Indian Journal of Geo Marine Sciences
Vol. 53 (11), November 2024, pp. 699-708
DOI: 10.56042/ijms.v53i11.14308

Emergence of coral rubble islet near Manoli Island, Gulf of Mannar, India

C H Ramesh*[,a,b,c], T Shunmugaraj[b], R Mani Murali[d], S Koushik[b] & M V R Murthy[e]

[a]Biological Oceanography Division (BOD), National Institute of Oceanography (CSIR-NIO), Dona Paula, Panaji, Goa – 403 004, India

[b]National Centre for Coastal Research (NCCR), NCCR Field Office, Ministry of Earth Sciences (MoES), Mandapam, Tamil Nadu – 623 519, India

[c]Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, Uttar Pradesh – 201 002, India

[d]Physical Oceanography Division (POD), National Institute of Oceanography (CSIR-NIO), Dona Paula, Panaji, Goa – 403 004, India

[e]National Centre for Coastal Research (NCCR), Ministry of Earth Sciences (MoES), Pallikaranai, Chennai, Tamil Nadu – 600 100, India

*[E-mail: chramesh.nio@csir.res.in]

Received 10 September 2024; revised 27 November 2024

Coral reefs of the Gulf of Mannar region, India, are damaged severely by bleaching events, anthropogenic stressors, coral diseases, and invasive species. The fate of dead corals has not been investigated in this region. In this study, dead corals forming a coral rubble islet was identified about 800 m away from the southeast of Manoliputti Island, Gulf of Mannar. The 50 m-long rubble islet consisted mainly of dead Acroporidae and Faviidae corals. Field observations indicate that the convergence of waves from various directions around the coral rubble islet may be a primary factor in its formation. Current velocity and wind patterns data from satellite support that the collision between wind and current would facilitate the formation of a coral rubble islet. Further studies are required to understand the long-term influence of extreme waves, currents, and longshore drifts on this coral rubble islet's accretion, shape, and shift. The study infers that the instability of the seafloor topography, combined with the vulnerability of Acroporidae and Faviidae corals to hydrodynamic forces, may have led to the substantial generation and accumulation of coral fragments over the past two decades. Thus, further studies on the sediment texture of reef flats and conservation and restoration of these corals are needed urgently to protect coral reefs in the Gulf of Mannar.

[**Keywords**: Coral bleaching, Coral rubble islet, Gulf of Mannar, Invasive species, Manoli Island]

Introduction

The ocean is a dynamic environment where several geological and biological phenomena are seen along the coastal areas. In geological aspects, the formation of sediment bars, bay mouth bars, sand dunes, sandbanks, barrier islands, sand spits, tombolos, ripples, massive sediment accretion, mega ripples, sand ridges, and shell depositions are some of the well-known geological processes that occur in the neritic region[1]. The deposition of these sediments is mainly controlled by strong waves and current patterns[2,3]. The aforementioned geological processes are of great importance to the researchers who monitor coastal structures, coastal hydrodynamics, sediment transport, remote sensing, and biodiversity conservation.

In biological aspects, based on Darwin's subsidence theory, the formation of various forms of coral reefs, such as fringing, barrier, and atoll reefs, are well-known evidences[4]. The underwater and emerged surface deposit forms in coastal areas can be made up of sand, mud, rocks, shells, macroalgae, seagrass, and corals and are not frequently encountered nearshore. While the formation of coral mounds is largely unknown among all other forms of depositions[5]. This might be due to a lack of regular field surveys or limited field surveys in intertidal regions. Regular field visits along the shoreline and coastal waters are always important to document such geological processes.

Unlike the well-known cold-water coral mounds in the global ocean[5], the occurrence of coral ridges and coral rubble islets formed around the islands or mainland regions are least investigated in the global ocean, except reefs from the Caribbean[6,7] and Great Barrier Reef[8,9]. These structures were reported to be formed by the orbital movement of waves and overwash during hurricane wave run-ups, storm surges, hurricanes, cyclones or tsunamis[10]. Recently, the formation of reef islands, also called 'motu', which are similar to coral rubble accretions found in this study, were reported to be formed due to morphodynamic feedbacks, *viz*., waves, and sea level conditions[11]. The coral rubble ridge formations were reported to be due to extreme waves and currents[2,3,11-15], hurricanes, tsunamis[6,7], typhoons[16], and storm surges[8,9,17].

Coral reefs in the Gulf of Mannar, southeast coast of Tamil Nadu, India, are degrading due to recurrent bleaching events, invasive biota, and diseases. In recent times, coral reefs in the Gulf of Mannar islands are experiencing frequent bleaching events due to increasing temperatures in the global scenario[18,19]. There is no real-time data to understand the dispersal and accretion of coral rubbles to form rubble islets and ridges in the Gulf of Mannar Islands. The coral rubbles are found around the reef flats in the Gulf of Mannar islands, which might have originated from the reef patches damaged by various threats such as coral diseases, algal invasions, coral-killing sponge invasions, and boat anchoring due to destructive fishing[18,20-35]. The occurrence of coral ridges was reported from Appa Island in the Gulf of Mannar region[36]. Since coral reefs are degrading in the Gulf of Mannar region, restoration activities have been undertaken[37]. However, the fate of dead corals in the reef flats is unaddressed and unknown in this region. In this study, a coral rubble islet, which is quite a ubiquitous geological structure formed by the accretion of dead corals near Manoliputti Island under the Gulf of Mannar region, was identified in November 2018 for the first time from the Indian coral reefs. This study aimed to report the first occurrence of the coral rubble islet and its biodiversity, and discuss the possible factors that might be linked to the formation of the rubble islet near Manoliputti Island.

Materials and Methods

Study area

The Gulf of Mannar Marine Biosphere Reserve is a biodiversity-rich region in southeast Asia, comprising a chain of 21 islands under the Mandapam, Keezhakkarai, Vembar, and Tuticorin regions. These islands are surrounded by fringing coral reefs. Manoliputti Island is about 7 km far from the mainland coast. This island is surrounded mainly by *Acropora*, *Favia*, and other massive *Porites* reef patches. Most of the reef patches around this island were bleached and invaded by algal profusion, resulting in dead reefs in this region.

