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Smart Dust for Chemical Mapping

*Indrajit Mondal and Hossam Haick**

This review article explores the transformative potential of smart dust systems by examining how existing chemical sensing technologies can be adapted and advanced to realize their full capabilities. Smart dust, characterized by submillimeter-scale autonomous sensing platforms, offers unparalleled opportunities for real-time, spatiotemporal chemical mapping across diverse environments. This article introduces the technological advancements underpinning these systems, critically evaluates current limitations, and outlines new avenues for development. Key challenges, including multi-compound detection, system control, environmental impact, and cost, are discussed alongside potential solutions. By leveraging innovations in miniaturization, wireless communication, AI-driven data analysis, and sustainable materials, this review highlights the promise of smart dust to address critical challenges in environmental monitoring, healthcare, agriculture, and defense sectors. Through this lens, the article provides a strategic roadmap for advancing smart dust from concept to practical application, emphasizing its role in transforming the understanding and management of complex chemical systems.

1. Introduction

Chemical compounds are vital to modern life, supporting essential sectors such as healthcare,[1–3] agriculture,[4–6] and industry.[7,8] However, they also present considerable environmental and health challenges. Examples include air pollution from industrial emissions,[9] damage caused by pesticide overuse, technological risks like nuclear waste, and biological weapons, and the rising occurrence of chronic diseases such as cancer, diabetes,[10] and neurological disorders like Alzheimer's and Parkinson's.[11] Incidents such as the COVID-19 pandemic, the Chernobyl nuclear disaster, and widespread industrial pollution illustrate the severe consequences of failing to manage chemical risks properly.[12,13]

A significant underlying challenge is the absence of real-time, local chemical data necessary for prompt and informed decision-making to prevent disasters. These challenges are further complicated by the inherent complexity of chemical mixtures, often involving a "cocktail" of hundreds or even thousands of unkown or poorly understood chemicals. Managing of these mixtures is particularly diffcult because: i) chemicals can contribute to toxicity or act as biomarkers even when present below their individual effect thresholds or detection limits; ii) chemicals with similar properties often act cumulatively ("concentration addition"),[14,15] while those with different modes of action may interact independently ("independent action"); and iii) the spatial distribution of these chemicals, whether within a single entity or across multiple locations, is frequently uneven, adding to the challenges of detection and analysis. Awareness of these risks has grown in light of findings that up to two-thirds of chronic disease risks and 16% of premature deaths may result from environmental factors or gene-environment interactions.[16] This underscores the urgency of proactive measures to monitor, manage, and mitigate the risks associated with chemical exposure while preserving their benefits for society.

To address these challenges and prevent further crises, three guiding principles must be adopted:[17] i) precaution, to address potential risks even when full scientific certainty is lacking; ii) prevention and remediation at the source, to reduce the release and impact of harmful chemicals; and iii) dynamic lifecycle monitoring, to track chemicals from production to disposal. The precautionary principle, a critical risk assessment tool, enables early intervention based on suspected threats to human health or the environment. These measures must be non-discriminatory, proportionate, and adaptable as new scientific insights emerge. Furthermore, continuous monitoring systems are essential to detect potential threats, such as accidental leaks of hazardous compounds or exposure to harmful chemicals, before they escalate into disasters. Advanced sensing technologies and wireless sensor networks can address these gaps by enabling real-time, spatially resolved identification and quantification of chemicals.[18,19]

I. Mondal, H. Haick
Department of Chemical Engineering and Russell Berrie Nanotechnology Institute
Technion – Israel Institute of Technology
Haifa 3200003, Israel
E-mail: hhossam@technion.ac.il
H. Haick
Life Science Technology (LiST) Group
Danube Private University
Fakultät Medizin/Zahnmedizin, Steiner Landstraße 124 , Krems-Stein, ÖSTERREICH 3500, Austria

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Such systems could track targeted and non-targeted chemical compounds within complex mixtures, providing critical data for timely responses to events like chemical leaks, bio-warfare outbreaks, or industrial emissions.

Among the variety of tools available, laboratory-based or even compact spectrometry is considered the most powerful.[20,21] This is because spectrometry offers comprehensive analysis, quantification, and identification of a wide range of chemical compounds, and is well suited to discovering small molecules.[22,23] Currently available spectrometers, often coupled with either gas or liquid chromatography, can detect tens of thousands of chemical compounds.[24] They offer the possibilities of routine target analysis, suspect screening, and discovery-based non-target analysis (NTA) in an all-in-one approach. However, in each operation scheme, most spectrometers in use are bulky and demand extensive sample pre-preparation and trained personnel. Therefore, they are not suitable for mapping mixtures to determine the distribution of chemicals across time, space, or various matrices.[25,26]

Recent years have witnessed significant advances in scaling down spectrometry to handheld or on-chip portable devices for attaining indicative, instantaneous, and on-the-spot results.[27–31] Although these devices have been used in a wide range of applications (e.g., soil and crop analysis, quality control of food products, and environmental scientific research), their minimization has been accompanied by decrease in resolution, dynamic range, and signal-to-noise ratio.[29,30,32–35] Nevertheless, further miniaturization of spectrometry down to the submillimeter scale, while maintaining high performance, could provide novel opportunities in a wide range of applications. These include, for example, in situ or even in vitro mapping of chemicals or disease biomarkers and correlation of spectral information with spatial data for revolutionizing large-scale monitoring, as in crop or contamination monitoring.[36]

As we and others have demonstrated, an alternative approach for spectrometry-based continuous monitoring involves the use of selective or "lock-and-key" sensors,[37,38] which can be fine-tuned to detect specific substances, or cross-reactive sensor arrays coupled with pattern recognition methods, which can identify chemical fingerprints of mixtures.[39,40] However, while these technologies are effective for detection per se, they fall short in their ability to map the spatial distribution of chemicals across time and space. This complexity significantly limits the ability to resolve individual components within real-world samples, making these technologies less reliable for precise mapping of chemical compounds in dynamic or heterogeneous environments. A transformative shift from the limitations of the traditional chemical sensing lies in the emergece of (sub-)millimeter-scale autonomous sensing platforms, often referred to as "smart dust".[41] These platforms hold the potential to detect, quantify, and map both targeted and non-targeted chemicals within complex mixtures, anytime and anywhere, while correlating spatial and temporal data. Such capabilities could enable proactive management of chemical risks, such as accidental leaks or bio-warfare outbreaks, and significantly enhance responses to events like industrial pollution or pandemics. **Figure 1** demonstrates the sampling and chemical analysis of complex mixtures via traditional and state-of-the-art strategies and via the chemical smart dust concept.

2. Smart Dust – Networks of (Sub)-Millimeter-Scale Autonomous Sensing Platforms

Smart dust represents a transformative network of highly miniaturized devices, often no larger than grains of sand, that integrates sensing, computation, communication, and energy-harvesting capabilities.[42,43] As illustrated in **Figure 2**a, each smart dust unit incorporates an array of micro- or nanoscale sensors, integrated interconnections, and a micro-antenna for wireless energy harvesting and communication.[44] These devices are engineered to operate autonomously or collaboratively within both physical and virtual frameworks, enabling advanced monitoring and data analysis across diverse environments. Physically, smart dust units are equipped with components that allow them to function as self-contained sensing platforms, detecting specific variables, wirelessly transmitting data, and sustaining long-term operation through energy-harvesting mechanisms.[45] In some cases, computational elements are embedded, enhancing their ability to process data locally.

The design philosophy of smart dust emphasizes minimal environmental impact, with devices engineered to be lightweight, energy-efficient, and potentially biodegradable to prevent ecological harm.[46] Advanced manufacturing techniques, such as printing and laser dicing (Figure 2b), enable scalable and cost-effective production of smart dust systems with structure design that support structural adaptability, swarming capabilities, and effecient deployment accross diverese environments .[47–50] These swarming devices can remain airborne for extended periods, leveraging ambient air currents for navigation and accessing regions that are remote, hazardous, or confined areas traditionally inaccessible to conventional sensing technologies (Figure 2c). This unique mobility allows smart dust to conduct real-time data acquisition in diverse scenarios, ranging from remote ecosystems to even biological systems.

The functionality of smart dust systems extends beyond physical sensing, as they establish a seamless interface between the physical world and virtual processing frameworks. Intra-dust communication enables these devices to function as a distributed sensing network, where data collected locally is transmitted wirelessly to base stations and cloud storage systems for further processing (Figure 2c,d).[51] Wireless interactions between motes and the cloud can be facilitated through near-field communication, optical signaling, or electromagnetic coupling, leveraging integrated microprocessors, Bluetooth connectivity, passive backscattering, RF transmission, and low-power memory for real-time processing, storage, and communication.[52–54] Thus, smart dust networks can collect critical data on variables such as chemical composition, radiation levels, temperature, or biological markers and utilize Internet of Things (IoT) infrastructures and advanced computational tools like machine learning for analysis (Figure 2e,f). This capability generates high-resolution spatial and temporal datasets, which enable comprehensive monitoring, detailed environmental assessments, and actionable insights that meet the demands of future sensing technologies.

Several categories of submillimeter-scale autonomous sensing platforms have been reported in various fields including sensor-transistor,[55] aerosolizable electronics,[54] wearable/implantable

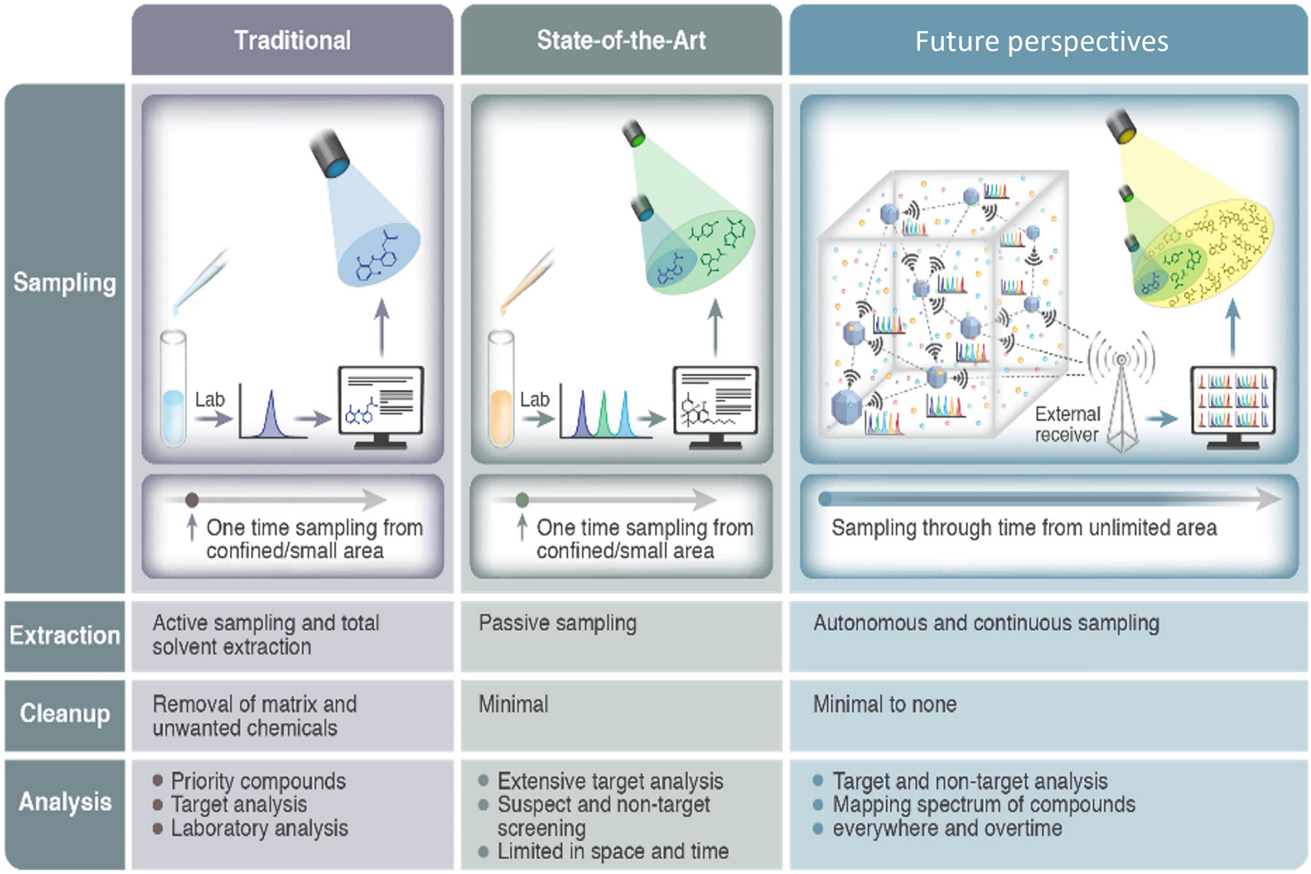

Figure 1. Depiction of traditional, state-of-the-art, and futuristic sampling and strategies for analyzing complex chemical mixtures: Compared with the traditional and state-of-the-art approaches, the goal of smart dust is to detect and track the widest spectrum of targeted and non-targeted chemicals within complex mixtures as a function of spatial locations and other parameters.

electronics,[56] colloidal state machines (CSMs),[57–61] etc. These technologies have been platformed on centimeter to micrometer scales, predominantly through standard lithography and micro-electromechanical system (MEMS)-based micro-machining. A recent report about an ingestible electronic sensor showed that it can measure different gases (e.g., oxygen, hydrogen, and carbon dioxide) in the gut to detect changes in a person's diet.[62] Colloidal nano-electronic state machines based on 2D materials for aerosolizable electronics can detect specific gases (e.g., triethylamine and ammonia) in a simulated environment.[54] Nonetheless, these technologies, along with other miniaturized sensors envisoned for smart dust appliations,[63] still face challanges, such as limited detection of compounds not predefined during their design as well as reduced precision in distinguishing complex gas mixtures compared to spectrometric methods. In scenarios marked by uncertainty, such as the COVID-19 pandemic, these limitations could lead to narrow evaluations and improper management of events or catastrophes. Beyond these technical constraints, the wide-scale adoption of smart dust introduces broader risks. The deployment of billions of submillimeter sensing devices would make retrieval or control difficult, posing regulatory, and operational challenges. Moreover, since these devices are often single-use, they risk polluting the environment and harming organisms if they are not fully degradable and non-toxic. Additionally, the high production costs of such devices currently render them inaccessible for many practical applications, limiting their widespread implementation.

For smart dust to be effective, hundreds or thousands of small units must function collaboratively, like a swarm, to analyze complex environments. This requires addressing several critical challenges during development. The integration of diverse detectors into a single platform capable of identifying multiple substances is essential. Equally important is the development of scalable, cost-effective, and printable production methods to ensure accessibility. Advanced data processing systems, powered by distributed computing and AI, must also be incorporated to handle the vast amounts of data these devices will generate. Furthermore, smart dust needs to be lightweight, biocompatible, eco-friendly, and, where necessary, edible, to minimize environmental impact.

Despite its promise, the development of smart dust has progressed more slowly than related technologies, such as wearable devices,[64–66] which were conceptualized around the same time but have reached greater milestones in implementation. Moving forward, smart dust systems require a balanced and integrative approach - one that harmonizes miniaturization with real-world functionality.[67] Key areas include enhancing

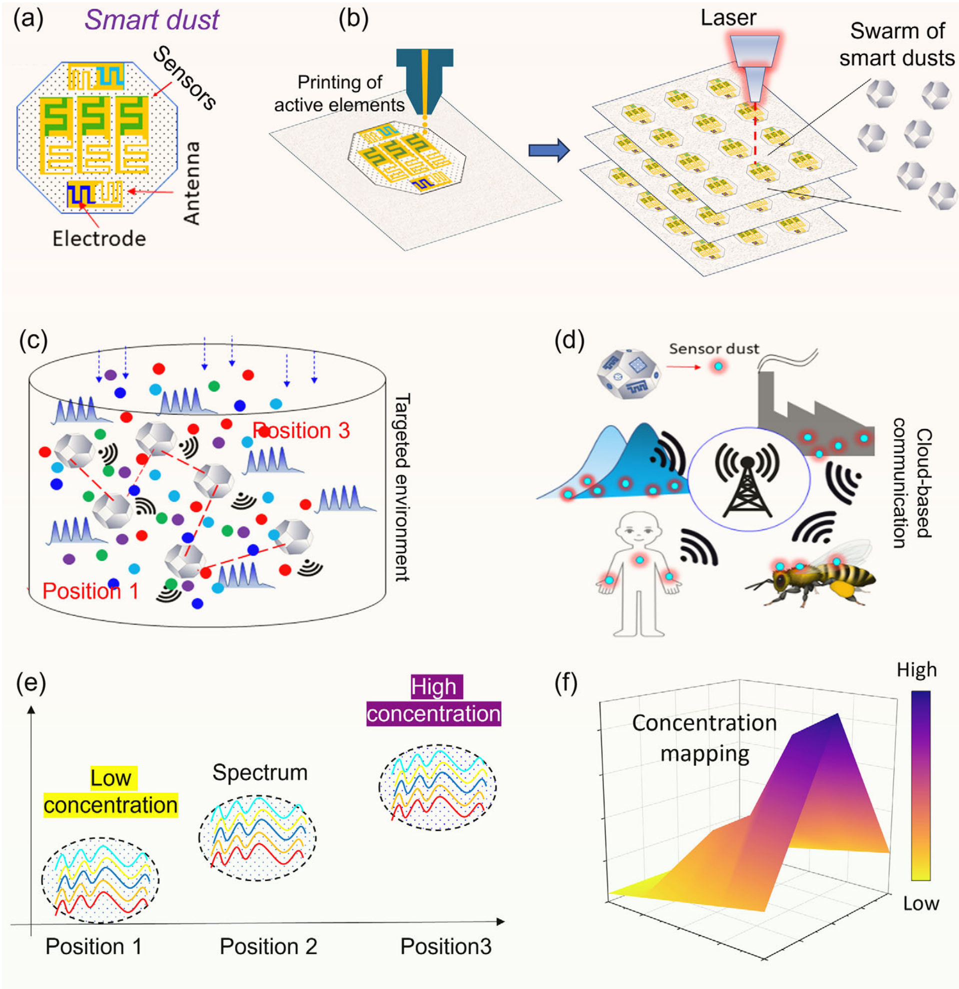

Figure 2. Smart dust: a) Conceptual illustration of a smart dust unit, comprising an array of sensors, integrated interconnections, and a micro-antenna for wireless energy harvesting and communication. b) Schematic representation of roll-to-roll fabrication utilizing techniques like printing and laser dicing enabling the production of origami-inspired, swarming smart dust capable of sustained airborne mobility facilitated by ambient airflow. c) Intra-dust sensor communication within a localized environment and subsequent wireless data transmission to the nearest base station and cloud storage for further processing. d) Schematic illustration of the wide applicability of smart dust technology across multiple platforms, including industrial, environmental, agricultural, and healthcare sectors, for real-time monitoring of diverse chemical species, organic compounds, and radiation hazards. e) Generation of extensive datasets by distributed smart dusts across various locations, which are analyzed using Internet of Things (IoT) frameworks and machine learning algorithms to produce high-resolution f) analyte concentration maps for comprehensive environmental assessment.

sensitivity and selectivity across multiple chemical targets, ensuring biodegradability and biocompatibility, enabling wireless powering and communication, and achieving sustainable, and cost-effective manufacturing. Equally important is the seamless integration of these sensors, which is critical for unlocking the full impact of smart dust in diverse applications into vast data analysis networks for real-time chemical mapping. With this in mind, the current review highlights the recent progress across these domains, emphasizing how such advancements can collectively overcome current challenges and unlock the full potential of smart dust. By exploring innovations in existing technological platforms, the review outlines also a vision for how emerging chemical sensing technologies can be adapted and applied to realize practical, scalable smart dust systems for diverse real-world applications.

3. Transforming Advanced Chemical Sensing Technologies into Smart Dust

As mentioned earlier, a combination of critical features, including appropriate micro- and nanoscale sensors, high sensitivity, selectivity, miniaturization, wireless powering, communication, flexibility, biocompatibility, and biodegradability, lays the foundation for the future of smart dust.[41,43,68–72] These features enable smart dust to operate autonomously in dispersed or embedded environments, enabling high-resolution, real-time data acquisition from complex systems. By integrating advanced materials and nano- and microelectronics, smart dust can sense, process, and communicate data with minimal human intervention, paving the way for intelligent, self-sufficient sensing platforms.

3.1. Enhancing Sensitivity for Smart Dust

Enhancing the sensitivity of chemical sensing technologies is crucial for transforming them into functional smart dust systems. The ability to distinguish between different states, such as normal and anomalous conditions, is a foundational requirement for sensing in complex environments. Advanced sensing systems must be able to detect subtle variations in chemical composition with high precision to enable autonomous, real-time detection. Achieving this sensitivity is the first step toward realizing the potential of smart dust for diverse applications, from healthcare diagnostics to environmental monitoring.

Chemiresistive sensors (**Figure 3a**)[73] and/or electrochemical sensors (Figure 3b)[74] are highly adaptable, offering customization to enhance functionality and improve sensitivity for the accurate detection of gases and volatile organic compounds (VOCs).[75–78] For example, doped SnO_2 chemiresistive sensors (Figure 3a) respond to interactions with adsorbed oxygen ions and VOCs under UV light, significantly amplifying their ability to detect even minute chemical changes.[73] When integrated with spatial and temporal mapping capabilities, these sensors enable smart dust systems to detect and track chemical fluctuations dynamically. Recent advances have expanded the application of chemiresistive sensors and their derivatives to create stationary sensing platforms with functionalities resembling those of gas chromatography-mass spectrometry (GC-MS),[79] radiation detectors,[80] and spectroscopic analyzers.[81,82] Innovations such as GC-inspired graphene-based chemiresistive sensing arrays [83,84] and carbon-nanotube-impregnated paper capable of generating ions from organic molecules at low potentials[85] are driving the miniaturization of these technologies.[86] These advancements have promise to enable precise detection and differentiation that is critical for monitoring complex chemical and biochemical conditions.[87–92] By adapting these sensing structures to operate autonomously and in distributed networks, smart dust systems can monitor dynamic environments, responding to chemical variations with precision and without the need for centralized control. Complementary optical technologies, including fiber optics and surface-enhanced Raman spectroscopy (SERS), offer exceptional sensitivity for detecting low-concentration compounds (Figure 3c).[93–100] Miniaturizing these systems enhances real-time detection capabilities, making them invaluable for smart dust applications. Triboelectric sensors (Figure 3d), which detect ion concentration variations via voltage generation, add further sensitivity for rapid, micro-scale monitoring of environmental and biological conditions.[101–103]

Integrating these advanced sensing technologies into autonomous smart dust networks enables continuous and precise monitoring of dynamic systems, significantly broadening their applications across diverse environments. However, achieving this integration presents substantial technical challenges. A major difficulty lies in miniaturizing these technologies while preserving their high sensitivity and specificity at submillimeter dimensions. Retaining performance at reduced scales necessitates overcoming limitations in sensor responsiveness and signal amplification, which become particularly problematic when aiming to maintain precision in detecting low concentrations of target analytes. Additionally, the integration of diverse sensing modalities—chemical, mechanical, and optical—into a single cohesive smart dust platform introduces significant fabrication and detection complexities.[104] Fabrication challenges, particularly those associated with MEMS and nanolithography processes, further complicate mass production, given their associated issues with scalability, yield, and high production costs. Moreover, the deployment of vast numbers of these devices raises environmental concerns, particularly related to the non-biodegradable nature of many of the materials currently used, posing potential ecological risks. To address these challenges, research efforts must prioritize the development of scalable and cost-effective fabrication techniques, such as inkjet and 3D printing, slot-die coating, and roll-to-roll processing.[105] These methods offer the potential to streamline production while maintaining precision at the micro- and nanoscale. Additionally, the adoption of flexible and organic electronic components is essential to facilitate the integration of multiple sensors without compromising cost-effectiveness or performance.[106] Hybrid integration strategies, wherein individual components are fabricated separately and subsequently assembled into a cohesive smart dust system, could further simplify manufacturing processes and enhance the overall efficiency and adaptability of these networks. Such approaches promise to accelerate the transition from conceptual prototypes to practical and deployable smart dust systems. By enhancing sensitivity and enabling real-time, precise detection of chemical changes, smart dust will transform the way we interact with and monitor our environments.

3.2. Enhancing Selectivity for Smart Dust

Enhancing selectivity in chemical sensing is the cornerstone for realizing the true potential of smart dust systems, designed to precisely discriminate analytes. Achieving this level of precision involves harnessing advanced techniques such as doping, surface functionalization, and sophisticated data processing methods—each contributing to the development of sensors capable of meeting the demands of smart dust applications.

