nature portfolio

Corresponding author(s): Carlo Bianco, carlo.bianco@polito.it

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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	n.a.
Data analysis	n.a.

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

Underlying data for the main manuscript figures are available as an excel file and can be accessed at 10.6084/m9.figshare.32253390

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 investigates an in-situ strategy for the synthesis of iron-based nanoparticles within porous media for groundwater remediation. Harmless precursor solutions were co-injected into aquifer-like porous media, where they reacted to form reactive iron-based nanoparticles capable of degrading chlorinated solvents. An analytical injection model was developed to support the design and placement of the reactive zone. The approach was validated experimentally in two laboratory/pilot-scale systems: a three-dimensional homogeneous aquifer model and a two-dimensional layered porous medium representative of heterogeneous aquifer conditions. The study combined transport/injection experiments, nanoparticle deposition assessment, and batch degradation tests for tetrachloroethylene and trichloroethylene.
Research sample	The research sample consisted of laboratory-scale porous media systems designed to reproduce relevant groundwater flow and transport conditions. Specifically, the study used a three-dimensional pilot-scale homogeneous aquifer and a two-dimensional layered porous medium including zones of different permeability. These systems were selected to evaluate the feasibility of forming reactive iron-based nanoparticles directly within the subsurface and to test the ability of the proposed injection strategy to control particle delivery in both homogeneous and heterogeneous aquifer conditions. The contaminants considered in the reactivity tests were tetrachloroethylene and trichloroethylene, selected as representative chlorinated solvents commonly encountered in contaminated groundwater.
Sampling strategy	Sample sizes and experimental configurations were selected to test the proposed in-situ nanoparticle synthesis approach under controlled but representative laboratory conditions. No formal statistical sample-size calculation was performed, as the study was based on mechanistic laboratory validation and process demonstration rather than population-level statistical inference.
Data collection	Data were collected during and after the injection experiments and subsequent reactivity tests. Injection-related data were obtained from the laboratory/pilot-scale porous media systems to assess the spatial distribution and yield of iron-based particle formation within the target treatment zone. Additional data were collected from batch degradation tests to quantify the removal of tetrachloroethylene and trichloroethylene by the generated particles over 21 days. Data collection was performed by the research team using the experimental procedures described in the Methods section of the manuscript.
Timing and spatial scale	The experiments were conducted at laboratory and pilot scale in 2023. The batch degradation tests lasted 21 days, the in-situ synthesis tests lasted less than 4 days each.
Data exclusions	No data were excluded from the analyses.
Reproducibility	Reproducibility was addressed by validating the proposed approach in two distinct porous media configurations: a three-dimensional homogeneous aquifer and a two-dimensional layered porous medium.
Randomization	Random allocation was not relevant to this study because the experiments did not involve biological organisms, human participants, or treatment groups requiring randomized assignment. The porous media configurations, injection conditions, and contaminant degradation tests were defined according to the experimental design and the objectives of the remediation study. Where applicable,

experimental conditions were controlled through the design of the aquifer models, hydraulic conditions, precursor injection strategy, and contaminant test conditions.

Blinding

Blinding was not relevant to this study because the work involved controlled physical, chemical, and hydrogeological experiments rather than subjective outcome assessment or allocation of participants to treatment groups.

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.