Data collection

Field surveys were conducted in November 2018. Coral rubble islet was observed near Manoliputti Island under the Mandapam region in the Gulf of Mannar, India (09°12.317' N, 079°08.365' E) (Fig. 1). Coral rubble islet dimensions such as length, width and height of the rubble islet and sandbar that connected to the coral rubble islet were obtained during low tide as well as high tide swashes using a measuring tape. The average exposed height of this coral rubble islet was measured by considering the heights between swash (high tide) and backwash zone marks (low tide). Satellite imagery of the study region (2007 to 2018) was retrieved from Landsat and Google Earth Pro programs, and documented the shape and transformation of the coral rubble islet in different years. Satellite images were not retrieved from a specified tidal level, but indicated yearly images, merely. Quantitative data collection (changes in rubble islet over the period) from the rubble islet was investigated during this study using Google Earth. The type of waves prevailing in this coral rubble islet was identified visually by counting the number of shallow water waves, also known as translatory waves per minute.

Sea Surface Temperature (SST)

The daily Sea Surface Temperature (SST) data (in degree Celsius) with a spatial resolution of 1 km was downloaded from the GHRSST Global 1-km Sea Surface Temperature (G1SST) for the period of 2007 to 2018 (https://podaac.jpl.nasa.gov/dataset/JPL_OUROCEAN-L4UHfnd-GLOB-G1SST). The results showed variations in SST during this time period, ranging from 26.5 °C to 31.5 °C. The high persistent SST conditions trigger coral bleaching and subsequently damage the corals.

Winds and currents

The monthly means of zonal wind stress (N m^{-2}), meridional wind stress (N m^{-2}), zonal currents (cm s^{-1}) and meridional currents (cm s^{-1}) with spatial resolution 0.1 degree × 0.1 degree for the period January 2007 to December 2018 was taken from the OGCM for the Earth Simulator (OFES) (source: http://apdrc.soest.hawaii.edu/datadoc/ofes/ncep_0.1_global_mmean.php). The above data were plotted and analysed using the FERRET software (http://ferret.pmel.noaa.gov/Ferret/)[38].

Species composition at the rubble islet

Biodiversity around the rubble islet was investigated to understand the current species composition and compare this data with future studies. Snorkelling was performed to document the

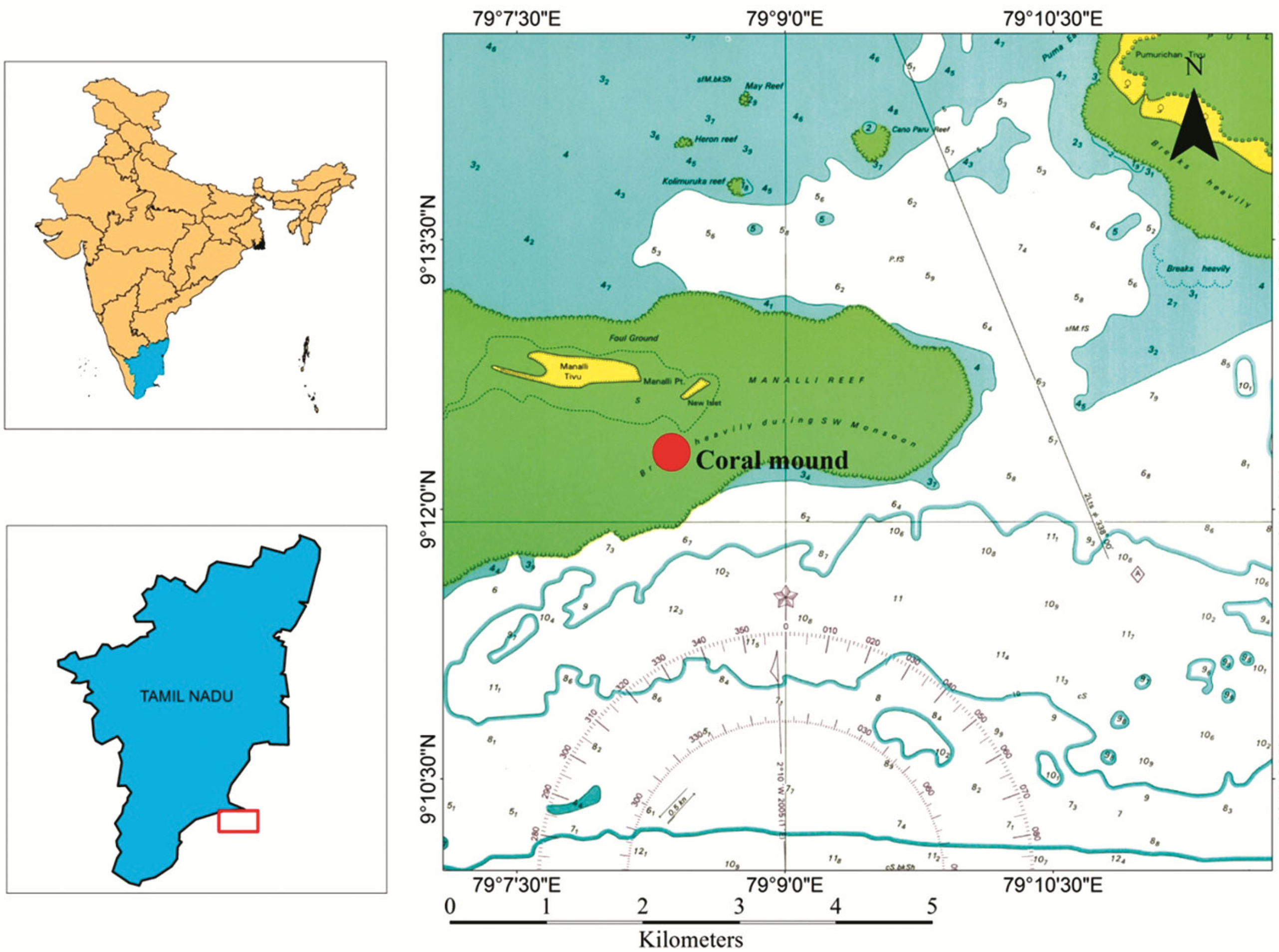

Fig. 1 — Map showing the coral rubble islet location near Manoliputti Island

flora and fauna distributed around the rubble islet. Underwater photography was carried out using a Nikon Coolpix camera. Species identification was confirmed with the Gulf of Mannar species database[39]. Coral species found in the rubble islet and sandbar were identified using standard coral identification keys[4].