Doping plays a foundational role in improving selectivity by altering the electronic or optical properties of sensor materials.[107–109] This allows sensors to interact more effectively with target analytes, enhancing their sensitivity and specificity. For instance, Pd-doping in metal oxides significantly improves selectivity for hydrogen detection,[110] while dopants like Ca, Al, and Ga help lower detection limits for a wide range of compounds.[111] These modifications not only amplify signal responses but also sharpen a sensor's ability to distinguish between the analytes of interest and potential interferents, a critical requirement for smart dust systems working in environments with a variety of chemical compounds.

Building on the concept of doping, surface functionalization introduces molecular recognition elements that allow sensors to selectively bind to specific analytes.[112,113] As demonstrated by Milyutin and colleagues, metal nanoparticles functionalized with thiol and amine groups can detect VOCs or specific biomarkers.[114] This approach transforms simple sensors into highly specialized tools that can detect and differentiate between a wide range of analytes in real time, making them well-suited for the dispersed, interconnected nature of smart dust applications. Emerging innovations such as Rashba

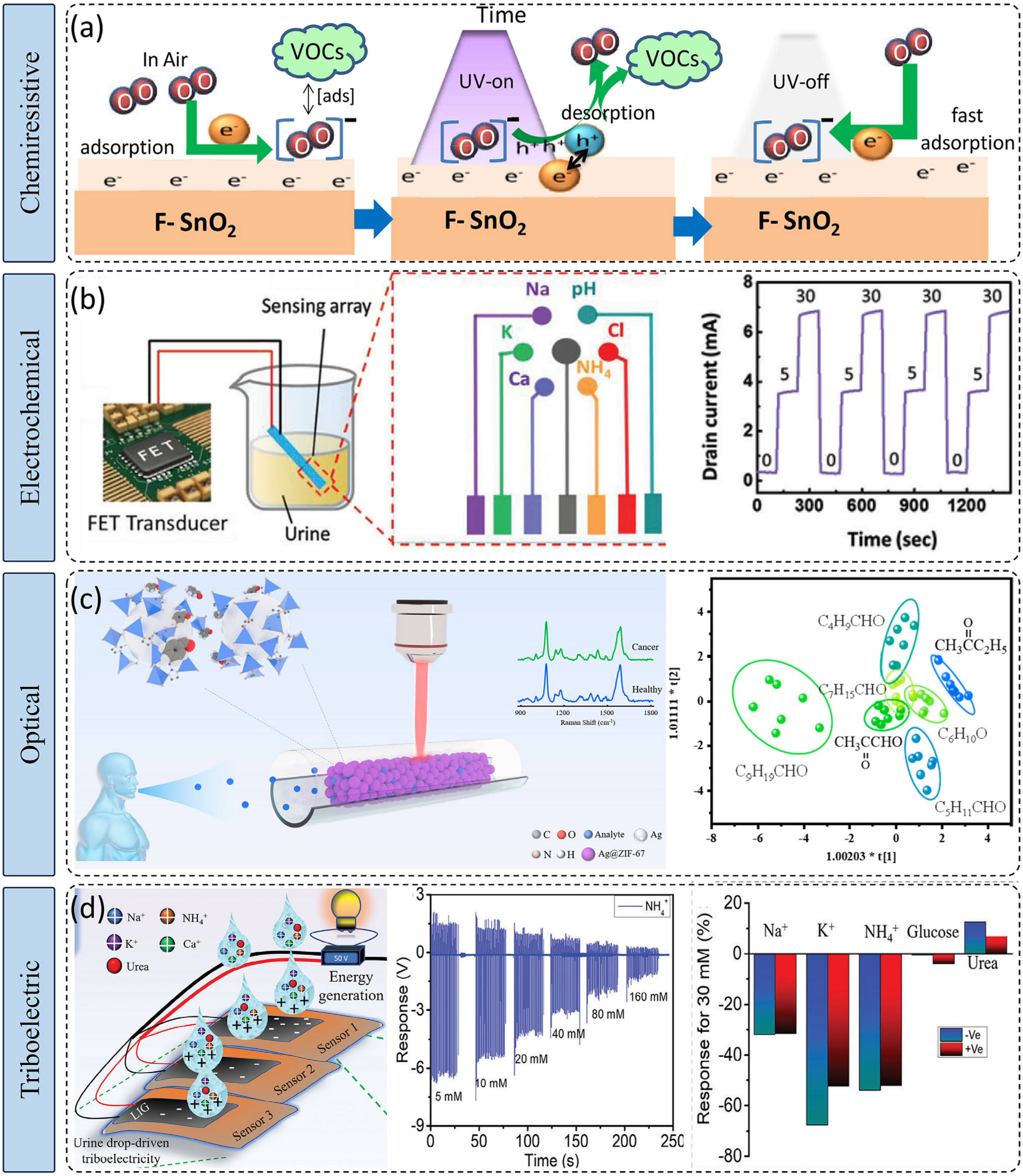

Figure 3. Sensors and Sensitivity: a) Functionality of a chemiresistive sensor showing reversible resistance changes due to charge carrier trapping and de-trapping during analyte adsorption and desorption. Reproduced with permission.[73] Copyright 2020, ACS Publications. b) An extended-gated electrochemical sensing array functionalized with selective materials that modulate the drain current in response to varying analyte concentrations, with a response curve illustrating Na^+ concentrations from 0 to 30 mM in a solution. Reproduced with permission.[74] Copyright 2024, Wiley-VCH. c) A SERS-based optical sensor where localized surface plasmon-enhanced Raman fingerprints of targeted and non-targeted molecules are detected for breath analysis. Reproduced with permission.[100] Copyright 2022, ACS Publications. d) A liquid-droplet-based triboelectric urine sensor array produces different output voltages and currents based on analyte concentrations in the droplet. Reproduced with permission.[101] Copyright 2024, Wiley-VCH.

spin-orbit coupling (SOC) represent the next frontier in enhancing selectivity.[84,115–119] SOC, a quantum phenomenon, induces spin-dependent energy shifts, enabling sensors to detect and distinguish chiral molecules based on their unique spin signatures. This capability is particularly valuable for applications like cancer diagnostics, where differentiating enantiomers can significantly improve the accuracy of detection and monitoring. By incorporating SOC into smart dust systems, we open the door to an entirely new level of selectivity, empowering these systems to handle the complexity of biological and chemical environments with exceptional precision.

To further elevate selectivity, advanced data processing techniques, such as machine learning and neural networks, can be employed to analyze the data obtained from smart dust.[120] In these systems, sensor arrays are designed to detect specific analytes or concentration ranges, generating rich datasets that capture subtle variations in chemical responses.[121] Machine learning algorithms analyze these complex patterns, identifying correlations that traditional methods might miss.[122] Neural networks refine the accuracy of analyte identification, even in cases where signals overlap or become ambiguous.[123–125] This computational power allows smart dust systems to simultaneously detect and differentiate multiple analytes in real time, even in chemically complex environments.

Despite these progresses, selectivity for smart dust systems remains a significant challenge, particularly in maintaining reliable performance across complex and dynamic environments. Achieving high selectivity for diverse analytes in real-world scenarios necessitates precise optimization of techniques such as doping and surface functionalization. These approaches must be complemented by advanced calibration strategies using machine learning and artificial neural networks to account for confounding factors and improve accuracy. Furthermore, emerging phenomena such as Rashba SOC offer intriguing potential for enhancing selectivity, though their practical implementation is hindered by the demanding quantum mechanical conditions required for their operation. To address these challenges, future research should emphasize the development of novel nanomaterials, such as functionalized nanoparticles, quantum dots, and metal-organic frameworks (MOFs), which can provide intrinsic selectivity at the nanoscale.[126] Advancements in ML models tailored for low-power, embedded systems, or neuromorphic hardware will enable rapid real-time data analysis while minimizing energy consumption.[127] Additionally, the integration of high-charge-mobility materials and asymmetric 2D materials exhibiting spin Hall effects could pave the way for spintronic devices that exploit SOC to achieve enhanced selectivity.[128] Hybrid systems capable of offloading computational tasks to external devices could further optimize energy efficiency without sacrificing performance, marking a significant step toward the practical realization of smart dust systems.

3.3. Transforming Wearable and Implantable Sensors into Smart Dust

Wearable and implantable devices represent a critical bridge toward the vision of smart dust systems, offering a more immediate, user-centered approach to autonomous sensing while sharing complementary goals.[132,133] Wearable devices are designed primarily for personal use, providing real-time feedback and monitoring of health, fitness, and communication metrics.[134,135] These devices, while larger and more conspicuous than smart dust, directly interact with users and focus on comfort, usability, and long-term data reliability. Conversely, smart dust systems are engineered for large-scale, environment-embedded applications, incorporating features such as extreme miniaturization, wireless power, biodegradable materials, and advanced communication modules.[136,137] These attributes enable smart dust to operate invisibly and sustainably, seamlessly integrating into industrial, environmental, and healthcare settings.

While wearable devices can function as standalone systems, they also hold potential as components or precursors to smart dust networks. For instance, microneedle-based sensors or implantable devices could complement smart dust systems by providing localized, high-resolution data within a larger distributed sensing framework.[138,139] This integration would allow for a dynamic interplay between personal monitoring and large-scale autonomous sensing. However, the miniaturization of wearable and implantable devices for smart dust applications introduces significant technical challenges. Achieving submillimeter-scale functionality while maintaining sensitivity, reliability, and durability is a formidable task. Mechanical integrity often becomes a limiting factor in fabricating microneedle sensors or flexible implants at such diminutive sizes. Similarly, integrating energy-harvesting components, such as solar cells, triboelectric or piezoelectric nanogenerators, or biocompatible batteries, into these devices is complicated by the need for consistent operation in harsh or confined environments, such as within the human body.[140] Advancements in biocompatible materials and flexible electronics, including the use of stretchable serpentine electrodes and van der Waals (vdW) materials, are critical to overcoming these hurdles.[141,142] High-resolution printing techniques capable of micro-scale precision, alongside innovations in biodegradable coatings and encapsulation, are essential to ensuring device longevity and biocompatibility.[143] Additionally, the development of ultra-low-power wireless communication protocols, such as Zigbee or passive power transmission via inductive coupling, will be vital for creating energy-efficient and secure sensing systems.[144] By integrating these advancements, wearable technologies have the potential to evolve into essential components of smart dust networks, bridging the gap between personal monitoring and distributed autonomous sensing. These devices, with their capacity for continuous, real-time data acquisition, demonstrate the possibilities when technology becomes intimately interwoven with our daily lives.[145–147] However, unlocking their full potential within the realm of smart dust requires more than miniaturization. It demands a transformation into tiny yet powerful nodes within a vast, self-organizing network. The ability of these nodes to harmoniously interact and exchange data will enable a new era of interconnectedness, where individual sensors contribute to a cohesive system capable of dynamically monitoring and responding to complex environments.

As depicted in **Figure 4**, wearable and implantable devices have already shown their transformative potential in real-time health assessments. Figures 4a–c illustrate flexible sensors made from functionalized reduced graphene oxide (rGO) on porous cellulose substrates, where the molecular sieving action of these

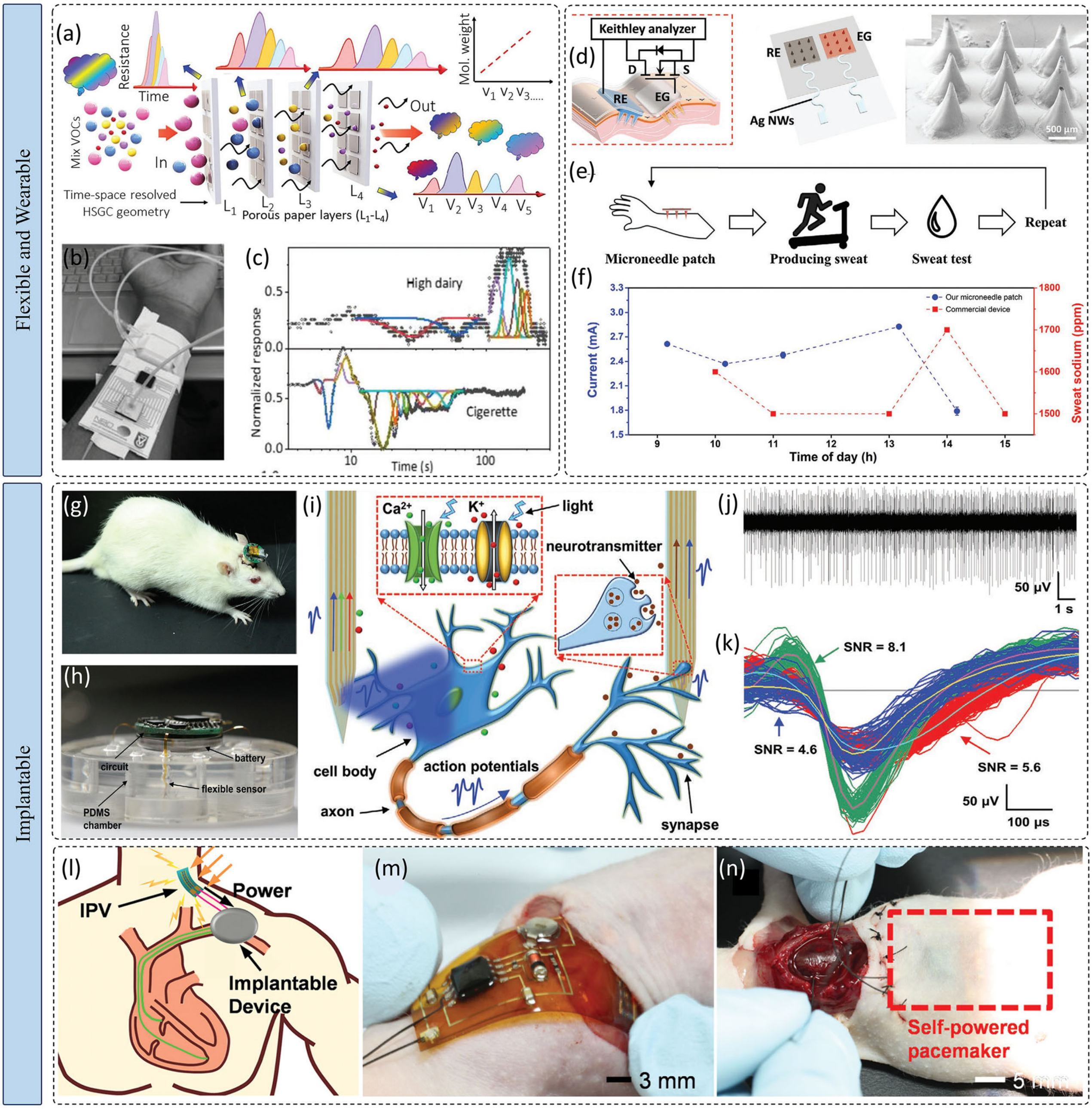

Figure 4. Flexibility and wearability: a–c) Working principle of a flexible and wearable sensing array that provides a spectrum of responses from sweat depending on dietary conditions. The porous substrate, made of cellulose nanofibers, performs molecular separation based on size and molecular weight, followed by detection via functionalized rGO. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[83] Copyright 2022, Wiley-VCH. d–f) A wearable microneedle sensor for real-time detection of Na^+ in sweat and interstitial fluid. Reproduced with permission.[129] Copyright 2021, Wiley-VCH. g–i) A battery-powered wireless implantable microneedle sensor that simultaneously stimulates neurons through optical and electrical means, and detects concentrations of K^+, Na^+, and Ca^{2+} in different regions of the brain, aiding in the understanding of neural pathways and neurotransmitter transport. j–k) Extracellular spiking signals recorded by the sensor. Reproduced with permission.[130] Copyright 2020, Wiley-VCH. l–n) An implantable flexible pacemaker powered by a flexible solar cell array. Reproduced with permission.[131] Copyright 2016, Wiley-VCH.

layers allows the differentiation of chemical components based on molecular weight and diffusivity.[83] This ability to identify and quantify chemical mixtures in real-time is a glimpse into the future of smart dust sensors capable of not just detecting but understanding the intricate chemical signatures of our environments and bodies. However, to truly fit the vision of smart dust, these devices must shrink to the size of particles so small that they seem to vanish, working invisibly yet powerfully in a synchronized network. They must not only detect but communicate, forming a seamless dialogue with the larger systems that surround them. Microneedle-based sensors (Figure 4d–k),[129,130] offering robust platforms for analyzing biological fluids, represent another significant stride toward the future of smart dust. These semi-implantable sensors, capable of detecting markers of health and disease, embody the potential to turn every interaction with the environment into a rich data exchange.[148–153] For example, Zheng et al.'s microneedle sensor, designed to monitor ion levels in sweat,[129] or Ling et al.'s electro-optic sensors for neural pathway monitoring, showcase the intricate connections that can be formed between the body, technology, and data (Figure 4g–k).[130] As we push forward, these technologies must evolve to operate autonomously, exchanging information not only with the human body but also with each other, creating a distributed network that is aware of itself and its surroundings. The miniaturization of these devices, combined with enhanced communication capabilities, will be the key to allowing them to work as a unified system, much like a colony of intelligent particles.

Fully implantable devices, as illustrated by Song et al.'s flexible pacemaker (Figure 4l–n),[131] bring the dream of seamless integration between technology and biology even closer. Powered by integrated solar cells, these devices represent the ideal self-sustained, autonomous systems capable of functioning continuously within the human body. For smart dust, such devices will need to be even more refined and networked, with the ability to communicate not just with the body, but also with the surrounding environment and the greater digital ecosystem.[154,155] The ability to seamlessly integrate into a vast, interconnected network will be key to unlocking their true potential.[156]

3.4. Integrating Sustainable Properties

As we envision the future of smart dust—millions of tiny sensors scattered across the environment and woven into the fabric of our biological systems—it is crucial to consider the material legacy they leave behind. In this endeavor, smart dust must not only enhance our lives but also respect the ecosystems and bodies it interacts with. This is where the concept of sustainability and harmony enters the equation. The widespread deployment of smart dust calls for materials that are not just functional, but that naturally dissolve and return to the earth or the body without leaving behind a trace of harm.[157] Biocompatible and biodegradable materials (**Table 1**) are the key to unlocking this potential, ensuring that the impact of these invisible sensors is not one of destruction, but of symbiosis.

Natural polymers like chitosan and polysaccharides, along with synthetic options such as polylactic acid (PLA), polycaprolactone (PCL), and poly(lactic-co-glycolic acid) (PLGA) are ideal for this purpose as they degrade harmlessly over time.[190–193] Additionally, biodegradable metals like Mg, Zn, and Fe can be used in micro-wiring and sensor components, ensuring that the materials dissolve after fulfilling their purpose in biomedical applications.[194,195] This approach is especially important for implanted sensors, as it prevents the need for chronic exposure or surgical removal. Furthermore, for enhancing the durability of smart dust, self-healing biocompatible materials can provide resilience under harsh conditions.[196,197] These materials allow for the repair of damaged components, maintaining functionality even in extreme environments. For instance, Tang et al. developed a self-healing elastomer that not only restores integrity after rupture but also accelerates healing in infected wounds,[198] demonstrating how self-repairing materials can improve the longevity of smart dust devices.

Table 1. List of materials for smart dust.

Substrates	Electrodes	Functional materials	Refs.
Cellulose	Mg	MgO	[158–161]
Chitosan	Mo	ZnO	[160,162–164]
Starch	Zn	MoS_2	[160,165–167]
Dextran	Fe	WS_2	[160,168–170]
Collagen	W	GO/rGO	[160,163,171,172]
Poly (glutamic acid)		Black phosphorous	[173,174]
Alginate		Mo_2C-PVA Mxene	[175,176]
Fibroin		SnS_2	[177,178]
Polylactic acid		$MoTe_2$	[179,180]
Polycaprolactone		MnO_2	[181,182]
Poly (glycolic acid)		Co_3O_4	[183,184]
Polyvinyl alcohol			[185]
Poly (lactic-co-glycolic acid)			[186]
Polyethylene glycol			[187]
Polycaprolactone			[188]
Polyorthoester			[189]

For sensing functions, lightweight and biodegradable 2D materials like MoS_2, WS_2, MXene, and black phosphorus offer exceptional electrical and chemical properties, ensuring high sensitivity and selectivity to environmental cues and analytes while maintaining compatibility with physiological systems.[202–204] These materials, with their high surface area, enable enhanced interaction with target analytes, leading to improved sensitivity and selectivity in sensing. Their structure allows for easy functionalization, facilitating targeted detection of specific environmental or biomedical markers. Additionally, 2D materials offer excellent processability, printability, and compatibility with solution-based production, which are essential for large-scale, low-cost fabrication of smart dust devices.[205] Being ultralightweight, they minimize energy requirements and device footprint, crucial for airborne or implantable applications. As quantum materials, they exhibit unique properties like chiral detection,[116] spin-dependent effects,[115] tunable bandgap,[206] and electronic responses, enabling advanced functionalities such as selective molecular recognition and environmental adaptability in diverse sensing environments. Collectively, these advantages make 2D materials an ideal choice for sustainable, high-performance sensing platforms in smart dust technology, aligning with the needs for scalability and ecological responsibility.

Phosphorene, derived from black phosphorus (BP), has garnered attention for its excellent electronic mobility, tunable bandgap, and notable mechanical properties. These characteristics arise from its anisotropic structure, enabling high sensitivity in optoelectronic and chemiresistive sensors.[174] Han et al. have leveraged this by using phosphorene to detect gases at sub-ppb levels, with performance attributed to ectopic interlayer stacking and thickness-dependent variations in work function (**Figure 5a–c**).[199] Similarly, tungsten disulfide (WS_2) (Figure 5d) has demonstrated efficacy in acetone detection

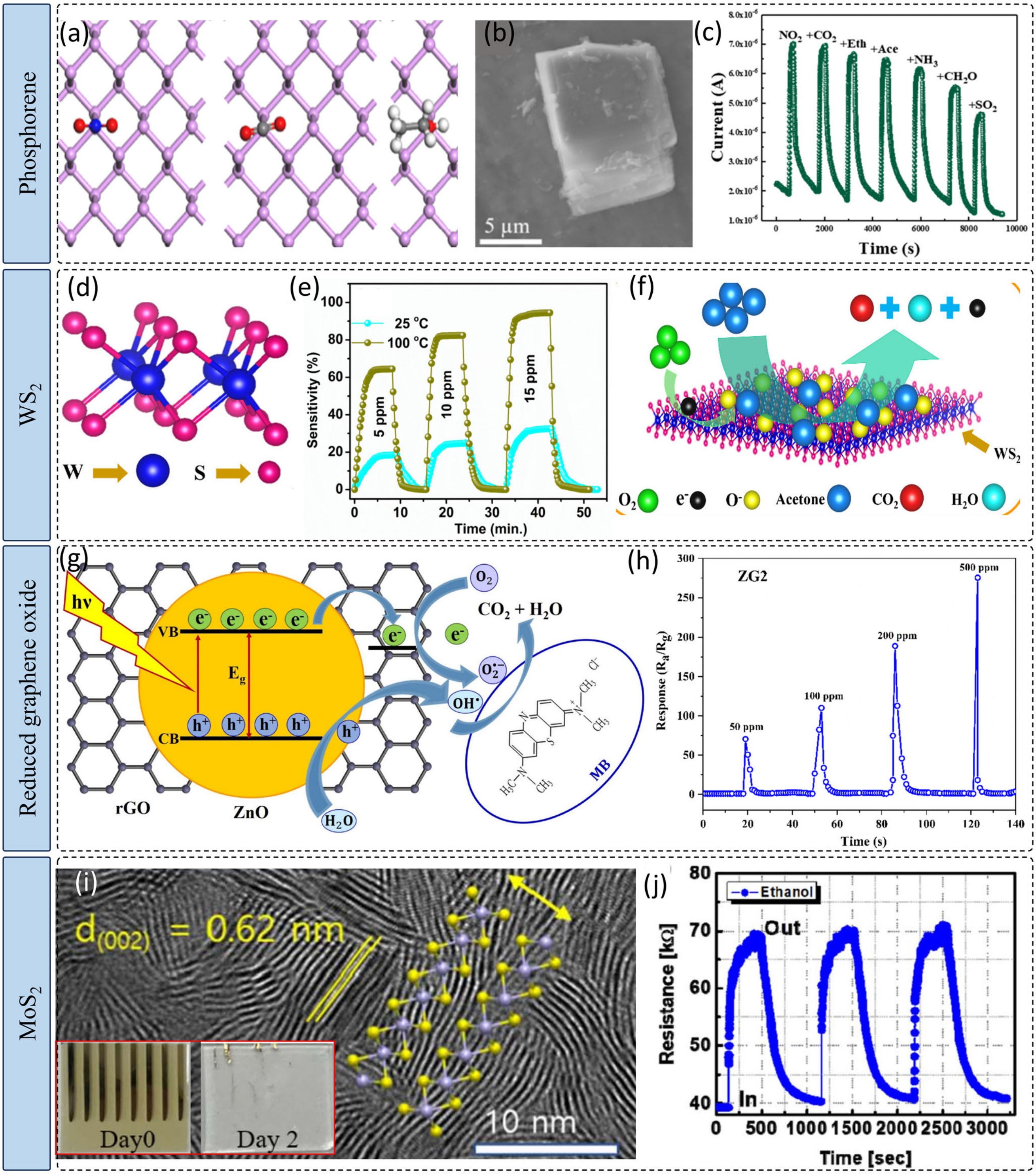

Figure 5. Biodegradable 2D materials: a) Top view of 2D phosphorene (black phosphorus, BP) in the presence of NO_2, CO_2, and ethanol. b) SEM image of a few-layered BP. c) Dynamic current response of a BP-based biodegradable gas sensor at room temperature and 26 RH%. Reproduced with permission.[199] Copyright 2022, ACS Publications. d) Crystallographic representation of WS_2, and e) its sensitivity towards acetone. f) The sensing mechanism is dependent on the adsorption of acetone at active sites on WS_2, leading to charge trapping and detrapping. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[200] Copyright 2022, MDPI. g) Reduced graphene oxide (rGO)-ZnO nanocomposite and its photocatalytic activity facilitating sensing. h) Response toward ethanol. Reproduced with permission.[201] Copyright 2022, Springer Science. i) HRTEM image of 2D MoS_2 layers, with inset showing biodegradation in phosphate-buffered saline (PBS) solution at 75 °C, and j) its VOC sensing demonstration. Reproduced with permission.[167] Copyright 2022, IOP Science.

