https://doi.org/10.1038/s41565-023-01402-6

Nanotechnology for coral reef conservation, restoration and rehabilitation

Liza Roger, Nastassja Lewinski, Hollie Putnam, Shaochen Chen, Daniel Roxbury, Martin Tresguerres & Daniel Wangpraseurt

The mounting environmental pressure on coral reefs calls for a rapid push towards innovative actions. Nanotechnology could help understand and protect present-day reefs to ensure their survival.

Coral reefs in the 21st century

Species richness and structural complexity have established coral reef ecosystems as one of the most productive biomes on Earth. The ability of scleractinian corals, that is, reef-building corals, to thrive in oligotrophic regions of our oceans hinges on a fragile equilibrium between the coral polyp (the biological unit of coral colonies), endosymbiotic dinoflagellate algae (Symbiodiniaceae, housed in a tight intracellular compartment called a symbiosome), and a plethora of bacteria, archaea, viruses, endolithic algae and fungi with mutualistic, commensal or pathogenic relationships (estimated between 100–1,000,000 cells cm^{-2}) (Fig. 1a). Cross-kingdom exchange of vital nutrients, including photosynthetic carbon, nitrogen and trace metal elements[1] has allowed scleractinian corals to build the calcium carbonate bedrock of tropical and subtropical coastal ecosystems over the last 25 million years.

The constant intensification of anthropogenic activities since the industrial revolution has led to shifting baselines and the impossible task of returning to pristine conditions[2]. Climate change-induced thermal stress, ocean acidification and deoxygenation, combined with coral diseases, eutrophication and pollution, are precipitating the destruction of coral reef ecosystems across the globe. Under business-as-usual practices, coral reef surface area is predicted to decrease by 90% in the next 30 years[3]. The loss of coral reefs would have devastating consequences on biodiversity, food security, coastal protection, tourism, trade and cultural heritage. Therefore, to rapidly catalyse transformative ocean solutions, the United Nations launched the Decade of Ocean Science for Sustainable Development (2021–2030) (https://en.unesco.org/ocean-decade).

Here, we argue that nanotechnology approaches can support current interventions developed for coral reef conservation, restoration and rehabilitation.

What has nanotechnology done for corals so far?

To preserve coral reefs, we first need to better understand the ecophysiology of scleractinian corals in response to present-day and future climate scenarios. The foundational mechanisms driving the formation of coral reefs, photosynthesis and biomineralization take place in host-controlled intracellular spaces characterized by nanoscale to microscale gradients of O_2, pH and nutrients[4]. Such fine-scale variations of critical environmental parameters present a grand challenge

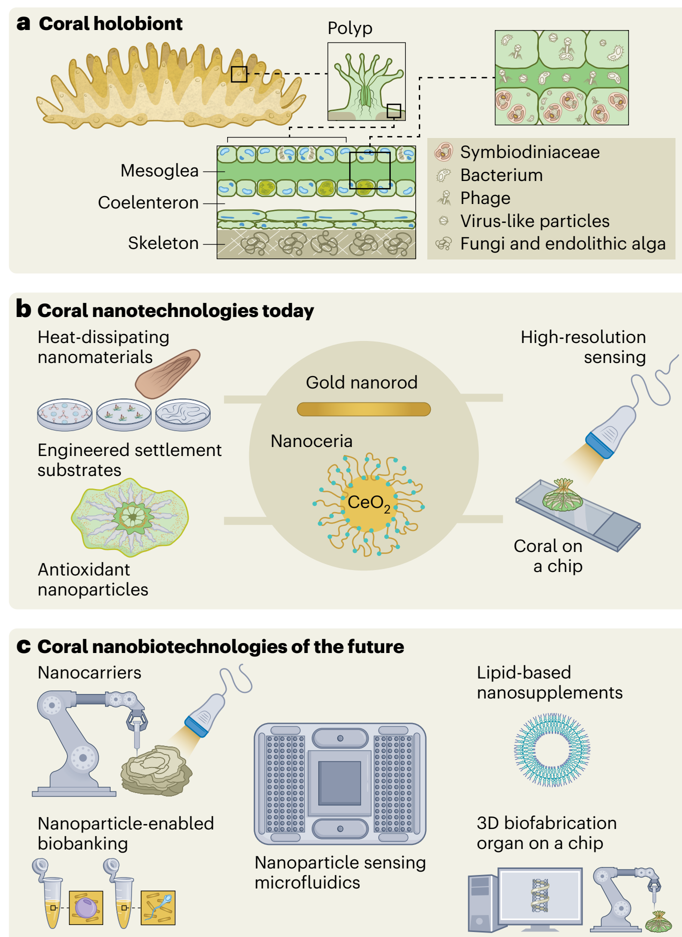

Fig. 1 | Overview of the coral holobiont partners, the existing nanotechnologies applied to reef-building corals, and promising applications to develop in the near future. **a**, Coral colonies are composed of clonal cnidarian polyps with a diverse microbiome and engaged in a mutualistic symbiosis with dinoflagellate algae. Together, these organisms form the coral holobiont. **b**, Among the nanotechnologies applied to coral today are gold nanorods for cryopreservation of larvae, engineered larvae settlement surfaces, antioxidant cerium dioxide nanoparticles, high-resolution sensing and coral-on-a-chip model. **c**, Some of the advances that could benefit coral research and preservation in the future are nanocarriers for targeted drug delivery, including lipid-based nanosupplements, nanoparticle-enabled biobanking, small molecule and nanoparticle sensing microfluidics, and three-dimensional biofabrication of coral tissue (organ on a chip) for high-throughput interrogations.

