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Review article

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# Materials advances for distributed environmental sensor networks at scale

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## Abstract

Historic and ongoing efforts in ecology and environmental science have highlighted the pressing need to monitor the health, sustainability and productivity of global and local ecosystems. Interest in these areas reflects a need both to determine the suitability of environments to support human activity (settlement, agriculture and industry) and to evaluate the impacts of such anthropogenic action. Of interest are chemical, biological and physical factors that reduce ecosystem viability owing to human intervention. Evaluating these factors and their impact on global health, ecological stability and resource availability demands improvements to existing environmental sensing technologies. Current methods to quantify chemical pollutants, biological factors and deleterious physical conditions affecting target ecosystems suffer from lack of automation and narrow spatiotemporal range. Recent advances in materials science, chemistry, electronics and robotics offer solutions to this problem. A vision emerges for fully autonomous, networked and ecoresorbable sensing systems that can be deployed over large aerial, terrestrial and aquatic environments. This Review describes ongoing efforts in these areas, focusing on materials advances supporting the accurate quantification of environmental factors with apparatus that accommodates full or partial device resorption. Discussion begins with an overview of hazards affecting global ecosystems, followed by a description of existing detection methods to quantify their severity. We proceed with an exploration of existing and developing technologies affecting sensor dispersion, motility, communication and power. Finally, we describe exciting recent efforts in the development of environmentally degradable materials that could prove beneficial in the realization of massively distributed (millions of individual sensors) transient sensor networks.

## Sections



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## Introduction

The rapid increase in global human population and the ever-evolving landscape of modern industrialization place a mounting burden on the availability of natural resources, as well as on the health and stability of the ecosystems that support them[1,2]. As worldwide demand for critical agricultural, mineral and petroleum feedstocks continues to rise[3], so does the impact of anthropogenic agents[4,5]. In 2019, atmospheric pollution alone was estimated to be responsible for ~9 million premature deaths[6]. To compound the problems imposed by known environmental hazards, ongoing efforts in ecology, analytical chemistry and conservation continue to identify new environmental agents with pernicious impacts on human health. This predicament positions the identification, elimination and remediation of environmental hazards as among the most essential endeavours for modern science.

As the starting point for targeted action, the quantitative evaluation of chemical, physical and biological factors impacting ecosystem viability is essential in characterizing both healthy and impacted environments. Generally, such evaluation is accomplished with the discrete collection of environmental samples, followed by standard laboratory analysis[7,8]. Unfortunately, despite the sophistication and maturity of laboratory-based methods, the spatial heterogeneity and temporal evolution of target ecosystems make high-resolution, large-scale sample collection and analysis non-trivial[7].

Spatial variability in environmental samples manifests across numerous length scales (millimetres to kilometres) and may be the result of random variance, sampling bias, true environmental patterns or a combination of all three. In addition to this spatial uncertainty, environmental samples also change with time (over the span of minutes to years), making the temporal characteristics of sampled environments equivalently important. These spatiotemporal variances represent serious concerns for the statistical validity of environmental characterization. Recommendations from the United States Environmental Protection Agency support the use of probabilistic sampling (characterized by large numbers of discrete sample collections over a broad area) to guarantee statistical inference[8]. Unfortunately, limitations in manpower, sample throughput, method availability and sampling time often preclude this approach, necessitating judgement-based sampling as a substitute.

These burdensome aspects of sample collection and analysis, as well as the accompanying lack of automation, present considerable barriers to detailed and statistically significant site analysis, especially over large areas (>1 $km^2$). To address these limitations, investigators in the fields of ecology, agriculture and environmental science are developing large, distributed networks of sensors for spatiotemporally resolved analysis of environmental samples[9]. Although sensor networks of this type have already proven useful in monitoring chemical pollutants[10,11], weather patterns[12] and agricultural site quality (such as mineral bioavailability, biological oxygen demand or soil humidity)[13,14], they generally require direct operator intervention for sensor installation, maintenance and removal. Similarly, detailed environmental profiling over a large area (~1 $km^2$) with high spatial resolution (~1 $m^2$) demands input from potentially millions of individual sensors whose deployment, communication, recovery and disposal present technological hurdles that have yet to be overcome.

Developments in materials science, chemistry, electronics design, microfabrication and data analysis have facilitated sensor miniaturization, automated deployment, wireless data transmission and cloud analysis, which could address some of these limitations. Additionally, physically transient biodegradable electronics could support temporary sensors capable of timed operation followed by complete hydrolytic disintegration without harmful effects on target ecosystems[15]. By integrating newly developed data acquisition and transmission protocols, these transient environmental sensors may prove useful in profiling environmental factors over large terrestrial and aquatic environments or in hazardous areas where post facto sensor retrieval is infeasible. Similarly, although other non-invasive sensing modalities, such as satellite-based methods, have been successfully used to profile environmental factors, they cannot provide the direct chemical information accessible to on-the-ground sensing elements.

In this Review, we aim to provide a concise picture of recent (emphasizing the past 5 years) results in the design, assembly, distribution and utilization of miniaturized, and potentially degradable, environmental sensors with a focus on materials that support the accurate spatiotemporal profiling of chemical, physical and biological hazards. We begin with a short overview of hazards relevant to modern environmental science, followed by an exploration of the most common analytical methods used for their quantification. Then, we discuss device platforms capable of sensor dispersal, communication, power and motility, along with ongoing efforts to realize complete or partial sensor transience. Throughout this discussion, we highlight practical considerations on the real-world assembly, performance, sustainability and system integration of these technologies and highlight the promise and limitations currently influencing the realization of massively distributed sensing networks. Similarly, we focus on emerging challenges presented by aquatic and soil environments. The short-term and medium-term monitoring of water and soil are critical for profiling acute instances of accidental hazard release[16], evaluation of agricultural and industrial sites for suitability or compliance[17] and ecological study of the environmental microbiome[18]. These use-cases present a strong case for temporary monitoring, followed by sensor collection or dissolution.

## Threats to soil and water

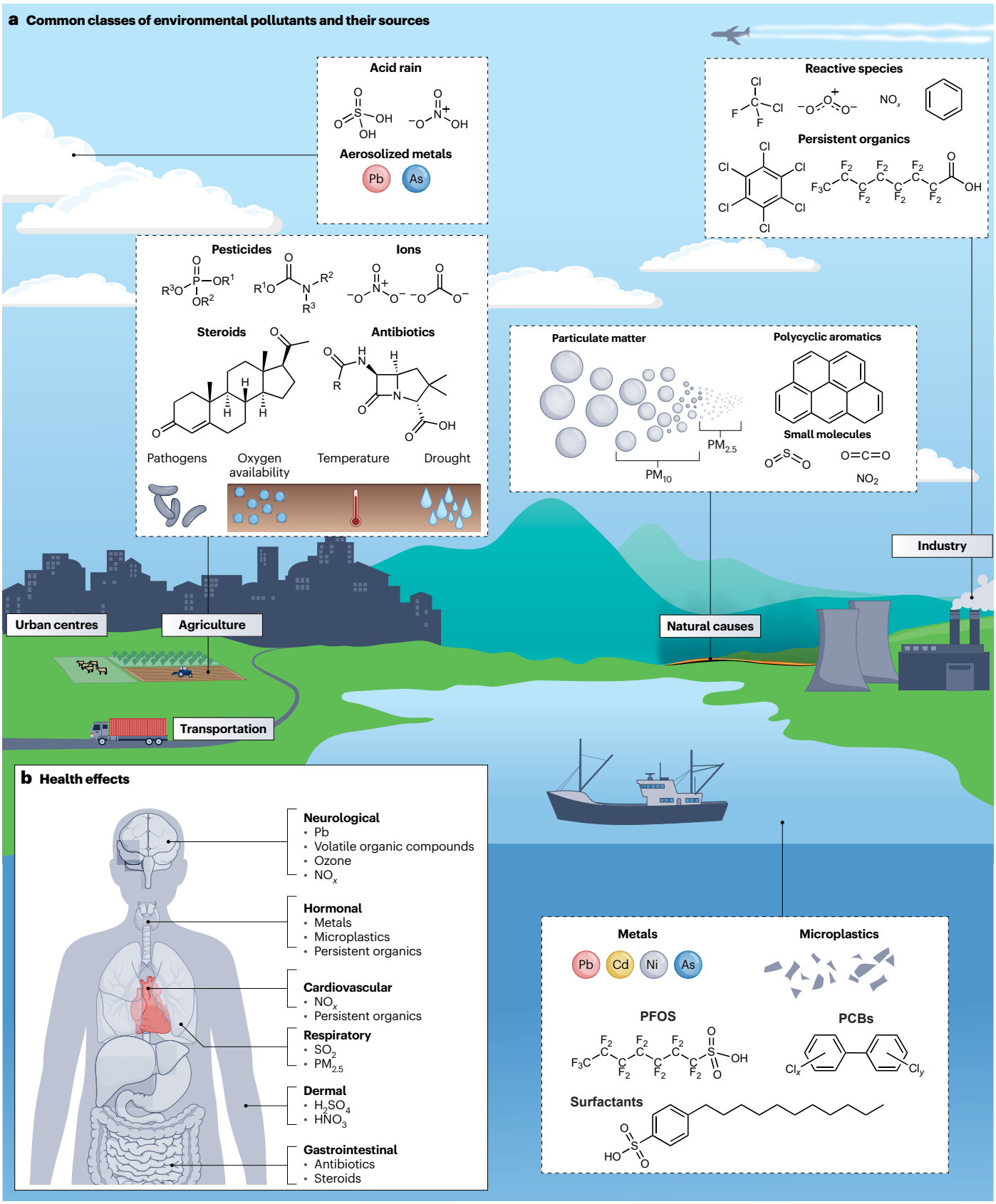
The hazardous nature of environmental threats such as heavy metals[19], pesticides[20], radiation[21] and increasing temperatures[22] has long been recognized, but new contaminants such as microplastics pose a similarly critical risk to environmental and ecological health. These threats present important risks to both ecological systems and human health. Here, we focus on environmental threats present in soil and water sources.

### Chemical factors

Pollutants cover a broad range of chemistries including meso-scale particulate matter, multifarious organic species, small molecules and metal ions[23] (Fig. 1a). Despite the broad range of known chemical pollutants, ongoing work in ecology continues to identify unforeseen chemistries negatively impacting environmental health.

A particularly important recent development in the understanding of chemical pollution is the identification of persistent organic pollutants (POPs) as nearly ubiquitous constituents of air, water and soil[24]. These pollutants, exemplified by per-fluoroalkyl and poly-fluoroalkyl

**Fig. 1 | Sources, types and health impacts of environmental pollutants. a**, Overview of common classes of environmental pollutants and their sources. **b**, Target body systems impacted by environmental pollution. PCB, polychlorinated biphenyl; PFOS, perfluorooctane sulfonate; PM, particulate matter.


a Common classes of environmental pollutants and their sources
Acid rain
Aerosolized metals
Pb
As
Reactive species
NOx
Persistent organics
Pesticides
Ions
Steroids
Antibiotics
Pathogens
Oxygen availability
Temperature
Drought
Particulate matter
PM2.5
PM10
Polycyclic aromatics
Small molecules
NO2
Industry
Urban centres
Agriculture
Natural causes
Transportation
b Health effects
Neurological
Pb
Volatile organic compounds
Ozone
NOx
Hormonal
Metals
Microplastics
Persistent organics
Cardiovascular
NOx
Persistent organics
Respiratory
SO2
PM2.5
Dermal
H2SO4
HNO3
Gastrointestinal
Antibiotics
Steroids
Metals
Pb
Cd
Ni
As
Microplastics
PFOS
PCBs
Surfactants

substances (PFAS), are industrially produced compounds with long lifetimes in environmental media. The high chemical stability of C–F bonds precludes the natural decomposition of these compounds, thereby promoting their distribution and bioaccumulation[25]. The accumulation of PFAS in human tissues has been linked to numerous pathologies including immune deficiencies, thyroid dysfunction, insulin dysregulation and cancers[26] (Fig. 1b).

