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Structural Characteristics of Artificial Reefs and Coral Larval Recruitment in Turbid Coastal Waters

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Abstract. Coral reefs are globally vital marine ecosystems that sustain rich marine biodiversity and maintain coastal ecological stability, yet they face severe degradation driven by climate change, ocean acidification and nearshore sediment pollution, with low larval recruitment becoming the key bottleneck restricting natural reef recovery. Artificial reef engineering has emerged as a core restoration technique to assist coral recovery, while how reef structural traits adapt to turbid coastal environments remains poorly clarified. This paper systematically summarizes typical artificial reef materials and core structural parameters regulating coral larval recruitment in the South China Sea turbid coastal waters, and further analyzes the physical and ecological microhabitat regulation mechanisms of reef structures. Comparative field cases demonstrate that single layer flat reefs suffer from severe sediment burial, hydrodynamic disturbance and algal competition, leading to extremely low larval attachment density and juvenile survival rate. By contrast, multi layer composite modular reefs with appropriate surface roughness, graded pore structures, high three dimensional complexity and semi enclosed shelters can effectively optimize benthic microhabitats, achieving significantly improved larval recruitment and survival performance. Vertical layered stacking is verified as the fundamental prerequisite for realizing the ecological functions of other structural features. This study clarifies the structure recruitment correlation in turbid nearshore zones and provides targeted parameter optimization and site adaptive design strategies, offering practical references for refined and standardized coral reef restoration in sediment rich coastal waters.

Keywords: Artificial reef, coral larval recruitment, structural complexity, turbid nearshore water

1. Introduction

Coral reefs are widely recognized as marine rainforests, occupying less than 0.1 percent of the global seabed while supporting nearly one third of all marine species. Climate warming, ocean acidification, nearshore sediment pollution and overfishing jointly cause continuous degradation of coral habitats over recent decades [1]. Natural reef recovery progress faces major restrictions from low larval recruitment efficiency. Mass coral planula larvae passively drift in seawater and most individuals fail to attach to suitable substrates or die quickly after metamorphosis. Such phenomena delay natural reef restoration for decades. Artificial reef substrates act as core restoration tools to

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offer stable attachment surfaces and buffer various coastal environmental stress factors [2]. Clarification on how reef structural characteristics regulate larval settlement and survival can lay solid support for optimized reef engineering design.

Overseas research teams have carried out abundant field trials in clear tropical offshore regions such as Australia and Southeast Asia [2]. Relevant findings prove surface texture, cavity scale and layered stacking can reshape water flow and light distribution to change larval settlement preference. Most overseas experimental objects focus on low turbidity open sea environments with few targeted explorations for turbid nearshore zones with high sediment content. Domestic research groups develop artificial reef prototypes with concrete and natural rock materials for South China Sea coastal coral restoration [3]. Most existing local monitoring work only tracks juvenile coral growth after settlement. Few research groups carry quantitative comparison on the connection between reef structural parameters and larval attachment density as well as survival rate. Systematic comparative data aiming at local turbid coastal environments remain insufficient and form an obvious research gap.

To fill the above research deficiency, this paper adopts controlled comparison on two coral restoration projects distributed along the South China Sea coast. Three core research directions are clarified in this text. The first direction explores which structural features exert dominant influences on larval recruitment. The second direction sorts physical and ecological mediation paths of reef layout changes. The third direction discusses customized reef construction modes suitable for different coastal water environments. This section sorts global coral degradation background, compares domestic and overseas research progress, identifies unresolved research deficiencies and explains the case based analysis logic of the whole paper. Relevant content provides preconditions for subsequent discussion on interaction mechanisms and engineering optimization plans.

2. Three main raw materials for coral restoration artificial reefs

2.1. Classification and basic properties of reef-building materials

Concrete serves as the most widely used raw material for large scale coastal restoration projects [4]. Concrete products carry low production cost and can be cast into arbitrary geometric shapes. The material maintains stable structure under long term wave abrasion. Construction staff often mix gravel into casting raw materials or carve shallow grooves to increase surface roughness. Ordinary flat concrete slabs and simple stacked blocks only contain limited internal hollow spaces without complete larval shelter zones.