CREDIT: ADAPTED FROM AN ORIGINAL FIGURE BY HOLLIE PUTNAM AND EMMA STRAND for coral ecophysiology as most probes and sensors lack the required spatial and temporal resolution. Nanoparticle technology should thus be exploited for improved coral health monitoring. For example, platinum-based nanoparticles combined with ratiometric imaging has been successfully developed to visualize O_2 concentration and flow across the coral tissue surface with nanoscale spatial resolution and rapid response time[5]. Dissolved oxygen levels in the coral micro-habitats are linked to photosynthesis and energy metabolism, and thus non-invasive nanoparticle-based sensing can help to identify the onset and progression of physiological stress across the coral landscape.

The applications of nanotechnology go well beyond sensors, and new approaches are being developed to actively manipulate processes relevant to coral ecophysiology. For example, reactive oxygen species (ROS) are a key trigger of bleaching and ROS scavengers hold the potential to enhance coral health. As recently shown in experimental trials, redox nanoparticles composed of a ROS-scavenging polymer (methoxy-poly(ethylene glycol)-b-poly[4-(2,2,6,6-tetramethylpiperidine-1-oxyl)oxymethylstyrene], MeO-PEG-b-PMOT) and antioxidant drugs increased survival of aposymbiotic coral larvae exposed to thermal stress[6]. Moreover, engineered nanoceria (cerium dioxide nanoparticles coated with poly(acrylic acid), PAA-CeO_2) delivered intracellularly to free-living symbiotic algae typically associated with reef-building corals reduced the concentration of ROS when cultures were exposed to thermal stress[7] (Fig. 1b). Antioxidant treatments could be coupled with "stress-training" – that is, pre-exposure to thermal stress to increase the thermal tolerance of coral genotypes[8] – in coral farm settings to boost acclimatory capacity ahead of reef restoration.

Another approach to reef restoration consists of fabricating larval settlement and metamorphosis-inducing nanoengineered substrates with antifouling characteristics (Fig. 1b). Coral larval settlement is a complicated process affected by various biotic and abiotic cues, including substrate biochemistry and microbial community dynamics, as well as substrate architecture and light availability. Several relevant biocompatible nano-substrates and coatings have been designed, such as porous ceramics for larval settlement[9], self-healing coral cell adhesion-promoting coatings[10,11], and CeO_2 nanoparticle-based antifouling coating[12]. While these success stories are currently only laboratory-based, they bode well for field deployments and the field promises further innovative approaches. Beyond restoration efforts, recent advances in coral genetic material cryopreservation now enable the preservation of fertilized coral larvae using gold nanorods to absorb laser radiation, progressively melting the cryoprotectant medium without damaging the larvae[13] (Fig. 1b).

What potential does nanotechnology still hold for corals?

We are just beginning to exploit the vast potential that nanotechnology holds for coral reef science and conservation. With the recent kick-off of the Climate Change National Nanotechnology Challenge in January 2023 (www.nano.gov/nano4EARTH), coral reef research could leverage the exciting developments in nanotechnology for new coral-specific diagnostic tools, rapid testing, high-resolution health monitoring, coral nanomedicines/pharmacology, novel bionano-fabrication and, more generally, to improve the coral research toolkit (Fig. 1c). We suggest that combining the known beneficial effects of ROS scavenging with lipid-based supplements or liposome encapsulation is a viable way forward to protect corals during periods of stress[6,7,14,15]. Likewise, the encapsulation of coral probiotic and antibiotic treatments[16,17] in highly modular, target-specific nanocarriers (Fig. 1c) is an important development that will reduce the severity of coral disease outbreaks. Today's technology could enable the biochemical, geochemical, architectural, fabrication/assembly and surface coating engineering of biohybrid nanoengineered materials to radically improve recruitment success and coral growth. Recent advances in coral cell culture methods[18,19], new coral-based applications of microfluidics[20] and three-dimensional biofabrication are paving the way towards biohybrid coral models and high-throughput systems[21,22] (Fig. 1c). Nanotechnology should be integrated with such systems to improve our understanding of molecular trafficking between holobiont partners in relation to environmental change. The successful fusion of nanotechnology and coral science holds the potential for cutting-edge transformative research across the different scales of the coral holobiont. We call for a critical dialogue between the nanotechnology and coral research communities to facilitate fundamental discoveries, and breakthroughs in coral conservation, reef restoration and rehabilitation. True organ-on-a-chip models of coral systems combined with CRISPR/Cas9 gene-editing techniques[23] have the potential to unlock high-throughput interrogations at the molecular level, while nano-enabled biobanking could preserve coral genetic material for future generations. Nanotechnological applications have far reaching consequences for coral research and should be driven by transdisciplinary collaborations to broaden the scope of coral sciences, address the critical issue of reef degradation, and promote innovations needed to safeguard coral reefs for future generations.

