef across El Niño (January March 2025) and post El Niño periods (January–March 2025). (a) Hard coral genera during the El Niño phase. (b) Macroalgal cover during the El Niño phase. (c) Hard coral genera during the post–El Niño phase. (d) Macroalgal cover during the post–El Niño phase.

Comparative Analysis of El Niño Impacts on Coral Reefs

El Niño events have led to widespread coral bleaching across multiple regions, with variable severity and recovery patterns. Table 01 summarises observed coral bleaching impacts and post-event recovery across selected countries in the Indian Ocean, Pacific, and African regions. In the Indian Ocean, coral bleaching of up to 82% was recorded in India (Lakshadweep) during the 1997–1998 El Niño, with additional bleaching events in 2010 and 2016. Regrowth was observed by 2006, and reef resilience persisted through 2022 (Rajan *et al*., 2018). In Sri Lanka (Pareiwella, Tangalle), 11.37% of hard corals were found fully bleached during the 2023 El Niño period. Hard coral cover increased from 40.8% in 2023 to 56.6% in 2025. In the Maldives, bleaching exceeded 60% during the 2016 event, with slow and uneven recovery reported in subsequent years (Morri *et al*., 2015). In Seychelles, coral mortality exceeded 90% during the 1998 El Niño, with little long-term recovery by 2016 (Graham *et al*., 2006; Claudet *et al*., 2011). In Indonesia, 90% of corals in Bali (Bondalem) bleached in December 2023 (Budiman, 2024). . In West Papua (Ayau Islands), coral cover declined by 9.9% during the 2015–2016 El Niño event, and no recovery had been reported as of 2019 (Maynard *et al*., 2018). In the Pacific, over 50% coral bleaching was observed in Fiji and Samoa during the 2015–2016 El Niño (Hughes *et al*., 2017). In East Africa, 30–50% bleaching was recorded in Kenya and Tanzania during the 1998 event. Partial reef recovery was observed in the following decades (McClanahan, 2000; Obura, 2005).

DISCUSSION

The observed temporal variations in the benthic composition of the PWCR during and after the El Niño event provide valuable insight into disturbance-driven changes in coral reef structure. The reduction in HCC during the El Niño period to 35.77 ± 3.97% represents a marked decline when compared with earlier baseline studies from the same reef system. Previous assessments at Pareiwella reef reported substantially higher live coral cover, including 64.7 ± 18.9% (Chamika *et al*., 2014) and 57.58 ± 11.77% (Fairoz *et al*., 2014), indicating a long-term degradation trajectory that intensified during the El Niño disturbance.

Comparable coral declines during thermal stress events have been documented globally. For example, extreme positive SST anomalies (>31 °C; ~2 °C above historical records) at Huatulco resulted in widespread bleaching and coral mortality ranging from 50–93% (Andrés *et al*., 2024). Similarly, the fourth Global Coral Bleaching Event during the austral summer of 2023/24 caused a 38.6% reduction in average coral cover in the Cooktown–Lizard Island sector of the Great Barrier Reef, associated with thermal stress levels of 5.9–8.2 °C-weeks (Michael *et al*., 2025). These global observations provide a broader context for the magnitude of coral cover decline recorded at PWCR during the El Niño period.

The concurrent increase in macroalgal cover (47.39 ± 4.80%) and other benthic components (16.84 ± 4.36%) during the El Niño period is consistent with the rapid colonisation of newly available benthic space following coral stress and partial mortality. Earlier studies at PWCR documented comparatively lower algal cover prior to major thermal disturbances, with Chamika *et al*. (2014) reporting macroalgal cover of 19.2 ± 13.4% and Fairoz *et al*. (2014) recording fleshy algal cover of 22.25 ± 15.46%. The elevated macroalgal cover observed during the El Niño period therefore reflects a short-term competitive response under reduced coral dominance rather than definitive evidence of a coral–algal phase shift.

Temporary increases in macroalgal abundance following coral mortality have been widely documented, as reduced coral cover can facilitate opportunistic algal expansion (McCook *et al*., 2001). The prominence of fast-growing macroalgal genera such as *Caulerpa* and *Padina* at PWCR during the El Niño period may have been further influenced by local environmental conditions, including potential nutrient enrichment from nearby wastewater discharges and canal effluents (Ukwatta & Fairoz, 2014). However, the subsequent partial recovery of hard coral cover during the post–El Niño period suggests that the system has not transitioned to a persistent algal-dominated state within the timeframe of this study.

