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# Sustainable artificial coral reef restoration using nanoclays and composite hydrogel microcapsules†

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This report assesses the potential of sustainably-produced artificial coral reef materials metakaolin clay, hydrogel microcapsules, and nanocomposite microcapsule-encapsulated calcifying bacteria as artificial coral reef constituents. The findings show that nanoclays and hydrogels can be considered safe, potential artificial reef constituents, and can improve the sustainability of artificial reefs.

**Sustainability spotlight**

In July 2023, the global ocean surface temperatures reached unprecedented levels due to anthropogenic global warming. Current projections for the coming decades spell doom for marine organisms not adapted to survive in warmer and more acidic seas. Among the most vulnerable are coral reefs, which form the backbone of numerous marine ecosystems. Coral reefs are under tremendous pressure from global warming, disease outbreaks, and pollution, losing substantial coverage every year. This short communication describes an interdisciplinary effort to assess the potential of novel, environmentally sustainable construction additives for coral reef restoration. The findings can lead to the construction of better performing and more sustainable artificial reefs, coastal and offshore structures, and coral nursery materials, firmly aligning the progress of the field with several United Nations Sustainable Development Goals (SDGs), namely SDG9 (Industry, Innovation and Infrastructure), SDG13 (Climate Action), and SDG 14 (Life Below Water), to address and mitigate the threats posed by global warming.

Coral reefs are mostly composed of hard corals with skeletons made of calcium carbonate. They are found in shallow waters of tropical and subtropical oceans worldwide, providing habitats for various marine organisms.[1,2] The Coral Triangle is an area with the highest marine biodiversity in the world,[3] and Malaysia is one of the countries located in this area. It is estimated that Malaysia contains 1595.21 km$^2$ of coral reefs and gains multiple environmental and economic benefits from its coral reefs.[4,5] The Department of Marine Park Malaysia evaluated that its marine protected areas with coral reefs generated approximately USD 1.93 billion in total economic value from its ecosystem services from 2011 to 2015.[6]

In recent decades, global coral reef cover has declined due to anthropogenic factors such as pollution, unsustainable coastal development, and destructive fishing practices.[7,8] However, climate change brought about by global warming has been identified as the main cause of the decline of coral reefs worldwide,[8,9] and various coral restoration efforts have been taken to assist in the recovery of degraded reefs.[10] According to a recent coral restoration review, 21% of coral restoration projects worldwide deploy artificial reef structures to increase habitat for marine life and fisheries production of coral reefs, provide coastal recreational activities (*i.e.*, SCUBA diving), and prevent destructive fishing activities.[2] In Malaysia, artificial reef structures have been deployed since 1975 to conserve marine areas by preventing trawling activities in nearshore areas, providing habitat for marine life, and boosting commercial fish populations to improve the catches of artisanal fishermen.[11,12] Another notable use of artificial reef structure is to provide an area for coral larvae to settle and thrive.[13] Mobile coral larvae depend on physical cues to determine their settlement location and often seek deposits of crustose coralline algae (CCA) with a rugose-textured surface.[14] Moreover, an *in situ* study by Goreau[15] found that increased calcium carbonate formation can stimulate the settlement of coral larvae, growth of coral, and other calcifying organisms. The importance of the presence of

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