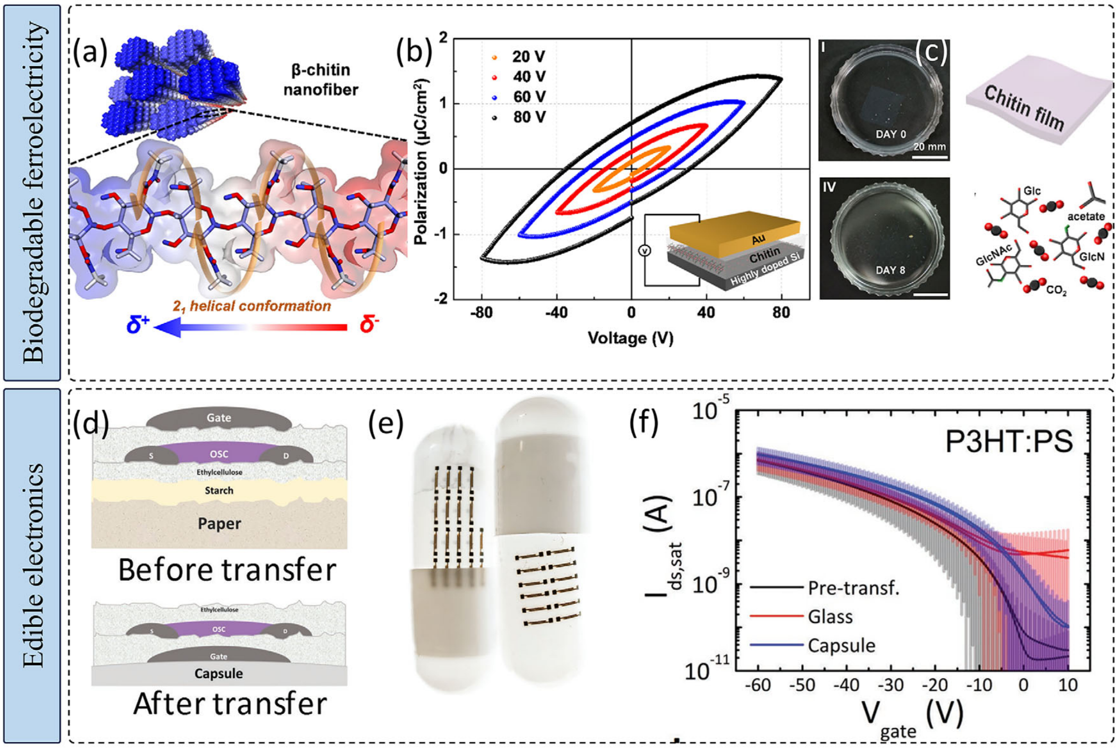

Figure 6. Biodegradable piezoelectric materials and edible electronics: a) Schematic of spontaneous polarization of β-chitin extracted from squid pen for a biodegradable piezoelectric transducer. b) Polarization versus electric field hysteresis of chitin thin film. c) Degradation of chitin film in chitinase solution. Reproduced with permission.[207] Copyright 2018, Elsevier. d) Schematic of an edible organic field-effect transistor (OFET) before and after transferring onto a capsule. e) Photographs of the device on a pharmaceutical capsule. f) Transfer characteristics of an OFET with a poly(3-hexylthiophene) (P3HT:PS) active layer before and after transferring. Reproduced with permission.[208] Copyright 2017, Wiley-VCH.

(Figure 5e), relying on active sites that facilitate acetone decomposition (Figure 5f).[200] This process is represented by the reaction $CH_3COCH_3 + 8O^- \leftrightarrow 3CO_2 + 3H_2O + 8e^-$.

rGO presents another promising material for sensing, with applications extending from enhanced electrocatalytic activity to photocatalytic processes. Its electronic spin sensitivity further enhances its sensing capabilities. A representative study demonstrated that an rGO-ZnO composite could degrade methylene blue (MB) in the presence of light, while concurrently enhancing ethanol detection by balancing the Fermi level at the p-n heterojunction (Figure 5g,h).[201] Further, MoS_2 integrated on cellulose nanofibers (CNFs) combines high mechanical flexibility with surface-rich dangling bonds, leading to high responsiveness to VOCs (Figure 5I,j).[167] As shown in the inset of Figure 5i, the MoS_2/CNFs system is fully dissolvable in buffer solutions, such as phosphate-buffered saline (PBS), without releasing toxins, making it a promising candidate for sustainable, biocompatible smart dust applications.

Biodegradable and biocompatible piezoelectric materials are pivotal for advancing smart dust technology, enabling environmentally safe, self-powered, and wirelessly communicating sensor systems.[209] These materials harness ambient mechanical energy from sources like movement, vibrations, and pressure to generate power, allowing for autonomous sensing and data transmission. Materials such as cellulose composites, ZnO, and polymers like poly(3-hydroxybutyrate) (PHB) and PLA are especially promising due to their inherent biodegradability and minimal ecological impact.[193] For example, β-chitin, a naturally derived polymer with spontaneous polarization, exhibits strong hysteresis, suitable for biocompatible, degradable, and sustainable sensing systems (**Figure 6**a–c).[207] Moreover, these piezoelectric materials serve as effective transducers in surface acoustic wave (SAW)-based devices,[210] supporting wireless power and communication, as detailed later. This convergence of piezoelectricity, biodegradability, and biocompatibility enables the development of transient, eco-friendly sensing technologies that align with the green design goals of smart dust networks. Parallelly, organic electronics offer significant advantages for the development of smart dust systems, particularly due to their flexibility, lightweight nature, and low-cost manufacturing.[211] These materials can be processed via scalable techniques such as inkjet printing or roll-to-roll methods, enabling the mass production of functional devices.[157] The biocompatibility and biodegradability of organic electronics also make them ideal for environmentally-conscious applications, such as medical implants or eco-friendly sensors. Similarly, edible electronics represent a novel category of devices made from safe, biodegradable, and ingestible materials, such as organic polymers, proteins, and edible metals.[212] These devices involving all-biodegradable components can safely dissolve in the human digestive system, providing non-invasive health monitoring through real-time data on biomarkers such as glucose levels or hydration status.[213] A representative example of an edible electronic device is shown in Figure 6d–f.[208] In this study, Bonacchini and colleagues developed an ingestible organic field-effect transistor (OFET) using biodegradable and edible materials, such as ethylcellulose, starch, and P3HT as the semiconducting polymer channel. This device showcases the potential for integrating organic, biodegradable components into smart dust devices that can safely dissolve within the human body.

Figure 7 showcases various examples of biocompatible and biodegradable sensing devices applied in healthcare, environmental monitoring and agricultural settings. Figure 7a illustrates a device composed of biodegradable elements like polyaniline (PANI), PEDOT:PSS, Mg, zinc nanoparticles (ZnNPs), and chitosan, designed for sensing pH, pressure, and VOCs.[214] These devices degrade completely, either naturally or with the help of catalytic components, ensuring no harmful residue remains (Figure 7b). Another example, from Yu et al., demonstrates a biodegradable system with SiO_2, Si_3N_4, Si, Mo, and PLGA layers, which degrade entirely in a PBS solution within hours (Figure 7c).[215] Figure 7d features a biodegradable storage unit by Hosseini et al., which uses rice paper and chitosan substrates for memristor devices that disintegrate in water within hours.[216]

Expanding on this concept, smart dust technologies push the boundaries of precision agriculture by incorporating biodegradable and environmentally sustainable sensing systems.[219–221] Leveraging eco-friendly materials such as CNF substrates, these devices degrade naturally, reducing waste. For example, a flexible amperometric sensor designed for nitrate detection in water and soil (Figure 7e) employs screen-printed copper nanoclusters and a solid-state ion-selective membrane (ISM) for high sensitivity and selectivity, degrading entirely within four weeks in compost soil.[217] Another innovation features capacitive moisture sensors screen-printed on CNF-infused substrates (Figure 7f), offering precise, real-time soil moisture monitoring and compatibility with wireless IoT systems due to their superior print trace quality and self-resonance frequency.[218] Together, these advancements demonstrate the synergy between biodegradable sensor technologies and sustainable applications across multiple domains. Nonetheless, the sustainability of smart dust systems represents a critical challenge, as it requires balancing high performance with environmental and biological compatibility. Natural polymers such as cellulose and chitosan offer biodegradability but often lack the mechanical stability or thermal resilience needed for extreme conditions. Synthetic alternatives like PLA and PCL, while more stable, degrade slowly in certain environments, leading to potential accumulation concerns. Similarly, biodegradable metals such as magnesium and Zn degrade rapidly in biological or humid environments, compromising the longevity of sensors and limiting their practical applications. Striking a balance between controlled biodegradability and robust performance remains a significant technical hurdle.

To address these challenges, the development of hybrid materials that combine biodegradability with high-performance characteristics is essential. For instance, bio-based polymers reinforced with nanomaterials such as graphene or carbon nanotubes could enhance mechanical and thermal properties while enabling controlled degradation.[222,223] Additionally, biodegradable alloys tailored for gradual corrosion in specific environments could improve sensor longevity without compromising eco-friendliness.[224,225] The requirement for biocompatibility and biodegradability also introduces significant challenges when integrating sensing elements with the essential circuits for communication and data collection, as conventional integrated circuits (ICs) are typically composed of non-biodegradable materials like silicon or metals. To address this, biodegradable alternatives must be explored. Promising strategies could include the use of organic conductors and semiconductors for the active components while leveraging passive powering and communication technologies that do not rely on complex ICs.[52,226,227] Thus, advancements in material science will play a pivotal role in achieving the delicate equilibrium between functionality, sustainability, and environmental stewardship for next-generation smart dust systems. By incorporating these sustainable, biocompatible materials, smart dust technologies can move toward more environmentally friendly and safer applications.

3.5. Miniaturization

Miniaturization lies at the heart of the vision for smart dust technology, unlocking the potential for compact, highly sensitive, and multi-functional sensors that can be deployed in environments where traditional devices are impractical or intrusive.[232] Achieving micro- to nano-scale dimensions is not merely a technical challenge but a key enabler of future possibilities.[43,69] Through miniaturization, smart dust can be transformed into self-propelled entities that navigate through air currents. This airborne capability ensures that sensors can cover vast areas or access challenging, remote locations, creating a truly adaptable and scalable solution for continuous, real-time data acquisition. This miniature design also brings significant advantages in power efficiency. Smaller devices inherently consume less energy, supporting long-term autonomous operation without the need for external recharging—an essential feature for monitoring in remote regions or inaccessible environments. Dense networks of these miniaturized smart dust particles can be deployed for high-resolution, continuous mapping of environmental or physiological parameters. In biomedical applications, this compact size minimizes invasiveness, allowing for real-time, in situ monitoring with minimal patient discomfort.

To realize the vision of sub-millimeter smart dust particles, advanced fabrication processes can be employed. Techniques such as oxidation, diffusion, ion implantation, chemical vapor deposition (CVD), and sputtering, combined with micromachining, advanced lithography, and 3D printing, will enable the creation of micron-sized devices (<500 µm). Batch fabrication - a process for producing large quantities at scale - will be essential to drive down costs and facilitate the mass production of millions of smart dust particles, making them accessible for widespread use in diverse applications. Innovative approaches such as origami-inspired folding,[233,234] vertical stacking,[235–238] and shape-changing smart materials will play pivotal roles in enabling the required miniaturization. Origami-inspired folding, for instance, offers dynamic, compact designs that unfold and adapt to optimize functionality in situ. As seen in **Figure 8a**,[228] folding designs allow for efficient deployment and flexible reconfiguration. Xu et al. demonstrated this concept by using 2D MoS_2 layers integrated into a photo-crosslinked SU8 film, which self-folds reversibly through solvent-induced swelling gradients (Figure 8b).[229] Vertical stacking further optimizes space, allowing for multi-layered architectures where

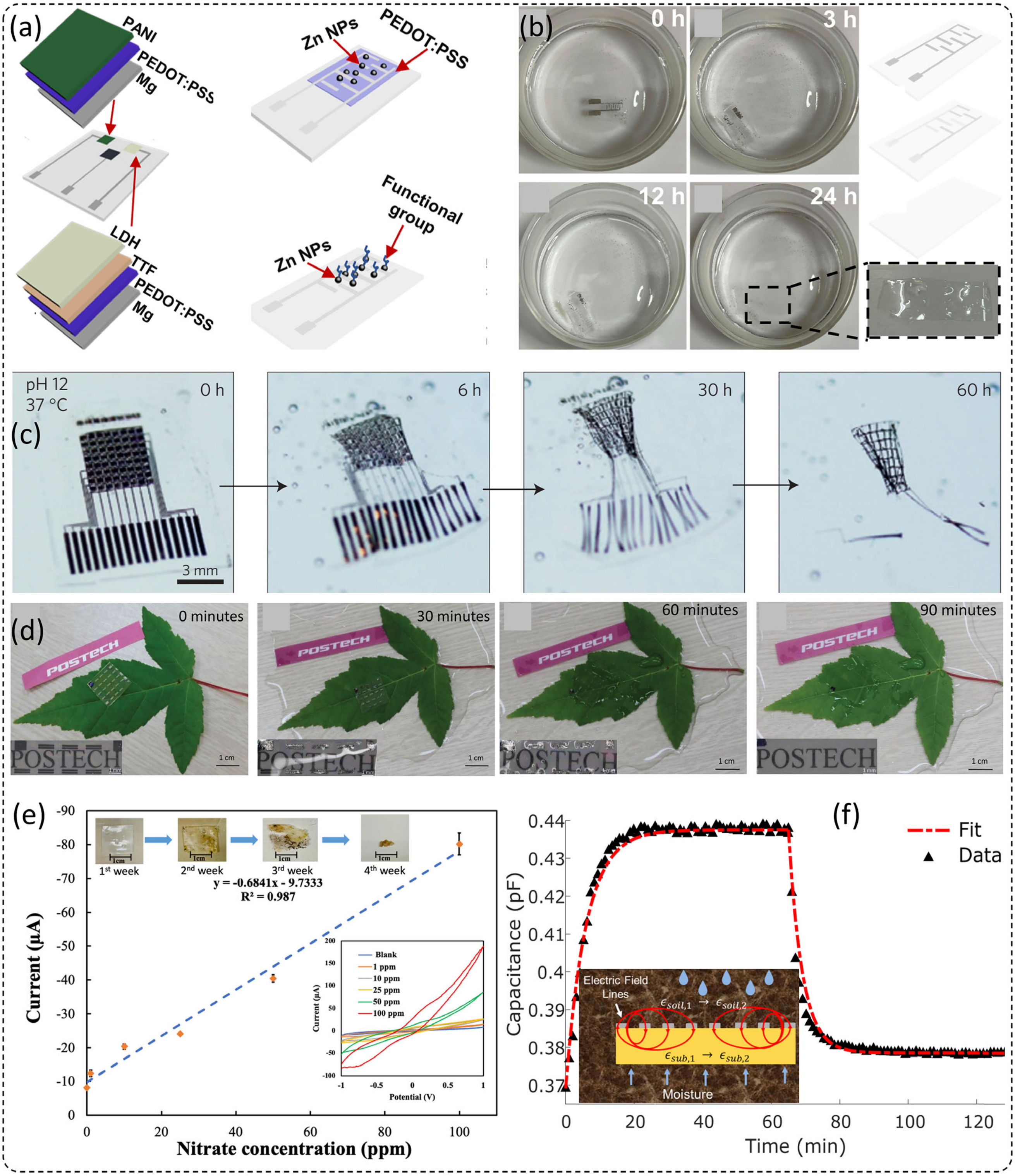

Figure 7. Biodegradability and biocompatibility: a) Schematic designs of pH, pressure, and VOC sensors with biocompatible and biodegradable components. b) Experimentation showing the biodegradation of the sensors in simulated body fluid (SBF). Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[214] Copyright 2024, ACS Publications. c) Degradation of a bioresorbable electrocorticography sensor on a PLGA substrate in an aqueous buffer solution (pH 12) at 37 °C. Reproduced with permission.[215] Copyright 2016, Nature Portfolio. d) Degradation of a decomposable device made with a chitosan substrate. Reproduced with permission.[216] Copyright 2015, Wiley-VCH. e) Biodegradable screen-printed electrochemical sensor featuring MoS_2 electrodes on a cellulose film, designed for nitrate concentration detection in agriculture, fully decomposing within four weeks in compost soil. Reproduced with permission.[217] Copyright 2023, IEEE. f) Cellulose-based moisture sensors exhibit capacitance variations corresponding to changes in soil relative humidity (RH%), enabling sustainable and precise environmental monitoring. Reproduced with permission.[218] Copyright 2023, IEEE.

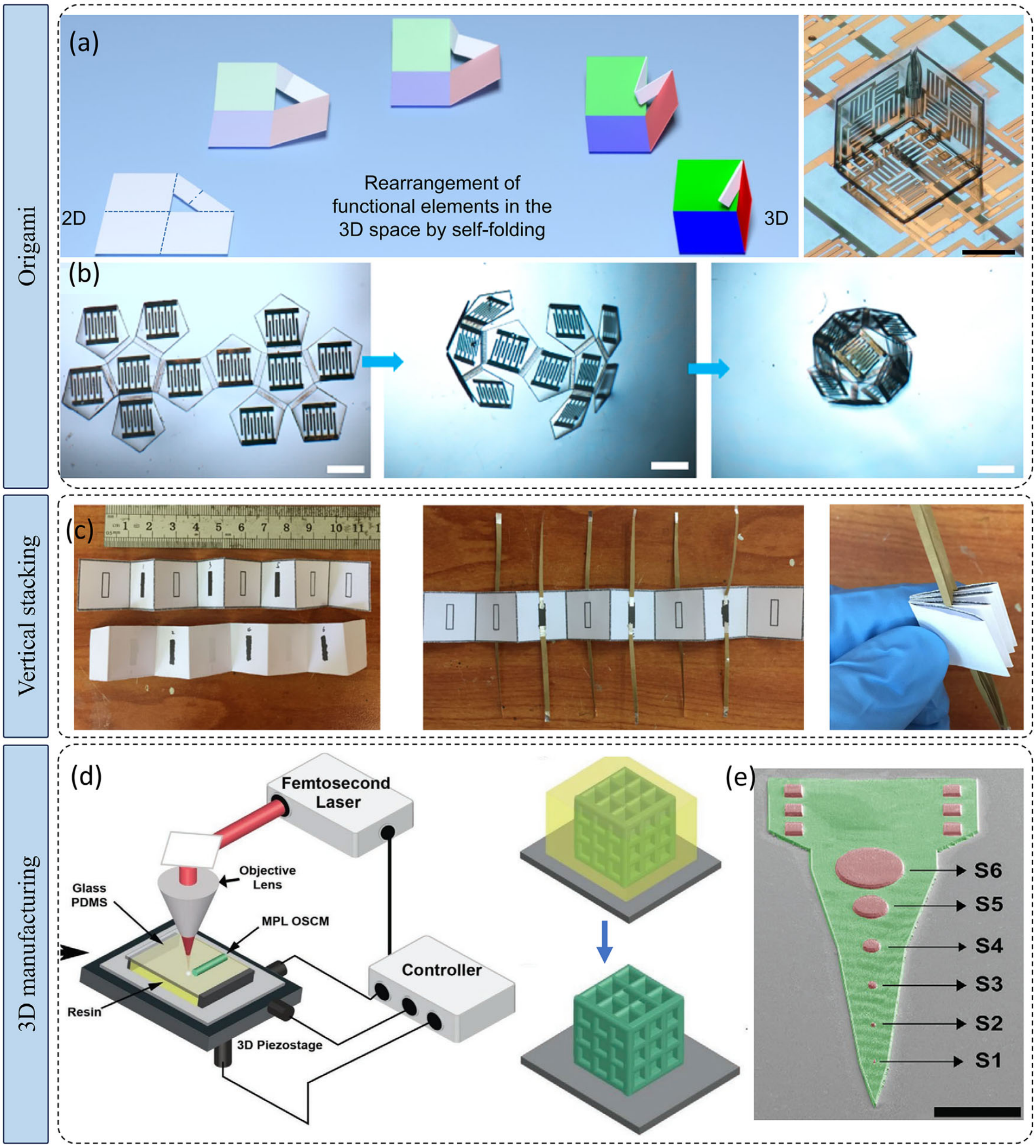

Figure 8. Miniaturization: a) A self-folding micro-origami sensor array designed for magneto-sensitive e-skin applications. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[228] Copyright 2022, Nature Portfolio. b) Design of hinged 3D photodetectors fabricated using a self-folding process. Reproduced with permission.[229] Copyright 2019, ACS Publications. c) Miniaturization of a complex and large sensor array is achieved through folding and vertical stacking. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[230] Copyright 2019, Nature Portfolio. d) 3D manufacturing of intricate microstructures via multiphoton lithography (MPL). e) Pseudo-colored SEM image of an MPL-formed biosensor, featuring functional polymer (green) and doped organic semiconductors (red) (scale bar: 100 µm). Reproduced with permission.[231] Copyright 2022, Wiley-VCH.

components like transducers, power sources, and wireless communication units are arranged to minimize interference while maximizing operational efficiency (Figure 8c).[230] 3D printing offers another key advantage, enabling the creation of intricate microstructures with integrated multifunctional layers.[239–241] As demonstrated by Toussi et al., multiphoton lithography (MPL) can be used to fabricate organic semiconductor microstructures that enhance glucose sensor sensitivity via glucose oxidase encapsulation (Figure 8d,e).[231] Furthermore, integrating shape-memory materials and smart alloys, such as Ni-Ti and Cu-Al-Ni,[242–244] adds a new dimension of adaptability to smart dust systems. These materials allow sensors to autonomously reconfigure in response to environmental stimuli, enhancing their performance in dynamic and unpredictable conditions.

Miniaturization, while essential for enhancing portability and minimizing environmental footprints, presents inherent challenges in fabrication, sensitivity and communication within smart dust systems. As sensor dimensions shrink, the surface area available for interaction with target analytes decreases, potentially reducing detection efficiency. In techniques like Raman spectroscopy, miniaturization reduces photon yield and detection accuracy. Nonetheless, these limitations can be mitigated by leveraging nanostructured materials with high surface area, surface plasmon resonance, metasurfaces, and high-efficiency photodetectors.[245,246] Communication also becomes more difficult as device size reduces, primarily due to reduced signal transmission range. To address these, backscattering communication, optical data transmission, and their hybrid strategies can help extend operational lifetimes while ensuring efficient data exchange.[53,247] As these technologies evolve, the convergence of portability, energy efficiency, and precision achievable through miniaturization will position smart dust as a transformative self-sustaining tool for advancing chemical surveillance.