Another important development is the quantification of microplastics in water, soil and living organisms[27,28]. Microplastics are recognized as among the most pervasive known environmental pollutants, exhibiting measurable concentrations in every ecosystem on the planet[29]. Similarly, microplastics have been measured in the lungs, circulatory systems and gastrointestinal tracts of human and animal hosts[30] and have demonstrated deleterious impacts on the viability of soil ecosystems[31]. The profound spread of microplastics is thought to contribute to consistent increases in cancer, immune disruption and neurological issues affecting the developed world[32].

In addition to PFAS and microplastics, surfactants[33] and flame-retardant compounds[34], used extensively in industry, have been widely detected in the environment and exhibit high biological activity. These contaminants, together with heavy metals, pesticides, phenols and volatile organic compounds, are now recognized as important environmental pollutants, making their detection and remediation outstanding problems.

### Biological and biochemical factors

In addition to synthetic chemical pollutants, bioactive compounds derived from both artificial and natural sources are of equivalent interests owing to their large ecological impact even at low concentrations. Pesticides[35], pharmaceuticals[36] and hormones[37] have come under scrutiny owing to their over-utilization in agriculture and medicine. Elevated levels of hormones and antibiotics have been measured in soil and water samples obtained at agricultural sites and in numerous aquatic environments[38,39]. The capacity of these compounds to alter local microbiomes represents an important risk to agricultural productivity and ecosystem viability.

Changes to topsoil microbiota have been observed in agricultural sites worldwide, causing a reduction in bioavailability and agricultural efficacy[40]. In addition to their impact on crop production, the evolution of antibiotic-resistant pathogens within affected soil remains a dire concern, with recent reports suggesting that many antibiotic-resistant infections originate from soil microbiota[41]. These resistant infections preclude treatment by conventional antibiotics and represent a major contributor of human mortality worldwide[42], making their detection and elimination a persistent goal for modern medicine and ecology. Together, these persistent environmental concerns make the detection and quantification of the water and soil microbiome an equally important endeavour to chemical monitoring.

### Physical factors

In addition to chemical and biological profiling, the quantification of physical environmental characteristics such as temperature and humidity is also imperative for evaluating changes in microclimates and macroclimates[43]. Global temperature characterization is typically accomplished using satellite-based instrumentation in conjunction with ground recording equipment. However, mapping local temperature changes in soil or water requires a more granular approach. Temperature increases associated with deforestation or soil decline contribute to substantial reductions in crop yield and biodiversity[44]. Therefore, distributed temperature measurement networks can be useful to identify deficiencies in hydration, vegetation cover and soil quality[45].

Humidity is also valuable as an indicator of environmental distress, finding use as a predictor for agricultural viability, ecosystem habitability and local weather patterns[46]. Further quantification of agricultural health can likewise be obtained from direct physical characterization of soil samples[47]. Quantification of soil hydration[48], microbial activity[49], compaction[50] and erosion[51] have proven invaluable in evaluating the health, stability and agricultural efficacy of target topsoil.

### Ecosystem stability, sustainability and productivity

Although the preceding sections have focused on hazardous conditions impacting ecosystems owing to anthropogenic action, there remains a concerted and equivalent interest in characterizing fundamental parameters related to the native health and sustainability of ecosystems even in the absence of any true threat. Considerable interest lies in the characterization of soil and water health in the context of agricultural productivity and viability[52]. Similarly, the evaluation of ecosystem vulnerability to human intervention remains an outstanding necessity considering ongoing global industrialization. In these regards, sensing systems that quantify chemical, physical and biological factors reflecting baseline ecosystem health, productivity and sustainability are sorely needed.

Factors of interest include crop yield, crop diversity, microbial diversity and activity, as well as chemical factors including humidity[53], soil $O_2$ and pH[54], and the concentration of other soil macronutrients (nitrogen, potassium and phosphorous)[54–56]. Regular variations in these parameters are key informants on the underlying dynamics of target ecosystems and provide an improved picture of the viability and robustness of these environments even in the absence of direct threat. Sensor networks capable of continuously reporting on these factors offer a wealth of information that could prove invaluable in agriculture and ecology, including the careful surveillance necessary to support ongoing efforts in forestry and wet land preservation[57,58]. Importantly, in the spatiotemporal evaluation of healthy ecosystems, distributed sensors must be environmentally benign to avoid any undue burden or influence on the ecosystem under consideration. Biodegradable sensors are an important step towards this goal, as they offer temporary environmental characterization followed by harmless dissolution at end-of-life.

## Principles of detection

Chemical (pollutants, nutrients, minerals and pH), physical (weather, humidity, pressure and temperature) and biological (microbiota, organism behaviour and biodiversity) signatures accompanying environmental action offer numerous avenues to evaluate the health of target ecosystems. Among these approaches, chemical analyses represent the most common and widely varied options, focusing on the detection of harmful atomic or molecular agents with either human or natural origin. Current ‘gold standard’ techniques for chemical profiling include atomic spectroscopies and/or X-ray methods for elemental analysis[59], chromatographic and spectrometric methods (gas chromatography, liquid chromatography and mass spectrometry) for organic species[60,61] and spectroscopic techniques (infrared, visible and NMR) for both organic and inorganic components.

Although some of these standard methods can be miniaturized to accommodate on-site chemical analysis[60,62], chromatography, atomic and X-ray spectroscopies and mass spectrometry remain too large, expensive and/or complicated for the level of mass distribution

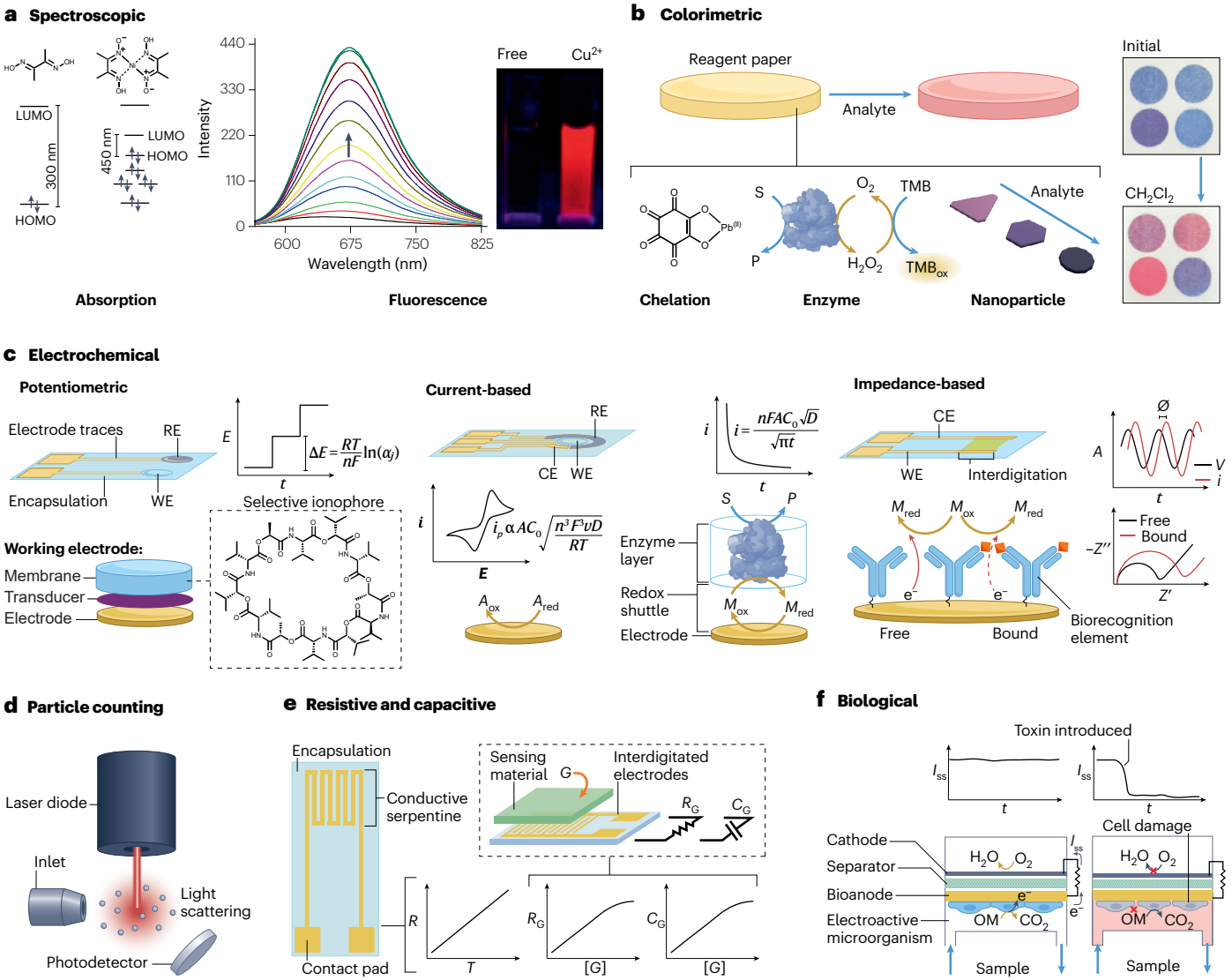



**Fig. 2 | Sensing modalities. a**, Simplified energy (*E*) diagram depicting the binding and optical detection of an analyte using chelating ligands leveraging changes in optical absorbance (left). Detection of trace metals in samples using optical fluorescence[72] (right). **b**, Schematic depiction of colorimetric approaches to analyte quantification (left). Application of colorimetric sensors for the rapid identification of organic species[104] (right). **c**, Schematic depictions of electrochemical sensing modalities relying on potentiometric changes (left), changes in oxidative or reductive current density (middle), and changes to the complex electrode impedance to evaluate the concentration of chemical targets (right). **d**, Schematic diagram of particle counting apparatus for air quality monitoring. **e**, Simplified schematics of resistive and capacitive sensors for temperature (left) and gas composition (right), in which *R* and *C* are resistance and capacitance, and [*G*] is the analyte concentration. **f**, Biological methods leveraging living cell lines to quantify environmental toxicity wherein loss of environmental viability changes the metabolic activity (and therefore electrode current density) of redox-active microorganisms. *υ*, scan rate; *ϕ*, phase shift; *A*, electrode area; $a_i$, ion activity; CE, counter electrode; *D*, diffusion coefficient; *F*, Faraday constant; HOMO, highest occupied molecular orbital; *i*, current; $I_{ss}$, steady-state current; LUMO, lowest unoccupied molecular orbital; *n*, number of electrons; OM, organic matter; *R*, gas constant; RE, reference electrode; *t*, time; *T*, temperature; TMB, tetramethylbenzidine; WE, working electrode; *Z′*, real impedance; *Z″*, imaginary impedance. Part **a** reprinted with permission from ref. 72, Elsevier. Part **b** adapted with permission from ref. 104, ACS.

envisioned here. Conversely, sensing modalities with the potential for miniaturization and simplification could enable mass deployment. These systems rely on diverse mechanisms for signal transduction, including spectroscopic, colorimetric, electrochemical, electronic and biological approaches (Fig. 2). Spectroscopic methods, in particular, remain closely tied to conventional laboratory-based analyses and benefit from the relative maturity of the materials and chemistries used for analyte quantification.

## Spectroscopic sensing

Spectroscopic methods leverage the wavelength-dependent absorption and emission of light by a sample to gain information about the

identity, concentration and properties of its constituents[63]. Owing to the chemical complexity of environmental samples, and the low concentrations of pollutants therein, most environmental spectroscopies rely on the addition of photochemically active probes to bind and amplify the absorption and/or emission of target analytes[64]. A simple example of this approach is Ni(II) (target) detection using dimethylglyoxime as a probe[65] (Fig. 2a, left), in which probe–target binding induces rearrangement of frontier molecular orbitals owing to Ni(II) *d*-orbital splitting. This rearrangement reduces the highest occupied molecular orbital–lowest unoccupied molecular orbital energy gap and shifts the main absorbance band of the Ni–dimethylglyoxime complex to visible wavelengths for direct optical detection[66]. This principle of ligand–target binding has been widely used to detect chemical pollutants at moderate concentrations (>100 nM) including heavy metals, pesticides[67] and antibiotics using organic ligands[68], polyaromatic ligands[69], metal organic frameworks[70] and covalent organic frameworks[71] as probes. To access lower concentration ranges, fluorescent methods have also been explored, replacing the absorbing probe with a fluorophore for the detection of trace pollutants[72] (Fig. 2a, right). These fluorophores undergo non-radiative relaxation and re-emission upon photoexcitation, resulting in a separation between the absorption and emission wavelengths. This separation markedly reduces background signal, resulting in a substantial increase in the sensitivity of the method[73]. Fluorescent detection schemes have realized extremely sensitive ($10^{-10}$ M) and selective detection of heavy metals[74,75], pesticides[76], warfare agents[77] and organic species[78].