Liza Roger [1,2,3] ✉, Nastassja Lewinski [1], Hollie Putnam[4], Shaochen Chen[5], Daniel Roxbury[6], Martin Tresguerres [7] & Daniel Wangpraseurt[5,7] ✉

[1]Chemical and Life Science Engineering, Virginia Commonwealth University, Richmond, VA, USA. [2]School of Molecular Sciences, Arizona State University, Tempe, AZ, USA. [3]School of Ocean Futures, Arizona State University, Tempe, AZ, USA. [4]College of Environment and Life Sciences, University of Rhode Island, Kingston, RI, USA. [5]Department of NanoEngineering, University of California San Diego, La Jolla, CA, USA. [6]Department of Chemical Engineering, University of Rhode Island, Kingston, RI, USA. [7]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA.
✉e-mail: liza.roger@asu.edu; dwangpraseurt@eng.ucsd.edu

Published online: 25 May 2023

References

1. Reich, H. G., Camp, E. F., Roger, L. M. & Putnam, H. M. *Biol. Rev.* https://doi.org/10.1111/brv.12922 (2022).
2. Hughes, T. et al. *Nature* **546**, 82–90 (2017).
3. IPCC *Climate Change 2022: Impacts, Adaptation, and Vulnerability* (eds Pörtner, H.-O. et al.) (Cambridge Univ. Press, 2022).
4. Tresguerres, M. et al. *J. Exp. Zool.* **333**, 449–465 (2020).
5. Ahmerkamp, S. et al. *Cell Rep. Methods* **2**, 100216 (2022).
6. Motone, K. et al. *Mar. Biotechnol.* **20**, 542–548 (2018).
7. Roger, L. M., Russo, J. A., Jinkerson, R. E., Giraldo, J. P. & Lewinski, N. A. *Front. Mar. Sci.* **9**, 1435 (2022).
8. DeMerlis, A. et al. *Coral Reefs* **41**, 435–445 (2022).
9. Hoog Antink, M. M. et al. *Ceram. Int.* **44**, 16561–16571 (2018).
10. Luo, C. et al. *ACS Appl. Bio Mater.* **3**, 1481–1495 (2020).
11. Ge, L. et al. *Colloids Surf. A Physicochem. Eng. Asp.* **628**, 127337 (2021).
12. Roepke, L. K. et al. *Sci. Rep.* **12**, 15935 (2022).
13. Cirino, L. et al. *Sci. Rep.* **9**, 18851 (2019).
14. Cirino, L. et al. *Cryobiology* **98**, 80–86 (2021).
15. Moros, M. et al. *MRS Commun.* **8**, 918–925 (2018).
16. Neely, K. L., Macaulay, K. A., Hower, E. K. & Dobler, M. A. *PeerJ* **8**, e9289 (2020).
17. Eaton, K. R. et al. *PLoS ONE* **17**, e0276902 (2022).
18. Nowotny, J. D., Connelly, M. T. & Traylor-Knowles, N. *Sci. Rep.* **11**, 1–9 (2021).
19. Snyder, G. A., Browne, W. E. & Traylor-Knowles, N. *J. Vis. Exp.* **159**, 2020.

20. Zhou, S., Fu, E. S., Chen, B. & Yan, H. *Micromachines* **13**, 832 (2022).
21. Wangpraseurt, D. et al. *Nature Commun.* **11**, 1748 (2020).
22. Wangpraseurt, D. et al. *Adv. Funct. Mater.* **32**, 2202273 (2022).
23. Cleves, P. A., Strader, M. E., Bay, L. K., Pringle, J. R. & Matz, M. V. *Proc. Natl Acad. Sci. USA* **115**, 5235 (2018).

Acknowledgements
This work was supported by National Science Foundation grants HDR 1939699 to N.A.L., HDR 1939795 to H.M.P., 1844536 and 2231621 to D.R., and 2149925 to D.W., the URI Research Council to H.M.P. and D.R., and the Gordon and Betty Moore Foundation Aquatic Symbiosis Model Systems (grant 9325) to S.C., D.W. and M.T. This material is based upon work supported by the Defense Advanced Research Projects Agency under the Reefense Program, BAA HR001121S0012 to D.W. The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the US Government.

Competing interests
The authors declare no competing interests.

Additional information
Peer review information *Nature Nanotechnology* thanks the anonymous reviewers for their contribution to the peer review of this work.