During the post–El Niño period, partial recovery of HCC was observed (56.61 ± 5.63%), coinciding with lower SST (27.1 ± 1.06 °C) and more stable pH conditions (7.9 ± 0.65). Although HCC did not fully return to baseline levels reported in earlier studies, the observed increase suggests short-term recovery following thermal disturbance. Improvements in the cover of dominant genera, including *Pocillopora*, *Montipora*, and *Acropora*, indicate a gradual re-establishment of hard corals during January–March 2025; however, longer-term monitoring is required to determine whether this recovery is sustained (Loya *et al*., 2001; Hughes *et al*., 2018).

Recovery dynamics varied among coral taxa, indicating that resilience was not uniform. Differential recovery rates can reshape coral assemblages and influence long-term community structure. Although hard coral cover showed partial recovery during the post–El Niño period, the continued dominance of fast-growing macroalgae such as *Caulerpa* sp. may limit coral recruitment and delay reef recovery (McCook *et al*., 2001). Reduced grazing pressure, commonly associated with trophic disruption or overfishing, can further promote macroalgal persistence and inhibit coral recovery (Hughes *et al*., 2007; Mumby *et al*., 2006). These observations highlight that modest improvements in abiotic conditions alone may be insufficient to ensure long-term reef stability without maintaining biotic balance.

In Sri Lanka, the 1998 El Niño event caused severe coral mortality, with national assessments reporting approximately 70–90% mortality of shallow-water corals, particularly branching taxa such as *Acropora*, across multiple reef systems (Wilkinson, 1998; Rajasuriya & Karunarathna, 2000; McClanahan, 2000). Live coral cover in several locations declined to below 10–20%, and recovery was slow and spatially variable, in some cases requiring more than a decade. Subsequent thermal anomalies in 2010 and 2016 again resulted in widespread bleaching across Sri Lankan reefs, with bleaching prevalence exceeding 60% in some areas during 2016 (Rajasuriya, 2016; NOAA Coral Reef Watch). Although mortality levels were generally lower than those reported in 1998, repeated thermal stress events contributed to shifts in coral community structure and may have constrained long-term recovery trajectories in certain reef systems.

Against this national backdrop, PWCR exhibited a moderate decline in hard coral cover (35.77 ± 3.97%) during the recent El Niño period, followed by measurable short-term recovery (56.61 ± 5.63%) within a 1.3-year observational window. This interpretation is strictly limited to within-site temporal changes before and after the recent thermal anomaly. The observed response likely reflects local environmental and ecological conditions specific to PWCR rather than indicating comparative resilience relative to other reef systems.

While Table 02 provides a broader global and regional context for the range of El Niño impacts reported in the literature, the resilience inference for PWCR is derived exclusively from site-specific temporal dynamics. The documented regrowth within two years suggests evidence of short-term recovery capacity under favourable post-disturbance conditions. Importantly, numerical declines in coral cover alone do not fully capture reef vulnerability; evaluating recovery trajectories provides a more comprehensive understanding of resistance and resilience under El Niño disturbances. These patterns underscore the influence of local stress regimes, historical disturbance exposure, reef structural complexity, and management context in shaping recovery outcomes.

Health assessments at PWCR further support the resilience hypothesis, with a reduction in totally bleached coral from 11.31 ± 3.46% to 1.93 ± 0.92% and an increase in healthy coral cover from 42.39 ± 7.85% to 53.26 ± 8.92% post-El Niño. These shifts align with coral degradation and recovery models (Kumara & Wijesekara, 2013; Rafferty, 2019), which suggest that coral communities can rebound from moderate disturbances if chronic pressures are alleviated.

Nevertheless, local anthropogenic pressures remain a critical constraint (Hughes *et al*., 2003). Reef sedimentation (Kumara *et al*., 2015), ornamental fish harvesting, waste disposal directly to the coral reef area and unregulated tourism (Kumara *et al*., 2008) directly compromise reef integrity. These chronic stressors, when superimposed on climate-induced disturbances, can decelerate recovery, amplify phase shifts, and push reefs beyond ecological tipping points. As such, resilience in PWCR remains fragile and conditional, warranting robust local conservation efforts.

Table 2: Impacts of El Niño on Coral Reefs in Various Countries/ Regions.