Results

The coral rubble islet (n = 1) was formed approximately 800 m away from Manoliputti Island. The maximum elevated height of the coral rubble islet was 1.10 m from the low tide mark. There were clear marks of spring, high, and low tides with lateral view heights of 0.72 m, 0.68 m, and 0.1 m, respectively (Fig. 2). The length and width of the coral rubble islet were 50 m each. The total length of sandbar that connected to the rubble islet edge was 110 m long and 18.6 m in width. The sandbar was visible only during low tide and was mainly composed of coral sand and rubbles (Fig. S1). Area of the rubble islet (Fig. 3) increased continuously (376 sq m in 2013, 444 sq.m in 2017, and 1217 sq.m in 2019). This was the maximum decadal growth of the rubble islet observed in the current study from the available satellite images in Google Earth Pro. Sediment size class observed around the rubble islet and sandbar was coarse to rubbles. The wave pattern around the coral rubble islet was not unidirectional and splashed from four corners of the coral rubble islet. The type of waves involved in forming this rubble islet were constructive waves, representing only eight waves per minute recorded by visual observations (Fig. S1).

Satellite images of the years between 2007 and 2018 revealed the formation of a clear rubble islet at different time intervals (Fig. 4a – e). During 2009, accretion of an enormous amount of dead *Acropora* corals had formed a large rubble islet and a sandbar

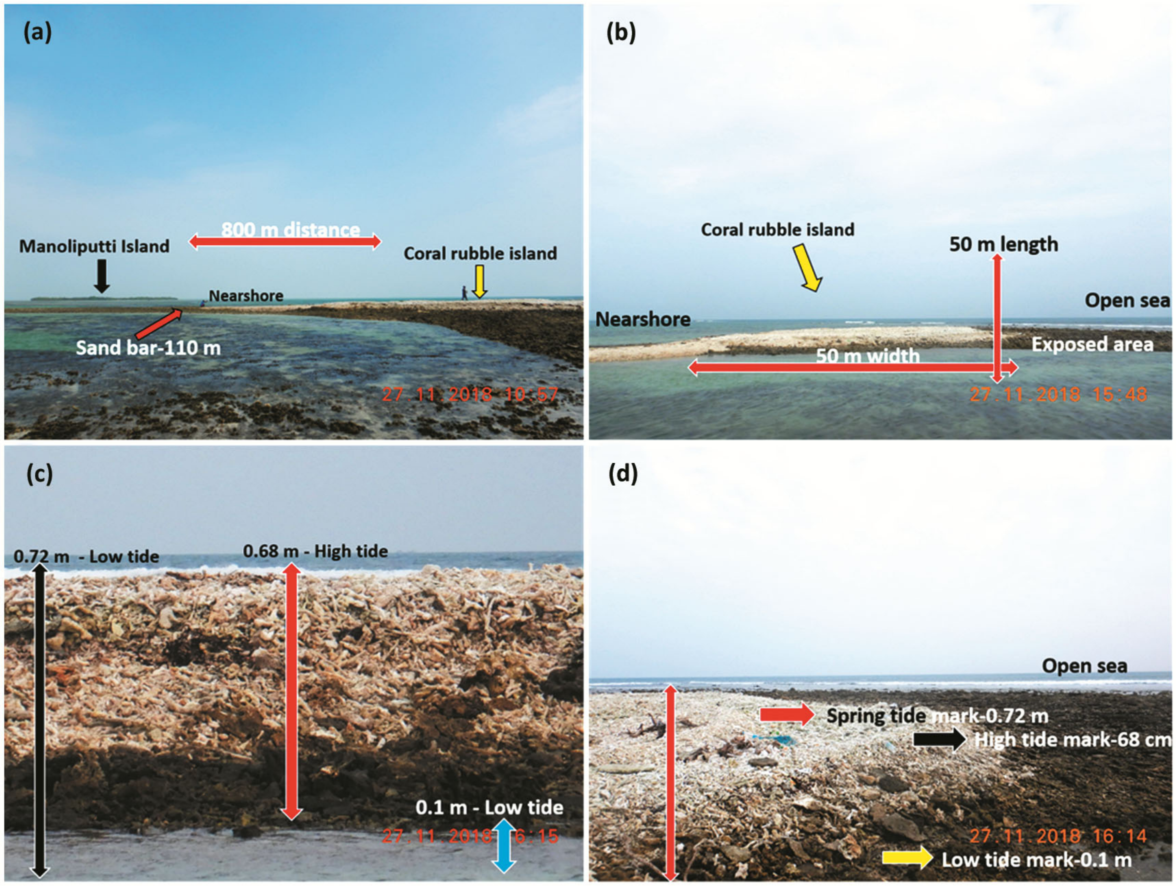

Fig. 2 — Illustration showing (a) Manoliputti Island, sandbar, and the coral rubble islet; (b) Maximum length and width of the coral rubble islet; (c) Lateral view measurements of the coral rubble islet; and (d) Upper view of the coral rubble islet with clear zonation pattern

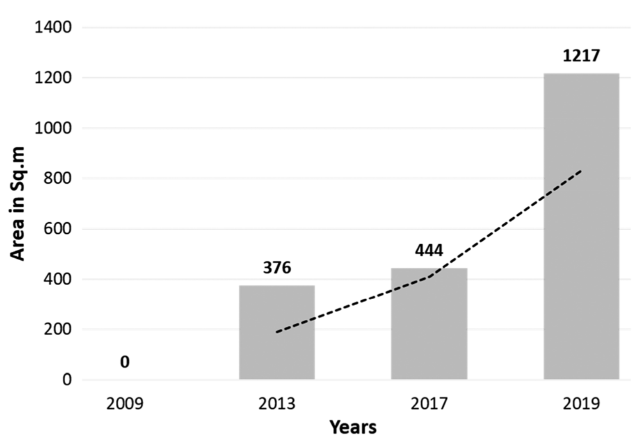

Fig. 3 — Quantitative data of the coral rubble islet with moving average trend line showing the development of rubble islet over the years

(Fig. 4b). A gradual development of the coral rubble islet and a partial development of sandbar were observed in 2013 (Fig. 4c). During 2013, middle part of the coral rubble islet was appeared to be filled with seawater but not corals (Fig. 4c). Later, satellite images of 2017 and 2018 revealed a complete formation of rubble islet filled with historical dead corals. Any signs of fresh coral depositions were not observed around the islet. The elevated sandbar formation was also observed during this study (Fig. 4d – f). Further, the study intended to combine historic depth profile data of the study area with Carbon-14 analysis and coral bleaching data to provide a more comprehensive understanding of this islet formation. The Chart No 3016 published by the National Hydrographic Office (NHO), Dehradun in 2005 shows a new islet formed adjacent to Manoli Island. However, NHO did not mention the materials of the island and its formation process. This study reports the formation of a coral rubble islet, which is geographically separate and distinct from the new islet indicated by NHO (Fig. S2).