Further improvements in sensitivity have been achieved with metallic or semiconducting nanomaterials as spectroscopic probes[79]. These materials leverage localized surface plasmon resonance (LSPR) to amplify the spectroscopic cross-section of molecules near the nanomaterial surface, with amplification factors as high as $10^{10}$ (ref. 80). This amplification accommodates the detection of trace ($10^{-12}$–$10^{-15}$ M) chemical species, with the addition of biorecognition elements (antibodies, aptamers, nanobodies and chelating agents) to the nanomaterial surface affording high analyte selectivity[81]. Sensing systems incorporating plasmonic nanomaterials have enabled the detection of metals[82], pesticides[83], antibiotics[84], PFAS[85] and pharmaceuticals[86] in soil and water samples with limits of detection (LODs) as low as 1 fM.

## Colorimetric sensing

The analytical power of spectroscopic methods comes with a reliance on accurate spectrometers to facilitate data acquisition. The cost and bulk of traditional spectrometers have precluded their widespread distribution as point-of-measurement sensors, despite several impressive demonstrations of portable spectroscopic apparatus[87]. To address this limitation, colorimetric chemical detection has been explored as an alternative technology[88,89]. Colorimetric platforms simplify spectroscopic detection by sequestering optically active probes within a porous matrix (typically an absorbent paper) that changes colour based on analyte concentration. These colour changes can be immediately detected by the human eye and processed digitally for quantification (Fig. 2b).

Although a wide range of colorimetric chemistries have been explored[90], they generally fall into three categories: direct chelation, enzymatic detection and plasmonic methods. Chelation assays operate following a similar mechanism to spectroscopic assays, through the formation of a probe–analyte complex (Fig. 2b, bottom left) whose colour is dependent on analyte concentration. Such assays are appropriate for the detection of high concentration analytes and are often used in the detection of heavy metals[91] and polyatomic ions[92].

In contrast to direct chelation, enzymatic reactions rely on the biochemical activity of isolated enzymes (or a similar catalyst) to produce optically active molecules by consumption of a target analyte[93] (Fig. 2b, bottom middle). In this scheme, the analyte is catalytically consumed by an appropriate enzyme resulting in the concomitant chemical oxidation of a redox active probe (often tetramethylbenzidine)[94]. The colour change associated with probe oxidation can then be used to quantify analyte concentration. These assays have been deployed to quantify biochemically active metabolites[95] and small molecules[96] with additional work investigating engineered nanozymes or DNAzymes to detect species for which no naturally occurring enzyme exists[97].

Finally, nanomaterial-based colorimetric sensors have been demonstrated, leveraging the high sensitivity of their plasmonic resonance to report on analyte concentration[98]. Although a wide range of mechanisms have been explored[99], one common approach involves modifying nanomaterials with biorecognition elements that trigger analyte-dependent flocculation and plasmonic deactivation. These changes reduce LSPR signal intensity, which can then be used to quantify analyte concentration[100]. Other approaches have even coupled nanomaterial assays with enzymes, using peroxide (generated during analyte consumption) to selectively etch the nanomaterial probe (Fig. 2b, bottom right). This coupling results in predictable changes to the LSPR wavelength and intensity[101].

Together, these approaches can accommodate the quantification of heavy metal concentrations in soil and water[102] and the on-site evaluation of soil pesticides[103]. Similarly, arrays of colorimetric sensors can be used to differentiate chemically similar species (Fig. 2b, right), enabling analyte identification in an unknown sample[78,104]. Owing to their low cost and easy fabrication, colorimetric assays remain an attractive alternative to existing spectroscopic methods. Unfortunately, the remote dispersal and analysis of colorimetric assays without human intervention remain a challenge.

## Electrochemical sensing

To address the limitations of spectroscopic and colorimetric sensing (moderate cost, lack of automation and non-continuous sensing), electrochemical approaches have also been explored for analyte detection[105]. Such approaches rely on changes in voltage (potentiometric), current (amperometric) or impedance (impedimetric) of a conductive working electrode to facilitate chemical quantification (Fig. 2c).

Potentiometric sensing represents the most mature mode of electrochemical quantification, relying on the voltage difference between two electrodes to elucidate analyte concentration. Sensors consist of a chemically insensitive reference electrode and an analyte-sensitive working electrode[106]. To accommodate the conversion of chemical activity to electrical potential at the working electrode, a transducing film (porous carbon[107], molecularly imprinted[108] and/or conducting polymers[109]) is layered with a chemoselective membrane (ionophore-loaded polymer) (Fig. 2c, bottom left). Together, these materials permit the exclusive transport of the target analyte to the electrode surface[110], resulting in a Nernstian electrode potential determined by exogenous analyte concentration (Fig. 2c, top left). This approach has been used to quantify ionic pollutants (particularly heavy metals) in environmental matrices including river water and soil[111,112].

Despite the widespread use of potentiometric sensors, they suffer from comparatively high LODs. Submicromolar ion concentrations

have proven extremely challenging to quantify, even in controlled laboratory settings. Higher analyte sensitivities have been realized through amperometric electrochemical platforms, relying on active electrode polarization to gain additional information about the sample[113]. Often, these platforms require a third electrode (counter electrode) to accommodate bulk current flow through the sample, where the magnitude of this current quantifies constituent concentrations. Amperometric measurements fall into two main categories: sweep methods (Fig. 2c, middle panel left), wherein the potential at the working electrode is changed continuously throughout the measurement; and chronoamperometric methods, wherein the working electrode is held at a fixed potential sufficient to induce an analyte-specific redox transition in the sample[114].

Although numerous sweep methods have been explored (linear sweep, staircase, differential pulse and alternating current methods), cyclic voltammetry remains the most widely implemented owing to its versatility and reliability[115]. Cyclic voltammetry measurements are accomplished by repeatedly sweeping the working electrode voltage between an upper and lower switching potential at a constant rate (volts per second). The peak current (oxidative or reductive) drawn by the working electrode can then be used to determine the concentration of redox active species using the Randles–Sevcik relation (Fig. 2c, middle panel upper right). This approach has been used extensively for the detection of redox-active environmental pollutants, including catecholamines, pesticides and textile dyes, at micromolar concentrations[116]. It has also been used to detect Hg (refs. 117,118), Pb (ref. 119), Cu (ref. 120) and phosphate[121] in water and/or soil samples.

In addition to potential sweep methods, static polarization methods are also common. These chronoamperometric measurements apply a time invariant potential to the working electrode to oxidize or reduce species of interest. During active polarization, the current developed at the working electrode obeys a Cottrellian profile (Fig. 2c, middle panel upper right) with its magnitude depending on the concentration and diffusion coefficient of the redox-active species. Measurements of this type have proven successful at elucidating the concentrations of redox-active pesticides and herbicides[122,123], as well as of pharmaceuticals[124].

Furthermore, when the electrode is modified with an appropriate enzyme or catalyst, static polarization measurements can yield results similar to colorimetric detection, albeit with much higher sensitivity[125]. Naturally occurring enzymes have been used in the amperometric detection of pesticides, pharmaceuticals, heavy metals and hormones[126,127]. For species without naturally occurring enzymes, engineered biomolecules with enzymatic functions may offer similar detection capabilities. In this regard, artificial enzymes and DNAzymes[128] can enable electrochemical detection of biologically inaccessible targets. Beyond biological agents, electrodes modified with inorganic catalysts including metals, organometallic species and nanozymes can be used to measure dissolved oxygen and nitrogen species as well as pesticides, heavy metals and halogenated compounds[97].

Although amperometric biosensing can exhibit greater sensitivities than those achievable with potentiometric or colorimetric methods, it is typically limited to the detection of species in the micromolar regime. To achieve even higher sensitivities, electrochemical methods relying on electrode impedance have been explored. Sensors relying on electrochemical impedance spectroscopy (Fig. 2c, right) probe the interfacial properties (resistive and capacitive) of the working electrode through the application of a small amplitude (~10 mV) sinusoidal voltage waveform over a range of frequencies ($10^{-2}$–$10^{6}$ Hz)[114]. The resulting current is highly sensitive to changes in both the capacitance and charge transfer dynamics of the interface. This sensitivity is exploited by decorating the electrode surface with a biorecognition element (antibody[129], aptamer[130], nanobody[131], DNA or RNA[132] and imprinted polymer[133]) whose confirmational changes during analyte binding alter electron transfer at the working electrode[134]. Sensitivity to these subtle interfacial changes gives electrochemical impedance spectroscopy-based methods exceptionally low LODs ($10^{-12}$–$10^{-16}$ M) and allows them to detect trace chemical species including pesticides[133], antibiotics[130], bacterial contamination[129,132], PFAS[135], microplastics[136] and endocrine disruptors[137].

Regardless of the application, the choice of biorecognition element is non-trivial. Natural biomolecules have been extensively studied as binding agents to capture nearby analyte. Native protein species such as antibodies represent the most heavily investigated class of recognition element, having proven capable of quantifying bacterial contamination[129], bisphenol A[138], oestradiol[139] and mycotoxins[140], among others. More recent work aims to increase the catalogue of biomolecules accessible to impedance-based sensing through engineered biorecognition elements.

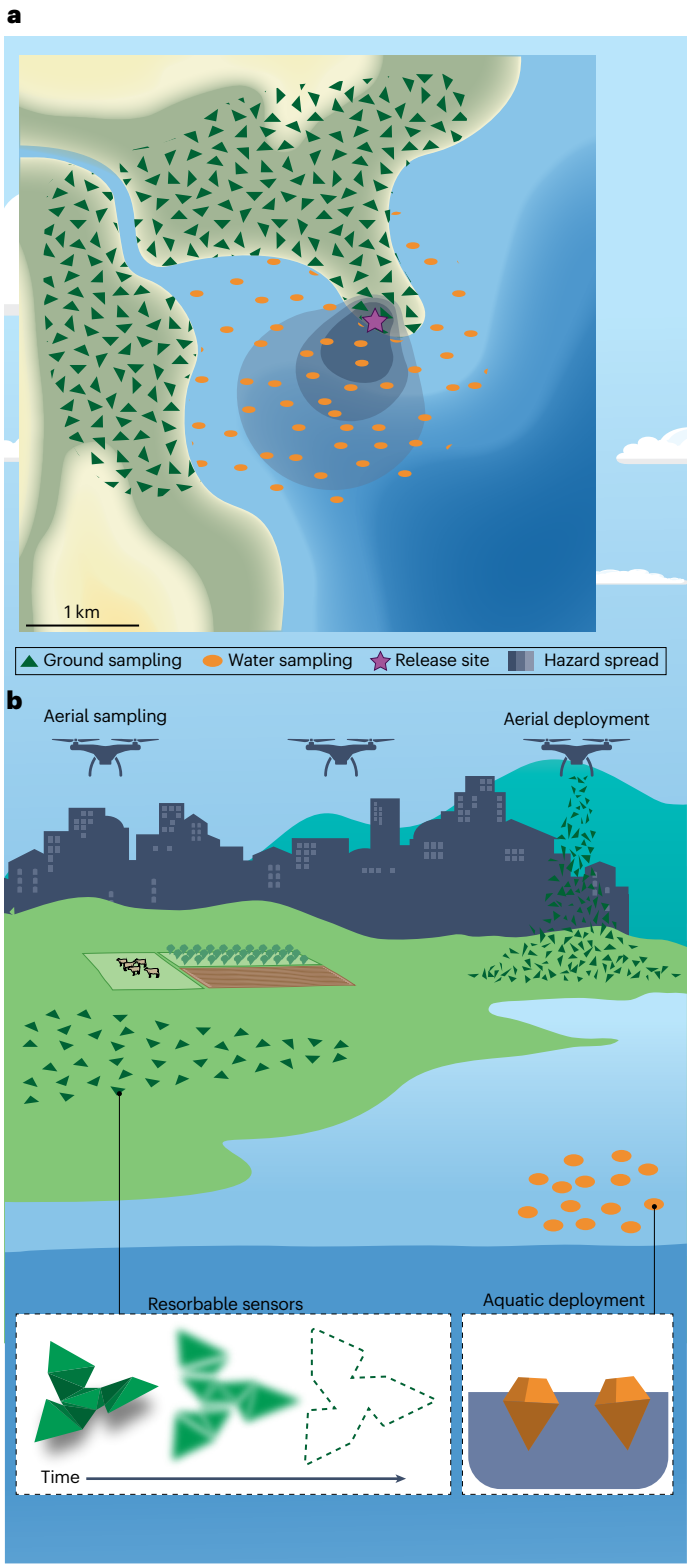
Synthetic peptides and nanobodies are exciting as alternatives to naturally occurring antibodies as they offer synthetic control over the binding affinity of target analytes and might provide higher chemical and/or physical stability than their naturally occurring counterparts[141]. Sensors that leverage these elements are promising for the detection of microalgae[131] and pesticides[142,143]. Nucleic-acid-based sensing elements (aptamers) have also been used for the detection of bacterial species[132], heavy metals[144], bisphenol A[145] and endocrine disruptors[146].