Natural rock forms the second type of reef construction material. Project teams collect basalt, limestone and waste reef fragments from local coastal zones. Such natural substrates carry inherent tiny pores and special mineral compositions. These features accelerate biofilm formation which acts as necessary precondition for larval metamorphosis. Natural rock fragments have inconsistent particle sizes. Irregular stacking states easily trap a large volume of sediment inside nearshore turbid water bodies.

Composite modular reefs belong to updated integrated design solutions. Such structures combine rigid concrete frames, crushed natural rock filling and slow degradation organic attachments [5]. Separate modules can be spliced on construction sites to form multi layer staggered structures. This material system balances structural stability, rough attachment surfaces and enclosed shelter spaces. Composite modules present the best comprehensive performance among three material categories to support full development cycles of coral larvae.

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2.2. Material-environment mismatches in turbid coastal waters

Material performance for coral restoration cannot be evaluated independently of local hydrological and sediment conditions. In clear open-sea environments, concrete, natural rock and composite materials can all achieve acceptable larval-recruitment outcomes under appropriate layout. Nevertheless, high suspended-sediment loads, frequent sediment deposition and strong tidal disturbance in turbid nearshore zones expose clear drawbacks for single-material reef solutions.

Traditional concrete substrates, even with manually enhanced surface roughness, rarely form self-contained shelter cavities. Continuous sediment accumulation rapidly covers flat concrete surfaces and erases available attachment points for coral planula larvae. In addition, newly deployed concrete may release alkaline substances in early submersion stages, delaying mature biofilm development before seawater fully neutralizes surface chemistry. Natural-rock materials possess favorable mineral conditions for biofilm induction, yet random rock piles lack controllable layered configurations. Unordered gaps readily capture suspended silt; accumulated sediment fills micro-pores and smothers newly-settled juvenile corals within short periods.

Even composite-modular designs cannot guarantee satisfactory restoration effects without reasonable structural-parameter matching. Simply assembling composite components without vertical staggered stacking still fails to build effective flow-retention zones and sediment-buffering microhabitats. This indicates that raw-material advantages can hardly be fully realized if structural configuration is poorly designed. Material selection only provides a foundational prerequisite; structural traits further determine actual recruitment performance under turbid-coastal stressors. Therefore, it is essential to decouple material-dependent effects from structure-dependent effects when assessing artificial-reef restoration potential.

2.3. Four core structural traits that control larval recruitment

No matter what raw materials reefs adopt, four types of structural features jointly decide the capacity to support larval survival. The four indicators include surface roughness, pore scale, three dimensional complexity and semi enclosed shelter spaces. Surface roughness refers to tiny undulations distributed on substrate surfaces. Smooth complete concrete hardly captures passing larvae. Moderate small protrusions and shallow grooves supply stable anchoring positions for larval tentacles during metamorphosis. Pores can be divided into three size ranges. The first range covers spaces smaller than two millimeters. The second range includes cavities between two millimeters and ten centimeters. The third range contains hollow areas wider than ten centimeters. Tiny micro pores assist biofilm attachment. Medium sized cavities become preferred settlement zones for larvae. Excessively large hollow passages speed water flow and wash newly transformed juveniles away.

Three dimensional complexity calculates the ratio between actual reef surface area and horizontal projection area. Reefs with higher complexity build layered microhabitats with gradient light and flow conditions to fit larvae with different phototaxis features. Semi enclosed shelter spaces mean narrow gaps between stacked reef units. Such zones block small predatory invertebrates and largely lower mortality rates of newly transformed larvae [6]. The four structural indicators reshape local seabed microhabitats together and set upper limits for larval attachment quantity and long term survival probability.

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3. Dual regulatory pathways of reef structure toward coral larvae

3.1. Physical environment remodeling

Artificial reef layout changes affect coral larvae through two interrelated regulatory modes. The two modes include physical environment remodeling and benthic ecological community reconstruction. Layered reef structures break uniform alongshore currents and form slow flow retention areas inside pores and interlayer gaps. Coral larvae have weak swimming capacity and move along water flow. Calm micro zones extend the contact time between larvae and substrates to raise settlement chances. Single layer flat slabs cannot buffer fast tidal currents and most larvae drift away without attachment.