The marine biota observed around coral rubble islet found in this study includes marine algae: *Turbinaria ornata*, *T. decurrens*, *Caulerpa racemosa*, *Padina*

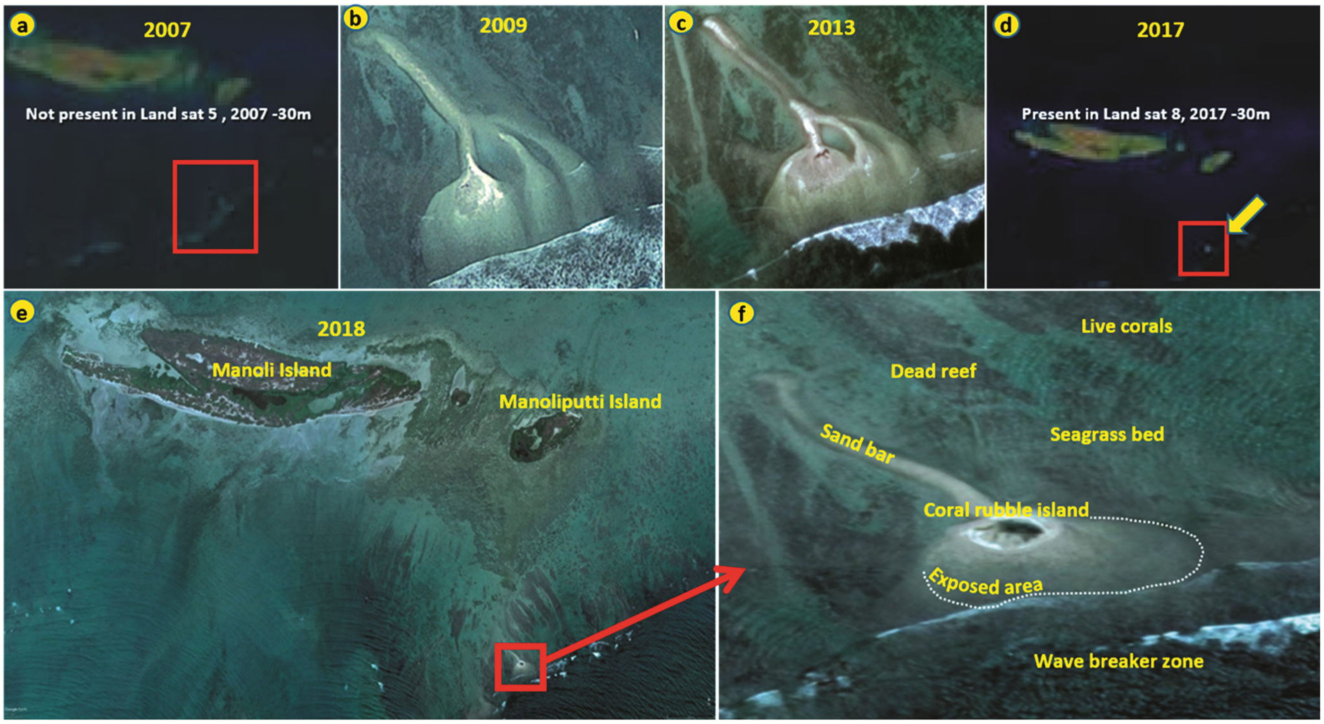

Fig. 4 — Satellite images (Land Sat and Google Earth) showing the rubble islet formation over a decade: (a) Rubble islet formation traces were not observed in 2007; (b) A piece of the coral rubble islet formation was detected in 2009; (c) In 2013, an enclosed coral rubble islet formation was observed. During this year, the centre of this rubble islet was in a pit shape filled with seawater; (d) A complete coral rubble islet formation was found in 2017; and (e & f) Current status of a fully formed coral rubble islet connected with well-developed sandbar

boergesenii, *Sargassum wightii*, *Colpomenia sinuosa*, *Portieria hornemannii*, *Halimeda tuna*, *H. opuntia*, *Lobophora variegata*, and other coralline algae; Invertebrates: unidentified sponges, *Periclimenes brevicarpalis*, *Stichodactyla* spp., *Trochus* spp., *Turbo* spp., *Holothuria atra*; Corals: *Porites solida*, *Montipora digitata*, *Acropora* spp., *Favites* spp.; vertebrates: *Canthigaster margaritata* and other reef fishes; and birds: hundreds of *Tringa hypoleucos*. Also, unidentified terrestrial plant species were found to grow on this coral rubble islet (Fig. S2).

Discussion

The coral rubble islet was mainly composed of *Acropora* and *Favia*, and other minor corals. Although massive corals of *Porites* species were observed around the rubble islet, there were no remnants of dead massive *Porites* corals on the rubble islet (Fig. S3). This indicates that irrespective of the topographic nature, the stability of coral fragments might have played a possible role in uprooting *Acropora* and *Favia* corals to generate a large amount of coral fragments in two decades. Unlike *Acropora* and *Favia* corals, massive corals *Porites* have high stability and the ability to withstand extreme waves and currents; thus, *Porites* skeletons might not have been found in the rubble islet. Although coral rubble ridges were documented seaward side from almost every island (data not shown), significant depositions of coral rubble ridges were observed from Shingle, Appa, and Puluvinichalli Islands. The sediment texture of the Mandapam region is mainly represented by coarse to medium sand[40]. Sediment texture from the rubble islet indicates that the rubbles found could be transported by high-energy waves and coarse coral sand by local currents and non-storm wave overtopping. However, the lack of different time series data on hydrodynamic conditions and storm events from the Mandapam group of islands limits the study in identifying the underlying factor linked to rubble coral islet formation.