3.6. Wireless Powering

The traditional reliance on batteries or capacitors to power smart dust sensors presents significant challenges, including issues with toxicity, limited lifespan, and bulkiness. These challenges make it difficult to deploy smart dust in sensitive environments, such as the human body or fragile ecosystems. To overcome these limitations, wireless powering emerges as a transformative solution, enabling smart dust to function autonomously, without the need for manual recharging or conventional power sources.[251–255] Wireless power allows for continuous, maintenance-free operation, even in remote or hard-to-reach locations, which is crucial for the large-scale, real-time environmental and biomedical monitoring that smart dust can offer.[256,257]

There are several methods for wireless power transfer, each leveraging different physical principles to deliver energy efficiently and remotely.[248] Inductive power transfer (IPT) (**Figure 9a**) uses alternating currents in a transmitter coil to generate magnetic fields, which induce currents in a receiver coil on the device. IPT is highly effective for near-field applications where smart dust devices are in close proximity to the power source.[258] Similarly, capacitive power transfer (CPT) (Figure 9b) generates high-frequency electric fields between two capacitive plates. While this method is particularly useful for compact designs, it is limited to short-range transmission due to the spatial constraints of electric fields.[259] To extend the range of wireless power delivery, far-field power transfer (FPT) utilizes electromagnetic waves, such as microwaves or RF, to transmit energy over greater distances (Figure 9c). FPT is ideal for long-range applications, allowing energy to travel significant distances before being harvested by a receiver.[260] However, precise alignment and tuning are required to maintain efficiency, as power transfer efficiency (PTE) decreases with increasing distance. This makes FPT particularly valuable in large-scale smart dust deployments where existing infrastructure, such as cellular towers, can be leveraged not only for power delivery but also for data communication. The ability to use aerial platforms like drones equipped with RF-transmitting capabilities can further expand the reach of FPT, enabling dynamic power and data collection across vast areas.

For medium-range applications, acoustic power transfer (APT) (Figure 9d) offers an alternative by using ultrasonic waves to induce mechanical vibrations in a piezoelectric receiver, which then converts these vibrations into electrical energy. APT can penetrate materials that electromagnetic waves cannot, making it particularly useful for embedded or subsurface devices.[261,262] This ability to transfer power in environments that RF waves might not reach broadens the operational scope of smart dust, especially in industrial or biomedical settings where sensors might be deployed in challenging conditions.

Advancements in wireless power technologies continue to demonstrate the potential for smart dust applications. For instance, as shown in Figure 9e–g, Garland et al. integrated an IPT-based wireless power transfer system with a biosensor for lactate monitoring, facilitating real-time tracking of diabetic conditions without the need for internal power storage.[249] Similarly, Kim et al. developed a SAW–based wireless system using a piezoelectric material, 2D GaN, as shown in Figure 9h,i.[52] This system allows non-invasive data collection by coupling electromagnetic signals with piezoelectric materials to generate surface-bound acoustic waves, enabling applications like pulse monitoring. In addition to inductive power transfer, piezoelectric, and triboelectric energy harvesting methods offer further opportunities for battery-free smart dust systems. As illustrated in Figure 9j,k, triboelectric receivers can harness acoustic waves to generate power, which can then be used to operate Bluetooth-enabled sensors for wireless data transmission.[250] These energy-harvesting methods enhance the sustainability of smart dust, ensuring uninterrupted real-time monitoring across large areas without the limitations of battery-powered devices. Such systems, however, present considerable challenges, particularly in achieving efficient energy transfer over long distances while maintaining compatibility with environmental and operational constraints. IPT offers high efficiency but is limited to short-range applications, while CPT similarly suffers from distance-related efficiency reductions due to its dependence on electric fields. FPT holds promise for long-range energy delivery but is hindered by significant efficiency losses with increasing distance, necessitating specialized infrastructure. APT provides the advantage of penetrating through certain materials, but its scalability and miniaturization remain challenging for the submillimeter dimensions of smart dust systems. Additionally, the miniaturization of wireless power receivers exacerbates these efficiency challenges, further complicating the design of energy systems for smart dust networks.

To address these limitations, advancements in high-efficiency, long-range wireless power transmission methods are essential. For instance, leveraging flexible materials with high ferroelectric properties or developing technologies to harvest electromagnetic energy from existing telecommunication systems could enhance energy transmission efficiency and focus precision.[263,264] Ultrasonic power transmission offers another avenue for sustainable long-range power delivery.[265,266] Hybrid approaches that combine multiple wireless power transfer techniques could adapt to varying environmental conditions, optimizing energy efficiency across diverse scenarios.[267] Additionally, integrating ambient energy harvesting systems that utilize vibrations, light, or thermal gradients can supplement wireless power transfer, reducing dependence on external power sources and enhancing the

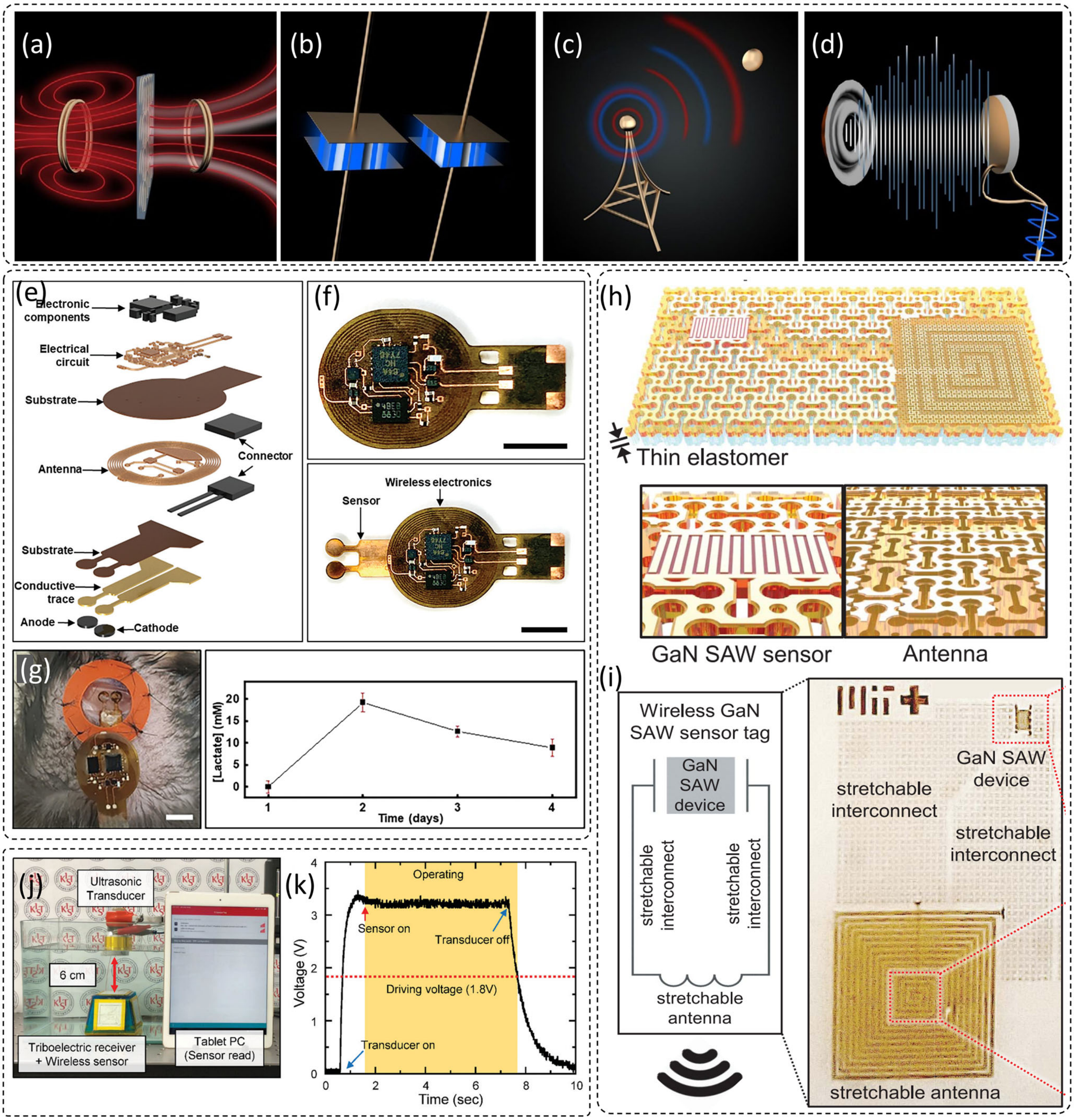

Figure 9. Wireless powering: a) Inductive power transfer (IPT), b) capacitive power transfer (CPT), and c) far-field power transfer (FPT), with red and blue lines representing magnetic and electric fields, respectively. d) Acoustic power transfer (APT). Reproduced with permission.[248] Copyright 2021, Nature Portfolio. e) Schematic design of a wireless, battery-free biosensor for lactate monitoring during the wound healing process. f) Photographs of the near-field communication (NFC)-based wireless sensor. g) Daily monitoring of lactate concentration by the wireless sensor in a diabetic mouse. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[249] Copyright 2023, Wiley-VCH. h) Schematic of a chip-less e-skin operated via SAW-based powering and communication. i) An optical image of the stretchable device where GaN functions as a 2D piezoelectric material for wireless operation. Reproduced with permission.[52] Copyright 2022, American Association for the Advancement of Science. j) Photograph of a triboelectric device used for underwater energy transfer through acoustic waves to operate a wireless sensor. k) Measured output voltage during wireless sensing operation. Reproduced with permission.[250] Copyright 2022, Royal Society of Chemistry.

sustainability of smart dust operations.[268] By harnessing ambient energy sources, wireless-powered smart dust systems will enable large-scale, autonomous operations that provide real-time, continuous data acquisition across diverse settings.[269] This evolution paves the way for smarter, more efficient monitoring systems that can operate seamlessly in dynamic, ever-changing environments.

3.7. Wireless Communication and Storage

Wireless communication and data storage are pivotal to the evolution of smart dust technology. To transform smart dust from a concept to a ubiquitous tool capable of operating in complex, often unreachable environments, reliable data transfer methods are crucial. Currently, wireless communication and powering are fundamental for transmitting data from dispersed devices without physical links, but further advancements are needed to refine these systems and integrate them more effectively into real-world applications.

As highlighted in previous discussions, core principles like near-field communication (NFC) and energy harvesting play a foundational role in smart dust's capabilities.[272–274] However, to fully realize the potential of these systems, optical phenomena, and elastic light scattering offer additional pathways for enhanced data transmission and detection.[275–277] For example, as shown in **Figure 10a**, poly(styrene-co-maleic anhydride) (PSMA)-based sensors for detecting volatile biogenic amines (VBAs) utilize NFC to facilitate remote food quality assessment.[270] The sensors respond to VBAs by shifting their permittivity, causing detectable capacitance changes. These shifts can be detected by NFC-enabled devices such as smartphones, as seen in Figure 10b,c. Similarly, Figure 10d and e showcase an e-skin capable of detecting subtle mechanical vibrations and transmitting signals through a SAW-based transducer for remote monitoring.[52] These techniques demonstrate the power of electromagnetic field-driven communication in real-time monitoring, providing a glimpse into the kind of high-efficiency, low-power data transmission that will be essential for the next generation of smart dust systems.

To enhance the versatility of smart dust, data storage mechanisms must also evolve.[278] For systems requiring embedded data retention, lightweight, microscopic data storage units will be a key area for improvement.[279,280] As illustrated in Figure 10f, submillimeter CSMs integrated with 2D materials such as graphene, hBN, MoS_2, and WSe_2 enable autonomous data processing and storage.[54] These components, including photodiodes, chemiresistors, and memristors, allow smart dust particles to perform logical operations and store data on analytes (Figure 10g). This autonomous data storage will help reduce dependence on continuous wireless communication, allowing for data retention even when real-time access is not possible. However, the challenge lies in balancing data storage with real-time access, as integrated storage systems may limit the ability to transmit data instantly when needed. On the other hand, optical communication systems can significantly improve real-time data access, enabling faster, more efficient transmissions. As shown by Schmedake et al. in Figure 10h, multilayered porous silicon particles can reflect light at specific wavelengths according to the Bragg equation.[271] When exposed to analytes, these materials undergo capillary condensation, shifting their reflectivity spectrum, which allows for analyte quantification through fixed-wavelength optical shifts (Figure 10i). This approach shows great promise for real-time sensing applications, where immediate access to data is essential for dynamic decision-making.

The integration of wireless communication and data storage within smart dust systems presents significant technical challenges, including restricted communication range, limited power efficiency, and constrained data storage capabilities. Conventional methods such as NFC and SAW-based transducers, while effective for short-range communication, are inherently limited by low data transfer speeds and susceptibility to environmental interference. For instance, the miniaturization of antennas drastically increases their resonance frequency, complicating signal detection and necessitating the use of sophisticated and expensive equipment such as vector network analyzers. Although emerging technologies like CSMs and memristors offer promising solutions for localized data retention, achieving an optimal balance between high storage capacity and real-time data accessibility remains a formidable challenge.[54] Moreover, these systems must demonstrate robustness under harsh environmental conditions, including extreme temperatures and exposure to corrosive chemicals, further complicating their practical deployment. To overcome these limitations, advanced optical communication systems leveraging plasmonic nanoparticles hold significant promise, offering enhanced data transfer rates and greater resistance to environmental interference.[281] For storage, novel 2D materials like graphene and MoS_2 provide compact, energy-efficient memory solutions capable of maintaining data integrity under demanding conditions.[149] Additionally, the development of adaptive storage architectures that dynamically adjust data retrieval processes based on environmental and power constraints will be critical to ensuring the seamless, efficient operation of smart dust systems across diverse real-world applications. Looking forward, the continued development of these wireless communication and data storage solutions is critical to achieving fully autonomous, real-time smart dust networks. As smart dust systems become more integrated into everyday applications, improving the efficiency and range of wireless communication and optimizing embedded storage systems will be necessary to make these devices more effective, scalable, and adaptable.

3.8. Analysis and Mapping

Smart dust systems represent a groundbreaking shift in environmental analysis and mapping by offering a multi-tiered approach to real-time data collection, processing, and visualization. The power of smart dust combined with computation systems lies not only in its ability to collect molecular and environmental data but in its ability to map these data points with incredible precision and in real-time (Figure 2). This spatial awareness is key for the next step in environmental and biomedical monitoring, creating highly detailed maps of molecular concentrations and their dynamics across complex, large-scale environments.

Wireless data collection forms the foundation of this approach, leveraging existing infrastructure like cell phone towers, drones, and other telemetry systems to gather data from dispersed,

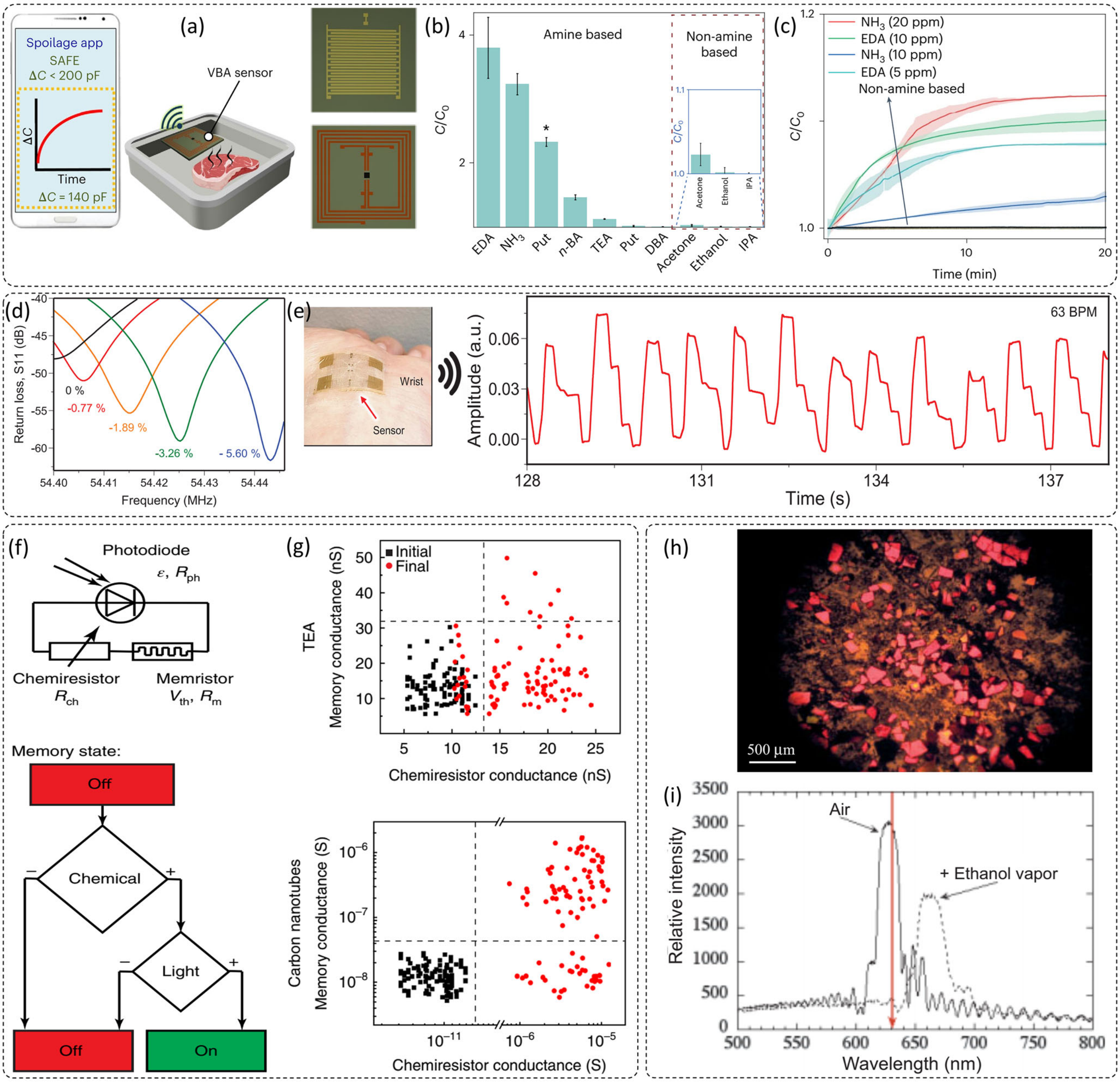

Figure 10. Wireless communication: a) A volatile biogenic amine (VBA) sensor for assessing food spoilage via wireless communication using an NFC chip. b) Device response measured using a mobile phone for different VOCs at a 40-ppm concentration, c) response at different concentrations. Reproduced with permission.[270] Copyright 2023, Nature Portfolio. d) Strain-dependent shift in resonance frequency of a SAW-assisted e-skin sensor free of a power source and communication chip, and e) corresponding response from wireless pulse measurement. Reproduced with permission.[52] Copyright 2022, American Association for the Advancement of Science. f) Electrical circuit and block diagram for a CSM or smart dust that utilizes a photodiode, a chemiresistor, and a memristor to memorize the surrounding chemical state, g) change in the conductance of the chemiresistor and the memristor due to exposure to triethyl amine (TEA, 10 mM) and carbon nanotube dispersion (0.2 g L^{-1}). Reproduced with permission.[54] Copyright 2018, Nature Portfolio. h) Optical microscopy image of porous Si particles used as smart dust, i) optical reflectivity spectra of a single dust particle in air and ethanol environments. Reproduced with permission.[271] Copyright 2002, Wiley-VCH.

hard-to-reach areas. By using advanced positioning systems, smart dust particles can be precisely localized, tracked, and mapped as they move through their environments. The integration of GPS, AI-driven algorithms, and drone-assisted tracking provides the spatial coordinates necessary to create highly detailed, 3D maps of molecular concentrations. To create these maps, the sensor data is transmitted to decentralized computational systems, where advanced data processing techniques, including machine learning, neural networks, and spatial analysis algorithms, are applied.[282–285] For instance, algorithms like k-means clustering or DBSCAN (Density-Based Spatial Clustering of Applications with Noise) can be used to identify distinct patterns or clusters within the data.[286–289] These algorithms group similar data points, whether pertaining to pollutant concentrations or biological markers, into meaningful clusters that can be visualized spatially. Principal Component Analysis (PCA) can reduce the dimensionality of complex data, highlighting key environmental variables while removing noise, allowing for more accurate and meaningful maps.[40] The integration of this data, both spatial and molecular, leads to the creation of 3D molecular concentration maps of target environments. These maps can be continuously updated as smart dust particles move and collect data over time, creating a dynamic and evolving picture of the environment. In pollution monitoring, this allows for the visualization of pollutant distribution across wide areas, identifying hotspots, and tracking the movement of contaminants. Models like convolutional neural networks (CNNs)[290,291] can be employed to analyze these maps in real-time, identifying correlations between molecular concentrations and specific geographical features or environmental conditions.

Advanced spatial analysis models also play a vital role in refining these maps. Geostatistical methods such as Kriging,[292,293] a form of spatial interpolation, allow smart dust systems to predict molecular concentrations in regions where data might be sparse. By using data from surrounding sensors, Kriging fills in gaps to create more accurate and complete maps. Additionally, Bayesian inference techniques enable the continuous updating of maps based on new sensor data, ensuring that the models stay accurate and relevant as environmental conditions change.[294,295] This 3D mapping capability opens new frontiers in numerous applications. For example, in industrial settings, smart dust can be used to map the chemical composition of the air, optimizing the manufacturing process by visualizing how different compounds are distributed across the workspace. In environmental protection, these systems can create highly detailed maps of pollution levels across urban, rural, or natural landscapes, providing real-time insights into air and water quality. These maps are invaluable for decision-making, allowing for immediate action in response to environmental hazards. In healthcare, smart dust could be used to map the spread of diseases or the distribution of therapeutic agents in the body. Through continuous monitoring and mapping of molecular changes, healthcare professionals could gain deeper insights into how diseases evolve over time and how treatments are distributed within the body. This could significantly enhance personalized medicine by offering a more accurate picture of a patient's health in real-time. Furthermore, the creation of these spatial maps will be essential in disaster management. Smart dust systems, equipped with sensors capable of detecting hazardous chemicals or biological agents, could map the spread of pollutants or contamination in real-time, providing critical data to emergency responders. These maps can guide efforts to mitigate harm and allocate resources more effectively, such as directing rescue teams to areas of greatest need or understanding the trajectory of a wildfire or chemical spill.

Ultimately, the integration of advanced data collection, sophisticated spatial algorithms, and real-time mapping will enable smart dust systems to create the next generation of environmental and biological monitoring tools. The continuous, evolving nature of these maps will allow for a deeper, more nuanced understanding of both natural and man-made systems, paving the way for Smarter, data-driven decisions. While the individual technologies discussed in this section represent significant advancements, their integration into a unified, functional smart dust system remains a highly complex challenge. This integration demands that miniaturization is not compromised, the performance of each component is preserved, and the system as a whole remains cost-effective and environmentally sustainable. Achieving such seamless synergy across multiple technologies is pivotal to realizing the vision of fully operational smart dust systems. Addressing these multifaceted challenges will require a combination of technological breakthroughs and interdisciplinary collaboration to develop scalable, cost-efficient, and eco-friendly solutions. Moreover, establishing clear regulatory frameworks will be essential to ensure the ethical deployment of smart dust systems. By overcoming these barriers, the transition from conceptual designs to practical implementations can unlock the immense potential of smart dust across diverse applications.

Early-stage prototypes and developmental efforts, as highlighted in the below section, offer valuable insights and serve as critical milestones in the journey toward this ambitious objective. These prototypes illustrate incremental progress, showcasing how individual sensing modalities, energy-harvesting mechanisms, and wireless communication technologies can be miniaturized and integrated into nascent systems. Although the comprehensive integration of all desired functionalities is still a work in progress, these early efforts highlight the importance of foundational research and iterative advancements in addressing key challenges, such as scalability, cost-effectiveness, and ecological sustainability. In the following section, we delve into specific applications where these emerging technologies have been deployed or hold transformative potential, demonstrating their capacity to drive innovation in areas such as environmental monitoring, defense, precision agriculture, and beyond.

4. Smart Dust Applications: Between the Present and Future

As smart dust technology evolves, its impact will expand, enabling real-time, high-resolution chemical mapping for varied applications.[55,68,69,296–304] Devices ranging from centimeter to micron scale, utilizing advanced fabrication techniques like lithography and micromachining, will continue to improve in sensitivity and functionality. By integrating improvements in sensitivity, power efficiency, and multi-functional capabilities, smart dust sensors are poised to transform a wide array of applications, particularly in the field of chemical mapping.[62,271,305–307] For instance, early demonstrations of smart dust in environmental monitoring have shown how these devices can be deployed across large areas to detect and track pollutants in real-time, providing a high-resolution map of chemical concentrations in the environment.[305] Similarly, in healthcare, wearable and ingestible sensors are beginning to show their potential for continuous monitoring of biomarkers and disease states.[307] While many of these applications in the precision agriculture and defense sectors are still in their infancy,[308–312] they represent a powerful glimpse into the future of smart dust technology and its transformative impact on multiple industries.

4.1. Environment Monitoring

The vision for smart dust in environmental monitoring is rapidly becoming a reality, with the potential to revolutionize how we collect and analyze data across vast and diverse environments.[313–316] These tiny, wireless sensor networks are capable of providing real-time, pervasive data on critical environmental parameters such as air quality, temperature, humidity, and pollutants.