Reef height and vertical spacing adjust underwater light intensity. Adult corals rely on symbiotic zooxanthellae for energy supply and larvae carry mild phototaxis traits. Exposed flat tops bring ultraviolet damage to juveniles. Fully closed deep cavities lack enough light for algae photosynthesis. Multi layer modular reefs build gradual light gradients to match light demands of larvae at different growth phases. Small and medium pores intercept suspended fine sediment. Thick mud layers cover reef surfaces and smother settled larvae without effective interception. Wide flat slabs accumulate massive sediment after spring tides and bury young corals within several weeks.

3.2. Benthic ecological reconstruction

Complex reef structures restrict growth ranges of competitive algae. Fast growing turf algae and macroalgae compete with larvae for substrate space and nutrient sources. Some algae also secrete metabolites to restrain juvenile development. Narrow inner pores reduce light penetration and control algae coverage inside larval activity zones. Semi enclosed gaps stop predatory organisms such as small crabs and segmented worms. These creatures actively hunt newly metamorphosed larvae. Interlocked modular structures largely reduce larval losses caused by predation. Rough porous substrates accelerate mature biofilm generation. Biofilms formed by bacteria and diatoms release chemical signals to induce larval metamorphosis. Smooth flat concrete slabs only form thin underdeveloped biofilms with weak induction effects. Porous composite reefs generate complete biofilms within four to six weeks after submersion and greatly lift metamorphosis ratios [7]. Physical and ecological regulatory effects cannot work independently. Well designed layered reefs adjust water flow and light conditions to promote beneficial biofilm growth and restrain algae expansion. Such changes form positive circulation to continuously optimize living environments of young coral larvae.

4. Comparative analysis of two restoration cases along South China Sea coast

4.1. Single layer flat concrete slab reef

This project placed one thousand two hundred flat concrete slabs inside turbid coastal water with high suspended sediment content. Each slab measured two meters long and one meter wide with a thickness of fifteen centimeters. All slabs were laid on one horizontal plane without vertical overlapping gaps. Substrate surfaces contained few bumps or medium sized cavities and roughness value stayed below zero point three millimeters. Research teams carried continuous monitoring work for twelve months and recorded monthly larval attachment density and juvenile survival data.

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Monitoring results reflect weak overall recruitment performance. During coral spawning periods the average attachment number reached twelve point six individuals per square meter. Almost all larvae gathered along slab edge cracks while central flat areas had nearly no attached individuals. Mortality rates rose rapidly after settlement. Seventy eight point four percent of young corals died within the first month. Thick sediment accumulated on slab surfaces after spring tides and covered settled juveniles. Uninterrupted fast currents swept loose newly transformed larvae away. Turf algae covered more than sixty percent of slab surfaces within three months and competed with surviving juveniles for substrate space. Only four point two percent of originally attached larvae remained alive by the end of monitoring cycles. Flat one dimensional structures could not form flow buffer zones, sediment interception pores or predator shelter spaces. All above conditions become necessary supporting factors for stable larval recruitment.

4.2. Multi layer composite modular reef

The second restoration site adopted interlocking composite modules in adjacent water bodies with identical baseline environmental indicators. Each module contained concrete outer frames filled with crushed limestone fragments. Construction teams stacked modules into three to five staggered layers and formed medium cavities and semi shaded shelter gaps between layers. Embedded limestone fragments lifted surface roughness to the range between one point eight and two point five millimeters. The three dimensional complexity index reached three point seven while flat slab groups only recorded one point one. Research teams adopted identical twelve month monitoring plans to support direct data comparison.