A recent study from the Great Barrier Reef reported the formation of rubble spits[3,13], which contributed to the development of rubble islets over decades[3]. In this study, rubble spits were not identified, but a clear sandbar formation was observed near the rubble islet. Unlike coral rubble ridges, which were mainly formed along the shores[13], rubble islets are formed away from the shore between the reef crest and reef flat regions. Previous studies indicate reef wave interactions, waves, and currents as the key factors involved in the transportation of coral sand and rubbles to form sand-apron[2] and rubble islet structures[3]. The elevated reef crest was also thought to control the development of the rubble flat[13]. However, the reef crest around the rubble islet found in this study was not elevated but flat, indicating that reef crest elevation may not be one of the factors controlling the rubble islet formation.

Mandapam region is a biodiversity-rich hotspot compared to other regions in the Gulf of Mannar[41]. Elevated temperatures recorded from the Mandapam group of Islands are known to cause partial to complete coral bleaching[19,31,32,42]. The temperature profile (Fig. S4) of this region indicates a possible role of temperature-mediated bleaching events, which are more likely to kill corals. Breakage of corals due to strong waves and currents has been reported earlier from the GoM islands[31,32]. Although bleaching events found in this region have not resulted in the uprooting of corals in a minimal or large amount, bleached coral fragments were (field observations) highly prone to breakage by strong waves and currents during pre-monsoon and monsoon. The tidal range in the Mandapam region is recorded to be between 0.05 – 0.7 m. Weather conditions around these islands and between the islands are rough, with heavy wind waves, turbulence, and strong currents[37]. These conditions limit most of the field surveys to focus on seasonal studies. Some islands in the GoM often face high wave action that damages corals[31] and forms coral rubble ridges in different islands of the Gulf of Mannar[43]. Studies reported the dominance of swells[44], surface waves[45], storm surge of 4 m[refs. 46,47], longshore sediment transport and waves[48] in the Gulf of Mannar region, indicating that these physical factors as the possible factors involved in reef damage and formation of coral rubble islets. Another possibility of rubble islet formation may be linked to the wave-induced longshore sediment transport process[48]. Storms must not have contributed as they did not cross the study region during the 2009 – 2019 period (Fig. 5). However, real-time data measurements on these processes are not monitored either in this study or in previous studies to track the coral ridge formation. The combined action of waves and currents might take more than two decades to form a rubble islet in this study area, indicating that the coral fragments deposited in this study might be of decadal origin, resulting from the breakage of reefs during storms, extreme wind waves, and currents. Current velocity and wind data (Figs. S5 & S6) also clearly suggest that the collision between wind and currents in this study region might be one of the reasons that appear to favour the formation of a coral rubble islet by the uprooted corals from the surrounding milieus.

Recently, a coral mound from the northeast Atlantic was reported to be generated due to current-associated processes[49]. Oceanic currents can contribute to the formation of coral rubble islets by transporting and depositing coral fragments, shells, and other reef materials. The accumulation and cementation of these materials, facilitated by ocean currents, can eventually form coral rubble islets or mounds. A recent study revealed that the Manoli Island region exhibits high bathymetric stability, surpassing that of other islands and mainland coastal areas[50]. Nevertheless, the limited availability of bathymetric data hinders the ability to pinpoint the precise hydrodynamic factors and other influences contributing to the formation of coral rubble islets in this region. A review of corals, rubble ridges, and coarse deposits on the Caribbean and Great Barrier Reef shores indicated that such depositions occurred due to tides and wave run-up, storm surges, hurricanes, and cyclones or tsunamis[6]. Particularly, during a storm surge, the orbital movement of waves and hurricane overwash has contributed predominantly to the formation of coral ridges on shore[6,10]. Recent studies from the Gulf of Mannar region observed the formation of a sand spit around Vaan Island under the Tuticorin region due to the hindrance of wave action by the artificial reef modules[51]. The formation of sand spit structures is believed to be due to the strong water movement, wave action, and current variability[51-53]. Although such natural hazards or breakwaters have not been reported from the Gulf of Mannar, it is believed that strong current velocity, heavy wind-driven waves (Figs. S5, S6), and wind patterns observed at this island may be sufficient to deposit these dead corals to form a coral rubble islet.

During this study, the dead reefs found in Manoliputti Island under the Gulf of Mannar region were intact, indicating that dead corals that formed a coral rubble islet near Manoliputti Island might not have originated from Manoliputti Island but instead originated from elsewhere or adjacent regions. The exact origin of these accreted corals is currently unknown.