Significant early work has laid the groundwork for these advancements. For example, recent developments in colloidal nano-electronic state machines based on 2D materials for aerosolized electronics have shown promise in detecting specific gases in simulated environments (**Figure 11**a–c).[54] Researchers created functional electronic circuits, transistors, and sensors at the micro-scale, such as photodiodes, chemiresistors, and memristors, and demonstrated the ability to read signals from individual particles using laser-scanning optical detection. This pioneering work has showcased the potential of miniaturized sensors to provide highly specific chemical detection in complex environments. Another noteworthy contribution comes from Tittl et al., who demonstrated the use of single-shell-isolated gold nanoparticles (AuNPs) as plasmonic smart dust for all-optical probing of local chemical reactions, such as hydrogen uptake in palladium (Pd) (Figure 11d–f).[305] The AuNPs placed at reaction sites enhanced electromagnetic fields near the Pd surface, enabling real-time monitoring of hydrogen dissociation and diffusion into palladium hydride. This approach integrates plasmonic sensing with SERS, allowing for simultaneous imaging of multiple reaction sites and offering a novel way to track chemical processes with high sensitivity.

In advancing the vision of smart dust, innovations like the HoverBot system introduced by Nemitz et al. (Figure 11g,h) also play a crucial role.[298] This levitating circuit board, which navigates by responding to magnetic anchors, demonstrates how low-cost sensors can be integrated into smart dust systems to extend their functionality. By analyzing magnetic field data from HoverBot's Hall-effect sensor, this system shows how such sensors can detect movement, rotation, and other environmental behaviors—paving the way for future smart dust systems that could dynamically respond to environmental changes. Additionally, the use of rugate filter-based photonic crystals in smart dust for detecting VOCs like toluene (Figure 11i) represents a major step forward in sensing technology.[69] The color shift in porous silicon particles, visible to the naked eye, allows for simpler detection of VOCs compared to conventional methods. This color shift occurs as the refractive index of the material changes when toluene vapor condenses in the nanopores. By employing microcavity structures or Bragg stacks, the sensitivity and specificity of these smart dust sensors can be further enhanced, enabling molecular-level chemical detection that is essential for precise environmental monitoring.

As technology continues to evolve, it will enable more widespread deployment of highly sensitive, real-time environmental monitoring systems that can track pollutants, greenhouse gases, and other critical environmental parameters with unprecedented precision. This will not only transform environmental management but also contribute to a more sustainable future by providing the data needed to make informed decisions on climate change, pollution control, and resource management.

4.2. Healthcare

The future of healthcare is poised for transformation through the visionary potential of smart dust technology, with applications like body dust and neural dust offering groundbreaking possibilities for continuous health monitoring.[56,317–321]

4.2.1. Neural Dust

Neural dust, a prime example of this innovation, consists of ultra-miniaturized, wireless sensors implanted in or around neural tissues to monitor electrical activity in the brain and nervous system. These sensors, often smaller than a millimeter, are designed for high biocompatibility, enabling them to remain within the body for long periods without causing adverse immune responses or tissue damage. By wirelessly transmitting data, neural dust provides the ability to monitor brain function in real time without the need for invasive wiring or frequent procedures, opening up new frontiers in both clinical and research settings.

The early work in this field has already demonstrated its vast potential. The development of neural dust has enabled new breakthroughs in brain-machine interfaces (BMIs), offering a promising pathway for treating neurological disorders and advancing cognitive research (**Figure 12**a).[317] These advancements hold the promise of seamlessly integrating with prosthetic devices, allowing for more natural control of artificial limbs, and supporting the development of advanced treatments for conditions such as paralysis, epilepsy, and neurodegenerative diseases. Significant progress has already been made in demonstrating the practical application of neural dust. For instance, the in vivo validation of a neural dust system by Seo et al. (Figure 12b) has shown how these millimeter-scale sensors can wirelessly capture electrophysiological data, such as electroneurogram (ENG) signals from the sciatic nerve and electromyogram (EMG) signals from muscles, in animal models.[318] These sensors, powered by an external ultrasonic transceiver, enable real-time, minimally invasive monitoring of neural and muscle activity (Figure 12c). Such work lays the foundation for the future scalability of neural dust systems in chronic brain-machine interfaces, where low-power CMOS technology, combined with ultrasound power delivery, could support large-scale, long-term brain monitoring, and treatment strategies (Figure 12a).

Looking forward, we envision a future where tiny, wireless sensors embedded in the body provide continuous, real-time data on brain activity, heart function, muscle performance, and other vital health indicators. This will not only enhance patient care but also enable personalized medicine at an unprecedented scale, offering proactive and tailored treatments. The early work in neural dust and its applications in brain-machine interfaces mark just the beginning of what could become a new era in healthcare, where smart dust sensors are integral to the future of medical diagnostics and treatment.

4.2.2. Body Dust

The future of healthcare is increasingly intertwined with the potential of body dust or ingestible devices, a network of

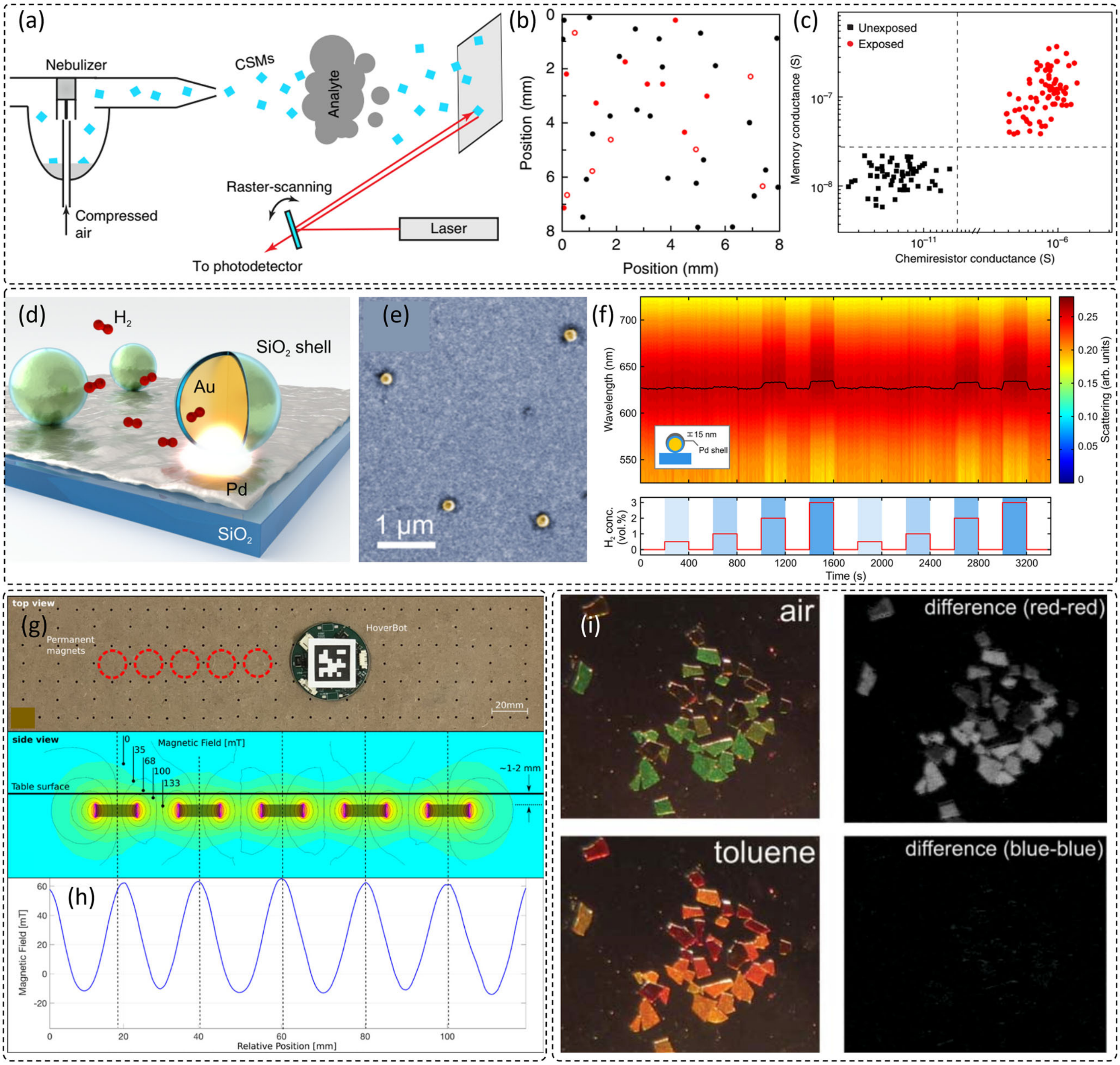

Figure 11. Environment monitoring through smart dust: a) Spraying smart dust into the environment and b) monitoring their position using a system consisting of a laser and photodetector. c) Response of devices with and without exposure to soot. Reproduced with permission.[54] Copyright 2018, Nature Portfolio. d) Schematic of plasmonic smart dust for monitoring local chemical reactions and e) its SEM image. f) Monitoring localized chemical reactions through the shift of the plasmonic frequency of a smart dust particle covered by a 15 nm Pd film. Reproduced with permission.[305] Copyright 2013, ACS Publications. g) Magnetic field readout by a HoverBot with a Hall-effect sensor that moves on a magnetic levitating table, and the corresponding simulated magnetic field. h) HoverBot measured the magnetic field showing a good correlation with the simulated result. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[298] Copyright 2018, Frontiers Media SA. i) VOC sensing using porous Si photonic crystals, which show changes in the refractive index based on the condensed VOC in micropores. Reproduced with permission.[69] Copyright 2005, Royal Society of Chemistry.

micro-scale, biocompatible, and often biodegradable sensors that promise to revolutionize non-invasive health monitoring and physiological tracking within the human body. These ultra-small sensors can be deployed both externally, on the skin, or internally, within body cavities, offering a continuous stream of data on a wide range of vital signs, biochemical markers, environmental exposures, and metabolic processes (**Figure 13a**).[56]

A recent pilot trial of an ingestible electronic sensor, capable of sensing oxygen, hydrogen, and carbon dioxide in the gut, marks a significant advancement in this field (Figure 13b,c).[62] By using thermal conductivity and semiconducting sensors to detect

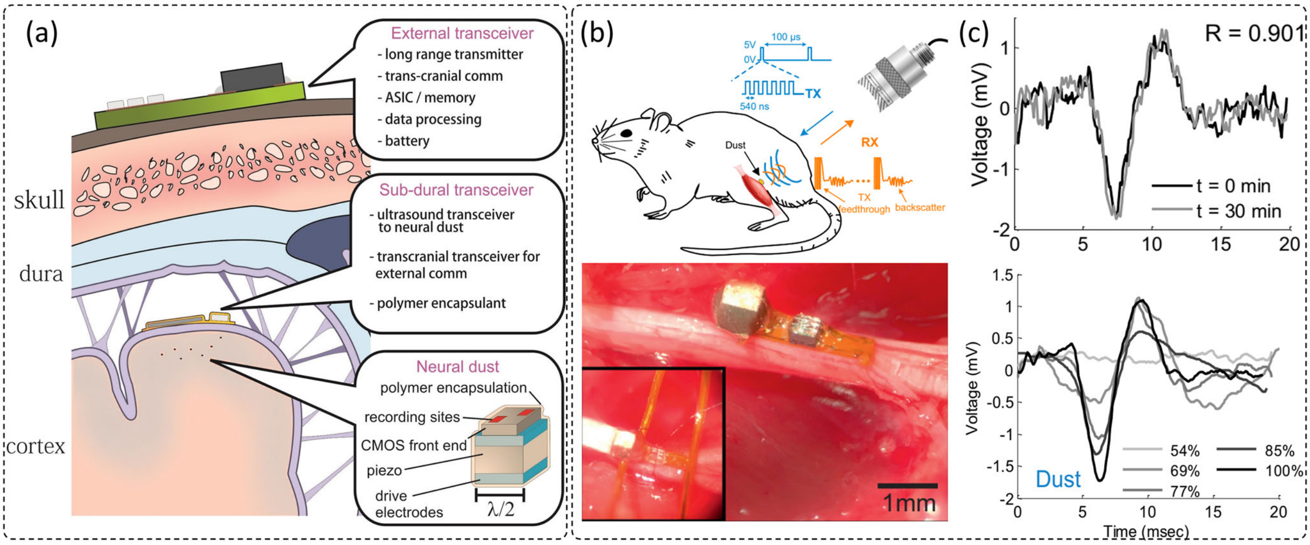

Figure 12. Neural dust: a) Schematic of a neural dust system where an ultrasonic interrogator is placed under the skull to receive information from independent sensing nodes dispersed throughout the brain. Reproduced with permission.[317] Copyright 2013, Cornell University. b) In vivo recordings of electromyogram (EMG) and electroneurogram (ENG) from the gastrocnemius muscle in rats. c) Corresponding wireless backscattered data. Reproduced with permission.[318] Copyright 2016, Cell Press.

gases, these capsules offer valuable insights into gut fermentation, digestive transit times, and overall gastrointestinal health. Further advancements in body dust technology are exemplified by the development of nano-biosupercapacitors (nBSCs), which represent a leap forward in energy storage for biomedical applications (Figure 13d–f).[307] These fully integrated, bio-enhanced systems function in biological electrolytes, such as medical saline, blood plasma, and blood, making them ideal for powering miniaturized medical implants and sensors. The self-assembled 3D tubular structure of the nBSC ensures stable operation even under dynamic conditions, like pulsating blood flow and varying temperatures. This robustness makes it a critical component in powering self-contained sensor systems, such as those used to monitor blood pH. As the development of these technologies progresses, they offer the potential to seamlessly integrate into smart dust systems, providing reliable power sources for continuous monitoring of health metrics within the human body.

Looking ahead, the integration of body dust and ingestible sensors into healthcare represents a transformative step towards continuous, non-invasive, and highly personalized health monitoring.[322–324] The ability to track physiological changes in real-time, without the need for intrusive procedures, will offer new insights into metabolic health, disease progression, and treatment efficacy.

4.3. Agriculture

Smart dust technology is poised to redefine agriculture, offering unparalleled potential for improving resource management, precision monitoring, and sustainable practices.[42,325–327] The transformative integration of smart dust in diverse agricultural scenarios positions as a cornerstone of next-generation farming systems. **Figure 14** provides a visual representation of these applications, highlighting the capabilities of smart dust networks in precision agriculture and beyond.

In soil management, smart dust networks enable real-time mapping of critical parameters, including pH, moisture, salinity, and nutrient composition with the aid of various associated sensors monitored via IoT platforms (Figure 14a,b).[325] For instance, as depicted in Figure 14c–e,[42] by distributing smart dust particles equipped with specialized sensors, such as thymol blue-based colorimetric pH sensors, hazardous zones and soil pH can be detected and mapped in real-time utilizing drone-based scanning and imaging systems, enabling precise spatial mapping of the pH and other imperative parameters. These visual mappings emphasize the efficiency of smart dust in detecting, analyzing, and responding to environmental challenges in agriculture and beyond. Furthermore, these ultra-miniaturized sensors offer a dynamic system for assessing soil health, ensuring resource-efficient irrigation and fertilization. The ability to detect nitrogen, phosphorus, and potassium (NPK) levels facilitates precise fertilizer application, reducing environmental pollution while maximizing crop yields. By leveraging drone-based systems, smart dust sensors can transmit spatially localized data to centralized systems, enabling precision interventions and minimizing operational inefficiencies.

In the context of precision agriculture (PA), the innovative development of Degradable Intelligent Radio Transmitting Sensors (DIRTS) represents a sustainable solution to traditional limitations in agricultural sensing (Figure 14f–h).[326] Unlike conventional IoT-based sensors, which are costly and environmentally persistent, DIRTS are fully biodegradable, low-cost, and designed for scalable production. These sensors consist of miniaturized resonating antennas encased in biodegradable polymers, allowing their resonant frequencies to be influenced by the soil's dielectric properties that depend on its water content. They enable remote monitoring of subsoil volumetric water content (VWC)

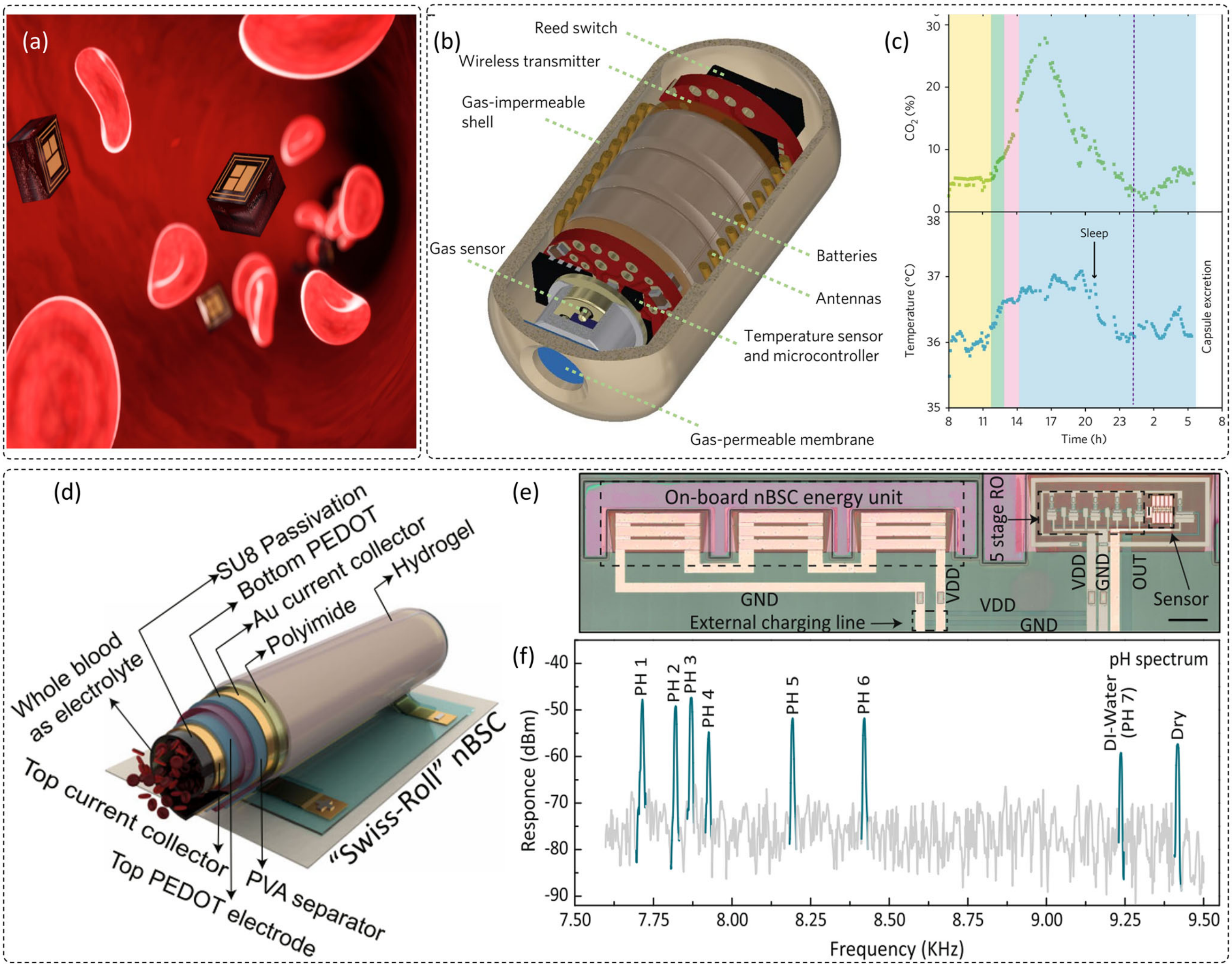

Figure 13. Body dust: a) Schematic representing the concept of body dust for metabolism monitoring. Reproduced with permission.[56] Copyright 2020, IEEE. b) A battery-powered ingestible electronic capsule consisting of a gas sensor, temperature sensor, and wireless chip for sensing gases in the gut. c) Corresponding gas and temperature profiles. Reproduced with permission.[62] Copyright 2018, Nature Portfolio. d) Structure of a nano-biosupercapacitor (nBSC) with a hollow core for blood flow. e) Optical microscopic image (scale bar 200 µm) of an nBSC pH sensor with various integrated components after roll-up. f) Frequency response of the sensor in electrolytes with varied pH. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[307] Copyright 2021, Nature Portfolio.

using drone-assisted wireless systems and vector network analyzers coupled wirelessly via an antenna (**Figure** 14g,h). Operating effectively for up to one year before significant biodegradation, these sensors offer real-time, eco-friendly monitoring while minimizing environmental impact, marking a critical step toward achieving sustainable PA practices. Similarly, a system developed by Kasuga et al. integrates biodegradable sensor networks by employing eco-friendly materials such as paper substrates, natural wax, and tin conductive lines (Figure 14i–l).[327] These sensors operate wirelessly, emitting thermal signals based on soil moisture levels, which are then captured by a thermal camera. Additionally, the system's biodegradable components minimize environmental impact, and residual materials either degrade harmlessly or contribute positively, such as by promoting plant growth (Figure 14k).

Beyond soil health, smart dust plays a pivotal role in plant disease detection. The sensors' capacity to identify VOCs and micro-environmental changes allows for the early diagnosis of plant stress and disease onset. For instance, fungal infections and bacterial blight often manifest as subtle changes in VOC profiles or temperature gradients, which smart dust can detect.[328,329] This enables targeted interventions that mitigate the spread of diseases, reducing reliance on broad-spectrum pesticide use. In controlled-environment agriculture, such as greenhouse, hydroponic, and vertical farming, smart dust is indispensable.[330–332] Sensors embedded in these systems continuously track temperature, humidity, CO_2 concentration, and nutrient levels, automating climate control and resource optimization. In aquaculture, smart dust sensors enable the monitoring of water quality indicators such as pH, temperature, dissolved oxygen, and ammonia

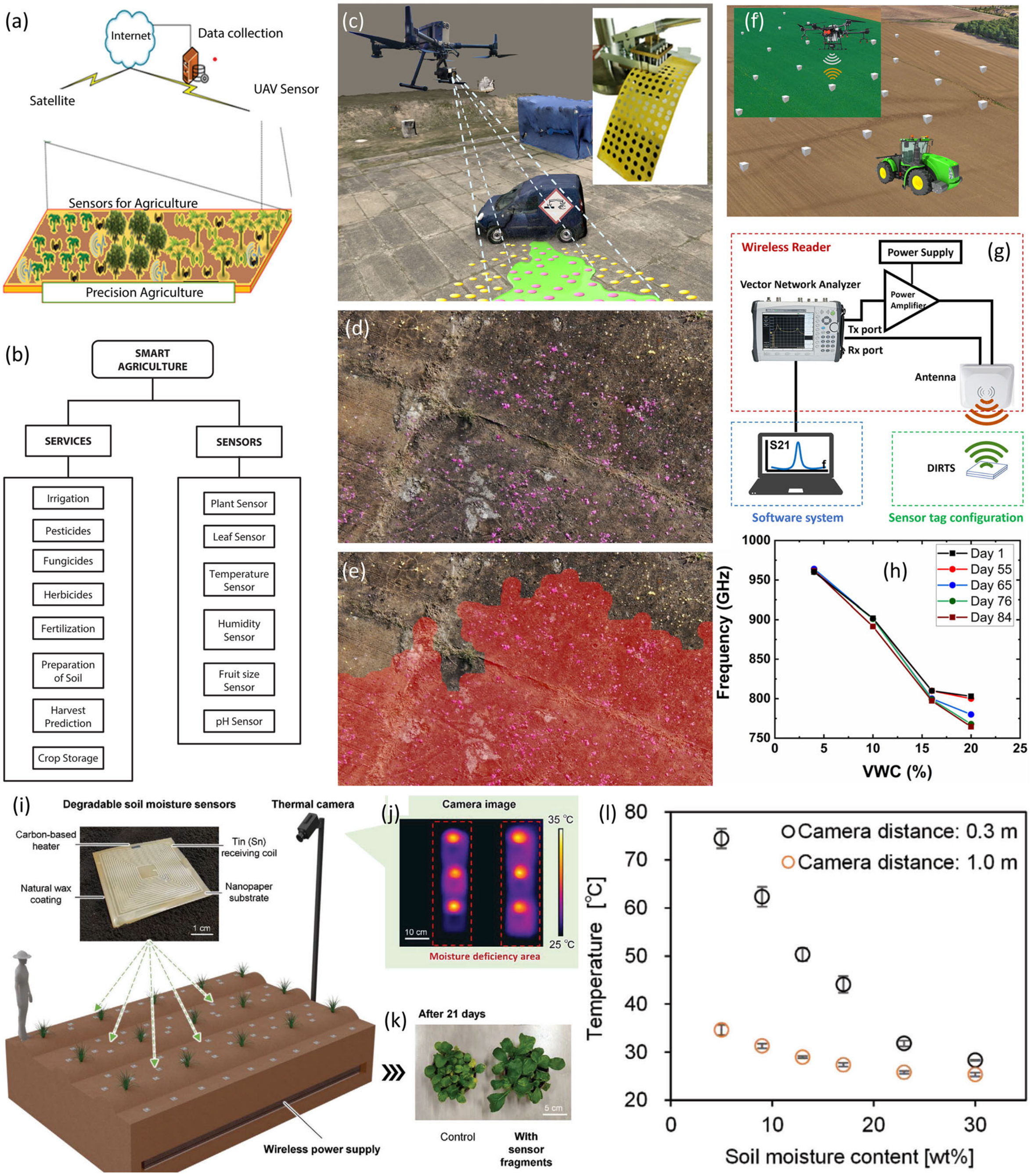

Figure 14. Agriculture: a) Schematic representation of a smart dust network integrated into a precision agriculture framework. b) Various sensors and associated services in precision agriculture, emphasize the expansive potential of smart dust systems for applications such as soil health monitoring, crop yield optimization, and environmental sustainability. Reproduced with permission.[325] Copyright 2025, Wiley-VCH. c) Demonstration of smart dust utility in hazardous liquid spillage detection and mapping, where yellow-circled smart dust particles equipped with functional sensors are distributed across the affected zone. Inset: polymer dyes (thymol blue)-based colorimetric pH sensors fabricated using a puncher. A drone equipped with an imaging system hovers over the site, enabling spatial mapping of contamination through sensor response signals. d–e) Drone-acquired images showcasing the visual mapping of acid spillage, with smart dust enabling high-resolution spatial analysis of hazardous zones (red). Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[42] Copyright 2024, MDPI. f,g,h) Deployment of Wirelessly Operable Degradable Intelligent Radio Transmitting Sensors (DIRTS) across agricultural fields, enabling real-time monitoring of volumetric water content (VWC) in soil through a wirelessly coupled vector network analyzer. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[326] Copyright 2022, Nature Portfolio. i) Biodegradable soil moisture sensor integrated with an induction coil and a heater, demonstrating variable heating responses based on soil moisture levels. j) Infrared images capturing moisture-dependent thermal variations, k) biodegradability assessment, and l) temperature fluctuations correlated with varying moisture levels. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[327] Copyright 2024, Wiley-VCH.