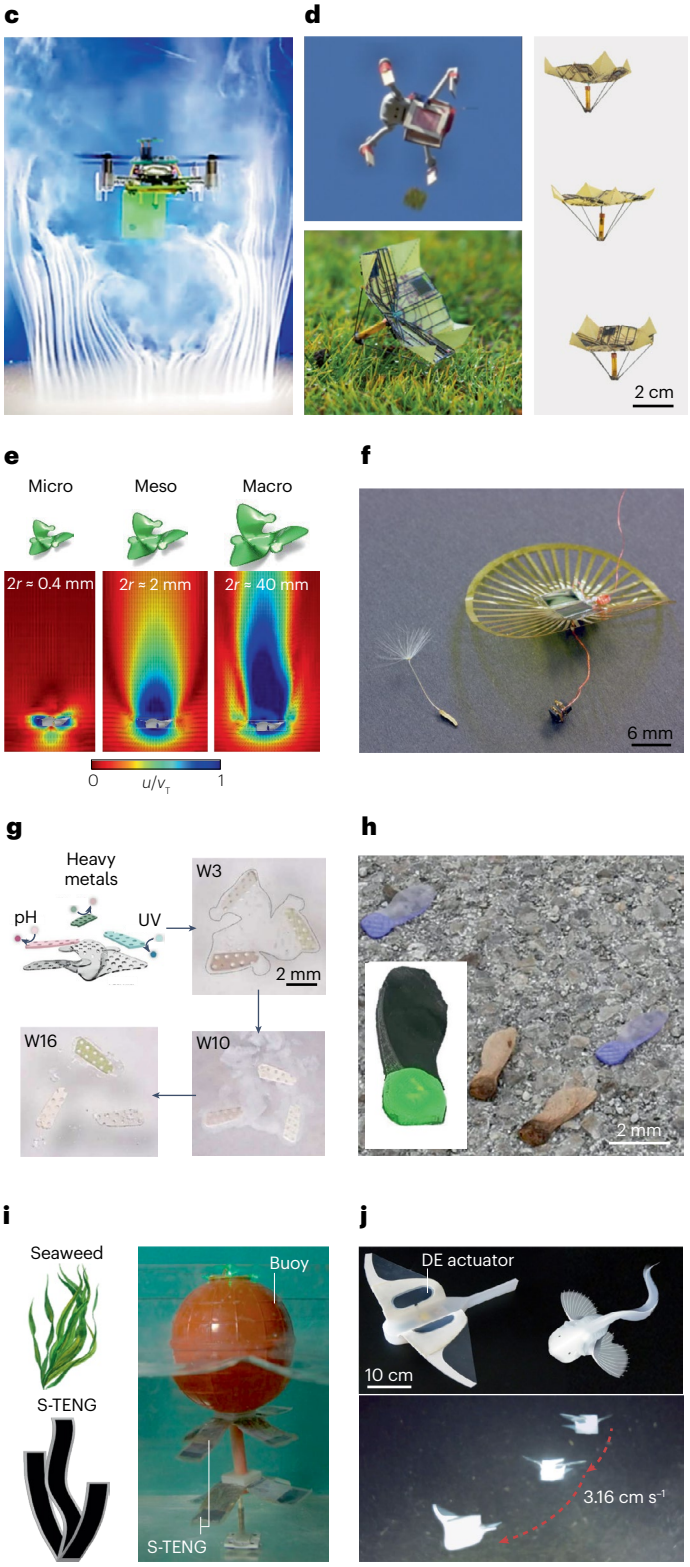
In addition to biomolecular recognition elements, purely synthetic recognition elements based on molecularly imprinted polymers have also been investigated. In this approach, electrode surfaces are modified (often by electrodeposition) with a selectively porous polymer layer. The pore size of the recognition layer is engineered to accommodate the binding of the exogenous analyte, resulting in changes in electron transfer within the polymer transducing film. Molecularly imprinted polymer-based sensors have been used for the detection of pesticides[133,147], sulfonamides[148] and biocides[149] in soil and water samples.

In many of these examples (particularly those relying on potentiometric detection), long-term drift represents an important issue that must be overcome to realize stable and reliable environmental profiling. Changes at electrode surfaces brought about by the adsorption of foreign species (referred to herein as fouling) can substantially alter the signals obtained from both working and reference electrodes[150]. These changes often limit the usable lifetime of these sensors to a few days at the most. Despite these challenges, recent work has improved the longevity and reliability of electrochemical platforms by adding protective coatings to mitigate fouling[150] and by using assemblies of multiple identical sensors to elucidate fouling effects and recover true signals[151,152].

### Particle counting, resistive and capacitive sensing

In addition to spectroscopic, colorimetric and electrochemical approaches, analytical methods leveraging optical, resistive and capacitive transduction mechanisms have proven suitable for widespread deployment in distributed networks of devices. One impressive example is the air quality monitors used in the detection of particulate organic materials by particle counting[153]. These sensors, often




consisting of a laser light source and photodiode to quantify scattered light (Fig. 2d), have been widely deployed to provide vital information on air pollution, particularly in urban settings[154]. To compliment these fixed installations, miniaturized sensors leveraging alternative sensing methods, including gravimetry[155] and capacitive detection[156,157], have been explored.

**Fig. 3 | Sampling and deployment strategies. a**, Map depicting the hypothetical spread of a hazard to nearby environments following release and illustrating the broad distribution of networked sensors to track the evolution of hazard distribution. **b**, Illustration of emerging strategies for dispersion and sampling. **c**, Drone-based sampling of air quality with a metal oxide gas sensor[177]. **d**, Release, descent and landing of solar-powered shape-changing origami microfliers[200]. **e**, Numerical simulation of the air velocity fields associated with 3D microfliers, mesofliers and macrofliers inspired by wind-dispersed seeds[183]. **f**, A battery-free wireless electronic flier capable of wind dispersal and, for comparison, a dandelion seed[196]. **g**, Biodegradation of a 3D flier and its embedded colorimetric sensors after 3, 10 and 16 weeks[186]. **h**, A printed luminescent flier inspired by plant seeds for physical sensing (inset shows temperature-responsive photoluminescence)[192]. **i**, Flexible seaweed-like triboelectric nanogenerator (S-TENG) as a wave energy harvester[262]. **j**, Self-powered soft robot driven by a dielectric elastomeric actuator for exploration of the Mariana Trench[223]. 2*r*, flier diameter; DE, dielectric elastomer; $v_T$, terminal velocity. Part **c** reprinted from ref. 177, CC BY 4.0. Part **d** reprinted with permission from ref. 200, AAAS. Part **e** adapted from ref. 183, Springer Nature Limited. Part **f** reprinted from ref. 196, Springer Nature Limited. Part **g** adapted with permission from ref. 186, AAAS. Part **h** adapted from ref. 192, CC BY 4.0. Part **i** reprinted with permission from ref. 262, ACS. Part **j** adapted from ref. 223., Springer Nature Limited.

Beyond optical methods, sensors leveraging changes to a transducer's resistance or capacitance have long been used to profile environmental characteristics. Resistive temperature sensors represent one of the most common examples, relying on the controlled thermoresistive properties of conductors (often carbonaceous materials or metals) (Fig. 2e, left), to quantify local temperature changes[158,159]. The chemoresistive behaviours of certain materials can also be used to quantify gas composition. Resistive gas sensors, often consisting of an interdigitated electrode array surmounted by an appropriate sensing material (Fig. 2e, right), are capable of selective gas detection with high sensitivity. Sensing materials range from polymers[160] to inorganic oxides[161] to metal organic frameworks[162] depending on the target analyte. The same geometry can also be used for the capacitive detection of gaseous species, exploiting the change in dielectric permittivity of sensing materials upon interaction with the target gas[163]. Together, resistive and capacitive sensors have found use in myriad applications including spatial profiling of microclimates[164], characterization of pollutant gradients generated by industry[165] and contaminant detection in urban environments[166].

### Biological sensing

Analytical approaches that exploit living biological organisms to detect chemical, physical and biological hazards have also been developed[167,168] and deployed to study water and soil quality[169,170]. These biological sensors rely on the health of living cell lines to report on the quality of the environment to which they are exposed. Signal transduction is thus a direct function of biological activity. The most common sensor configuration operates by confining an electroactive microorganism to an electrode surface such that the metabolic by-products generated by cellular respiration can be continuously monitored. When exposed to non-hazardous conditions, cells continuously generate these metabolism-dependent by-products. Upon the introduction of biologically hazardous agents or conditions, cell lines suffer a reduction or total loss in their metabolic efficacy (Fig. 2f). In addition, ongoing work aims to improve the stability of immobilized cell lines and to broaden the range of analytes accessible to these sensors[171].

## Device delivery, power and communication

Considering the potentially large number of individual sensors, the broad areas affected during hazard release (Fig. 3a) and the extended recording durations necessary to collect critical environmental information, the delivery mechanisms, power architectures and communication protocols applied to networked sensors are critical considerations for device form and function. Although technologies exist to accommodate device automation, power and communication, the vast distances (kilometres) and long-time scales (months or years) relevant to environmental phenomena generally necessitate larger device footprints, masses and costs challenging scalability and environmental compatibility. Similarly, although myriad approaches have been explored for device distribution and motility, active mechanisms (motor-driven or actuator-driven locomotion) demand larger on-board power circuitry than passive elements (fliers, gliders, drifters and so on). These aspects of device construction are crucial to deploy sensing systems to disparate areas without loss of communication or device function.

### Aerial delivery and dispersion

Unmanned aerial vehicles (UAVs) have emerged as powerful tools for environmental and agricultural applications, as they can cover large distances providing access to areas that would prove challenging for manual field sampling. With remote-sensing capabilities[172,173], UAVs have been widely explored for applications including agricultural growth monitoring[174] and forest fire surveillance[175]. They can also carry chemical sensors, making them useful for precise spatial mapping of atmospheric gas concentrations[176,177]. Despite these capabilities, take-off and landing are energy-intensive and typically require user intervention, limiting the utility of UAVs for direct-contact sensing in remote or complex terrain (Fig. 3b–d).

To overcome these limitations, alternative field deployment strategies have emerged. Nature establishes a sophisticated set of design principles for aerial dispersal, evolved to passively transport seeds across great distances under the driving force of wind[178,179]. Two different seed behaviours are common: gliding or rotating with wing-shaped appendages and floating with plume-based structures[180]. In the case of winged seeds such as maple seeds, leading edge vortices generated during autorotation allow slow descent times with comparatively heavy payloads[181]. Plumed seeds such as dandelion seeds rely on drag-enhancing mechanisms such as a separated vortex ring, which are effective even at low release heights from short plants[182].

