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Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

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	For data collection in the study, a range of commercial equipment was employed, including: a Hitachi SU8220 Scanning Electron Microscope (SEM) with energy-dispersive X-ray spectroscopy (EDS) from Hitachi High-Technologies Corporation for material morphological characterization and elemental distribution analysis; a Bruker D8 Advance X-ray Diffractometer (XRD) from Bruker Corporation for crystallographic structure analysis of ZIF-8, F-TiO_2, and MRSD-PLA membranes; a PerkinElmer Spectrum 3 Fourier-Transform Infrared Spectrometer (FTIR) from PerkinElmer Inc. for chemical functional group identification; a Mettler Toledo TGA/DSC 2 Thermogravimetric Analyzer for thermal stability evaluation, component content quantification (e.g., actual F-TiO_2 loading), and degradation behavior analysis; a Kino SL200B Contact Angle Goniometer from Kino Industry Co., Ltd. for static water contact angle measurement and surface wettability evaluation; a Gaotai GT-7010 Universal Testing Machine from Gaotai Testing Machine Co., Ltd. for membrane tensile strength and elastic modulus testing; a JH-TEST Non-contact Electrostatic Voltmeter from JH Technology Co., Ltd. for surface potential measurement; a Wayne Kerr WK-6500B Precision Dielectric Analyzer for relative dielectric constant testing; a Micromeritics Micro VacPrep061 Nitrogen Adsorption-Desorption Analyzer for specific surface area (BET) and pore size distribution (NLDFT) analysis; a Porous Materials CFP-1100AI Capillary Flow Porometer for membrane pore size distribution characterization; a TSI Model 8026 NaCl Aerosol Generator and TSI Model 3910 Nanoparticle Analyzer from TSI Incorporated for generating test aerosols and measuring aerosol concentrations to calculate filtration efficiency; an MCE-3G servo-electric cylinder system (domestic high-precision CNC) for realizing periodic contact-separation motion in triboelectric tests; Keithley 6514 Electrometer and Keithley 2400 Source Meter from Keithley Instruments for measuring open-circuit voltage, short-circuit current, and transferred charge in triboelectric tests; a Beijing Perfect Light PL-X300DUV Photocatalytic Reactor for simulated sunlight irradiation in antibacterial tests. The only open-source software used was ImageJ 2.x, applied for quantitative analysis of fiber diameter distribution and SEM image processing. Additionally, three commercial software tools were utilized: GaussView and Gaussian 09 (from Gaussian, Inc.) for calculating electrostatic potential (ESP)-mapped electron densities of PLA chains and COMSOL Multiphysics (from COMSOL Group) for simulating potential distribution during contact-separation cycles in triboelectric tests. Materials Studio 2023 is used for molecular mechanics and dynamics simulations, as well as energy level and energy barrier calculations.

Data analysis	Origin 2024, ImageJ 2.x, MDI Jade 6.

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 Portfolio 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 description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The authors declare that the data supporting the findings of this study are included within the paper and its supplementary Information. Source data are provided with this paper.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	N/A
Reporting on race, ethnicity, or other socially relevant groupings	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

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

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

Ecological, evolutionary & environmental sciences study design

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

Study description	This study investigated the synergistic effects of embedding ZIF-8 nanocrystals and surface-anchoring F-TiO_2 nanoblocks on the performance of electrospun poly(lactic acid) membranes. The experimental design was a multi-factor study with two primary treatment factors: (1) the presence/absence of ZIF-8, and (2) the mass fraction of F-TiO_2 (0%, 2%, 4%, 6%). This resulted in a completely randomized design with four distinct material groups (P-PLA, MRSD-PLA2, MRSD-PLA4, MRSD-PLA6). The fundamental experimental unit was each independently fabricated membrane batch. All quantitative characterizations (e.g., filtration efficiency, mechanical testing, surface potential) were performed with a minimum of n = 3 independent replicate batches, and key measurements (e.g., water contact angle, fiber diameter) involved n ≥ 5 technical replicates per batch to ensure statistical robustness.
Research sample	The research samples consisted of a series of poly(lactic acid) (PLA)-based nanofiber membranes. This group included pristine PLA (P-PLA) membranes and microenvironment-regulating, self-decontaminating meta-membranes (MRSD-PLA) functionalized with zeolitic imidazolate framework-8 (ZIF-8) nanocrystals and fluorinated titanium dioxide (F-TiO_2) nanoblocks. All samples were synthesized in-house via electrospinning and electrospray techniques. The sample choice was rationalized as follows: P-PLA served as a biodegradable structural scaffold and control; ZIF-8 was embedded to introduce microporosity, enhance electroactivity, and facilitate molecular transport; and F-TiO_2 was anchored to confer hydrophobicity, photocatalytic self-cleaning, and deep charge traps. The manipulations involved the co-axial electrospinning of a PLA/ZIF-8 solution with simultaneous electrospray of F-TiO_2 suspensions. This sample set is designed to represent a model material system for investigating the structure-property relationships arising from hierarchically heterogeneous interfaces in advanced protective membranes, rather than representing a natural population.
Sampling strategy	No statistical methods were used to predetermine sample size. The sample size for materials characterization and performance evaluation (e.g., n ≥ 3 independent membrane fabrication batches and n ≥ 5 measurements per property) was chosen based on

established practices in the field of materials science and our prior experience with similar electrospun systems. This approach ensures the assessment of experimental reproducibility and material consistency. The reported data represent the mean values with standard deviations, demonstrating the robustness of our findings. We are confident that the chosen sample sizes are sufficient to support the conclusions drawn, as the observed effects and performance metrics were consistently reproducible and statistically significant across independent samples.

Data collection	Data collection was performed using the standard method in this type of work. The relevant experimental methods are described in the Supplementary Methods section of the Supplementary Information.
Timing and spatial scale	Data collection was performed at predetermined times.
Data exclusions	No data were excluded from the analyses.
Reproducibility	In order to verify the reproducibility of the work, we prepared multiple samples. We tested the performance of these samples. Evaluate the reproducibility of the work based on how similar results are.
Randomization	In our work, the sample is the prepared nanofibrous membrane material, which does not include randomization.
Blinding	in our work, data collection is accomplished through cross-flow filtering devices. We substitute the data recorded in the experiment, including test time, volume of exudate, and concentration of solute, into the formula to calculate the performance of the nanofibrous membrane. Data are analyzed through various software, Therefore, no blinding is involved in this process.

Did the study involve field work? ☐ Yes ☒ No

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
☒	☐	Clinical data
☒	☐	Dual use research of concern
☒	☐	Plants

Methods

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

Plants

Seed stocks	N/A
Novel plant genotypes	N/A
Authentication	N/A