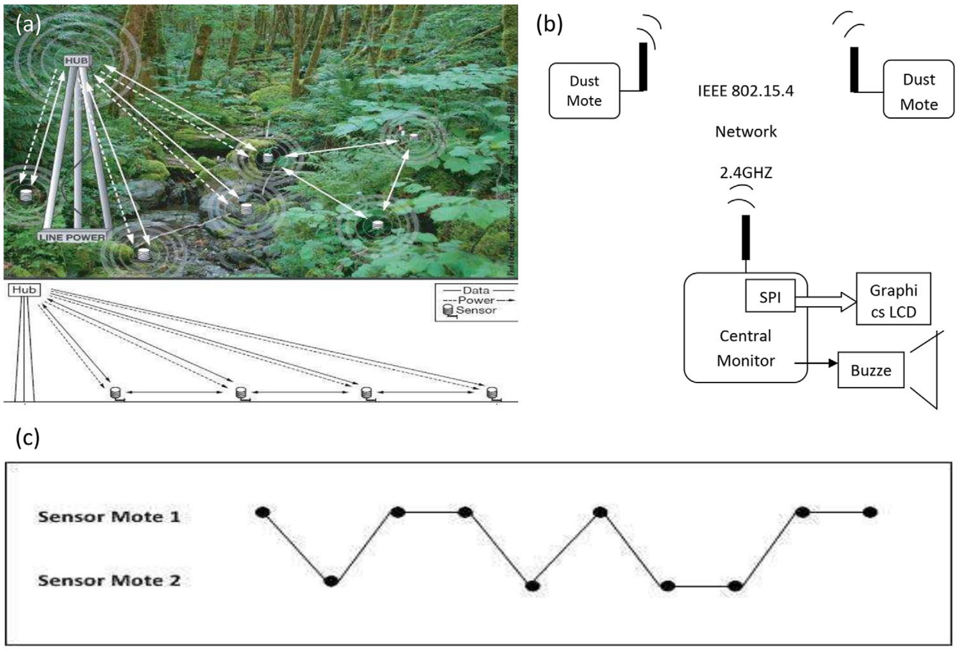

Figure 15. Defense and security: a) Deployment of a smart dust network in a forested area for advanced intrusion detection, demonstrating its utility in tactical surveillance. b) Block diagram of the smart dust system comprising two dust motes, each equipped with a microcontroller, wireless communication modules, thermal sensors, MEMS accelerometers for vibration detection, acoustic sensors, and magnetic sensors. c) Graphical representation of intrusion detection by the two dust motes, illustrating their synchronized responses to multiple signatures such as thermal, acoustic, and vibrational inputs. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license.[334] Copyright 2013, International Organization Of Scientific Research.

levels, preventing fish mortality and promoting sustainable farming practices.[333]

These applications emphasize that smart dust is not merely an incremental technological innovation but a transformative force in agriculture. By offering granular insights into environmental parameters and integrating seamlessly with IoT and machine learning platforms, smart dust addresses key challenges in food security, resource efficiency, and climate resilience. However, to fully exploit the potential of smart dust in precision agriculture, several challenges remain. These include improving sensor miniaturization, enhancing sensitivity and selectivity, refining data processing capabilities, and ensuring cost-effectiveness.

4.4. Defense and Security

The integration of smart dust networks into defense and security applications presents a paradigm shift in the way military surveillance, urban safety, and counterterrorism operations are conducted.[311,334,335] **Figure 15a** shows the deployment of a smart dust network in a forested environment for advanced intrusion detection, demonstrating its value in tactical surveillance.[334] Smart dust, by leveraging miniature sensor nodes, provides real-time data collection in remote or hostile regions, enabling autonomous monitoring and analysis without requiring human intervention. As illustrated in Figure 15b, a typical smart dust system consists of multiple sensor motes equipped with a variety of detectors including a microcontroller, wireless communication modules, and sensors such as thermal sensors, MEMS accelerometers, acoustic sensors, and magnetic sensors. These sensors capture multiple environmental signatures—thermal, vibrations, and acoustic—which are crucial for detecting intrusions or unauthorized activities in sensitive areas. Figure 15c displays a graphical representation of how two dust motes synchronize their responses to these signatures, effectively detecting and tracking intruders by correlating multiple factors in real-time. Also, smart dust networks can significantly enhance tactical operations by providing high-resolution, detailed data on enemy movements, explosives, and environmental conditions.[335] Chemically sensitive nodes can detect trace amounts of explosives or biological agents, and gather data to help in optimizing mission strategies, improving safety, and minimizing risks to personnel.

Beyond military use, smart dust has significant potential for enhancing urban security and public safety.[312] Its ability to continuously monitor large public spaces allows for real-time population density tracking, behavioral analysis, and threat detection.[336] In crowded environments such as airports, government buildings, or large events, the system can provide early warnings, allowing timely intervention to prevent accidents or security breaches. During emergencies like chemical spills or terrorist incidents, smart dust can identify hazardous materials, enabling more effective containment and evacuation measures. These sensors are capable of detecting chemical, biological, radiological, and nuclear agents, ensuring rapid response to these potential threats. Smart dust's application in smart city frameworks is a growing field, where its real-time monitoring capabilities contribute to enhanced security measures. Thus, smart dust, with its advanced chemical hazard detection and real-time tracking of object movements, enhances situational awareness and safety in both military and civilian contexts via offering precise and automated sensing.

5. Perspectives on Smart Dust for Spatiotemporal Chemical Mapping

To fully realize the transformative potential of smart dust for dynamic, spatiotemporal chemical mapping, we must address a number of technological, logistical, and economic challenges. As we integrate the advancements needed to make smart dust a reality—such as enhanced sensor sensitivity, wireless communication, AI-powered data analysis, and real-time mapping—we must also consider the broader implications, including the cost-effectiveness of these systems and their potential economic and societal impact.

At the heart of smart dust's potential is its ability to collect real-time, high-resolution data from dispersed, often inaccessible locations. The sensors must be highly sensitive, capable of differentiating between a wide array of chemical compounds, and able to operate autonomously over large areas. Advances in miniaturization, such as the development of submillimeter-scale sensors, will allow these systems to function in complex and dynamic environments, whether within the human body, urban centers, or natural ecosystems. Moreover, the ability to transmit data wirelessly, using low-power communication systems like RF energy harvesting or optical communication, will enable the seamless operation of these sensors without the need for physical connections or frequent recharging. Equally critical is the integration of AI for processing and analyzing the vast amounts of data these systems will generate. Machine learning models, such as neural networks and clustering algorithms, will be necessary to interpret the data in real-time, providing actionable insights and creating dynamic, spatiotemporal maps of chemical concentrations. These AI-driven systems will continuously refine the data, allowing for predictive modeling and proactive decision-making. For instance, in environmental monitoring, smart dust could track pollutants in real-time, enabling immediate action before concentrations reach harmful levels.

While the technological advancements in smart dust offer immense promise, the economic feasibility of widespread deployment remains a critical challenge. The cost of manufacturing smart dust devices must be significantly reduced to enable large-scale adoption, particularly in healthcare and environmental monitoring. Current fabrication processes, though advancing, are still expensive, especially when considering the need for miniaturization and integration of advanced features like wireless communication and energy harvesting. Traditional fabrication techniques such as lithography and micromachining, though effective for prototype development, can be costly at scale. To make smart dust a viable solution on a global scale, new fabrication methods such as 3D printing, batch processing, and other cost-effective manufacturing techniques must be further developed and optimized. Additionally, integrating energy-harvesting technologies into the sensors will reduce the need for external power sources, making the devices more self-sustaining and cost-effective in the long run. Innovations like triboelectric and piezoelectric energy harvesting could be key in reducing operational costs, making these systems more feasible for large-scale deployment. The widespread adoption of smart dust systems also presents broader economic implications. In healthcare, for example, the ability to continuously monitor patients using noninvasive, real-time sensors could reduce the cost of routine checkups, early diagnosis, and chronic disease management. By enabling proactive rather than reactive healthcare, smart dust could reduce hospital admissions and emergency treatments, leading to significant cost savings across the healthcare system. Additionally, smart dust could enable the development of more personalized medicine, where treatments are tailored to real-time data, improving efficacy and reducing unnecessary interventions. In environmental monitoring, the ability to deploy smart dust networks to monitor pollution and track environmental conditions could revolutionize how we manage resources, address climate change, and prevent environmental disasters. Smart dust systems could enable real-time, localized monitoring of air and water quality, allowing for faster responses to pollution events and more efficient regulation of environmental policies. The economic benefits of such systems could include reduced healthcare costs associated with pollution, more efficient resource allocation, and better-informed policy decisions.

While the potential benefits of smart dust are clear, there are also societal considerations that must be addressed as these technologies develop. Cost-effectiveness is not just a concern for manufacturers but also for ensuring equitable access to these technologies across different regions and populations. For smart dust to be truly transformative, it must be accessible to both developed and developing economies. Reducing costs through advances in manufacturing and energy efficiency is crucial to ensuring that the benefits of smart dust can be realized globally. Moreover, the widespread use of smart dust in healthcare and environmental monitoring raises privacy and ethical concerns. Continuous, real-time data collection has the potential to create privacy issues, particularly in healthcare, where sensitive health data could be transmitted without appropriate safeguards. Ensuring that data is encrypted, anonymized, and used responsibly will be critical to maintaining public trust and ensuring the technology is used ethically. Additionally, the societal impact of smart dust must be considered in terms of employment and industry disruption. As smart dust systems become more autonomous, they could reduce the need for traditional monitoring and data collection jobs. Addressing these challenges through reskilling programs and new economic models will be essential to ensuring that the transition to a smart dust-enabled future benefits all members of society.

By overcoming the technological, economic, and societal challenges ahead, smart dust has the potential to reshape the way we interact with and monitor our environments. The combination of highly sensitive sensors, wireless communication, and AI-powered analysis will allow for dynamic, spatiotemporal mapping that enables real-time, predictive monitoring of both environmental and health-related parameters. The vision for the future of smart dust is one where these systems are seamlessly integrated into everyday life, providing a constant stream of data that improves decision-making, enhances safety, and drives efficiency across industries. From healthcare to environmental management, the advancements in smart dust will enable a world where proactive responses replace reactive actions, where pollution is tracked in real-time, and where personalized medicine becomes the standard. By addressing the cost challenges and ensuring that smart dust systems are accessible, sustainable, and ethically deployed, we can move toward a future where these systems are not just a technological innovation but a critical tool in safeguarding public health, improving quality of life, and protecting our environment.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

agriculture, artificial intelligence, environment, health, sensor, Smart dust, wireless

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[1] V. K. Sarhadi, G. Armengol, *Biomolecules* **2022**, *12*, 1021.
[2] G. A. Kwong, S. Ghosh, L. Gamboa, C. Patriotis, S. Srivastava, S. N. Bhatia, *Nat. Rev. Cancer* **2021**, *21*, 655.
[3] A. Bodaghi, N. Fattahi, A. Ramazani, *Heliyon* **2023**, *9*, 13323.
[4] R. K. Agrahari, Y. Kobayashi, T. S. T. Tanaka, S. K. Panda, H. Koyama, *Soil Sci. Plant Nutr.* **2021**, *67*, 248.
[5] Z. Li, T. Yu, R. Paul, J. Fan, Y. Yang, Q. Wei, *Nanoscale Adv.* **2020**, *2*, 3083.
[6] A. Ghaffar, R. Hussain, N. Ahmad, R. Ghafoor, M. W. Akram, I. Khan, A. Khan, *Chem. Ecol.* **2021**, *37*, 646.
[7] T. Jia, W. Guo, Y. Xing, R. Lei, X. Wu, S. Sun, Y. He, W. Liu, *Environ. Pollut.* **2021**, *283*, 117121.
[8] N. Alygizakis, A. Galani, N. I. Rousis, R. Aalizadeh, M.-A. Dimopoulos, N. S. Thomaidis, *Sci. Total Environ.* **2021**, *799*, 149230.
[9] R. Munsif, M. Zubair, A. Aziz, M. N. Zafar, in *Environmental Emissions*, IntechOpen, England **2021**.
[10] T. To, J. Zhu, P. J. Villeneuve, J. Simatovic, L. Feldman, C. Gao, D. Williams, H. Chen, S. Weichenthal, C. Wall, *Environ. int.* **2015**, *80*, 26.
[11] M. Chin-Chan, J. Navarro-Yepes, B. Quintanilla-Vega, *Front. cell. neurosci.* **2015**, *9*, 124.
[12] X. Chen, L. Lei, S. Liu, J. Han, R. Li, J. Men, L. Li, L. Wei, Y. Sheng, L. Yang, *Sci. Total Environ.* **2021**, *792*, 148352.
[13] S. Begichev, A. Borovoj, E. Burlakov, A. J. Gagarinsky, V. Demin, A. Khrulev, I. Khodakovsky, in *Fission Product Processes In Reactor Accidents*, CRC Press, Boca Raton, FL **2020**.
[14] D. A. Sarigiannis, U. Hansen, *Environ. Health* **2012**, *11*, S18.
[15] A. M. Ragas, R. Oldenkamp, N. Preeker, J. Wernicke, U. Schlink, *Environ. int.* **2011**, *37*, 872.
[16] S. J. Virolainen, A. VonHandorf, K. C. Viel, M. T. Weirauch, L. C. Kottyan, *Genes Immun.* **2023**, *24*, 1.
[17] A. Mondal, N. K. Mondal, in *Intelligent Modeling, Prediction, and Diagnosis from Epidemiological Data*, Chapman and Hall/CRC, Boca Raton, FL **2021**.
[18] C. Peng, K. Qian, C. Wang, *IEEE Sens. J.* **2014**, *15*, 2255.
[19] Y. Yang, J. Zhou, C. Xie, W. Tian, M. Xue, T. Han, K. Chen, Y. Zhang, Y. Liu, Y. Huang, *Environ. Sci. Technol.* **2024**, *58*, 12488.
[20] W. Hadibrata, H. Noh, H. Wei, S. Krishnaswamy, K. Aydin, *Laser Photonics Rev.* **2021**, *15*, 2000556.
[21] Q. Xue, Y. Yang, W. Ma, H. Zhang, D. Zhang, X. Lan, L. Gao, J. Zhang, J. Tang, *Adv. Sci.* **2024**, *11*, 2404448.
[22] R. Vishinkin, R. Busool, E. Mansour, F. Fish, A. Esmail, P. Kumar, A. Gharaa, J. C. Cancilla, J. S. Torrecilla, G. Skenders, *Adv. Sci.* **2021**, *8*, 2100235.
[23] B. I. Escher, H. M. Stapleton, E. L. Schymanski, *Science* **2020**, *367*, 388.
[24] E. L. Schymanski, H. P. Singer, J. Slobodnik, I. M. Ipolyi, P. Oswald, M. Krauss, T. Schulze, P. Haglund, T. Letzel, S. Grosse, *Anal. Bioanal. Chem.* **2015**, *407*, 6237.
[25] D. S. Tavares, P. R. Mesquita, V. R. Salgado, F. d. M. Rodrigues, J. C. Miranda, M. Barral-Netto, J. B. de Andrade, A. Barral, *Molecules* **2019**, *24*, 2964.
[26] N. A. Alygizakis, P. Oswald, N. S. Thomaidis, E. L. Schymanski, R. Aalizadeh, T. Schulze, M. Oswaldova, J. Slobodnik, *TrAC, Trends Anal. Chem.* **2019**, *115*, 129.
[27] R. Napolitano, W. Reinhart, J. P. Gevaudan, *Science* **2021**, *371*, 1200.
[28] Z. Yang, T. Albrow-Owen, W. Cai, T. Hasan, *Science* **2021**, *371*, abe0722.
[29] R. A. Crocombe, *Appl. Spectrosc.* **2018**, *72*, 1701.
[30] M. Manley, *Chem. Soc. Rev.* **2014**, *43*, 8200.
[31] C. Dincer, R. Bruch, E. Costa-Rama, M. T. Fernández-Abedul, A. Merkoçi, A. Manz, G. A. Urban, F. Güder, *Adv. Mater.* **2019**, *31*, 1806739.
[32] L. P. Schuler, J. S. Milne, J. M. Dell, L. Faraone, *J. Phys. D: Appl. Phys.* **2009**, *42*, 133001.
[33] J. Malinen, A. Rissanen, H. Saari, P. Karioja, M. Karppinen, T. Aalto, K. Tukkiniemi, *Next-Generation Spectroscopic Technologies VII* **2014**, *9101*, 83.
[34] R. F. Wolffenbuttel, *J. Micromech. Microeng.* **2005**, *15*, S145.
[35] E. Ryckeboer, R. Bockstaele, M. Vanslembrouck, R. Baets, *Biomed. Opt. Express* **2014**, *5*, 1636.
[36] N. Peled, R. Ionescu, P. Nol, O. Barash, M. McCollum, K. VerCauteren, M. Koslow, R. Stahl, J. Rhyan, H. Haick, *Sens. Actuators, B* **2012**, *171*, 588.
[37] M. Khatib, H. Haick, *ACS Nano* **2022**, *16*, 7080.
[38] K. Vellingiri, D. W. Boukhvalov, K.-H. Kim, L. Philip, *RSC Adv.* **2019**, *9*, 7818.
[39] Y. Robin, J. Amann, T. Baur, P. Goodarzi, C. Schultealbert, T. Schneider, A. Schütze, *Atmosphere* **2021**, *12*, 1487.
[40] R. J. Rath, S. Farajikhah, F. Oveissi, F. Dehghani, S. Naficy, *Adv. Eng. Mater.* **2023**, *25*, 2200830.
[41] J. M. Kahn, R. H. Katz, K. S. Pister, Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking, IEEE, Piscataway, NJ **1999**.
[42] T. Nerger, P. P. Neumann, M. G. Weller, *Sensors* **2024**, *24*, 6195.
[43] B. Warneke, M. Last, B. Liebowitz, K. S. Pister, *Computer* **2001**, *34*, 44.
[44] D. Li, J. Zhou, Z. Zhao, X. Huang, H. Li, Q. a. Qu, C. Zhou, K. Yao, Y. Liu, M. Wu, *Sci. Adv.* **2024**, *10*, adk6301.
[45] M. Xu, Y. Liu, K. Yang, S. Li, M. Wang, J. Wang, D. Yang, M. Shkunov, S. R. P. Silva, F. A. Castro, *Exploration* **2024**, *4*, 20220106.
[46] J. K. Choe, S. Kim, A. y. Lee, C. Choi, J. H. Cho, W. Jo, M. H. Song, C. Cha, J. Kim, *Adv. Mater.* **2024**, *36*, 2311154.
[47] J. M. Kronenfeld, L. Rother, M. A. Saccone, M. T. Dulay, J. M. DeSimone, *Nature* **2024**, *627*, 306.