These design principles have been applied to artificial 3D microstructures, mesostructures and macrostructures, enabling passive flight when released aerially[183] (Fig. 3e). The aerodynamic profile of these structures arises from the compressive mechanical buckling of planar precursors[184,185], which are composed of polymeric substrates patterned through laser etching and photolithography. The addition of conductive traces and integrated circuits to microfliers imparts electronic functionality necessary for data acquisition, storage and communication. Furthermore, modifications to flier geometry provide control over device dispersal and transport, enabling additional environmental characterization methods based on flier travel distance.

Regarding device geometry, both wing-based[183,186–195] and plume-based[196–199] (Fig. 3f) designs have been demonstrated. The

**Table 1 | Materials enabling autonomous mechanical actuation in distributed microfliers**

| Material | Driving force | Refs. |
|---|---|---|
| Liquid crystals | Light | 195,197 |
| Graphene–agar–silk fibroin | Light | 190 |
| MXene–polyethylene | Light | 198 |
| PNIPAM–carbon nanotubes | Light | 187 |
| Polyethylene–gold nanorods | Light | 199 |
| Superhydrophobic aluminium | Rain impact | 194 |
| Polyimide origami structure | Light | 200 |

PNIPAM, poly(*N*-isopropylacrylamide).

selection of an appropriate flier design is constrained by several considerations including the desired dispersal distance, payload capacity and sensor robustness. Although low terminal velocities ($V_T \approx 1\ m\ s^{-1}$) are achievable for both plume-based[196] and wing-based[183,186] fliers, plume-based assemblies are more susceptible to wind transport, making them potentially useful in sensor dispersal over large (~100 m) distances[196,200]. As a trade-off for their high dispersibility, plume-based fliers are generally more fragile than wing-based assemblies owing to the filamentary structures used to increase drag[195]. This design choice limits their robustness, reusability and payload capacity, making autorotating or gliding fliers potentially beneficial in dispersing heavier payloads in adverse conditions. Regardless of the choice of assembly, however, fliers are inherently limited by the lack of precise control over their ultimate location.

A range of sensing modalities have been deployed on passive fliers such as integrated circuits for physical sensing of humidity, temperature, atmospheric pressure, UV exposure and soil moisture[189,196]. These integrated circuit-based sensing systems also accommodate data transmission to proximal recording installations using near-field communication (range ~ 10 cm)[183], Bluetooth (range ~ 10 m)[200] or radiofrequency backscatter (range ~ 1 km)[196]. Similarly, integrated circuit-based platforms could potentially support chemical sensing based on electrochemical and spectroscopic measurements, increasing the analytical capabilities of these devices[201]. Fliers can also carry colorimetric sensors for pH[183], heavy metals[186], air pollutants[202], temperature[192] and humidity[193] (Fig. 3g,h) and can be constructed from fully ecoresorbable materials[186].

Beyond purely passive devices, functional materials have enabled responsive actuation in aerial fliers[203]. Structural composites constructed from natural materials, synthetic polymers, liquid crystals and nanomaterials have been explored leveraging light, humidity, mechanical force and wind to induce device actuation (Table 1). Although not necessarily biodegradable, these materials support greater control over device deployment and environmental responsiveness. Even more precise control over seed delivery can be achieved with UAVs[174] including a recent example with self-burying, wood-based carriers for aerial seeding[204].

Driven by advances in robotics, other delivery strategies are being explored for applications in which UAVs are not well suited. For example, miniature fliers capable of powered flight might provide additional control over sensor dispersal[205,206]. Miniaturization of electronic systems has even enabled the development of 'living robots'[207], in which the electronics is combined, for example, with living systems such as beetles, moths or fish[208,209] for the transport of networked, sensorized payloads. Small-scale terrestrial robots that use soft and flexible functional materials for actuation have been shown to successfully navigate complex terrains[210–212]. Deployed in a distributed manner on a large scale, these living-based and soft materials-based robots have the potential to reach locations that would otherwise be thoroughly inaccessible.

## Aquatic delivery and dispersion

Along with microflier-based sensing for soil, parallel efforts aim to provide similar functionality in aquatic environments. Many pollutants — although originating in either soil or water — ultimately affect the ecosystems of both[213–215], making the detailed analysis of seas, rivers, lakes and other bodies of water essential. To assess water quality, the Marine Strategy Framework Directive sets out descriptors of good environmental status, which include biological diversity, seafloor integrity, contaminant concentration and underwater noise[216]. Quantifying these features (and their freshwater analogues) calls for new detection principles that autonomous systems are well suited to address.

Although similar sensing goals exist across air and water, aquatic environments present distinct challenges. Autonomous underwater vehicles (AUVs)[217] and unmanned surface vehicles (USVs)[218] operate under a different set of constraints. For example, spatial scales in a marine environment are much larger, making power and communication requirements more demanding. At the same time, natural buoyancy allows efficient movements of comparatively large robotic units (Fig. 3i). For environmental monitoring, these considerations have led to strategies including propeller-driven vehicles, underwater gliders and seafloor crawlers[219]. However, these systems often incorporate rigid mechanical elements, which can limit their performance in challenging environments[220], such as turbulent surface waters[221].

This limitation has motivated the integration of soft, compliant materials[222]. Aquatic robots encapsulated with stretchable materials can absorb much more energy from collisions than those constructed entirely from rigid elements. Furthermore, soft materials leveraging dielectric elastomers[223], hydrogels[224], ionic polymer–metal composites[225], liquid crystal polymers[226], shape-memory polymers[227], magnetic composites[228] and even living tissue[229] have been explored for actuation and motility. These materials enable electrostatic and electro-osmotic mechanisms that can outperform conventional electromagnetic actuators. For example, hydraulically amplified electrostatic actuators offer high energy density and muscle-like performance[230,231], whereas hydrogel turgor actuators, although slower, can generate huge swelling pressures[232]. Pneumatic[233] and hydraulic systems[234,235] can also transmit mechanical power through networks of soft compartments, even using combustion to generate thrust[236]. Finally, as in aerial dispersion, passive gliders can be constructed for aquatic deployment by leveraging hydrodynamic phenomena[237].

Current applications of AUVs include monitoring geological and ecological features, as well as assessing the impact of human activity on marine systems. Acoustic and visual sensing modalities are useful for studying submarine volcanic activity, mapping benthic habitats, evaluating seafloor morphological features and surveying areas for placement of subsea infrastructure. Sensors for temperature[238], chemical composition[239] and hydrodynamic properties[240] of water are also commonly used to quantify the effect of human disturbances, such as those brought about by oil and gas industry operations[217]. Flexible sensors inspired by seal whiskers provide new mechanisms for detecting waterborne vortices[241], and biohybrid systems using *Escherichia coli* as a sensing layer offer new opportunities for aquatic chemical detection[224].

Although these technologies cannot be easily distributed at large scale similar to their terrestrial counterparts, they help in extending distributed sensing into aquatic environments. Continued advances

in soft materials and biohybrid systems may eventually enable more scalable, environmentally compatible underwater sensor networks.

### Wireless networks of environmental sensors and actuators

Wireless sensor networks are decentralized systems established to monitor physical conditions over a conceptual region. They have been developed to serve a broad range of applications[242], including medical sensing, industrial compliance, supply chain oversight and environmental monitoring[243,244]. These networks are built on common communication protocols — many of which can be found in modern smartphones — to transmit data across varying distances (Fig. 4). Near-field communication operates at distances of <10 cm and is useful for interacting with passive, unpowered devices. Personal area networks, including Thread, Zigbee and Bluetooth Low-Energy, are designed to interconnect devices within 1–100 m. Wide-area networks, such as SigFox and LoRa, extend beyond 1 km. Meanwhile, cellular networks (such as LTE-M and NB-IoT) offer direct internet connectivity without a dedicated gateway or router. Finally, in regions without terrestrial telecommunications coverage, satellite networks can be used. Aerially dispersed fliers have previously utilized approaches such as Bluetooth[188,189,200], radiofrequency backscatter[196] and near-field communication[183] (Fig. 4b).

Compared with aerial and terrestrial systems, AUVs and USVs face important challenges in communicating with remote operators and observers[245]. Various communication methods — acoustic[246], optical[247] and electromagnetic[248,249] — have been used in underwater environments, each offering different advantages. For instance, electromagnetic communications such as Bluetooth[208,209,235] and Zigbee[250] have been demonstrated in soft underwater devices. Similarly, acoustic communications have been implemented in a soft robotic fish[234]. In addition to communication, GPS-integrated circuits could be used to facilitate, or even automate, collection and disposal of distributed sensing elements after a predetermined operating period[251].

### Powering distributed networks

New strategies for dispersing sensor networks introduce new challenges for maintaining persistent remote operation. In systems using passive fliers, sensor data can be retrieved manually using colorimetry or near-field communications[183,186,202]. However, for applications requiring powered movement or capabilities for wireless communication over large distances, onboard energy sources are essential. Rechargeable batteries are commonly used[189,207,223,234], and supercapacitors — allowing faster charging and recharging — can also be used. Alternatively, power can be generated in situ[252]. Photovoltaics is widely utilized to power Internet-of-Things systems[253], including passive flier devices[196,200]. Meanwhile, soil microbial fuel cells[254–256] and small-scale thermoelectric generators[257,258] are promising for low-light environments. These developments have enabled new power cells capable of supporting environmental monitoring tasks — such as detecting soil moisture[254], heavy metals[256] and atmospheric conditions[257] — while also powering wireless protocols such as LoRa[258] and Bluetooth[255]. Thermoelectric generators are particularly effective when a large temperature gradient is present, whereas microbial fuel cells offer stable power outputs when optimal soil conditions (pH, moisture, nutrient presence and microbial composition) are met.

In aquatic environments, kinetic energy can be harvested from waves and currents. Traditional electromagnetic generators, such as tidal turbines, have been successfully applied for decades. Building on these principles, newer systems have adapted similar principles for use in AUVs, USVs, drifters and buoys[259]. Recent approaches have expanded the range of materials and mechanisms used for energy harvesting, leveraging piezoelectric materials[260], ionic polymer–metal composites[261], triboelectric nanogenerators[262,263] (Fig. 3i) or dielectric elastomeric generators[223,264] (Fig. 3j). Kinetic energy harvesters have demonstrated the ability to power various sensors, enabling the monitoring of wave dynamics[240], water quality[265], electrolyte concentration[239] and temperature[238]. They have also demonstrated capabilities for powering acoustic[266] and radiofrequency[267] communications. To enhance system stability, multiple harvesting modalities can be integrated on one system[268,269].

## Environmentally degradable materials and platforms

Sensors that can controllably degrade in an environmentally benign manner are particularly well suited for monitoring tasks that demand the evaluation of large or inaccessible environments, as well as those where considerable hazards impede direct operator involvement. In these instances, transient sensors deployed to evaluate ecosystem health offer distinct advantages over conventional methods in alleviating the need for device recovery following measurement. Rather, these systems use degradable materials to assemble functional devices that slowly dissolve after a predetermined operating duration.

### Materials considerations

Despite the utility of current automated sensing systems, operator intervention is typically required to retrieve recording apparatus following a period of use. This necessity places a burden on researchers and poses some risk to the environment if recording equipment becomes inaccessible. To address some of these concerns, functional electronic materials (insulators, semiconductors and conductors) capable of timed dissolution in aqueous media are being explored[270] (Table 2). The use of these bioresorbable and ecoresorbable materials is attractive for short-term to medium-term chemical and physical sensing as no waste is left after deterministic disintegration. Such sensing devices would contain conductive traces, semiconducting elements and an insulating encapsulant capable of full dissolution after a predetermined duration (Fig. 5a). Most transient materials rely on oxidation and hydrolysis to affect bulk structural disintegration, with three factors constraining material selection: materials must contain chemical linkages amenable to oxidative or hydrolytic cleavage, the fragments of this process must be environmentally benign and the rate of decomposition must be sufficiently low to accommodate device function for a known and controllable recording duration.