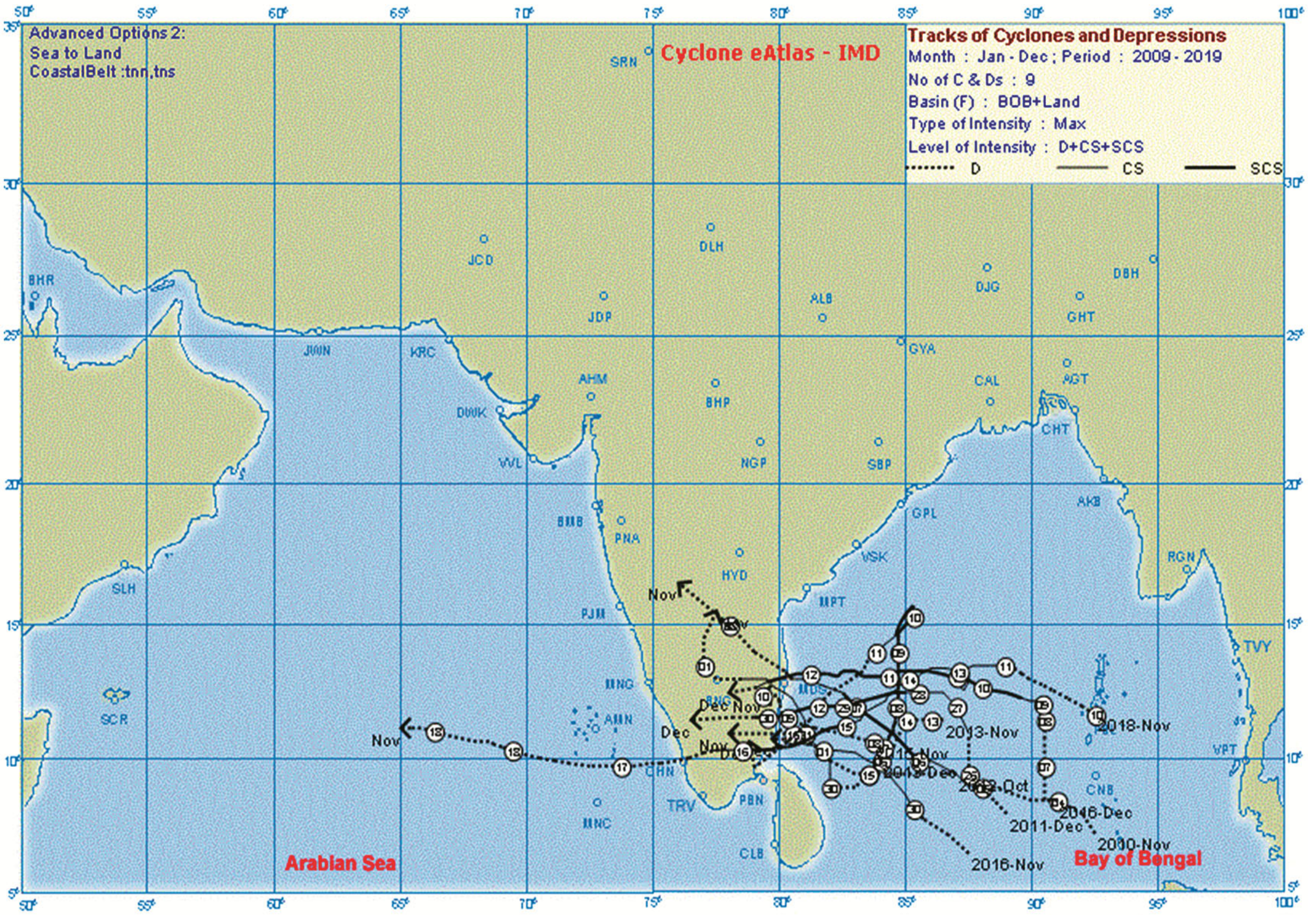

Fig. 5 — History of cyclones during 2009 – 2019 showing no storm events in the study region

Therefore, reef conservation and hydrographic research remain a primary concern in identifying the source of such large amounts of dead corals deposited at this spot. There were no signs of live coral depositions in this study area. Further studies on the topography, wave motion, heavy winds, currents, and storms at this island are required to understand these factors' direct or indirect roles in the construction and dissipation of this rubble islet. The development of terrestrial plants on this rubble islet has influenced the initiation of the plantation of mangrove species like Rhizophora apiculata and Ceriops tagal at this coral rubble islet to see whether this rubble islet would become a permanent island with the aid of roots. Thus, further studies are underway to fill the research gaps on rubble islet formation in the Gulf of Mannar region.

Conclusion

Coral rubble islet formation is being reported for the first time from the Indian waters, which is distinct from the NHO indicated new islet. It took more than two decades to form a complete rubble islet near Manoli Island. Although documenting this rubble islet is important, further studies are needed to identify the underlying hydrodynamic conditions and the degrading coral reef flats in this region. Coral reefs are important for regulating the reef ecosystem structure and health. Thus, it is essential to monitor the physicochemical parameters and hydrodynamic conditions that are detrimental to the corals in this region. The stability of major reef-building coral species in the Gulf of Mannar region also needs to be studied with respect to the topography and sediment characteristics. Studies on seasonal sedimentation rate and transportation around the islands are important to link the impacts of sedimentation, wind waves, currents, and storms on dead reefs, coral ridges, and rubble islet. Thus, further observations are being monitored to understand the effect of longshore drift on this rubble islet's progradation, extension, depletion, and permanence. The rate of sediment and coral sand deposition around this rubble islet and the spatial and temporal shift of the rubble islet are yet to be investigated.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at https://nopr.niscpr.res.in/jinfo/ijms/IJMS_53(11)699-708_SupplData.pdf

Acknowledgments

The authors are thankful to the Ministry of Earth Sciences, New Delhi, for the financial support under the CRAM project. The authors are thankful to the PCCF, Tamil Nadu, for granting permission to work on the coral reefs of the Gulf of Mannar. This is NIO's contribution number: 7505.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Author Contributions

CHR, TS & SK: Field surveys; CHR, TS, RMM, SK & MVRM: Manuscript writing and reviewing; CHR & RMM: Data visualization and preparation of figures; and TS & MVRM: Project supervision.

Data Availability

The datasets generated during the current study are available from the corresponding author on reasonable request for research purposes with an appropriate citation.

References

1 Dronkers J, *Dynamics of Coastal Systems*, 2nd edn, (World Scientific Publishing Co. Pte. Ltd., Singapore), 2016, pp. 780.

2 Vila-Concejo A, Harris D L, Shannon A M, Webster J M & Power H E, Coral reef sediment dynamics: Evidence of sand-apron evolution on a daily and decadal scale, *J Coast Res*, 65 (2013) 606–611. https://doi.org/10.2112/SI65-103.1

3 Talavera L, Vila-Concejo A, Webster J M, Smith C, Duce S, *et al*., Morphodynamic controls for growth and evolution of a rubble coral island, *Remote Sens*, 13 (2021) p. 1582. https://doi.org/10.3390/rs13081582

4 Veron J E N, *Corals of the World*, (Australian Institute of Marine Science, Townsville), 2000, 3 volumes.

5 Soetaert K, Mohn C, Rengstorf A, Grehan A & van Oevelen D, Ecosystem engineering creates a direct nutritional link between 600-m deep cold-water coral mounds and surface productivity, *Sci Rep*, 6 (2016) p. 35057. https://doi.org/10.1038/srep35057

6 Scheffers S R, Haviser J, Browne T & Scheffers A, Tsunamis, hurricanes, the demise of coral reefs and shifts in prehistorichuman populations in the Caribbean, *Quat Int*, 195 (2009) 69–87. https://doi.org/10.1016/j.quaint.2008.07.016

7 Engel M, Oetjen J, May S M & Brückner H, Tsunami deposits of the Caribbean – Towards an improved coastal hazard assessment, *Earth-Sci Rev*, 163 (2016) 260–296. https://doi.org/10.1016/j.earscirev.2016.10.010

8 Liu E, Zhao J, Feng Y, Leonard N D, Clark T R, *et al.*, U-Th age distribution of coral fragments from multiple rubble ridges within the Frankland Islands, Great Barrier Reef: Implications for past storminess history, *Quat Sci Rev*, 143 (2016) 51–68. https://doi.org/10.1016/j.quascirev.2016.05.006

9 Vila-Concejo A & Kench P, Storms in coral reefs, In: *Coastal Storms: Processes and Impacts*, First Edn, edited by P Ciavola & G Coco, (John Wiley & Sons Ltd.), 2017, pp. 127–149.