[48] E. Jansson, A. Korhonen, M. Hietala, T. Kololuoma, *Int. J. Adv. Manuf. Technol.* **2020**, *111*, 3017.
[49] M. R. Marks, K. Y. Cheong, Z. Hassan, *Precis. Eng.* **2022**, *73*, 377.
[50] I. Mondal, A. Zoabi, H. Haick, *Adv. Funct. Mater.* **2025**, 2425193.
[51] L. Yang, J. Jiang, X. Gao, Q. Wang, Q. Dou, L. Zhang, *Nat. Mach. Intell.* **2022**, *4*, 480.
[52] Y. Kim, J. M. Suh, J. Shin, Y. Liu, H. Yeon, K. Qiao, H. S. Kum, C. Kim, H. E. Lee, C. Choi, *Science* **2022**, *377*, 859.
[53] W. Liu, K. Huang, X. Zhou, S. Durrani, *EURASIP J. Wireless Commun. Networking* **2019**, *2019*, 1.
[54] V. B. Koman, P. Liu, D. Kozawa, A. T. Liu, A. L. Cottrill, Y. Son, J. A. Lebron, M. S. Strano, *Nat. Nanotechnol.* **2018**, *13*, 819.
[55] G. Li, Z. Ma, C. You, G. Huang, E. Song, R. Pan, H. Zhu, J. Xin, B. Xu, T. Lee, *Sci. Adv.* **2020**, *6*, aaz6511.
[56] S. Carrara, *IEEE Sens. J.* **2020**, *21*, 12398.
[57] H. Lu, P. Wang, R. Tan, X. Yang, Y. Shen, *IEEE Rob. Autom. Lett.* **2018**, *3*, 2846.
[58] H. Lu, W. Shang, X. Wei, Z. Yang, T. Fukuda, Y. Shen, *Sci. Rep.* **2017**, *7*, 3077.
[59] A. Benouhiba, L. Wurtz, J. Y. Rauch, J. Agnus, K. Rabenorosoa, C. Clévy, *Adv. Mater.* **2021**, *33*, 2103371.
[60] L. Mehrvar, H. Hajihoseini, H. Mahmoodi, S. Tavassoli, M. Fathipour, S. Mohseni, *Nanotechnology* **2017**, *28*, 315301.
[61] A. T. Liu, J. F. Yang, L. N. LeMar, G. Zhang, A. Pervan, T. D. Murphey, M. S. Strano, *Faraday Discuss.* **2021**, *227*, 213.
[62] K. Kalantar-Zadeh, K. J. Berean, N. Ha, A. F. Chrimes, K. Xu, D. Grando, J. Z. Ou, N. Pillai, J. L. Campbell, R. Brkljača, *Nat. Electron.* **2018**, *1*, 79.
[63] R. Manikandan, T. Rajarathinam, S. Jayaraman, H.-G. Jang, J.-H. Yoon, J. Lee, H.-j. Paik, S.-C. Chang, *Coord. Chem. Rev.* **2024**, *499*, 215487.
[64] M. Chen, M. Zhang, Z. Yang, C. Zhou, D. Cui, H. Haick, N. Tang, *Adv. Funct. Mater.* **2024**, *34*, 2309732.
[65] F. Binabaji, K. Dashtian, R. Zare-Dorabei, N. Naseri, M. Noroozifar, K. Kerman, *Anal. Chem.* **2024**, *96*, 13522.
[66] T. He, F. Wen, Y. Yang, X. Le, W. Liu, C. Lee, *Anal. Chem.* **2023**, *95*, 490.
[67] R. M. Aileni, G. Suciu, M. Serrano, R. Maheswar, C. A. Valderrama Sakuyama, S. Pasca, *Integr. WSN IoT smart cities* **2020**, 151.
[68] L. Niccolai, M. Bassetto, A. A. Quarta, G. Mengali, *Prog. Aerosp. Sci.* **2019**, *106*, 1.
[69] M. J. Sailor, J. R. Link, *Chem. Commun.* **2005**, 1375.
[70] M. Ilyas, I. Mahgoub, *Smart Dust: Sensor network applications, architecture and design*, CRC press, Boca Raton **2018**.
[71] V. Hsu, J. M. Kahn, K. S. Pister, *Wireless communications for smart dust*, Electronics Research Laboratory, College of Engineering, University California Berkeley, **1998**.
[72] M. Buettner, B. Greenstein, A. Sample, J. R. Smith, D. Wetherall, et al., In *Proceedings of the 7th ACM Workshop on Hot Topics in Networks (HotNets-VII)*, **2008**, pp. 1–6.
[73] G. Bahuguna, I. Mondal, M. Verma, M. Kumar, S. Bhattacharya, R. Gupta, G. U. Kulkarni, *ACS Appl. Mater. Interfaces* **2020**, *12*, 37320.
[74] D. Panigrahi, Y. Zheng, J. Wang, M. Sublaban, H. Haick, *Adv. Mater. Technol.* **2024**, *9*, 2400329.
[75] V. G. Nath, S. Ray, J. D. Rodney, S. P. Bharath, S. Roy, K. Tarafder, A. Subramanian, B. C. Kim, *Chem. Eng. J.* **2024**, *490*, 151873.
[76] A. Sharma, S. B. Eadi, H. Noothalapati, M. Otyepka, H.-D. Lee, K. Jayaramulu, *Chem. Soc. Rev.* **2024**, *53*, 2530.
[77] H. Mei, J. Peng, T. Wang, T. Zhou, H. Zhao, T. Zhang, Z. Yang, *Nano-Micro Lett.* **2024**, *16*, 269.
[78] G. Shang, D. Dinh, H. W. Cheng, L. Gebre, T. Yuan, S. Yan, J. Luo, S. Lu, C. J. Zhong, *Adv. Sens. Res.* **2024**, *3*, 2300119.
[79] N. Feizi, F. S. Hashemi-Nasab, F. Golpelichi, N. Saburouh, H. Parastar, *TrAC, Trends Anal. Chem.* **2021**, *138*, 116239.
[80] G. Kakavelakis, M. Gedda, A. Panagiotopoulos, E. Kymakis, T. D. Anthopoulos, K. Petridis, *Adv. Sci.* **2020**, *7*, 2002098.
[81] K. B. Beć, J. Grabska, C. W. Huck, *Foods* **2022**, *11*, 1465.
[82] Z. Guo, X. Wu, H. Jayan, L. Yin, S. Xue, H. R. El-Seedi, X. Zou, *Food Chem.* **2024**, *434*, 137469.
[83] A. Maity, Y. Milyutin, V. D. Maidantchik, Y. H. Pollak, Y. Broza, R. Omar, Y. Zheng, W. Saliba, T. P. Huynh, H. Haick, *Adv. Sci.* **2022**, *9*, 2203693.
[84] A. Maity, Y. Hershkovitz-Pollak, R. Gupta, W. Wu, H. Haick, *Adv. Mater.* **2023**, *35*, 2209125.
[85] R. Narayanan, D. Sarkar, R. G. Cooks, T. Pradeep, *Angew. Chem., Int. Ed.* **2014**, *53*, 5936.
[86] B. Dash, M. H. Goerz, A. Duspayev, S. C. Carrasco, V. S. Malinovsky, G. Raithel, *AVS Quantum Sci.* **2024**, *6*, 014407.
[87] H. Meskher, T. Ragdi, A. K. Thakur, S. Ha, I. Khelfaoui, R. Sathyamurthy, S. W. Sharshir, A. Pandey, R. Saidur, P. Singh, *Crit. Rev. Anal. Chem.* **2024**, *54*, 2398.
[88] M. Adampourezare, M. Hasanzadeh, M.-A. Hoseinpourefeizi, F. Seidi, *RSC Adv.* **2023**, *13*, 12760.
[89] L. Jiao, W. Xu, Y. Wu, H. Wang, L. Hu, W. Gu, C. Zhu, *Anal. Chem.* **2023**, *95*, 433.
[90] P. Kannan, G. Maduraiveeran, *Biosensors* **2023**, *13*, 542.
[91] L. Fu, Y. Zheng, X. Li, X. Liu, C.-T. Lin, H. Karimi-Maleh, *Molecules* **2023**, *28*, 6719.
[92] M.-A. Nalepa, D. Panáček, I. Dědek, P. Jakubec, V. Kupka, V. Hrubý, M. Petr, M. Otyepka, *Biosens. Bioelectron.* **2024**, *256*, 116277.
[93] N. Kazanskiy, S. Khonina, M. A. Butt, A. Kaźmierczak, R. Piramidowicz, *Electronics* **2021**, *10*, 973.
[94] Y. Wang, Y. Huang, H. Bai, G. Wang, X. Hu, S. Kumar, R. Min, *Biosensors* **2021**, *11*, 472.
[95] M. R. Sarabi, N. Jiang, E. Ozturk, A. K. Yetisen, S. Tasoglu, *Lab Chip* **2021**, *21*, 627.
[96] C. Liu, D. Xu, X. Dong, Q. Huang, *Trends Food Sci. Technol.* **2022**, *128*, 90.
[97] H. J. Han, S. H. Cho, S. Han, J. S. Jang, G. R. Lee, E. N. Cho, S. J. Kim, I. D. Kim, M. S. Jang, H. L. Tuller, *Adv. Mater.* **2021**, *33*, 2105199.
[98] L. Ma, M. Liu, X. Zhou, C. Li, T. Wang, *Mater. Chem. Front.* **2023**, *7*, 4880.
[99] L. Vázquez-Iglesias, G. M. S. Casagrande, D. García-Lojo, L. F. Leal, T. A. Ngo, J. Pérez-Juste, R. M. Reis, K. Kant, I. Pastoriza-Santos, *Bioact. Mater.* **2024**, *34*, 248.
[100] L. Huang, Y. Zhu, C. Xu, Y. Cai, Y. Yi, K. Li, X. Ren, D. Jiang, Y. Ge, X. Liu, *ACS Sens.* **2022**, *7*, 1439.
[101] I. Mondal, E. Mansour, Y. Zheng, R. Gupta, H. Haick, *Small* **2024**, *20*, 2403385.
[102] S. Roy Barman, Y.-J. Lin, K.-M. Lee, A. Pal, N. Tiwari, S. Lee, Z.-H. Lin, *ACS Nano* **2023**, *17*, 2689.
[103] S. Chatterjee, S. Saha, S. R. Barman, I. Khan, Y.-P. Pao, S. Lee, D. Choi, Z.-H. Lin, *Nano Energy* **2020**, *77*, 105093.
[104] R. Yang, W. Zhang, N. Tiwari, H. Yan, T. Li, H. Cheng, *Adv. Sci.* **2022**, *9*, 2202470.
[105] Z. Huang, G. Shao, L. Li, *Prog. Mater. Sci.* **2023**, *131*, 101020.
[106] J. H. Lee, K. Cho, J. K. Kim, *Adv. Mater.* **2024**, *36*, 2310505.
[107] P. Patial, M. Deshwal, *Trans. Electr. Electron. Mater.* **2022**, *23*, 6.
[108] M. Souri, H. S. Amoli, Y. Yamini, *Sens. Actuators, B* **2024**, *404*, 135213.
[109] N. Sharma, S. P. Choudhury, *Mater. Sci. Eng., B* **2024**, *307*, 117505.
[110] N. L. Kazanskiy, S. N. Khonina, M. A. Butt, *Sens. Actuators, A* **2024**, *366*, 114993.
[111] M. Benamara, A. Ly, S. Soltani, M. Essid, H. Dahman, R. Dhahri, L. El Mir, M. Debliquy, D. Lahem, *RSC Adv.* **2023**, *13*, 30230.
[112] C. Day, N. Barua, T. Hutter, *Appl. Phys. Rev.* **2023**, *10*, 021401.

[113] N. Alzate-Carvajal, J. Park, I. Bargaoui, R. Rautela, Z. J. Comeau, L. Scarfe, J.-M. Ménard, S. B. Darling, B. H. Lessard, A. Luican-Mayer, *ACS Appl. Electron. Mater.* **2023**, *5*, 1514.
[114] Y. Milyutin, M. Abud-Hawa, V. Kloper-Weidenfeld, E. Mansour, Y. Y. Broza, G. Shani, H. Haick, *Nat. Protoc.* **2021**, *16*, 2968.
[115] A. Maity, H. Haick, *Appl. Phys. Rev.* **2023**, *10*, 031301.
[116] A. Maity, S. Rapoport, H. Haick, *Small* **2023**, *19*, 2205038.
[117] B. P. Bloom, Y. Paltiel, R. Naaman, D. H. Waldeck, *Chem. Rev.* **2024**, *124*, 1950.
[118] C. D. Aiello, J. M. Abendroth, M. Abbas, A. Afanasev, S. Agarwal, A. S. Banerjee, D. N. Beratan, J. N. Belling, B. Berche, A. Botana, *ACS Nano* **2022**, *16*, 4989.
[119] A. Chiesa, A. Privitera, E. Macaluso, M. Mannini, R. Bittl, R. Naaman, M. R. Wasielewski, R. Sessoli, S. Carretta, *Adv. Mater.* **2023**, *35*, 2300472.
[120] M. Bhaiyya, D. Panigrahi, P. Rewatkar, H. Haick, *ACS Sens.* **2024**, *9*, 4495.
[121] S. Acharyya, P. K. Bhowmick, P. K. Guha, *J. Alloys Compd.* **2023**, *968*, 171891.
[122] Y. Li, X. Huang, E. Witherspoon, Z. Wang, P. Dong, Q. Li, *IEEE Sens. J.* **2024**, *24*, 15011.
[123] S. Mu, W. Shen, D. Lv, W. Song, R. Tan, *Sens. Actuators, A* **2024**, *369*, 115210.
[124] N. Lim, S. Hong, J. Jung, G. Y. Jung, D. H. Woo, J. Park, D. Kong, C. Balamurugan, S. Kwon, Y. Pak, *J. Ind. Inf. Integr.* **2024**, *42*, 100715.
[125] S. Y. Heng, K. Z. Yap, W. Y. Lim, N. Ramakrishnan, *Sens. Imag.* **2024**, *25*, 51.
[126] Y. M. Jo, Y. K. Jo, J. H. Lee, H. W. Jang, I. S. Hwang, D. J. Yoo, *Adv. Mater.* **2023**, *35*, 2206842.
[127] N. Schizas, A. Karras, C. Karras, S. Sioutas, *Future Internet* **2022**, *14*, 363.
[128] E. Elahi, G. Dastgeer, G. Nazir, S. Nisar, M. Bashir, H. A. Qureshi, D.-k. Kim, J. Aziz, M. Aslam, K. Hussain, *Comput. Mater. Sci.* **2022**, *213*, 111670.
[129] Y. Zheng, R. Omar, R. Zhang, N. Tang, M. Khatib, Q. Xu, Y. Milyutin, W. Saliba, Y. Y. Broza, W. Wu, *Adv. Mater.* **2022**, *34*, 2108607.
[130] W. Ling, J. Yu, N. Ma, Y. Li, Z. Wu, R. Liang, Y. Hao, H. Pan, W. Liu, B. Fu, *Adv. Funct. Mater.* **2020**, *30*, 2002644.
[131] K. Song, J. H. Han, T. Lim, N. Kim, S. Shin, J. Kim, H. Choo, S. Jeong, Y.-C. Kim, Z. L. Wang, *Adv. Health Mater* **2016**, *5*, 1572.
[132] A. H. Lee, J. Lee, V. Leung, A. Nurmikko, *Adv. Sci.* **2023**, *10*, 2306111.
[133] C. Hu, L. Wang, S. Liu, X. Sheng, L. Yin, *ACS Nano* **2024**, *18*, 3969.
[134] M. Babu, Z. Lautman, X. Lin, M. H. Sobota, M. P. Snyder, *Annu. Rev. Med.* **2024**, *75*, 401.
[135] M. Azeem, M. Shahid, I. Masin, M. Petru, *J. Textile Inst.* **2025**, *116*, 80.
[136] T. Lu, S. Ji, W. Jin, Q. Yang, Q. Luo, T.-L. Ren, *Sensors* **2023**, *23*, 2991.
[137] B. Sadri, W. Gao, *Appl. Phys. Rev.* **2023**, *10*, 031303.
[138] Z. Liu, X. Huang, Z. Liu, S. Zheng, C. Yao, T. Zhang, S. Huang, J. Zhang, J. Wang, S. Farah, *ACS Sens.* **2025**, *10*, 159.
[139] W. Yue, Y. Guo, J. C. Lee, E. Ganbold, J.-K. Wu, Y. Li, C. Wang, H. S. Kim, Y.-K. Shin, J.-G. Liang, *Nano-Micro Lett.* **2025**, *17*, 106.
[140] Y. Xin, B. Sun, Y. Kong, B. Zhao, J. Chen, K. Shen, Y. Zhang, *Nanoscale* **2025**, *17*, 2423.
[141] C. Yang, H. Su, S. Zhang, H. Ji, Z. Qi, Y. Wang, E. Cheng, L. Zhao, N. Hu, *ACS Appl. Nano Mater.* **2025**, *8*, 1129.
[142] Z. Yan, D. Xu, Z. Lin, P. Wang, B. Cao, H. Ren, F. Song, C. Wan, L. Wang, J. Zhou, *Science* **2022**, *375*, 852.
[143] Y. Li, G. Zhang, J. Zhang, D. Song, C. Guo, W. Zhou, Z. Fu, X. Zhu, F. Wang, Y. Duan, *Int. J. Extreme Manuf.* **2024**, *7*, 012008.
[144] N. Ruzibaeva, S. Makhmaraimova, I. Khaydarov, B. Mukhitdinova, Y. Ne'matova, K. Fayziyeva, Z. Sattorova, K. Mirzakhmedova, *J. Wireless Mob. Netw., Ubiq. Comput.., Depend. Appl.* **2024**, *15*, 125.
[145] D. Kim, J. Min, S. H. Ko, *Adv. Sens. Res.* **2024**, *3*, 2300118.
[146] D. Pan, J. Hu, B. Wang, X. Xia, Y. Cheng, C. H. Wang, Y. Lu, *Adv. Sci.* **2024**, *11*, 2303264.
[147] A. Yu, M. Zhu, C. Chen, Y. Li, H. Cui, S. Liu, Q. Zhao, *Adv. Healthcare Mater.* **2024**, *13*, 2302460.
[148] X. Luo, L. Yang, Y. Cui, *Biomed. Microdevices* **2023**, *25*, 20.
[149] X. D. Li, N. K. Chen, B. Q. Wang, M. Niu, M. Xu, X. Miao, X. B. Li, *Adv. Mater.* **2024**, *36*, 2307951.
[150] Z. Wu, Z. Qiao, S. Chen, S. Fan, Y. Liu, J. Qi, C. T. Lim, *Commun. Mater.* **2024**, *5*, 33.
[151] D. Kulkarni, D. Gadade, N. Chapaitkar, S. Shelke, S. Pekamwar, R. Aher, A. Ahire, M. Avhale, R. Badgule, R. Bansode, *Sci. Pharm.* **2023**, *91*, 27.
[152] Y. Hu, E. Chatzilakou, Z. Pan, G. Traverso, A. K. Yetisen, *Adv. Sci.* **2024**, *11*, 2306560.
[153] M. Sang, M. Cho, S. Lim, I. S. Min, Y. Han, C. Lee, J. Shin, K. Yoon, W.-H. Yeo, T. Lee, *Sci. Adv.* **2023**, *9*, adh1765.
[154] H. Kim, B. Rigo, G. Wong, Y. J. Lee, W.-H. Yeo, *Nano-Micro Lett.* **2024**, *16*, 52.
[155] J. Wan, Z. Nie, J. Xu, Z. Zhang, S. Yao, Z. Xiang, X. Lin, Y. Lu, C. Xu, P. Zhao, *Sci. Adv.* **2024**, *10*, adm9314.
[156] A. T. Liu, M. Hempel, J. F. Yang, A. M. Brooks, A. Pervan, V. B. Koman, G. Zhang, D. Kozawa, S. Yang, D. I. Goldman, *Nat. Mater.* **2023**, *22*, 1453.
[157] W. Li, Q. Liu, Y. Zhang, C. a. Li, Z. He, W. C. Choy, P. J. Low, P. Sonar, A. K. K. Kyaw, *Adv. Mater.* **2020**, *32*, 2001591.
[158] N. Nath, S. Chakroborty, D. P. Vishwakarma, G. Goga, A. S. Yadav, R. Mohan, *Environ. Sci. Pollut. Res.* **2024**, *31*, 57289.
[159] W. Cheng, Y. Zhu, G. Jiang, K. Cao, S. Zeng, W. Chen, D. Zhao, H. Yu, *Prog. Mater. Sci.* **2023**, *138*, 101152.
[160] J. Min, Y. Jung, J. Ahn, J. G. Lee, J. Lee, S. H. Ko, *Adv. Mater.* **2023**, *35*, 2211273.
[161] P.-H. Yang, J.-M. Huang, Y.-S. Chang, C.-T. Chan, H.-J. Hu, *IEEE Sens. J.* **2023**, *35*, 2211273.
[162] X. Peng, K. Dong, Y. Zhang, L. Wang, C. Wei, T. Lv, Z. L. Wang, Z. Wu, *Adv. Funct. Mater.* **2022**, *32*, 2112241.
[163] C. Fernandes, I. Taurino, *Sensors* **2022**, *22*, 3062.
[164] B. P. Yalagala, A. S. Dahiya, R. Dahiya, *Opto-Electron. Adv.* **2023**, *6*, 220020.
[165] H. Xiang, Z. Li, H. Liu, T. Chen, H. Zhou, W. Huang, *npj Flexible Electron.* **2022**, *6*, 15.
[166] W. Tian, Y. Li, J. Zhou, T. Wang, R. Zhang, J. Cao, M. Luo, N. Li, N. Zhang, H. Gong, *ACS Appl. Mater. Interfaces* **2021**, *13*, 8285.
[167] C. Yoo, J. Yoon, M. G. Kaium, B. Osorto, S. S. Han, J. H. Kim, B. K. Kim, H.-S. Chung, D.-J. Kim, Y. Jung, *Nanotechnology* **2022**, *33*, 475502.
[168] B. Darmau, M. Sacchi, I. Texier, A. J. Gross, *Adv. Healthcare Mater.* **2024**, *14*, 2403209.
[169] W.-H. Chen, S. Maheshwaran, Y.-K. Park, H. C. Ong, *Sci. Total Environ.* **2024**, *953*, 176128.
[170] U. Uthappa, M. Nehra, R. Kumar, N. Dilbaghi, G. Marrazza, A. Kaushik, S. Kumar, *Adv. Colloid Interface Sci.* **2023**, *322*, 103024.
[171] M. Andonegi, R. M. Meira, D. M. Correia, N. Pereira, C. M. Costa, S. Lanceros-Mendez, K. de la Caba, P. Guerrero, *Int. J. Biol. Macromol.* **2024**, *256*, 128486.
[172] G. Gopal, N. Roy, A. Mukherjee, *Biosensors* **2023**, *13*, 488.
[173] L. Wang, S. Chen, B. Yu, *Trends Food Sci. Technol.* **2022**, *119*, 1.
[174] S. C. Kishore, S. Perumal, R. Atchudan, M. Alagan, A. K. Sundramoorthy, S. Ramalingam, D. Manoj, S. Sambasivam, *Sens. Actuators, A* **2024**, *377*, 115719.
[175] R. Tong, Z. Ma, R. Yao, P. Gu, T. Li, L. Liu, F. Guo, M. Zeng, J. Xu, *Int. J. Biol. Macromol.* **2023**, *246*, 125667.
[176] W. Feng, R. Wang, Y. Zhou, L. Ding, X. Gao, B. Zhou, P. Hu, Y. Chen, *Adv. Funct. Mater.* **2019**, *29*, 1901942.