**Substrates and encapsulation.** A broad range of substrate and encapsulating materials have been explored to support or insulate the functional electronic components comprising transient devices. These materials are broadly separable into organic and inorganic categories based on their composition. Inorganic materials, commonly metals, metalloids and their oxides and nitrides, accommodate resorption through the slow oxidation and hydrolytic cleavage of M–M, M–O–M and M–N–M bonds to M–OH. This bond cleavage is followed by dissolution of the resulting inorganic hydroxide[271]. Silicon[272] and its oxides ($SiO_x$)[273] and nitrides ($Si_3N_4$)[274] are the most commonly used materials for inorganic substrates and encapsulants owing to the extensive microelectronics infrastructure devoted to Si processing. Beyond Si, MgO dielectrics have also been explored to serve as encapsulating materials, albeit they have much faster dissolution kinetics[275]. Although these materials have been successfully integrated into functional transient devices, they often suffer stability limitations owing to cracking, pitting and/or delamination of the brittle inorganic film. Furthermore, the dissolution

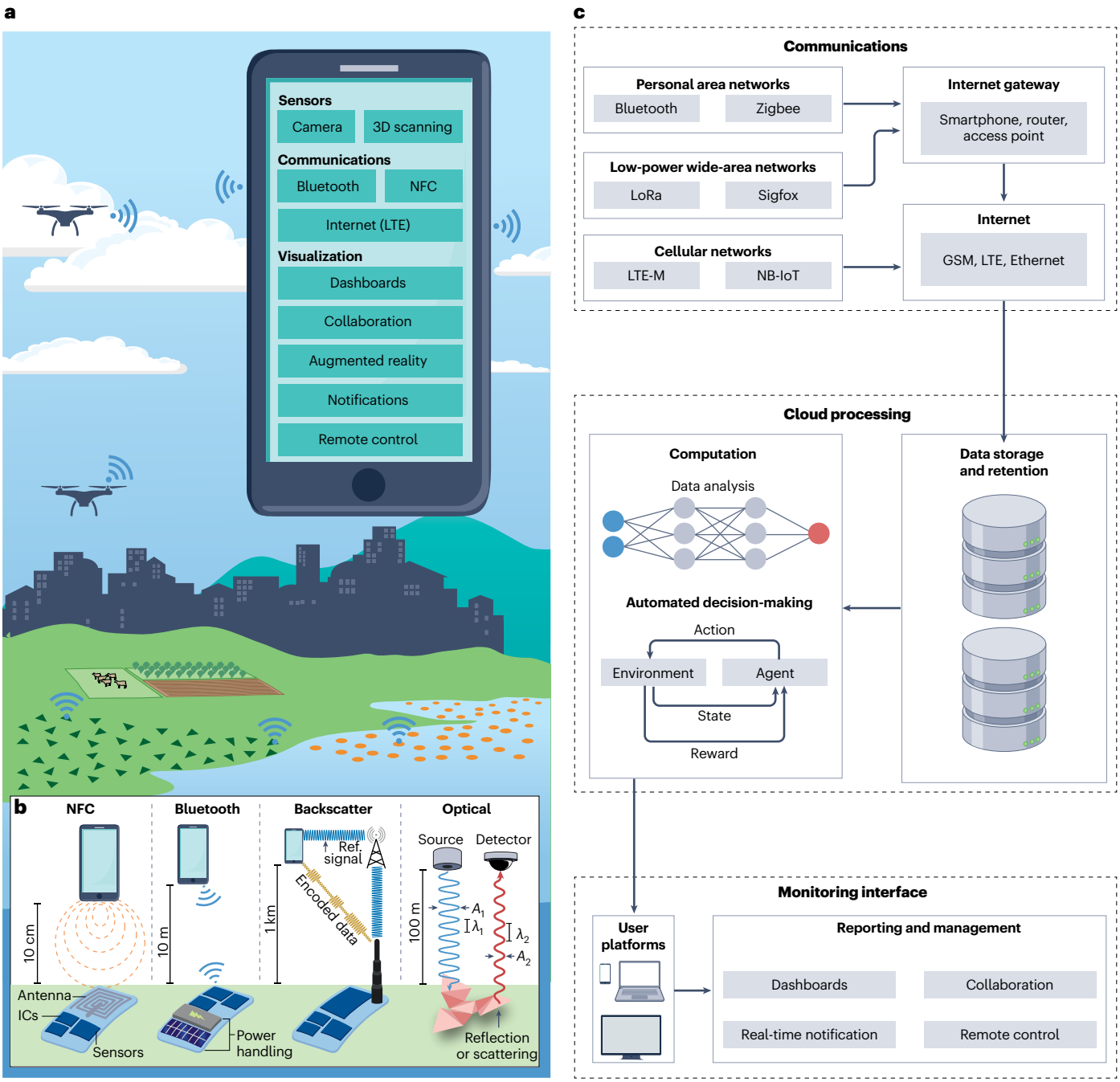



**Fig. 4 | Communication networks and data processing. a**, Environmental monitoring systems linked by Internet-of-Things. Illustration of networked sensors and the use of a smartphone as a gateway to cloud services. **b**, Common communication protocols along with the distances over which they operate. **c**, Block diagram showing how the distributed sensors integrate their information through cloud services, allowing analysis, visualization and control through common user platforms. IC, integrated circuit.

kinetics of inorganic barrier films varies widely depending on the deposition method, film density and film stoichiometry[270].

To address these concerns, mechanically compliant organic macromolecules have been explored as alternatives to inorganic encapsulating films. Polymers, obtained either synthetically or from natural products, offer greater flexibility, solution processability and structural versatility than their inorganic counterparts. They can also accommodate more precise control of hydrolytic decomposition. Natural materials such as cellulose[276,277], silk[278], waxes[279], shellac[280,281] and polysaccharides[282,283] have proven successful as barrier polymers for short-term (hours to days)

stimulating and recording devices. In these examples, complete transience is mediated by the solubilization of individual polymer chains, followed by slow enzymatic degradation. Similar behaviours have been obtained from synthetic polymers. Polymer chains containing ester[284,285], ether[286], alcohol[287], amide[288] and anhydride[289] subunits demonstrate controlled dissolution under aqueous action (Fig. 5b,c).

Regardless of material, the functional lifetimes of encapsulating films dictate the overall lifetime of devices assembled from them. Given the extended recording durations (weeks to months) necessary for comprehensive environmental characterization, the dissolution rates of existing degradable encapsulants are often insufficient to guarantee device function for the entire recording period. To address this challenge, synthetic modifications to the primary and secondary structures of polymeric encapsulants have been explored to directly control the dissolution rate[289], accommodating device function over the span of weeks to months[290]. Furthermore, polymer composites assembled with inorganic fillers ($SiO_2$ beads, $SiO_2$ flakes and ZnO beads) can extend device lifetimes by increasing the hydrophobicity of the encapsulant and by suppressing water diffusion through the barrier film[291,292].

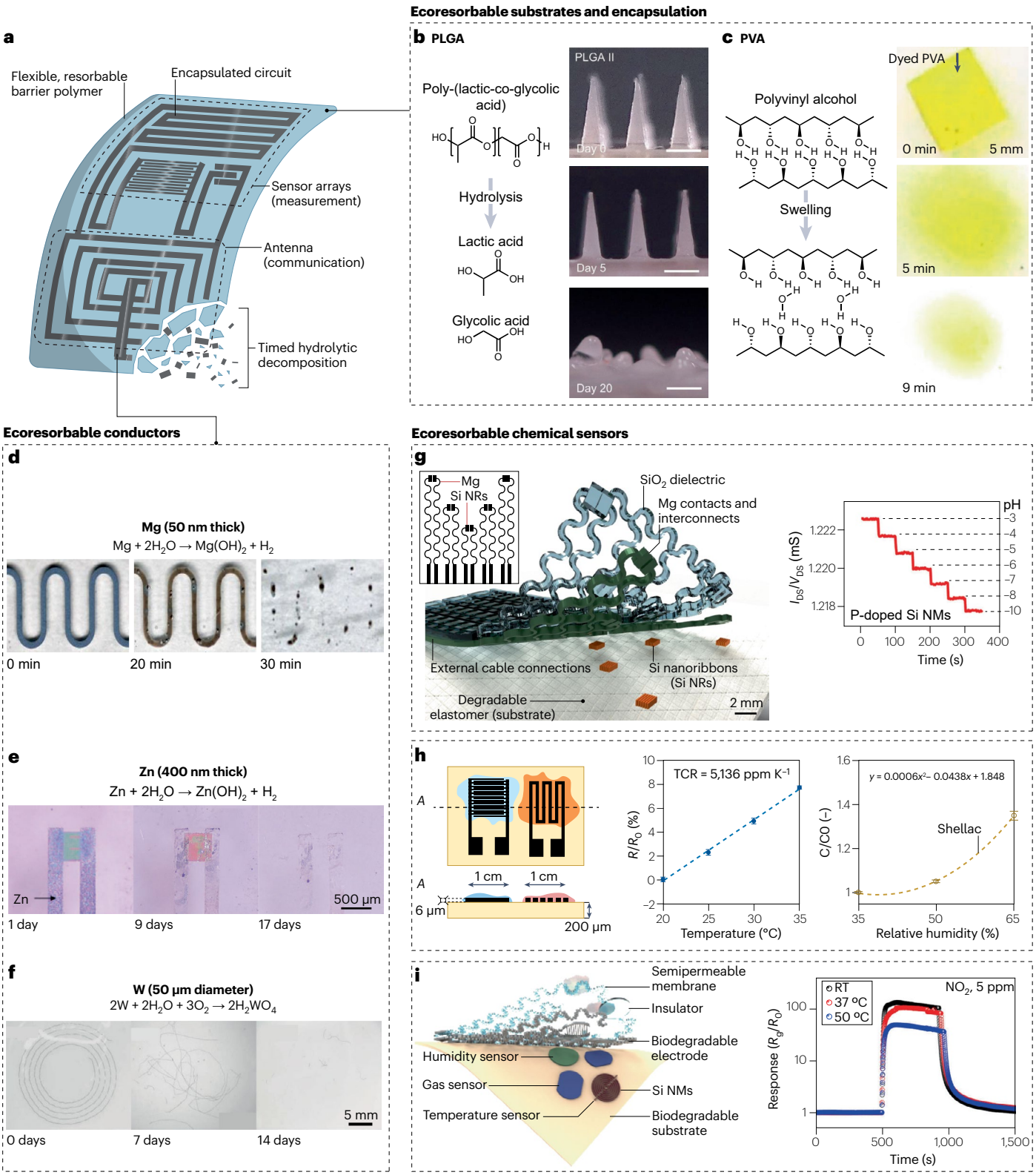
Beyond extending the lifetime of encapsulants, the on-demand degradation of these materials under specific stimuli, such as temperature[293] or light[294,295], has also been demonstrated. These approaches offer greater control over degradation kinetics and may accommodate encapsulation with extremely long-lived materials whose decomposition is induced only under certain predetermined conditions.

