

Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- ☐ ☒ The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
- ☐ ☒ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
- ☐ ☒ The statistical test(s) used AND whether they are one- or two-sided
Only common tests should be described solely by name; describe more complex techniques in the Methods section.
- ☐ ☒ A description of all covariates tested
- ☐ ☒ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
- ☐ ☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
- ☐ ☒ For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
Give P values as exact values whenever suitable.
- ☒ ☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- ☒ ☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- ☒ ☐ Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	The fluorescence imaging data were collected with MAPS, an IDL-based program developed in-house (J. Phys. IV Proc. 2003, 104, 635–638). Ptychography measurements were collected using a custom code written in Python 2.8 with PyEpics package(3.3.3).
Data analysis	Scanning electron microscopy data were analyzed using ImageJ 1.52a. Transmission electron microscopy or scanning transmission electron microscopy data were analyzed using DigitalMicrograph 3.42.3048.0, ImageJ 1.52a and AZtec4.3.2D ptychographic reconstructions were processed using a GPU open source library, Ptycholib, written in C++. 3D ptychography was reconstructed by PtychoShelves in Matlab R2018a. The ptychography and fluorescence images after reconstruction were also registered and analyzed using VivoQuant 4.0 patch 1. Plottings were performed with Origin 2019b (32-bit) 9.6.5.169 and Adobe Illustrator 21.0.0. Laser confocal scanning microscope images were analyzed with OLYMPUS OLS 5000 1.1.1.55. Micro-CT data were analyzed using Amira 5.6. Histology images and data were analyzed with CaseViewer 2.4. Optical images were analyzed with ImageJ 1.52a. TOF-SIMS data were analyzed with WinCadence software. Statistical analysis were performed with Graphpad Prism 9.4.0.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

All the data supporting the findings of this study are available within the paper, the supplementary materials or the source data. The data are available from the corresponding authors upon reasonable request. Source data are also available at https://osf.io/muc9g/?view_only=971b8fde8562427ab619bc30c2624cb7

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	Sample size was determined based on extensive laboratory experience and literature in the field. The number of biological replicates we aimed for was at least 3 with technical replicates in each group so that the number of biological and technical replicates is necessary to convince us that the effect was real. The number of biological replicates in animal test was at least 5 in each group.
Data exclusions	Representative images were shown in the manuscripts; similar results from experimental repeats were not shown. No data excluded for statistical analyses.
Replication	All experimental findings, including TEM and SEM images, Micro-CT images, confocal laser microscopy images, EDS spectra, FTIR spectra, TOF-SIMS spectra, x-ray fluorescence and ptychography, bacteria experiments and animal experiments, were reliably reproduced. For materials characterizations, all the SEM or TEM images were individually repeated more than five times at different sample spots. The X-ray ptychography and fluorescence imaging were repeated two times. Bacterial experiments were individually repeated for at least three times. Animal experiments were individually repeated three times except the DSS-induced colitis test in figure 5 was only done once. These experiments were replicated from every week to every month and all the experiments were successful.
Randomization	Experimental groups were formed based on what was being tested with random sections. The same type of material, bacterial cells and animals were used for all experiments. The bacteria from the same flask culture were randomly allocated into different groups for testing the modulation activity of the materials. The animals were purchased from the Jackson Laboratory and were randomly allocated into different groups for testing the modulation activity of the materials. The same ratio/number of commercially purchased male and female mice were randomly allocated into all individual experimental groups. These mice were all in the same age range (6-8 weeks) and body weight range (20-25 grams).
Blinding	Experimenters were blinded during imaging experiments. Biocompatibility tests and tetracyclin-treated experiments were not performed blind to the conditions of the experiments as treatments were determined beforehand and animal were selected in order to acquire sufficient sample size per experimental group. All subsequent samples were blinded to group allocation during data collection and analysis.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☐	☒ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Animals and other organisms

Policy information about [studies involving animals](#); [ARRIVE guidelines](#) recommended for reporting animal research

Laboratory animals	6-8 week old C57BL/6J mice (female and male) purchased from the Jackson Laboratory were used in in vivo biocompatibility experiments (tissue harvesting after euthanasia for H&E staining, fecal sample collecting and body weight monitoring). Mice were housed in the animal facility of the University of Chicago. The animal room was maintained in an environment with the humidity of 40-60 % and the temperature of 18-23 °C under a 12-h light/12-h dark cycle. The animals were allowed free access to food and water.All animal procedures were approved by the Institutional Animal Care and Use Committees (IACUC) of the University of Chicago under the protocol # 72621."
Wild animals	No wild animals were used.
Field-collected samples	No field-collected samples were used.
Ethics oversight	All animals were housed under pathogen-free conditions and all animal procedures were approved by the Institutional Animal Care and Use Committees (IACUC) of the University of Chicago.

Note that full information on the approval of the study protocol must also be provided in the manuscript.