[177] J. W. Chae, D. Lee, A. Osman, B. Kang, J. Hwang, W. Kim, D. Kim, W. H. Lee, S. M. Won, *ACS Appl. Electron. Mater.* **2024**, *6*, 1746.
[178] N. Bokka, V. Selamneni, P. Sahatiya, *Mater. Adv.* **2020**, *1*, 2818.
[179] N. Chaiya, D. Daranarong, P. Worajittiphon, R. Somsunan, P. Meepowpan, A. Tuantranont, N. Rakbamrung, P. D. Topham, B. J. Tighe, A. Mahomed, *Food Packag. Shelf Life* **2022**, *32*, 100829.
[180] S. Lakshmy, A. Kundu, N. Kalarikkal, S. M. Ali, B. Chakraborty, *Appl. Surf. Sci.* **2023**, *631*, 157525.
[181] X. Yan, S. Wang, G. Nie, Y. Gao, L. Li, T. Zhang, Y.-Z. Long, W. Han, *J. Mater. Sci.: Mater. Electron.* **2024**, *35*, 1.
[182] S. Sisakhtnezhad, M. Rahimi, S. Mohammadi, *Biomed. Pharmacother.* **2023**, *163*, 114833.
[183] P. K. Samantaray, A. Little, D. M. Haddleton, T. McNally, B. Tan, Z. Sun, W. Huang, Y. Ji, C. Wan, *Green Chem.* **2020**, *22*, 4055.
[184] X. Xie, Y. Li, Y. Xiu, H. Yuan, T. Hu, Y. Yang, *Mater. Des.* **2023**, *233*, 112267.
[185] L. Liu, X. Xu, M. Zhu, X. Cui, J. Feng, Z. F. Rad, H. Wang, P. Song, *Adv. Mater. Technol.* **2023**, *8*, 2201414.
[186] C. I. Idumah, *Cleaner Mater.* **2022**, *5*, 100102.
[187] A. Babaei-Ghazvini, B. Acharya, *Polymers* **2021**, *13*, 3695.
[188] J. Wei, N.-E. Oyunbaatar, Y.-J. Jeong, J. Park, S.-H. Kim, K. Kwon, H. Lee, Y. Won, D.-S. Kim, D.-W. Lee, *Sens. Actuators, B* **2025**, *422*, 136667.
[189] T. Urbánek, E. Jäger, A. Jäger, M. Hrubý, *Polymers* **2019**, *11*, 1061.
[190] J. A. Chiong, H. Tran, Y. Lin, Y. Zheng, Z. Bao, *Adv. Sci.* **2021**, *8*, 2101233.
[191] J. Tropp, J. Rivnay, *J. Mater. Chem. C* **2021**, *9*, 13543.
[192] C. Mukherjee, D. Varghese, J. Krishna, T. Boominathan, R. Rakeshkumar, S. Dineshkumar, C. B. Rao, A. Sivaramakrishna, *Eur. Polym. J.* **2023**, *192*, 112068.
[193] M. Ali, M. J. Bathaei, E. Istif, S. N. H. Karimi, L. Beker, *Adv. Healthcare Mater.* **2023**, *12*, 2300318.
[194] A. R. Khan, N. S. Grewal, C. Zhou, K. Yuan, H.-J. Zhang, Z. Jun, *Results Eng.* **2023**, *20*, 101526.
[195] N. Ashammakhi, A. L. Hernandez, B. D. Unluturk, S. A. Quintero, N. R. de Barros, E. Hoque Apu, A. Bin Shams, S. Ostrovidov, J. Li, C. Contag, *Adv. Funct. Mater.* **2021**, *31*, 2104149.
[196] M. Khatib, O. Zohar, H. Haick, *Adv. Mater.* **2021**, *33*, 2004190.
[197] M. Zhu, J. Liu, L. Gan, M. Long, *Eur. Polym. J.* **2020**, *129*, 109651.
[198] N. Tang, R. Zhang, Y. Zheng, J. Wang, M. Khatib, X. Jiang, C. Zhou, R. Omar, W. Saliba, W. Wu, *Adv. Mater.* **2022**, *34*, 2106842.
[199] D. Han, X. Han, L. Liu, D. Li, Y. Liu, Z. Liu, D. Liu, Y. Chen, K. Zhuo, S. Sang, *ACS Appl. Mater. Interfaces* **2022**, *14*, 13942.
[200] R. K. Mishra, V. Kumar, L. G. Trung, G. J. Choi, J. W. Ryu, S. M. Mane, J. C. Shin, P. Kumar, S. H. Lee, J. S. Gwag, *Sensors* **2022**, *22*, 8609.
[201] S. Saadat Niavol, H. Milani Moghaddam, A. Bagheri Khatibani, S. F. Hashemi Karouei, F. Hermerschmidt, G. Ligorio, E. J. List-Kratochvil, *Appl. Phys. A* **2022**, *128*, 733.
[202] C. Martín, K. Kostarelos, M. Prato, A. Bianco, *Chem. Commun.* **2019**, *55*, 5540.
[203] X. Chen, J.-H. Ahn, *J. Mater. Chem. B* **2020**, *8*, 1082.
[204] S. Wang, X. Yang, L. Zhou, J. Li, H. Chen, *J. Mater. Chem. B* **2020**, *8*, 2974.
[205] K. Hassan, M. J. Nine, T. T. Tung, N. Stanley, P. L. Yap, H. Rastin, L. Yu, D. Losic, *Nanoscale* **2020**, *12*, 19007.
[206] A. Chaves, J. G. Azadani, H. Alsalman, D. Da Costa, R. Frisenda, A. Chaves, S. H. Song, Y. D. Kim, D. He, J. Zhou, *npj 2D Mater. Appl.* **2020**, *4*, 29.
[207] K. Kim, M. Ha, B. Choi, S. H. Joo, H. S. Kang, J. H. Park, B. Gu, C. Park, C. Park, J. Kim, *Nano Energy* **2018**, *48*, 275.
[208] G. E. Bonacchini, C. Bossio, F. Greco, V. Mattoli, Y. H. Kim, G. Lanzani, M. Caironi, *Adv. Mater.* **2018**, *30*, 1706091.
[209] A. Khan, R. Joshi, M. K. Sharma, C.-J. Huang, J.-H. Yu, Y.-L. Wang, Z.-H. Lin, *Nano Trends* **2024**, *6*, 100032.
[210] D. Mandal, S. Banerjee, *Sensors* **2022**, *22*, 820.
[211] E. Di Mauro, D. Rho, C. Santato, *Nat. Commun.* **2021**, *12*, 3167.
[212] A. S. Sharova, F. Melloni, G. Lanzani, C. J. Bettinger, M. Caironi, *Adv. Mater. Technol.* **2021**, *6*, 2000757.
[213] Y. Wu, D. Ye, Y. Shan, S. He, Z. Su, J. Liang, J. Zheng, Z. Yang, H. Yang, W. Xu, *Adv. Mater. Technol.* **2020**, *5*, 2000100.
[214] R. Omar, W. Saliba, M. Khatib, Y. Zheng, C. Pieters, H. Oved, E. Silberman, O. Zohar, Z. Hu, V. Kloper, *ACS Sens.* **2024**, *9*, 126.
[215] K. J. Yu, D. Kuzum, S.-W. Hwang, B. H. Kim, H. Juul, N. H. Kim, S. M. Won, K. Chiang, M. Trumpis, A. G. Richardson, *Nat. Mater.* **2016**, *15*, 782.
[216] N. R. Hosseini, J. S. Lee, *Adv. Funct. Mater.* **2015**, *25*, 5586.
[217] A. S. Inam, M. N. Islam, S. Z. Riam, F. Perez, C. Delhom, N. Abidi, S. Tabassum, *IEEE Sens. Lett.* **2023**, *7*, 1.
[218] A.-M. Zaccarin, G. M. Iyer, R. H. Olsson, K. T. Turner, *IEEE Sens. J.* **2024**, *24*, 7235.
[219] S. C. Teixeira, N. O. Gomes, M. L. Calegaro, S. A. Machado, T. V. de Oliveira, N. d. F. F. Soares, P. A. Raymundo-Pereira, *Biomater. Adv.* **2023**, *155*, 213676.
[220] P. G. Steeneken, E. Kaiser, G. J. Verbiest, M.-C. ten Veldhuis, *Nat. Rev. Methods Primers* **2023**, *3*, 60.
[221] H. Yin, Y. Cao, B. Marelli, X. Zeng, A. J. Mason, C. Cao, *Adv. Mater.* **2021**, *33*, 2007764.
[222] M. Furko, R. Detsch, Z. E. Horváth, K. Balázsi, A. R. Boccaccini, C. Balázsi, *Nanomaterials* **2024**, *14*, 279.
[223] B. Jebasingh, P. Muralkar, S. Nadiger, M. E. N. Balakrishnan, K. Thushara, in *Graphene-Based Nanomaterials*, CRC Press, Boca Raton **2024**.
[224] J. Rao, H. Gao, J. Sun, R. Yu, D. Zhao, Y. Ding, *ACS Biomater. Sci. Eng.* **2024**, *10*, 5454.
[225] B. Peng, H. Xu, F. Song, P. Wen, Y. Tian, Y. Zheng, *J. Mater. Sci. Technol.* **2024**, *182*, 79.
[226] R. Granelli, I. Alessandri, P. Gkoupidenis, I. Vassalini, Z. M. Kovács-Vajna, P. W. Blom, F. Torricelli, *Small* **2022**, *18*, 2108077.
[227] W. B. Han, S. M. Yang, K. Rajaram, S. W. Hwang, *Adv. Sustainable Syst.* **2022**, *6*, 2100075.
[228] C. Becker, B. Bao, D. D. Karnaushenko, V. K. Bandari, B. Rivkin, Z. Li, M. Faghih, D. Karnaushenko, O. G. Schmidt, *Nat. Commun.* **2022**, *13*, 2121.
[229] W. Xu, T. Li, Z. Qin, Q. Huang, H. Gao, K. Kang, J. Park, M. J. Buehler, J. B. Khurgin, D. H. Gracias, *Nano Lett.* **2019**, *19*, 7941.
[230] M. Zhang, J. J. Sun, M. Khatib, Z.-Y. Lin, Z.-H. Chen, W. Saliba, A. l. Gharra, Y. D. Horev, V. Kloper, Y. Milyutin, *Nat. Commun.* **2019**, *10*, 1120.
[231] O. Dadras-Toussi, M. Khorrami, A. S. C. Louis Sam Titus, S. Majd, C. Mohan, M. R. Abidian, *Adv. Mater.* **2022**, *34*, 2200512.
[232] C.-Y. You, B.-F. Hu, B.-R. Xu, Z.-Y. Zhang, B.-M. Wu, G.-S. Huang, E.-M. Song, Y.-F. Mei, *Chip* **2022**, *1*, 100034.
[233] J. Tang, F. Wei, *Macromol. Mater. Eng.* **2022**, *307*, 2100671.
[234] L. Merces, L. M. M. Ferro, A. Thomas, D. D. Karnaushenko, Y. Luo, A. I. Egunov, W. Zhang, V. K. Bandari, Y. Lee, J. S. McCaskill, *Adv. Mater.* **2024**, *36*, 2313327.
[235] S. Kim, J. Seo, J. Choi, H. Yoo, *Nano-Micro Lett.* **2022**, *14*, 201.
[236] C. Zhang, C. Liu, B. Li, C. Ma, X. Li, S. Niu, H. Song, J. Fan, T. Zhang, Z. Han, *Nano Lett.* **2024**, *24*, 3186.
[237] Y. Song, Q. Jiang, D. Liu, *Small* **2024**, *20*, 2305973.
[238] D. Jayachandran, R. Pendurthi, M. U. K. Sadaf, N. U. Sakib, A. Pannone, C. Chen, Y. Han, N. Trainor, S. Kumari, T. V. Mc Knight, *Nature* **2024**, *625*, 276.
[239] N. C. de Moraes, E. N. T. da Silva, J. M. Petroni, V. S. Ferreira, B. G. Lucca, *Electrophoresis* **2020**, *41*, 278.
[240] J. M. Mohan, K. Amreen, A. Javed, S. K. Dubey, S. Goel, *Curr. Opin. Electrochem.* **2022**, *33*, 100930.

[241] E. M. Materon, A. Wong, L. M. Gomes, G. Ibanez-Redin, N. Joshi, O. N. Oliveira, R. C. Faria, *J. Mater. Chem. C* **2021**, *9*, 5633.
[242] E. K. Kumar, S. S. Patel, S. K. Panda, B. K. Patle, E. Makki, J. Giri, *Mech. Adv. Mater. Struct.* **2024**, *31*, 11450.
[243] P. Velvaluri, A. Soor, P. Plucinsky, R. L. de Miranda, R. D. James, E. Quandt, *Sci. Rep.* **2021**, *11*, 10988.
[244] H. T. Lee, F. Seichepine, G. Z. Yang, *Adv. Funct. Mater.* **2020**, *30*, 2002510.
[245] Y. Zeng, R. Ananth, T. J. Dill, A. Rodarte, M. J. Rozin, N. Bradshaw, E. R. Brown, A. R. Tao, *ACS Appl. Mater. Interfaces* **2022**, *14*, 32598.
[246] S. C. Denson, C. J. Pommier, M. B. Denton, *J. Chem. Educ.* **2007**, *84*, 67.
[247] A. Ren, H. Wang, W. Zhang, J. Wu, Z. Wang, R. V. Penty, I. H. White, *Nat. Electron.* **2021**, *4*, 559.
[248] M. Song, P. Jayathurathnage, E. Zanganeh, M. Krasikova, P. Smirnov, P. Belov, P. Kapitanova, C. Simovski, S. Tretyakov, A. Krasnok, *Nat. Electron.* **2021**, *4*, 707.
[249] N. T. Garland, J. W. Song, T. Ma, Y. J. Kim, A. Vázquez-Guardado, A. B. Hashkavayi, S. K. Ganeshan, N. Sharma, H. Ryu, M. K. Lee, *Adv. Healthcare Mater.* **2023**, *12*, 2301280.
[250] H. S. Kim, S. Hur, D.-G. Lee, J. Shin, H. Qiao, S. Mun, H. Lee, W. Moon, Y. Kim, J. M. Baik, *Energy Environ. Sci.* **2022**, *15*, 1243.
[251] S. Han, J. Kim, S. M. Won, Y. Ma, D. Kang, Z. Xie, K.-T. Lee, H. U. Chung, A. Banks, S. Min, *Sci. Transl. Med.* **2018**, *10*, aan4950.
[252] Y. S. Oh, J.-H. Kim, Z. Xie, S. Cho, H. Han, S. W. Jeon, M. Park, M. Namkoong, R. Avila, Z. Song, *Nat. Commun.* **2021**, *12*, 5008.
[253] S. M. Won, L. Cai, P. Gutruf, J. A. Rogers, *Nat. Biomed. Eng.* **2023**, *7*, 405.
[254] J. Kim, P. Gutruf, A. M. Chiarelli, S. Y. Heo, K. Cho, Z. Xie, A. Banks, S. Han, K. I. Jang, J. W. Lee, *Adv. Funct. Mater.* **2017**, *27*, 1604373.
[255] K. Kwon, J. U. Kim, S. M. Won, J. Zhao, R. Avila, H. Wang, K. S. Chun, H. Jang, K. H. Lee, J.-H. Kim, *Nat. Biomed. Eng.* **2023**, *7*, 1215.
[256] Y. Song, J. Min, Y. Yu, H. Wang, Y. Yang, H. Zhang, W. Gao, *Sci. Adv.* **2020**, *6*, aay9842.
[257] Y. Wang, Z. Chen, T. Huang, J. Ren, J. Zhang, Z. Yuan, G. Shen, *Nano Energy* **2024**, *133*, 110492.
[258] Y. C. Lee, V. A. Hoang, *Sensors* **2023**, *23*, 558.
[259] L. Yang, B. Feng, Y. Zhang, X. Li, L. Zhang, X. Chen, J. Nie, H. Wen, J. Tian, J. Jian, *IEEE Trans. Biomed. Circ. Syst.* **2022**, *16*, 1337.
[260] G. Moloudian, M. Hosseinifard, S. Kumar, R. B. Simorangkir, J. L. Buckley, C. Song, G. Fantoni, B. O'Flynn, *IEEE Sens. J.* **2024**, *24*, 5732.
[261] P. Oppermann, B.-C. Renner, *Sensors* **2023**, *23*, 3617.
[262] H. Fu, J. Rao, M. S. Harb, S. Theodossiades, *Ultrasonics* **2021**, *114*, 106395.
[263] B. Luo, P. Velvaluri, Y. Liu, N.-X. Sun, *Micromachines* **2024**, *15*, 1471.
[264] Y. Xue, Y. Liu, C. Zhou, X. Y. Zhang, *Ceram. Int.* **2024**, *50*, 52051.
[265] J. Ji, H. Heo, J. Zhong, M. Oudich, Y. Jing, *Phys. Rev. Appl.* **2024**, *21*, 014059.
[266] A. Allam, H. Patel, C. Sugino, C. S. John, J. Steinfeldt, C. Reinke, A. Erturk, I. El-Kady, *Ultrasonics* **2024**, *141*, 107339.
[267] W. Zhu, X. Yang, T. Wu, Y. Qiu, *IEEE Sens. J.* **2024**, *24*, 17116.
[268] A. Baburaj, S. Banerjee, A. K. Aliyana, C. Shee, M. Banakar, S. Bairagi, S. N. Kumar, S. W. Ali, *Nano Energy* **2024**, *127*, 109785.
[269] C. Jiang, X. Li, S. W. M. Lian, Y. Ying, J. S. Ho, J. Ping, *ACS Nano* **2021**, *15*, 9328.
[270] E. Istif, H. Mirzajani, Ç. Dağ, F. Mirlou, E. Y. Ozuaciksoz, C. Cakır, H. C. Koydemir, I. Yilgor, E. Yilgor, L. Beker, *Nature Food* **2023**, *4*, 427.
[271] T. A. Schmedake, F. Cunin, J. R. Link, M. J. Sailor, *Adv. Mater.* **2002**, *14*, 1270.
[272] S. Olenik, H. S. Lee, F. Güder, *Nat. Rev. Mater.* **2021**, *6*, 286.
[273] X. Sun, C. Zhao, H. Li, H. Yu, J. Zhang, H. Qiu, J. Liang, J. Wu, M. Su, Y. Shi, *Micromachines* **2022**, *13*, 784.
[274] H. El Matbouly, F. Nikbakhtnasrabadi, R. Dahiya, in *Biosensing and Micro-Nano Devices: Design Aspects and Implementation in Food Industries*, Springer, Berlin **2022**, 219.
[275] H. Haas, J. Elmirghani, I. White, *Royal Soc. Publ.* **2020**, *378*, 20200051.
[276] R. Jiang, C. Sun, L. Zhang, X. Tang, H. Wang, A. Zhang, *IEEE Access* **2020**, *8*, 20363.
[277] I. Tavakkolnia, L. K. Jagadamma, R. Bian, P. P. Manousiadis, S. Videv, G. A. Turnbull, I. D. Samuel, H. Haas, *Light: Sci. Appl.* **2021**, *10*, 41.
[278] I. Mondal, R. Attri, T. S. Rao, B. Yadav, G. U. Kulkarni, *Appl. Phys. Rev.* **2024**, *11*, 041304.
[279] S. K. Mehta, I. Mondal, B. Yadav, G. U. Kulkarni, *Nanoscale* **2024**, *16*, 18365.
[280] B. Yadav, I. Mondal, B. Bannur, G. U. Kulkarni, *Nanotechnology* **2023**, *35*, 015205.
[281] T. Sangeeta, J. Deny, 2022 IEEE International Conference on Nanoelectronics, Nanophotonics, Nanomaterials, Nanobioscience & Nanotechnology (5NANO),IEEE, Piscataway, NJ **2022**.
[282] R. Krishnamurthi, A. Kumar, D. Gopinathan, A. Nayyar, B. Qureshi, *Sensors* **2020**, *20*, 6076.
[283] M. A. I. Mozumder, M. M. Sheeraz, A. Athar, S. Aich, H.-C. Kim, *2022 24th International Conference on Advanced Communication Technology (ICACT)*, PyeongChang Kwangwoon_Do, Republic of Korea **2022**, pp. 256–261. https://doi.org/10.23919/ICACT53585.2022.9728808.
[284] C. Pan, G. Zhou, K. Zhi, S. Hong, T. Wu, Y. Pan, H. Ren, M. Di Renzo, A. L. Swindlehurst, R. Zhang, *IEEE J. Sel. Top. Signal Process.* **2022**, *16*, 883.
[285] X. Wu, D. Hong, J. Chanussot, *IEEE Trans. Geosci. Remote Sens.* **2021**, *60*, 1.
[286] A. M. Ikotun, A. E. Ezugwu, L. Abualigah, B. Abuhaija, J. Heming, *Inf. Sci.* **2023**, *622*, 178.
[287] T.-N. Tran, T.-L. Nguyen, V. T. Hoang, M. Voznak, *Sensors* **2023**, *23*, 2345.
[288] D. K. Kotary, S. J. Nanda, *Wirel. Pers. Commun.* **2021**, *121*, 2545.
[289] S. Regilan, L. Hema, *Int. J. Comput. Appl.* **2024**, *46*, 21.
[290] Y. Oh, C. Lim, J. Lee, S. Kim, S. Kim, *Ann. Oper. Res.* **2024**, *339*, 261.
[291] J. Chu, W. Li, X. Yang, Y. Wu, D. Wang, A. Yang, H. Yuan, X. Wang, Y. Li, M. Rong, *Sens. Actuators, B* **2021**, *329*, 129090.
[292] Y. M. Idir, O. Orfila, V. Judalet, B. Sagot, P. Chatellier, *Sensors* **2021**, *21*, 4717.
[293] T.-H. Chen, Y.-C. Hsu, Y.-T. Zeng, S.-C. C. Lung, H.-J. Su, H. J. Chao, C.-D. Wu, *Environ. Pollut.* **2020**, *259*, 113875.
[294] A. Affholder, F. Guyot, B. Sauterey, R. Ferrière, S. Mazevet, *Nat. Astron.* **2021**, *5*, 805.
[295] J. P. Bharadiya, *Int. J. Innov. Sci. Res. Technol.* **2023**, *8*, 2033.
[296] K. Römer, *Tracking Real-World Phenomena with Smart Dust, Wireless Sensor Networks, EWSN*, vol. *2920*, (Eds: H. Karl, A. Wolisz, A. Willig), Springer, Berlin, Heidelberg **2004**, https://doi.org/10.1007/978-3-540-24606-0_3.
[297] C.-Y. Liu, C.-K. Huang, Y.-Y. Huang, K.-C. Chang, K.-L. Yu, C.-H. Chiang, C.-G. Wu, S.-C. Lee, W.-Y. Yen, J.-K. Sheu, *Appl. Energy* **2022**, *306*, 117970.
[298] M. P. Nemitz, R. J. Marcotte, M. E. Sayed, G. Ferrer, A. O. Hero, E. Olson, A. A. Stokes, *Front. Robot. AI* **2018**, *5*, 55.
[299] K. Kalantar-Zadeh, *Nat. Nanotechnol.* **2018**, *13*, 770.
[300] D. Spirjakin, A. M. Baranov, V. Sleptsov, *2015 Federated Conference on Computer Science and Information Systems (FedCSIS)*, Lodz, Poland **2015**, pp. 1279–1283, https://doi.org/10.15439/2015F172.
[301] J. Entrialgo, M. S. Obaidat, *Perv. Comput. Netw.* **2011**, 203, https://doi.org/10.1002/9781119970422.ch13.
[302] G. D. Bachand, H. Hess, B. Ratna, P. Satir, V. Vogel, *Lab Chip* **2009**, *9*, 1661.
[303] S. R. Mousavi, M. Rezaei, *J. Appl. Environ. Biol. Sci.* **2011**, *1*, 414.

[304] H. Chen, R. Yada, *Trends Food Sci. Technol.* **2011**, *22*, 585.
[305] A. Tittl, X. Yin, H. Giessen, X.-D. Tian, Z.-Q. Tian, C. Kremers, D. N. Chigrin, N. Liu, *Nano Lett.* **2013**, *13*, 1816.
[306] M. Mimee, P. Nadeau, A. Hayward, S. Carim, S. Flanagan, L. Jerger, J. Collins, S. McDonnell, R. Swartwout, R. J. Citorik, *Science* **2018**, *360*, 915.
[307] Y. Lee, V. K. Bandari, Z. Li, M. Medina-Sánchez, M. F. Maitz, D. Karnaushenko, M. V. Tsurkan, D. D. Karnaushenko, O. G. Schmidt, *Nat. Commun.* **2021**, *12*, 4967.
[308] T. Alahmad, M. Neményi, A. Nyéki, *Agronomy* **2023**, *13*, 2603.
[309] R. Rayhana, G. G. Xiao, Z. Liu, *IEEE Trans. Instrum. Meas.* **2021**, *70*, 1.
[310] G. Rameshaiah, J. Pallavi, S. Shabnam, *Int. J. Eng. Res. Gen. Sci.* **2015**, *3*, 314.
[311] S. Habib, D. J. Zukor, S. D. Ambrose, *Spaceborne Sensors* **2004**, *5418*, 1.
[312] S. Rani, R. Maheswar, G. Kanagachidambaresan, P. Jayarajan, *Integration of WSN and IoT for smart cities*, Springer, Berlin **2020**.
[313] M. Shaik, N. Shaik, W. Ullah, *Int. Res. J. Eng. Technol.* **2016**, *3*, 910.
[314] J. M. Kahn, R. H. Katz, K. S. Pister, *J. Commun. Networks* **2000**, *2*, 188.
[315] H. Saleem, L. Shah, A. Rehman, H. Saif, R. Ramzan, *2023 IEEE 36th International System-on-Chip Conference (SOCC)*, Santa Clara, CA, USA, **2023**, pp. 1–5, https://doi.org/10.1109/SOCC58585.2023.10256939.
[316] S. D. Bawankar, S. B. Bhople, V. D. Jaiswal, *Network* **2012**, *2*, 11.
[317] D. Seo, J. M. Carmena, J. M. Rabaey, E. Alon, M. M. Maharbiz, arXiv preprint arXiv:1307.2196 **2013**.
[318] D. Seo, R. M. Neely, K. Shen, U. Singhal, E. Alon, J. M. Rabaey, J. M. Carmena, M. M. Maharbiz, *Neuron* **2016**, *91*, 529.
[319] R. M. Neely, D. K. Piech, S. R. Santacruz, M. M. Maharbiz, J. M. Carmena, *Curr. Opin. Neurobiol.* **2018**, *50*, 64.
[320] J. Snoeijs, P. Georgiou, S. Carrara, 2017 IEEE Biomedical Circuits and Systems Conference (BioCAS) IEEE, Piscataway, NJ **2017**.
[321] S. Carrara, P. Georgiou, arXiv preprint arXiv:1805.05840 **2018**.
[322] A. Joshuva, B. Lingampalli, P. K. Lingampally, M. Arjun, V. Shridhar, *Procedia Comput. Sci.* **2019**, *165*, 97.
[323] D. Seo, J. M. Carmena, J. M. Rabaey, M. M. Maharbiz, E. Alon, *J. Neurosci. Methods* **2015**, *244*, 114.
[324] M. M. Maharbiz, *Fut. Brain: Essays World's Lead. Neurosci.* **2024**, *146*, 243.
[325] M. Yogeshwari, A. Prasanth, *Comput. Vis. Smart Agri. Crop Manag.* **2025**, 123, https://doi.org/10.1002/9781394186686.ch6.
[326] S. Gopalakrishnan, J. Waimin, A. Zareei, S. Sedaghat, N. Raghunathan, A. Shakouri, R. Rahimi, *Sci. Rep.* **2022**, *12*, 8011.
[327] T. Kasuga, A. Mizui, H. Koga, M. Nogi, *Adv. Sustainable Syst.* **2024**, *8*, 2300314.
[328] S. Werner, A. Polle, N. Brinkmann, *Appl. Microbiol. Biotechnol.* **2016**, *100*, 8651.
[329] K. Moisan, V. Cordovez, E. M. van de Zande, J. M. Raaijmakers, M. Dicke, D. Lucas-Barbosa, *Oecologia* **2019**, *190*, 589.
[330] M. S. Kabir, S. Islam, M. Ali, M. Chowdhury, S.-O. Chung, D.-H. Noh, *Precis Agric* **2022**, *4*, 12972.
[331] K. M. Hosny, W. M. El-Hady, F. M. Samy, *Inf. Process. Agric.* **2024**, *12*, 91.
[332] C. Prakash, L. P. Singh, A. Gupta, S. K. Lohan, *Sens. Actuators, A* **2023**, 114605.
[333] W.-T. Sung, I. G. T. Isa, S.-J. Hsiao, *Sens. Mater.* **2024**, 36.
[334] S. C. Mohan, S. Arulselvi, *IOSR-JECE* **2013**, *5*, 1.
[335] A. E. Kovalev, M. G. Bray, E. A. Hernandez-Pagan, T. S. Mayer, D. H. Werner, In *Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) Sensing X*, Vol. *7304*, SPIE, pp. 319–326. SPIE .
[336] J. Cechak, *Photonics Appl. Astron., Commun., Indus., High-Energy Phys. Exper.* **2007**, *6937*, 1100.

Indrajit Mondal is a Postdoctoral Fellow at Technion-IIT, Israel, developing miniaturized sensors for nature-inspired molecular communication, wireless toxicity detection, and non-invasive biomedical diagnostics. He earned his Ph.D. in 2021 from CeNS, India, researching nanoscience applications in optoelectronic devices and wearable sensors. He then joined JNCASR, India, as a Postdoctoral Fellow, focusing on self-assembled nano-architectures for neuromorphic in-memory computing. His research interests span nanotechnology, bioinspired electronics, and next-generation sensors.

Hossam Haick, professor at the Technion, is an expert in the field of nanotechnology and smart sensors. He is the founder and leader of several European consortiums for the development of advanced generations of nanosensors for the fourth industrial revolution and disease diagnosis. His areas of research expertise encompass nanomaterial-based chemical sensors that are flexible, electronic skin, nanoarray devices that can screen, diagnose and monitor diseases, breath analysis, volatile biomarkers, and molecular electronic devices.