**Conductors and semiconductors.** Similar to their oxides, many metals support resorption through oxidation and subsequent hydrolysis by air and water[271]. Oxo-philic metals (Zn, Mg and Al) are the most active in this regard, exhibiting rapid degradation in water[271,296,297] (Fig. 5d,e). Other metals and alloys have been explored to extend the lifetime of transient conductors, although the toxicity of the resulting oxidized metal species needs to be carefully considered. Alloys of Mg, Zn and Al exhibit enhanced lifetimes relative to their individual constituents when immersed in biofluid[298,299]. Similarly, Fe, W and Mo have shown prolonged operational lifetimes relative to Mg and Zn (Fig. 5f), with the resulting transition metal ions proving environmentally and physiologically benign[300–302]. This collection of metals canvases a large range

**Table 2 | Overview of biodegradable electronic materials supporting transient sensing platforms**

| Function | Material class | Examples | Dissolution rate (sensor lifetime) | Conditions | Degradation mechanism | Ref. |
|---|---|---|---|---|---|---|
| Encapsulation and insulation | Metals and metal oxides | Si | 4.8 nm per day | PBS, 37 °C | Oxidation and hydrolysis | 272 |
| | | $SiO_x$ | 0.005–10 nm per day | PBS, 37 °C | | 273 |
| | | $Si_3N_4$ | 1–5 nm per day | PBS, 37 °C | | 274 |
| | | MgO | 6.3 µm per day | DI water | | 275 |
| | Natural polymers | Cellulose | 58 days | Soil | Dissolution, enzymatic decomposition, hydrolysis and/or direct oxidation | 277 |
| | | Silk | 10 min | DI water | | 278 |
| | | Wax | 10–100 days | Soil | | 279 |
| | | Shellac | 10–50 days | Soil | | 281 |
| | | Polysaccharides | ~10 min | PBS, RT | | 310 |
| | Synthetic polymers | Polyesters | 7 weeks | PBS, 37 °C | Hydrolytic cleavage, oxidation | 365 |
| | | Polyethers | 30 days | – | | 365 |
| | | Poly-ols | 20 min | PBS, 37 °C | | 287 |
| | | Amides | 10–100 days | Seawater | | 366 |
| | | Polyanhydrides | 1–5 days | PBS, 37 °C | | 289 |
| Conductors | Metals | Mg | 480 nm per day | HBSS, 37 °C | Oxidation and subsequent hydrolysis | 271 |
| | | Zn | 300 nm per day | HBSS, 37 °C | | 271 |
| | | Fe | 7 nm per day | HBSS, 37 °C | | 367 |
| | | Mo | 0.7 nm per day | HBSS, 37 °C | | 367 |
| | | W | 20 nm per day | HBSS, 37 °C | | 367 |
| | Organic | PEDOT:PSS | 4 weeks | Protease solution[a] | Oxidative cleavage, enzymatic decomposition | 368 |
| | | Polyaniline | 7–14 days | PBS, 37 °C | | 369 |
| | | Polypyrrole | 24 h | pH 8.2 | | 370 |
| | Carbon-based | Activated carbon, carbon nanotubes, graphene | – | – | Biocompatible but not degradable | 312 |
| Semiconductors | Metalloids | Si | 4.8 nm per day | PBS, 37 °C | Oxidation and hydrolysis | 272 |
| | | Ge | ~3 nm per day | PBS, 37 °C | | 371 |
| | Metal oxide | ZnO | 4 nm per day | PBS, 37 °C | Oxidation and hydrolysis | 372 |
| | | MgO | 6.3 µm per day | DI water | | 275 |
| | Dichalcogenides | $MoS_2$ | ~75 days | PBS, 37 °C | Oxidation and hydrolysis | 373 |
| | | $WS_2$ | – | – | | 374 |

DI, deionized; HBSS, Hanks' balanced salt solution; PBS, phosphate-buffered saline; RT, room temperature. [a]Protease solution: 1 U $mg^{-1}$ protease XIV from *Streptomyces griseus*[368].




of timescales for bioresorption or ecoresorption, accommodating the fabrication of recording devices that can dissolve within minutes to weeks.

Similar approaches have been taken to assemble transient semiconducting structures, typically relying on Si thin films as the base material. A wide variety of electronic components can be realized in transient

**Fig. 5 | Designs and materials for bioresorbable environmental sensors.** **a**, Schematics of a transient environmental sensing platform, highlighting key components of the assembly and its eventual hydrolytic decomposition. **b**,**c**, Dissolution patterns of insulating materials used for encapsulation. **b**, Poly-(lactic co-glycolic acid) (PLGA) (65:35, $M_w$ = 60,000; 37 °C in phosphate-buffered saline)[285]. **c**, Polyvinyl alcohol (PVA) (200 µm thick, $M_w$ = 31,000; 37 °C in phosphate-buffered saline)[287]. **d**–**f**, Dissolution patterns of electrically conductive materials. **d**, Mg (50 nm thick; in phosphate-buffered saline at room temperature (RT))[296]. **e**, Zn (400 nm thick; 37 °C in phosphate-buffered saline)[297]. **f**, W (50 µm diameter wire)[302]. **g**–**i**, Examples of ecoresorbable chemical sensors. **g**, Left: exploded view of a doped silicon nanoribbon (Si NR) pH sensor. Right: measurement of conductance as a function of surrounding pH for P-doped silicon nanoribbons[316]. **h**, Schematic illustration of a resistive temperature sensor and capacitive humidity sensor constructed from conducting carbon electrodes on a shellac substrate(left). Resistive temperature coefficient (TCR) of the temperature sensor (middle). Capacitive response of the humidity sensor[317] (right). **i**, Exploded view of a silicon nanomembrane (Si NM) $NO_x$ sensor with integrated gas, temperature and humidity sensor on a PLGA substrate (left). Resistive response of $NO_2$ (ref. 318) (right). Part **b** adapted with permission from ref. 285, ACS. Part **c** adapted with permission from ref. 287, ACS. Part **d** adapted with permission from ref. 296, ACS. Part **e** adapted from ref. 297, Springer Nature Limited. Part **f** adapted from ref. 302, CC BY 4.0. Part **g** adapted with permission from ref. 316, ACS. Part **h** adapted from ref. 317, CC BY 4.0. Part **i** adapted with permission from ref. 318, Springer Nature Limited.

forms, including resistors, diodes, transistors and light-emitting diodes[270]. Access to these conventional electronic components in transient devices advances the data acquisition and processing modalities achievable with such recording platforms. Likewise, the incorporation of semiconducting materials such as Ge (ref. 303), ZnO (ref. 304), MgO (ref. 305) and $Si_3N_4$ (ref. 306) presents new prospects for transient, functional systems.

**Material sustainability and cost.** Given the potentially massive scale of sensor fabrication and distribution, the availability and sustainability of component materials become real concerns for system-level implementation. In this regard, materials that can be sourced and processed economically en masse present a distinct advantage. The importance of sustainable device assembly has motivated efforts to establish materials strategies relying on readily available chemical feedstocks with low processing costs.

Sensor assembly from agricultural and natural sources represents a promising approach to sustainable environmental sensing. Advances in paper-based sensors have demonstrated the feasibility of fabricating electrochemical[307] and colorimetric devices[308] from cellulose precursors. Flexible and bioresorbable sensing systems have also been assembled from agricultural by-products such as polysaccharides extracted from starchy crops[309,310]. As with synthetic polymers, polysaccharide degradation kinetics can be controlled by chemically modifying amylose and amylopectin chains[311].

The conductive components of transient sensors are an important source of material cost. In this regard, carbon-based materials present a promising alternative to metals as they can be produced at low cost from diverse precursors[312]. Patterning can also be accommodated by screen or inkjet printing or by direct laser writing[312–314]. Conducting polymer composites have also been explored as conductive materials for sensing systems. Unfortunately, the synthesis and purification of these materials generally impose a substantial cost overhead, reducing their competitiveness compared with carbon-based alternatives[315].

Overall, great progress has been made in the identification of active (conductors and semiconductors) and passive (encapsulants and substrates) materials from which transient assemblies can be fabricated. To date, however, these assemblies still present limitations associated with long-term stability and operational efficacy when compared with their non-transient counterparts. In this regard, the development of transient but long-lived structural components that can guarantee prolonged sensor function represents a prime area for future investigation. Likewise, further research is necessary to tailor active materials (possibly through alloying, doping or synthetic modification) to realize operating characteristics equivalent to those achievable in non-transient electronic assemblies.

## Device-level components

At the device level, sensors and power sources must perform reliably within a required operational lifetime, while still accommodating biodegradable materials.

**Chemical and electronic sensors.** Some examples of functional environmental sensors integrating transient materials include a fully transient sensing array of Si nanoribbon transistors to quantify local pH over several days[316] (Fig. 5g), sensors assembled from serpentine or interdigitated carbon electrodes encapsulated with shellac (Fig. 5h) for week-long temperature or humidity measurements[317], and electrochemical gas-sensing systems for the quantitative detection of atmospheric nitrogen pollutants[318] (Fig. 5i). The efficacy of fully transient sensors for soil health and microbial activity has also been demonstrated[49,319]. Although widespread deployment of these devices is limited at present, the exceptional functionality and controlled lifetime of these recording platforms could prove impactful for the distributed characterization of environmental factors.

**Power sources.** To support untethered operation and eliminate the need for retrieval, sensor platforms rely on onboard power sources that should themselves be biodegradable. Presently, a wide range of solutions exist for creating power units from transient, ecoresorbable materials. Transient batteries[320–322] and supercapacitors[323–325] have been demonstrated, providing a means of storing energy. Numerous battery chemistries are capable of hydrolytic decomposition, with the most prominent examples leveraging reducing metal anodes (Mg, Zn)[321,326] and water-soluble cathodes based on metals[326], metal oxides[327], organic species[328] or small molecules[320,322]. Biodegradable supercapacitors leveraging carbon-based[329], metal composite[324,325] and metal oxide or sulfide[323] electrodes have also shown promise.

Beyond power storage, in situ power generation has been demonstrated with ecoresorbable materials. Recent work has shown power harvesting with fully degradable microbial fuel cells[330], relying on enzymatic activity to convert local chemical fuels into usable power. Other efforts have demonstrated physically transient photovoltaic assemblies using both silicon[331,332] and perovskite[333] electrodes displaying performance (specific power: >250 W $m^{-2}$, power conversion efficiency (PCE): 17.51%)[333] comparable with conventional photovoltaics (specific power: >250 W $m^{-2}$, PCE: 31%)[200] under AM1.5 illumination. However, it is important to note that some components of these cells (principally silver nanowire conductors) remain largely non-transient. Likewise, the use of

## Box 1 | Sensor manufacturing and platform-level integration

With the possibility of deploying thousands to millions of individual sensors, the cost-effective and scalable manufacturing of these devices becomes a non-trivial concern. Although fabrication methods vary considerably depending on the specific application, desired operating duration and technological maturity, many of the materials and assemblies described in preceding sections are amenable to manufacturing at scale using existing technologies[270].

Photolithographic patterning and wet or dry etching techniques represent the most common approaches for assembling arrays of both transient and conventional sensors. Devices comprising silicon-based materials are already well suited for assembly with conventional lithographic techniques using standard mask aligners, chemical or plasma etching and vapour deposition[375]. Assembling these structures on silicon-on-insulator substrates facilitates their subsequent removal from the parent wafer using transfer printing[347]. In this fashion, arrays of sensing elements can be combined with biodegradable substrate materials and/or encapsulants to produce batches of tens to hundreds of individual devices. In some cases, simpler patterning methods may also be available in the form of vapour deposition of metal components through shadow masks[376]. Although this approach limits the feature sizes of metal components (~10 μm), it avoids much of the complexity of conventional lithography.

In addition to lithographic methods, additive printing methods have been used to fabricate devices. Screen printing[344], laser printing[377], stencil printing[378,379], inkjet printing[380,381], electrohydrodynamic printing[382,383] and aerosol printing[384] are all capable of patterning sensing elements onto biodegradable substrates with feature sizes as small as 40 μm. These approaches are powerful for the mass production of sensors at low cost as they require less equipment than analogous lithographic methods, increasing their accessibility. Similarly, ink formulations incorporating environmentally benign and sustainable components including ecofriendly solvents[385–387], binders[388,389] and solid components[390,391], are well matched — both in cost and in sustainability — for the fabrication of large numbers of individual sensors.

As a compromise between the high spatial resolution of photolithography and the approachability of additive methods, laser ablation is also used in the fabrication of sensing devices. Existing laser writing systems offer high alignment accuracy (2–3 μm) and can achieve feature sizes as low as 5 μm (ref. 392). Similarly, through careful control of laser power, scan speed, frequency, number of repetitions and ablation grid density, the material can either be completely removed or deterministically thinned depending on the specific assembly needs.

In addition to processing considerations, integrating soft and biodegradable sensing components with their associated recording circuitry poses a challenge. Although soldered connections remain the standard approach for rigid electronics assembly, the necessary use of high temperatures makes this connection strategy incompatible with many sensor materials. Numerous efforts have aimed to address these issues through alternative interconnect strategies[393]. Electrically conductive adhesives and epoxies[394], anisotropic conducting film adhesives[395] and various mechanical fittings[396] have all shown promise in reliably forming electrical contacts with critical sensing components. Similarly, the availability of biodegradable substrates, adhesives and conductors make the assembly of transient connectors a possibility, supporting the programmed separation of sensing components from readout circuitry at end-of-life.

Outside interconnect formulations, the manipulation, transport and placement of sensing elements post-assembly is imperative in the construction of large sensing arrays. To date, automated pick-and-place assemblers are promising, as they can accommodate the transfer of individual sensors from substrate to system rapidly and reliably[397]. Likewise, laser-based material transfer methods offer additional control over the patterning and assembly of small components[398]. Together, these approaches facilitate the accurate and high-throughput assembly of conventional and transient devices to meet the needs imposed by large-scale environmental monitoring.