10 Spiske M & Halley R B, A coral-rubble ridge as evidence for hurricane overwash, Anegada (British Virgin Islands), *Adv Geosci*, 38 (2014) 9–20. https://doi.org/10.5194/adgeo-38-9-2014

11 Ortiz A C & Ashton A D, Exploring carbonate reef flat hydrodynamics and potential formation and growth mechanisms for motu, *Mar Geol*, 412 (2019) 173–186. https://doi.org/10.1016/j.margeo.2019.03.005

12 Engel M, Bruckner H, Messenzehl K, Frenzel P, May S M, *et al.*, Shoreline changes and high-energy wave impacts at the leeward coast of Bonaire (Netherlands Antilles), *Earth Planets Sp*, 64 (2012) 905–921. https://doi.org/10.5047/eps.2011.08.011

13 Shannon A M, Power H E, Webster J M & Vila-Concejo A, Evolution of coral rubble deposits on a reef platform as detected by remote sensing, *Remote Sens*, 5 (2012) 1–18. https://doi.org/10.3390/rs5010001

14 Scheffers A M, Engel M, May S M, Scheffers S R, Joannes-Boyau R, *et al*., Potential and limits of combining studies of coarse- and fine-grained sediments for the coastal event history of a Caribbean carbonate environment, *Geol Soc Spec Publ*, 388 (2013) 503–531. https://doi.org/10.1144/SP388.4

15 Oliveira M A, Llop E, Andrade C, Goble R, Queiroz S, *et al.*, Estimating the age and mechanism of boulder transport related with extreme waves using lichenometry, *Prog Phys Geogr*, 44 (6) (2020) 1–28. https://doi.org/10.1177/0309133320927629

16 Brill D, May S M, Engel M, Reyes M, Pintet A, *et al.*, Typhoon Haiyan's sedimentary record in coastal environments of the Philippines and its palaeotempestological implications, *Nat Hazards Earth Syst Sci*, 16 (2016) 2799–2822. https://doi.org/10.5194/nhess-16-2799-2016

17 O'Dea A, Lepore M, Altieri A H, Chan M, Morales-Saldaña J M, *et al.*, Defning variation in pre-human ecosystems can guide conservation: An example from a Caribbean coral reef, *Sci Rep*, 10 (2020) p. 2922. https://doi.org/10.1038/s41598-020-59436-y

18 Edward J K P, Mathews G, Raj D K, Laju R L, Bharath M S, *et al.*, Severe coral bleaching in the Gulf of Mannar, southeastern India: a status update, *News J Int Soc Reef Stud*, 32 (2017) 65–68.

19 Koushik S, Ramesh C H, Shunmugaraj T & Murthy M V R, High sea surface temperature induces local coral bleaching in Gulf of Mannar and Palk Bay regions, south east coast of India – a status report, *Int J Wildl Endanger Species Conserv*, 3 (2020) 131–138.

20 Raj K D, Mathews G & Edward J K P, Macro algal assemblage structure on the reefs of Tuticorin group of islands in the Gulf of Mannar, *J Mar Biol Assoc India*, 48 (2006) 166–172.

21 Raj K D, Mathews G & Edward J K P, Vaan Island of Gulf of Mannar, Southeast coast of India - on the verge of submergence, *Indian J Geo-Mar Sci*, 44 (2015) 519–522.

22 Raj K D, Bharath M S, Mathews G, Aeby G S & Edward J K P, Coral-killing sponge *Terpios hoshinota* invades the corals of Gulf of Mannar, Southeast India, *Curr Sci*, 114 (2018) 1117–1119. https://doi.org/10.18520/cs/v114/i05/1117-1119

23 Raj K D, Kumar P D, Mathews G & Edward J K P, Spear-fishing with surface supplied diving disturbs the ecological balance in Gulf of Mannar, southeast India, *Ind J Geo-Mar Sci*, 50 (2021) 71–74.

24 Thinesh T, Mathews G & Edward J K P, Occurrence of cyanobacterial infection (black band disease) in Mandapam group of islands (Gulf of Mannar) southeast Tamil Nadu, *Seaweed Res Util*, 30 (2008) 67–75.

25 Thinesh T, Mathews G & Edward J K P, Coral disease prevalence in the Palk Bay, Southeastern India - with special emphasis to black band, *Indian J Geo-Mar Sci*, 40 (2011) 813–820.

26 Thinesh T, Mathews G, Raj K D & Edward J K P, Variation in black and white band disease progression in corals of the Gulf of Mannar and Palk Bay, Southeastern India, *Dis Aquat Organ*, 110 (2014) 227–234.

27 Thinesh T, Mathews G, Raj K D & Edward J K P, Outbreaks of Acropora white syndrome and Terpios sponge overgrowth combined with coral mortality in Palk Bay, southeast coast of India, *Dis Aquat Organ*, 126 (2017) 63–70. https://doi.org/10.3354/dao

28 Thinesh T, Jose P A, Ramasamy P, Meenatchi R, Selvan K M, *et al.*, Differential coral response to algae contact: Porites tissue loss, praise for Halimeda interaction at southeast coast of India, *Environ Sci Pollut Res*, 26 (2019) 17845–17852. https://doi.org/10.1007/s11356-019-05024-1

29 Edward J K P, Mathews G, Raj K D, Laju R L, Bharath M S, *et al.*, Coral mortality in the Gulf of Mannar, southeastern India, due to bleaching caused by elevated sea temperature in 2016, *Curr Sci*, 114 (2018) 1967–1972. https://doi.org/10.13057/oceanlife/o060201

30 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Infestation of corallivorous gastropod, *Drupella cornus* (Gastropoda: Muricidae) on corals of Mandapam group of Islands, Gulf of Mannar, India, *J Terrest Mar Res*, 3 (2019) 1–3. https://doi.org/10.32610/JTMR.2019.V03I01.001

31 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Baseline survey on coral diseases, stress factors and new threats in coral reefs of Gulf of Mannar Marine Biosphere, India, *J Mar Sci*, 1 (2019) 31–48. https://doi.org/10.30564/jms.v1i1.835

32 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Factors affecting coral reefs in the Gulf of Mannar, *J Wildl Res*, 7 (2019) 16–22.