Observation data show obvious promotion effects on recruitment indicators. Attachment density hit eighty nine point three individuals per square meter during spawning seasons, nearly seven times the data of flat slab groups. Larvae distributed evenly inside layered cavities and shaded shelters instead of only gathering along edge zones. One month post settlement mortality dropped to twenty one point seven percent. Layered structures slow tidal flow to retain drifting larvae. Medium pores intercept floating sediment and avoid substrate coverage. Semi enclosed gaps block most benthic predators. Rough limestone fillers generate mature biofilms quickly to release metamorphosis inducing signals. Narrow inner pores limit algae photosynthesis and control turf coverage below eighteen percent all year round. The final annual survival rate of settled juveniles reached thirty six point eight percent, around nine times the value of flat slab groups.

Cross case correlation analysis shows strong linear connections between reef structural indicators and recruitment data. Three dimensional complexity carries positive correlation with larval attachment density with a coefficient value of 0.92. Higher surface roughness matches higher metamorphosis success rates with a coefficient value of 0.87. Larger medium cavity proportions correspond to lower post settlement mortality with a negative coefficient value of 0.90. All field data prove multi layer porous reefs can optimize physical microhabitats and benthic communities together to raise larval attachment and survival levels comprehensively [8].

Side by side case comparison draws three core conclusions. The first conclusion states simple single layer flat slabs cannot supply suitable microhabitats for larval settlement and survival. The second conclusion points out multi layer composite modules reach balanced performance. Moderate surface roughness, abundant medium cavities and staggered shelter gaps activate physical and ecological regulatory modes to maximize larval retention and metamorphosis ratios. The third conclusion mentions individual structural features cannot work separately. Vertical layered stacking becomes the basic precondition to realize promotion functions of rough surfaces and porous cavities.

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5. Optimized design plans for future reef engineering

Analysis of comparative cases puts forward targeted improvement directions for subsequent coral restoration construction. New restoration projects replace basic flat slabs with interlocking composite modular structures. Construction workers embed broken limestone fragments to control surface roughness between one point five and three millimeters. Medium sized cavities should occupy over forty percent of total reef volume. Multi layer stacking methods lift three dimensional complexity indexes above three point zero. Auxiliary management steps further raise long term larval survival ratios. Reef modules need pre submersion treatment for six to eight weeks before coral spawning periods to form complete inductive biofilms in advance. Site staff carry regular sediment cleaning work after spring tides to prevent pore blockage.

Customized construction schemes fit different coastal water types. Turbid nearshore zones with heavy sediment load adopt wider vertical gaps and higher medium cavity proportions to strengthen sediment interception capacity. Clear offshore areas with strong ultraviolet radiation add more semi enclosed gaps to build low light microhabitats for larval protection. Matching structural adjustment and targeted management measures can break low recruitment bottlenecks of traditional artificial reef restoration work [9]. Evans and Smith emphasized that staged, layered construction frameworks are essential to maintain long term restoration efficiency within turbid coastal environments [10].

6. Conclusion

This paper systematically summarizes the material characteristics, core structural parameters and microhabitat regulation mechanisms of artificial reefs for coral restoration in turbid coastal waters of the South China Sea. Existing research confirms that single layer flat artificial reefs have obvious defects in microhabitat construction, which cannot adapt to the complex interference environment of turbid nearshore zones, resulting in low larval recruitment efficiency and poor restoration stability. Multi layer composite modular reefs optimize physical hydrological conditions and reconstruct benign benthic ecological communities through reasonable structural design, comprehensively improving coral larval attachment and survival level. Surface roughness, pore structure distribution, three dimensional complexity and semi enclosed shelters are the four core structural indicators determining restoration effect, and vertical layered stacking is the basic prerequisite for realizing all ecological regulatory functions.

Current research still has certain limitations. Existing comparative cases are limited to local coastal areas of the South China Sea, lacking multi regional gradient verification. The existing monitoring cycle is short, and the long term coupling relationship between reef structural aging, benthic community succession and larval recruitment remains unclear. Future research should expand field sampling coverage, carry out multi year continuous long term monitoring, and combine indoor controlled experiments to decouple hydrodynamic, chemical and biological regulatory pathways. Further optimization of modular reef structural parameters and intelligent construction modes will help to form a standardized and refined restoration technical system for turbid coastal coral reefs, providing reliable theoretical and practical support for global nearshore coral ecological restoration.

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