Pb-based perovskites imposes a potential hazard to target environments owing to the introduction of soluble Pb ions. This problem may be circumvented with Pb-free perovskites as the photoactive layer, although challenges remain in the efficiency and stability of these materials[334].

Thermal energy has also been effectively captured using cellulose-based thermoelectric films impregnated with CuI (output power density: 10 μW $m^{-2}$)[335,336]. Finally, mechanical energy has been harvested using triboelectric nanogenerators assembled from microcrystalline cellulose composites (output power density: 1 W $m^{-2}$)[337] or agar and carrageenan composites (output power density: 150 μW $m^{-2}$)[338]. Although the specific power produced by non-photovoltaic generators is substantially lower than solar-based methods, they may act as supporting supplies under dark conditions where solar energy is insufficient for device function. Similarly, the variable lighting conditions involved in aquatic monitoring may demand alternative power sources such as triboelectric or piezoelectric generators to accommodate extended device operation.

### Platform integration and environmental deployment

Successful deployment at scale is strongly dependent on both the manufacturing of sensing platforms and the mechanisms used to accomplish their dispersal. Even though manufacturing practices for non-transient devices are already well established, new and emerging technologies are necessary to support the efficient fabrication and integration of transient sensing platforms. Manufacturing approaches that can accommodate the precise manipulation of soft or delicate sensing components are essential in this regard. Fortunately, numerous options exist to accomplish these manipulations at industrially relevant scales (Box 1). Following manufacturing, several practical constraints must be considered regarding device deployment, communication and recovery.

**Dispersal and motility.** The incorporation of transient components to delivery systems could prove valuable in reducing operator intervention and alleviating inadvertent burdens on target ecosystems.

Aerial dispersal structures have leveraged transient materials such as PLGA[186,202], cellulose–nanofibre–gelatin composite films[191] and cellulose acetate with lignin[193] to realize complete system disintegration when in prolonged contact with aqueous media. Similarly, partially transient systems have been explored for monitoring in aquatic environments, including a surface drifter with a transient hull and non-transient electronics[339]. Soft, ecoresorbable actuators for device motility have also been demonstrated[230,340], but they have not been paired with equally transient communication modules capable of controlling them.

**Long-range communication.** Implementing a wireless sensor network with ecoresorbable materials is challenging as protocols such as Bluetooth, LoRa, Sigfox, Thread, Zigbee and LTE require computational elements that only exist in integrated circuits. Simple transient antennas have been demonstrated for receiving power[341–343] and transmitting sensor data[344–346] over short distances (~1 m), but they cannot support longer range data transmission protocols. Although challenging, the incorporation of transient materials into foundry-level assembly could enable fully degradable integrated circuits supporting data acquisition, storage and transmission[347]. A polymer-based circuit with 1,000 stretchable transistors has also been recently demonstrated[348] – albeit in a non-transient form – illustrating the feasibility of patterning computational elements on non-conventional substrates and supports. Soon, analogous principles could enable flexible, ecoresorbable, large-scale integrated circuits capable of digital wireless communication.

New capabilities to increase communication range with transient materials may be achievable by leveraging chip-less radiofrequency identification (RFID) systems. Using temporal and frequency domain modulation, passive RF communication can enable operating distances of <1 m (ref. 349). Such an approach has been demonstrated for printed humidity and temperature sensors constructed from a combination of cellulose paper and Zn microparticles and encapsulated using wax[350]. Despite their utility in close proximity, however, small antennas yield weak return signals that are challenging to subtract from the background without sophisticated encoding and decoding schemes[351,352]. Longer distances are achievable by integrating piezoelectric materials and surface acoustic wave (SAW) phenomena[353]. For example, an ecoresorbable piezoelectric antenna made from PHBV/PLLA/KNN was recently demonstrated[354], and further development could present a building block for a transient SAW-based RFID device.

Long-range readout may also be possible using passive return of optical signals. Retroreflectors, combined with colorimetric dyes, can detect chemical contaminants from distances of 150 m (refs. 355,356). Transient retroreflectors constructed from agar and silk have also been demonstrated[356,357]. Microfliers leveraging these materials could be dispersed over large areas and interrogated remotely using drones. Then, they could be allowed to dissolve safely into the environment.

**Sensor network operation, end-of-life management and application space.** Transient sensing assemblies complement ongoing efforts in automation and robotics, as a parsimonious collection of aerial, terrestrial or aquatic drones can interface with many individual sensors to accommodate data collection and transmission[358]. Such approaches have been explored with RFID-based soil sensors probed by a roving and autonomous recording station[359]. Individual units, each containing an RF resonating antenna, can readout chemical or physical information to the rover, allowing data acquisition from potentially thousands of individual sensing agents with a single recording robot. Aerial approaches have also been used, deploying UAVs to image fluorescent and optical sensing components distributed across terrestrial environments[186]. In these instances, transient sensing elements are preferred as complications and power consumption associated with drone take-off and landing makes physical placement and recovery of sensors unrealistic. Within this paradigm, the simplicity of the sensing elements themselves accommodates transience without sacrificing accuracy or facile sensor distribution.

Beyond robotic data collection, sensors relying on either RF backscatter or SAWs may prove useful. In both instances, high fidelity data may be collected and transmitted over comparatively large distances, using a central data collection installation to facilitate indexing and storage. The utility of such a fully integrated system has notably been demonstrated for the profiling of environmental parameters over reasonable distances (~100 m)[200] albeit without the integration of transient components. Despite this promise, however, the necessary inclusion of integrated circuits facilitating RF data transmission over these distances frustrates total sensor transience, making ultimate device recovery imperative.

Regarding semi-transient or non-transient systems, the recovery of permanent components remains a major consideration in realizing massive environmental sensing networks. Fortunately, options are available to accommodate the location of these components using low power GPS circuitry[251] or by the inclusion of fluorescent, reflective or magnetic tags to allow for their location and ultimate retrieval. Similar developments in autonomous terrestrial, aquatic and aerial vehicles may accommodate device retrieval from challenging or hazardous environments[360].

## Concluding remarks, recommendations and outlook

The detection of known chemical, physical and biological hazards in an ever-broadening collection of ecological niches, coupled with the persistent discovery of new, potentially harmful, environmental agents, highlights the pressing need to identify, quantify, sequester and remove hazards from affected ecosystems. Given the severity of anthropogenic action on target ecosystems, the exploration of materials that support selective and sensitive detection of environmental hazards is imperative to address these pressing concerns. Similarly, material technologies affecting the distribution, protection and collection (or ultimate dissolution) of sensing architectures are sorely needed.

Fortunately, the potential severity of these environmental challenges has been met with concerted efforts from both academic and industrial sectors. An enormous catalogue of analytical technologies has been developed to quantify environmental characteristics and to evaluate their effects in myriad environments. Sensors leverage a broad collection of transduction methods to accommodate quantification, including spectroscopic, colorimetric, electrochemical, resistive, capacitive and biological modalities. Importantly, the success of these sensors has been demonstrated for target quantification in a distributed fashion even when analysing complex samples. Despite this promise, however, continued exploration of new analytical methods and improvements to the stability, longevity and controllability of existing measurement platforms are imperative in providing accurate environmental data to guide conservation and remediation efforts.

Although the development of new materials supporting chemical detection is largely keeping pace with ongoing developments in pollutant

discovery, the implementation of these materials into widely distributed sensing systems remains comparatively nascent. In this regard, colorimetric and electronic methods are among the most promising technologies for massively distributed sensor networks. Beyond these methods, electrochemical methods are promising in supporting the detection of low-concentration species, having already proven useful in conventional environmental sensing applications. However, the long-term stability of most electrochemical biosensors is insufficient, at present, to meet the needs of environmental characterization over the span of days to weeks. The development of material strategies that mitigate electrode fouling and improve sensor longevity will prove important in bringing advanced electrochemical sensors to a greater level of feasibility. In either case, the field deployment of these sensing technologies to evaluate their utility in real-world applications is necessary to advance autonomous and widespread environmental characterization.

In addition to the limitations of existing sensing technologies, their sparse incorporation into routine environmental monitoring reflects disconnects between the technological development of chemical and biological sensors and the platforms necessary to deploy and automate them. Given the broad range of device technologies capable of supporting sensor distribution, modern environmental science is in a unique position to combine advancements from analytical chemistry and materials science with those of robotics and distributed networks. Indeed, ground-based, aquatic and aerial dispersal systems have shown great promise in characterizing wide expanses of diverse terrain. Aerial dispersal could prove crucial in the chemical and physical profiling of broad land areas for agricultural applications, or for targeted action in response to accidental hazard release. Likewise, the large streams of data collected from distributed networks could be paired with emerging machine-learning approaches for advanced, real-time data analysis to guide subsequent intervention[361–364].

Despite the promise of these systems, several limitations must be addressed to realize their full functionality. Owing to the large spatial and temporal scales of environmental phenomena, sensor networks would ideally facilitate coverage over broad areas without direct human intervention. This extended deployment makes the collection and streaming of data a challenge. Similarly, long recording durations present limitations on battery life and power management. Although these issues can be addressed by solar, thermal, mechanical or chemical power harvesting, they remain important considerations in device development and deployment. New materials supporting thermoelectric, piezoelectric and biofuel cell generators may prove crucial in powering devices in low-light conditions (aquatic or heavily forested environments) in which photovoltaics are insufficient. Finally, the demand for direct user intervention to collect distributed sensors post facto further reduces their utility.

Transient materials offer an important contribution to the latter challenge, as they relieve the burden of device collection after sensor lifetime has elapsed. Although progress has been made in the use of transient colorimetric, electrical and bacterial sensing elements, current transient environmental sensors are extremely simple in their construction, generally consisting of resistive or capacitive sensing elements to characterize environmental factors. Realizing more complex detection schemes in transient forms is non-trivial, and much work remains in the exploration of active (conductors and semiconductors) and passive (substrates, encapsulants and insulators) materials that can ensure the stable operation of these devices. A persistent problem in this area is a lack of control over the hydrolytic decomposition of sensing elements. To accommodate medium-term to long-term environmental monitoring, such devices must degrade in a deterministic fashion without deleterious effects from premature water infiltration. Addressing these considerations demands greater focus on the stability and synthetic modification of degradable encapsulants to realize extended operating lifetimes. Likewise, investigations into stimuli-responsive materials that only degrade under certain conditions (temperature, irradiation and voltage) will prove important in achieving the level of control necessary for extended environmental monitoring. Finally, there remains a lack of real-world examples of transient sensing.

Unfortunately, even if new sensing modalities become tractable, current transient systems only support simple circuit elements (resistors, capacitors, diodes and transistors), making the development of circuitry capable of data collection, storage and transmission a distant goal. At present, the greatest utility for transient materials in distributed environmental characterization is in the consumables, sensing components and structural aspects of devices, with data acquisition and transmission architectures retaining their non-transient assemblies. Given these limitations, greater attention must be devoted to system-level integration if fully functional transient sensing networks are to become a reality. In particular, the development of autonomous sensing systems that can maximize the benefits of transient sensing elements (biocompatibility, widespread deployability and cost economy) should be regarded as a high priority.

Given the comparative maturity of environmental sensing technologies and autonomous robotic assemblies, coherent efforts to bridge the gap between these areas are needed to address global issues in ecology, human health and environmental remediation. Efforts to deploy networks of chemical sensors to monitor new classes of water and soil pollutants represent a profound, yet uninvestigated, area of study. Similarly, the adoption of widespread networks of aquatic (for both fresh water and sea water) devices supporting advanced chemical, physical and biological sensing will be extremely important in assessing water quality, ecosystem health and environmental stability. Finally, the integration, wherever possible, of transient components (sensors, encapsulants and device assemblies) to minimize device impact on target environments and assist in terminal device collection will prove beneficial in the wider adoption of these technologies.

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## Author contributions
K.E.M. and M.T.F. researched data for the article and led drafting of the manuscript. J.A.R. reviewed and edited the manuscript before submission. All authors contributed substantially to the content and discussion disclosed within the manuscript.

## Competing interests
The authors declare no competing interests.

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