33 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Bioinvasive seaweed genus, *Turbinaria* in coral reefs of Gulf of Mannar, *J Life Sci*, 6 (2019) 1–4. https://doi.org/10.20448/journal.504.2019.61.1.4

34 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Impact of toxic cyanobacterium *Lyngbya majuscula* and green algae *Ulva reticulata* blooms on corals reefs of Gulf of Mannar Marine Biosphere Reserve, Southeast coast of Tamil Nadu, India, *IJSR*, 10 (2019) 34581–34583. http://dx.doi.org/10.24327/ijrsr.2019.1009.3926

35 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Exhibition of bleaching resistance via adaptive bleaching pattern by coral reefs of the Gulf of Mannar during massive bleaching event 2019, *J Mar Sci*, 02 (2020) 1–5. https://doi.org/10.30564/jms.v2i2.1666

36 Magesh N S & Krishnakumar S, The Gulf of Mannar Marine Biosphere Reserve, Southern India, In: *World Seas: An Environmental Evaluation*, edited by C Sheppard, (Elsevier), 2019, pp. 169–184.

37 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Seasonal studies on in situ coral transplantation in the Gulf of Mannar Marine Biosphere Reserve, Southeast coast of Tamil Nadu, India, *Ecol Eng*, 152 (2020) p. 105884.

38 Masumoto Y, Sasaki H, Kagimoto T, Komori N, Ishida A, *et al*., A fifty-year eddy-resolving simulation of the world ocean – preliminary outcomes of OFES (OGCM for the Earth Simulator), *J Earth Simulator*, 1 (2004) 35–56.

39 ENVIS, *Database on Gulf of Mannar Biosphere Reserve*, (Department of Environment and Forest, Government of Tamilnadu, Chennai), 2015.

40 Karikalan R, Priyanga S B & Rakkiannan S, Textural analysis of coastal sediments in Mandapam area, Gulf of Mannar coast, Tamilnadu, India, *Infokara Res*, 9 (2020) 780–790.

41 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Current biodiversity of Mandapam group of Islands in Gulf of Mannar Marine Biosphere Reserve, Southeast coast of Tamil Nadu, India, *Reg Stud Mar Sci*, 39 (2020) p. 101429. https://doi.org/10.1016/j.rsma.2020.101429

42 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Purple-blue pigmentation production as a sign of immune response by bleached corals to elevated sea surface temperature, *Int J Hydrol Res*, 4 (2019) 13–15.

43 Ramesh C H, Koushik S, Shunmugaraj T & Murthy M V R, Documentation of rare coral reef mounds and other geological processes in Gulf of Mannar Marine Biosphere Reserve, southeast coast of India, Tamil Nadu, *Int J Recent Sci Res*, 11 (2020) 36845–36847. http://dx.doi.org/10.24327/ijrsr.2020.1101.5007

44 Amrutha M M & Sanil V K, Observation of dominance of swells over wind seas in the coastal waters of the Gulf of Mannar, India, *Ocean Sci*, 13 (2017) 703–717. https://doi.org/10.5194/os-13-703-2017

45 Gowthaman R, Sanil V K, Dwarakish G S, Mohan S S, Singh J, *et al.*, Waves in Gulf of Mannar and Palk Bay around Dhanushkodi, Tamil Nadu, India, *Curr Sci*, 104 (2013) 1431–1435.

46 Dube S K, Jain I, Rao A D & Murty T S, Storm surge modelling for the Bay of Bengal and Arabian Sea, *Nat Hazards*, 51 (2009) 3–27. https://doi.org/10.1007/s11069-009-9397-9

47 Shaji C, Kar S K & Vishal T, Storm surge studies in the North Indian Ocean: a review, *Indian J Geo-Mar Sci*, 43 (2014) 125–147.

48 Gowthaman R, Sanil V K, Dwarakish G S, Shanas P R, Jena

B K, *et al*., Nearshore waves and longshore sediment transport along Rameshwaram island off the east coast of India, *Int J Nav Archit Ocean Eng*, 7 (2015) 939–950. https://doi.org/10.1515/ijnaoe-2015-0065

49 Lim A, Huvenne V A I, Vertino A, Spezzaferri S & Wheeler A J, New insights on coral mound development from groundtruthed high-resolution ROV-mounted multibeam imaging, *Mar Geol*, 403 (2018) 225–237. https://doi.org/10.1016/j.margeo.2018.06.006

50 Hossain S K A & Murali M R, Assessing the potential effects of climate change on the morphodynamics of the tropical coral reef islands in the Gulf of Mannar, Indian Ocean, *J Environ Manag*, 375 (2025) p. 124122. https://doi.org/10.1016/j.jenvman.2025.124122

51 Asir N G G, Mathews G, Raj K D, Kumar P D, Arasamuthu A, *et al*., The formation and spatio-temporal variations of a new sand spit in Vaan Island, India—An influence of the multipurpose artificial reefs deployed to restore the sinking island, *Reg Stud Mar Sci*, 51 (2022) p. 102173. https://doi.org/10.1016/j.rsma.2022.102173

52 Jagadeesan L, Jyothibabu R, Anjusha A, Mohan A P & Madhu N V, *et al.*, Ocean currents structuring the mesozooplankton in the Gulf of Mannar and the Palk Bay, southeast coast of India, *Prog Oceanogr*, 110 (2013) 27–48. https://doi.org/10.1016/j.pocean.2012.12.002

53 Jain V, Amol P, Fernando V, Michael G S, Aparna S G, *et al.*, Observed current variability in Gulf of Mannar, *J Earth Syst Sci*, 130 (2021) p. 197. https://doi.org/10.1038/s41598-024-65908-2