Country / Region	El Niño Year (s)	Impact on Coral Cover / Bleaching	Recovery Status & Timeline	Source
Brazil (Bahia)	1997–1998	Significant loss of coral species and colonies.	Assemblage took ~13 years post-event to return to pre-El Niño state (~2011).	Kelmo et al 2013
Costa Rica (Cocos Is.)	1982–1983	Live coral cover fell to <4% after El Niño.	Recovered to ~23% cover by 2002; one site reached >58%.	Guzmán, H. M., & Cortés, J. (1992)
Mexico (Central Pacific)	1997–1998	Live coral cover dropped dramatically.	Regained ~50% of pre-event live coral cover over 20 years.	Martínez-Castillo et al 2022
Indonesia (Bali)	2023	~90% bleaching in Bondalem in Dec 2023.	Recovery uncertain; future bleaching anticipated.	Budiman, 2024
Kiribati (Gilbert Is.)	2004–2010	Severe bleaching across *Acropora* spp. (~70–90%).	2015 surveys showed abundant recovery of *Acropora*.	Donner et al. 2010
Maldives	1997–1998; 2015–2016	>98% coral mortality (1998); ~60–95% bleaching (2016).	Partial recovery by 2013; restoration ongoing after 2016.	Pisapia et al. 2016, Morri et al. 2015
India (Lakshadweep)	2010; 2016	Up to 82% bleaching, repeated events later.	Initial regrowth by 2006; resilience still observed in 2022.	Rajan et al. 2018
Chagos Archipelago	2015–2016	>70% drop in coral cover.	Positive growth resumed by 2021.	Head et al. 2019, Lange et al. 2019
Aldabra (Seychelles)	2016	>50% hard coral loss; >90% soft coral loss.	Signs of juvenile coral recruitment; recovery in progress.	Wild et al 2020
Seychelles (broad region)	1997–1998	Up to 90% coral loss in shallow reefs.	Good recovery in many sites, aided by protection.	Koester et al. 2020
Sri Lanka (Pareiwella, Tangalle)	2023 – 2025	11.37% of hard corals at shallow reef areas were completely bleached	Hard coral cover increased from 40.8% (2023) to 56.6% (2025)	In this study

From a management perspective, these findings underscore the urgency of mitigating land-based sources of pollution and enforcing sustainable tourism practices to maintain ecological balance. Without such interventions, the observed coral recovery may be temporary, and the reef could remain vulnerable to future thermal anomalies or anthropogenic degradation.

It is important to acknowledge a methodological constraint related to the timing of this investigation. The El Niño and post–El Niño assessments were conducted during two different monsoonal periods, which are characterised by distinct physicochemical oceanographic conditions, including variations in SST, light penetration, and nutrient availability. This seasonal variability may have influenced benthic community structure independently of thermal stress, thereby limiting our ability to fully isolate the specific drivers of the observed changes. Nevertheless, this limitation does not diminish the value of the dataset. To the best of our knowledge, this study represents the first documented assessment of coral bleaching impacts and short-term recovery dynamics from a Sri Lankan reef system. As such, it establishes a critical baseline for future investigations into reef resilience in the region. Future research should implement continuous, long-term monitoring programmes that encompass both seasonal cycles and inter-annual variability to enable a more robust understanding of coral–macroalgal interactions and recovery trajectories at PWCR and comparable reef ecosystems.

This study shows that the recent El Niño event temporarily affected coral cover at PWCR, with a small proportion of corals experiencing severe bleaching (TBC: 1.93%), suggesting that the reef largely recovered in the post-event period. While some thermally sensitive taxa showed slower recovery, the overall coral assemblage exhibited resilience under prevailing environmental conditions. Continued monitoring and management are recommended to maintain reef health, particularly in the presence of ongoing local anthropogenic stressors.

CONCLUSION

This study documents the ecological response of the PWCR to the 2023 El Niño event. Hard coral cover (HCC) declined during the event, while macroalgal cover (MaC), including *Caulerpa* spp., increased. By early 2025, HCC of dominant genera such as *Montipora* and *Pocillopora* showed measurable recovery. The post–El Niño persistence of macroalgal cover, although reduced compared to peak levels, suggests that reef recovery is ongoing. Local anthropogenic inputs, including wastewater discharge from nearby hotels and effluents from the harbour, may influence benthic dynamics and contribute to slower macroalgal decline. These observations indicate that PWCR exhibits short-term resilience under current environmental conditions. Significant interaction effects between coral taxa and time reflect species-specific and temporally variable responses to environmental stress. While SST and pH were considered, broader environmental monitoring should incorporate additional physico-chemical parameters such as salinity, turbidity, precipitation, nutrient levels, water flow and sedimentation, especially during the southwest monsoon. The findings emphasise the need for integrated management strategies that couple climate adaptation with pollution mitigation to enhance reef resilience and sustain ecosystem services vital to coastal communities in southern Sri Lanka.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

K.G.M.N.D Geeganage: Data collecting, data analysis and writing original draft. Diyasen Jayasundara, M.M.T Madushan, N.A.C.S Nadeniya: Data collecting. R.K.N.P.N Ranaweera: preparation of map. Wickrama-Arachchige A.U. K: conceptualization, methodology, Laboratory support, data analysis, Supervision, and review and editing. All authors have read and agreed to the published version of the manuscript.

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